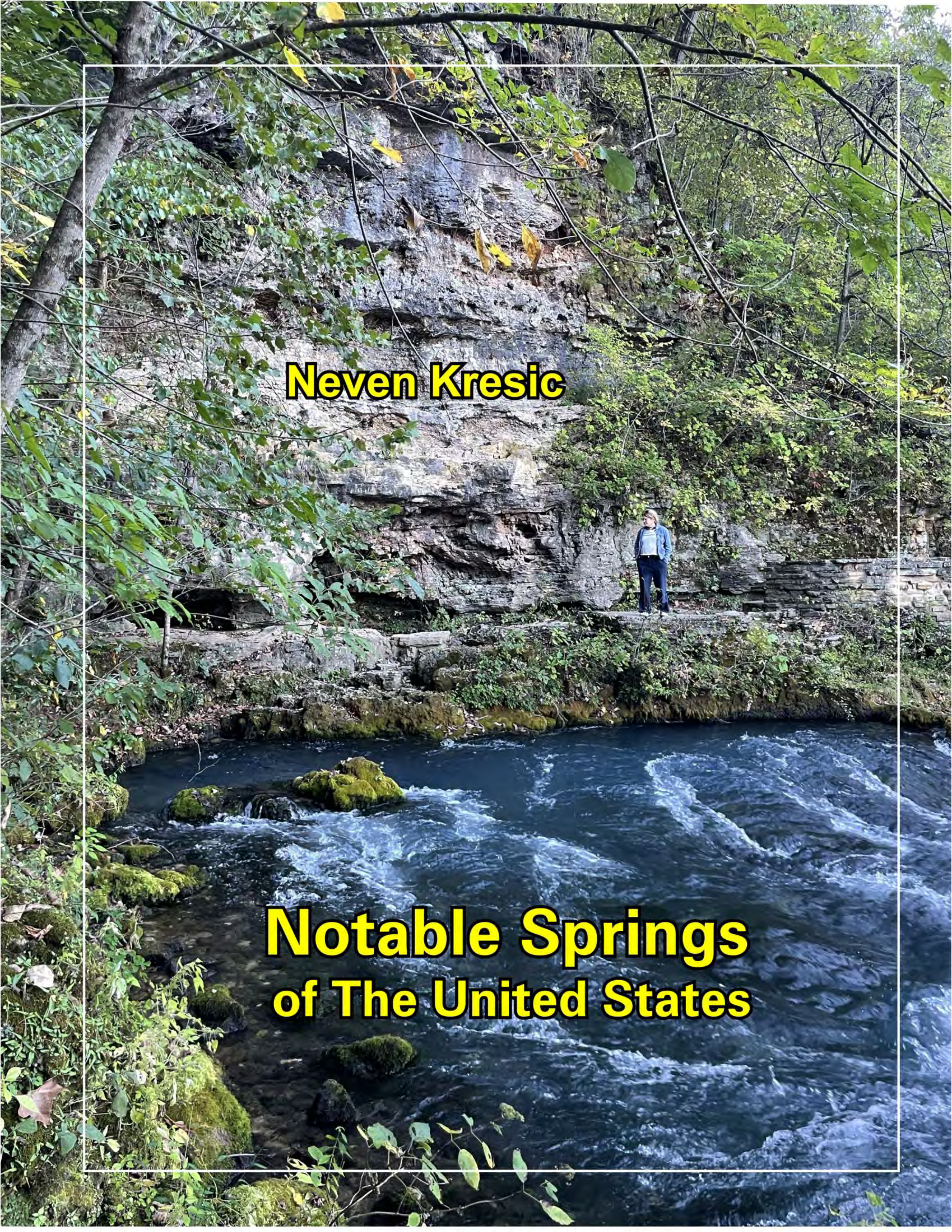

Neven Kresic

Notable Springs of The United States

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BLUE RIDGE Press

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Front cover: Big Spring in Missouri, the largest individual spring in the United States.
Back cover photographs, from top left to right: Big Springs on McCloud River, California (photo copyright Bill Tuthill, all rights reserved); Peacock Springs, Florida (photo copyright John Moran; all rights reserved); Box Canyon Spring, Idaho; Blue Spring, Shannon County, Missouri; Alley Spring, Missouri; Gilchrist Blue Spring, Florida. Descriptions for all springs are provided in the text.
Cover design: Marin Kresic

Foreword

This book is a natural outgrowth of a project by Karst Commission (KC) of the International Association of Hydrogeologists (IAH) called MIKAS ("Most Important Karst Aquifer Springs" in the world) and initiated by Dr. Zoran Stevanovic, Co-chair of KC at the time. Zoran asked me if I would be willing to help coordinate the effort for North America and I had to agree because it was more of a demand than a request: we together edited the book "Groundwater Hydrology of Springs" for Elsevier, and it was me who dragged Zoran into it since he was quite busy at the time, teaching several hydrogeology courses at the University of Belgrade and consulting internationally; this was his payback. However, two other events made me embark on writing yet another book: The KC committee was evaluating many nominations for the MIKAS list from around the world and my proposal to also include springs issuing from "pseudokarst" (more on this term is given in Chapter 4 on springs in East Snake River Plain Aquifer, Idaho) was unanimously rejected. I was very disappointed because some of the most spectacular and largest springs in the United States such as Thousand Springs in Idaho are in pseudokarst, but I had to agree with the democratic process. Secondly, Professor Dr. John Van Brahana of University of Arkansas in Fayetteville submitted proposals for a dozen or so outstanding springs in the Ozarks of Missouri and Arkansas.

I happened to be staying in Conway, Arkansas on unrelated business when I received the materials on the Ozarks springs from Van. I decided to visit the springs myself because they all looked quite spectacular. I knew of the large springs in Missouri ever since Gerald Feder, one of the authors of a classic book entitled "Springs of Missouri" (Vineyard and Feder, 1974) personally gave me an autographed copy when we were working together at the United States Geological Survey headquarters in Reston, Virginia in 1991-92. However, nothing prepared me for what I saw with my own eyes—I was simply blown away. Then I took my family to see the springs, and it all became a family affair of sorts, and very personal. As to the Thousand Springs and other large, beautiful springs issuing from pseudokarst and other rocks—well, they are now in this book, together with many other springs in the United States that did not make to the list of "most important" in the world, not because they did not deserve it, but because the number of such springs was limited to 200 worldwide, for one reason or another.

Going back to the fact that this book became very personal to me: I was not quite prepared for what I learned while gathering the materials, searching the web, and reaching out to various people and institutions asking for information. Over the last 33 years I spent working in the United States, I first briefly taught hydrogeology at TCU in Ft. Worth, Texas and then travelled extensively around the country, working as a consultant on various groundwater-related engineering projects. This provided me with the opportunity to visit many springs, big and small. Along the way, and very quickly, I learned that groundwaters of our nation, and many springs by extension, are threatened or extensively damaged, sometimes beyond repair for all practical purposes. I featured a few drastic examples in some of my previous books, such as the sad destiny of Kissingen Spring in Florida and Comanche Springs in Texas which flow no more.

However, I was deeply disturbed to learn there are many springs facing the possibility of a similar destiny, including some of the most famous and cherished, and that our actions or inactions are destroying them and the environments that depend on them as we speak. In the end, it is a personal decision whether to accept what is happening or to try to fight against it.

As one of my famous compatriots, Nikola Tesla, said long time ago: "*Of all frictional resistances, the one that most retards human movement is ignorance, what Buddha called the greatest evil in the world. The friction which results from ignorance can be reduced only by the spread of knowledge and the unification of the heterogeneous elements of humanity. No effort could be better spent*."

This book is a small personal contribution to spreading the knowledge about our nation's springs.

Personal efforts toward the larger good are inspiring to me. Here are two examples, one from Florida, and one from Missouri (Greer Spring), the states with some of the most mesmerizing springs of them all, anywhere in the entire world.

> *"The Springs Eternal Project is an evolving series of creative partnerships initiated by Lesley Gamble, John Moran and Rick Kilby in collaboration with a diverse community of springs scientists, researchers, artists, and advocates. Our goal is to inspire Floridians to value our springs and the diverse ecosystems they support as fundamental to the health and wellbeing of us all, human, and non-human; to redefine these relationships in socially just and ecologically sustainable terms; and to work collaboratively to conserve, restore and protect Florida's precious waters for our children and theirs, for generations to come.*
>
> *The Springs Eternal Project is a celebration of the springs we were given, a meditation on the springs we could lose, and an invitation to the people of Florida to fall in love with our springs all over again, mindful that the choices we make today foretell the Florida of tomorrow."* http://springseternalproject.org/
>
> *"In the days when water power was the wave of the future, engineers dreamed of taming the wild Greer Spring branch, with a flow said to be " ... two hundred and eighty yards per minute, With no appreciable variation," by building a dam across the precipitous gorge carved by the spring branch. However, Miss Owen showed foresight far in advance of her time when she said, "The high walls of Greer Spring gorge will, of course, far more than double the value it would otherwise possess, when it becomes desirable to control and turn to practical account the power now going so cheerily to waste, but the artistic loss will be proportionately severe." Fortunately for this generation and others to come, those who have owned the spring since it was named for Captain Greer nearly a hundred years ago, appreciated its beauty and no dam was ever built in the gorge. Greer Spring is as wild and beautiful today as it was in the 1880's."* Vineyard and Feder, 1974.

Arguably, the most important decision I made about this book is to make it widely available and free of charge, thanks to understanding and support of Blue Ridge Press. The pdf file of the book is free for downloading, posting, and re-posting on any non-commercial, non-profit sites including all educational and academic institutions for use by their students and others. The printed, full-color, full-resolution version is available on Amazon, at nominal cost, for those that still like "coffee table books".

I am indebted to many institutions for various materials and photographs without which this book would not be possible: United States Geological Survey, Alabama Geological Survey, Florida Geological Survey, The Howard T. Odum Florida Springs Institute, Florida Water Management Districts, Missouri Geological Survey, Missouri Department of Natural Resources, Missouri Department of Conservation, Arkansas Geological Survey, Utah Geological Survey, State Parks of various states, National Park Service, USDA Forest Service, Grand Canyon Trust, Karst Waters Institute, The Ozark Cave Diving Alliance, The Havasu Tribe, Karst Underwater Research (KUR), Idaho Conservation League, Winchester-Frederick County Historical Society, Global Underwater Explorers (GUI), ADM Exploration Foundation, California Trout, Nature Conservancy, Utah Geological Association, Utah Water Research Laboratory, Virginia Department of Environmental Quality, West Virginia Geological Survey, and others.

Many colleagues, friends, nature lovers, and spring enthusiasts provided materials and amazing photographs and contributed to this book: John Moran, Jennifer Idol, Michael Wier, Gregg Eckhardt, John Van Brahana, Geary Schindel, Frank Moore, David Price, Phil Lucas, Bill Jones, Art and Peggy Palmer, Jack Hess, Mike Young and the KISS Dive Team, Todd Kinckaid, David Rhea, Andrew Pitkin, Thomas Scott, Harley Means, Ryan Means, Josh Johnson, David Kreamer, Gordon Grant, Bill Tuthill, Chris Groves, Marina Marcelli, Lawrence Spangler, Gheorghe Ponta, Michael Smith, Gregory Guthrie, Hyrum Tennant, Bethany Neilson, Alan Fryar, Katarina Kosič Ficco, Mike Ficco, John Tudek, Ryan Mauer, Joel Maynard, Kathryn Phillippe, Nenad Maric, Amy Hourigan, and others.

The Author

About The Author

Neven Kresic, Ph.D., P.G. is an independent groundwater consultant with more than 40 years of experience focused on groundwater and surface water consulting, research, and teaching. He specializes in characterizing and analyzing complex groundwater systems for water supply and groundwater remediation projects and is an expert in the application of numerical models for simulating groundwater flow, and contaminant fate and transport in groundwater. Over the course of his career, Dr. Kresic served in lead technical roles at major national and international engineering and environmental consulting companies based in the United States.

Dr. Kresic has worked on numerous projects for a variety of U.S. and international clients including federal, state, and local agencies; industries such as water, transportation, and power utilities; and oil, petrochemical, chemical, mining, and construction companies. He was Senior Fulbright Scholar at the United States Geological Survey in Reston, Virginia, and the George Washington University, Washington, D.C. where he conducted novel research on characterizing and modeling groundwater flow and contaminant fate and transport in fractured rock and karst aquifers. Prior to coming to the United States in 1991, Dr. Kresic was professor of groundwater dynamics at the University of Belgrade, former Yugoslavia. He taught academic courses and professional workshops in hydrogeology, groundwater resources, groundwater modeling, and groundwater remediation at universities, government agencies, and conferences around the World. Dr. Kresic authored and co-authored numerous papers and eight books on the topic of groundwater. He is former Co-chair of the Karst Commission of the International Association of Hydrogeologists, past Vice President for International Affairs of the American Institute of Hydrology, was committee member of the Groundwater Management and Remediation Specialty Group of the International Water Association, and currently serves on the Board of Directors, Karst Waters Institute (KWI).

This book is dedicated to all those
who work hard to protect Springs.

The author is grateful to the following organizations for hosting the electronic (pdf) version of *Notable Springs of The United States* on their web sites for free download.

IGRAC, the International Groundwater Resources Assessment Centre, is a research and data centre dedicated to providing data and information to enhance knowledge and wisdom on groundwater, and to support decision-making on global, regional or national levels. This data and information cover both quantity and quality, and is the result of both assessment and monitoring. Dealing with data provided by governments and groundwater institutions, we highly value transparency, accountability, independency and integrity. We also connect the scientific, hydrogeology sector on one hand and the water governance and diplomacy world on the other hand. Since our ultimate goal is a world where groundwater is both sustainably and equitably managed, we work on an open access (and easy access) basis. IGRAC is financially supported by the Dutch government and programmatically supported by UNESCO-IHP and WMO. (https://www.un-igrac.org/downloads)

The National Ground Water Association is a not-for-profit professional society and trade association for the global groundwater industry. Our members around the world include leading public and private sector groundwater scientists, engineers, water well system professionals, manufacturers, and suppliers of groundwater-related products and services. The Association's vision is to be the leading groundwater association advocating for responsible development, management, and use of water. Visit us at https://www.ngwa.org/ (https://my.ngwa.org/nc__Store)

The International Association of Hydrogeologists (IAH/AIH) is a scientific and educational charitable organization for scientists, engineers, water managers and other professionals working in the fields of groundwater resource planning, management and protection. Founded in 1956, it has grown to a world-wide membership of more than 4000 individuals. IAH publishes two book series and a scientific journal, all containing essential material for individuals undertaking groundwater-related research, work and study. Find out more at Publications - IAH - The International Association of Hydrogeologists.

HydroGeoCenter specializes in providing training and expertise in hydrogeology, groundwater modeling, and groundwater remediation for industry, regulatory agencies, and academia. With our video courses, online and on-demand training, and consulting services, you can learn directly from the experts and take your skills to the next level. Covering an extensive range of topics, with solutions to real-life problems including case studies, we can help you with consulting and groundwater modeling for the following: water supply; sustainable agriculture; contaminant fate and transport; groundwater remediation; hydraulic control in mining and construction. We offer on-demand training for environmental consulting and engineering companies, industry professionals, and regulatory agencies. This personalized approach enables you to find optimal solution for your unique situation, tailored to your specific needs. Visit us at www.hydrogeocenter.com

The Karst Waters Institute (KWI) is a nonprofit institution whose mission is to improve the fundamental understanding of karst water systems for professionals and the public. KWI seeks to advance karst science through the engagement of professionals in small conferences and workshops, to increase the recognition and publication of karst science, to foster the development of karst professionals, and to communicate and disseminate information to the public. KWI supports these activities by acting as a coordinating agency for funding and personnel. The volunteers constituting the Board of Directors make an annual presentation of a Karst Award to an outstanding member of the cave and karst field, oversee an annual award of a graduate-student scholarship, and have convened and produced numerous conferences and special publications on various karst topics including geology, hydrology, biology, and water resources. https://karstwaters.org/

The aim of the MIKAS (Most Important Karst Aquifer Springs) project is to create the first complete list of the most important karst springs at the global and national levels. This project by the Karst Commission of the International Association of Hydrogeologists (IAH) is overseen by the Advisory Board and executed by numerous national experts. Please visit us at https://mikasproject.org/

CONTENTS

Chapter 1 Introduction

Springs are locations at the land surface where groundwater discharges from aquifers (water-bearing geologic units) and becomes visible. There are many different types of springs, but they all have two things in common: (1) they are a window into the health of the groundwater that feeds them, and (2) they sustain the biota and the environment that depend on them, whatever their size may be. Unfortunately, just like our environment, springs are under constant threat from a variety of anthropogenic influences. In many cases, the quality, and the amount of water they provide have been seriously impacted, sometimes to the point of no return, as illustrated further in this chapter and throughout the book.

Examples of catastrophic consequences of indiscriminate groundwater pumping on springs are numerous, both in the United States and around the world. One such example is Comanche Springs in Fort Stockton, Pecos County, Texas, described by Gunnar Brune in his seminal publication *Major and Historical Springs of Texas* (Texas Water Development Board Report 189, Austin, TX, 1975): "*These artesian springs, issuing from a Comanchean limestone groundwater reservoir, formerly flowed as much as 66 ft^3/s, and served the Comanche and other Indians for uncounted hundreds of years. From 1875 on the springs were the basis for an irrigation district which supplied water to 6,200 acres of cropland. Heavy pumping of the aquifer lowered the water table so that the spring discharge began to fall off in May 1947. The irrigation district sought an injunction in 1954 to restrain pumping which interfered with the normal flow of Comanche Springs. The injunction was denied by the courts, and the springs ceased to flow in March 1961*." (See Figure 1.1).

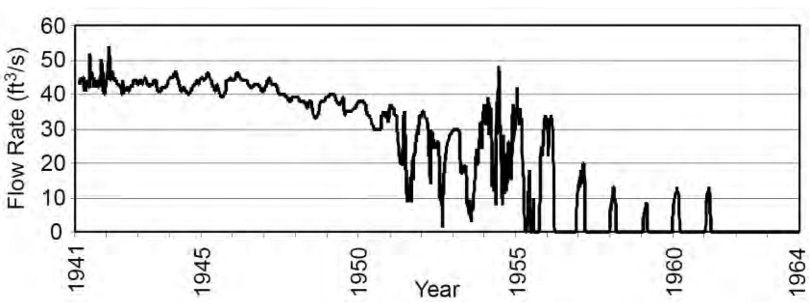

Figure 1.1 *Top*: Mean daily discharge hydrograph of Comanche Springs recorded at United States Geological Survey (USGS) USGS gaging station 08444500 Comanche Springs at Ft Stockton, TX; available at https://waterdata.usgs.gov/. *Bottom*: Aerial view of Comanche Springs pool in 1938, at the time a popular tourist destination in Fort Stockton, Texas. The springs ceased to flow due to excessive groundwater pumping for irrigation. Photo courtesy of Fort Stockton Historical Society.

The disappearance of springs due to large-scale groundwater withdrawals from aquifers is not unique to arid or semi-arid regions with low rainfall and low natural aquifer recharge such as the case with Comanche Springs. Figure 1.2 shows recorded discharge rate of Kissengen Spring in Florida. This historic large spring, located near the city of Bartow in Polk County, served as a popular recreational area for decades and had an average flow of about 29 ft^3/s (19 million gallons per day, MGD). Kissengen Spring was included in the anthological publication by Oscar Meinzer of the USGS titled *Large Spring in The United States*, published in 1927, as one of the largest in Florida (table on page 11). The cessation of flow, both at Kissengen Spring and at many minor springs in the upper Peace River basin, was related to the regional lowering of the potentiometric surfaces of the intermediate aquifer system and the Upper Floridan aquifer from 1937 to 1950 for as much as 60 feet, mainly due to phosphate mining (Peek, 1951; Stewart, 1966; Lewelling et al., 1998). Permanent cessation of the spring flow occurred in April 1960. The spring never flowed again and today only a small mud pot marks the location where, for many years, it provided joy to countless visitors.

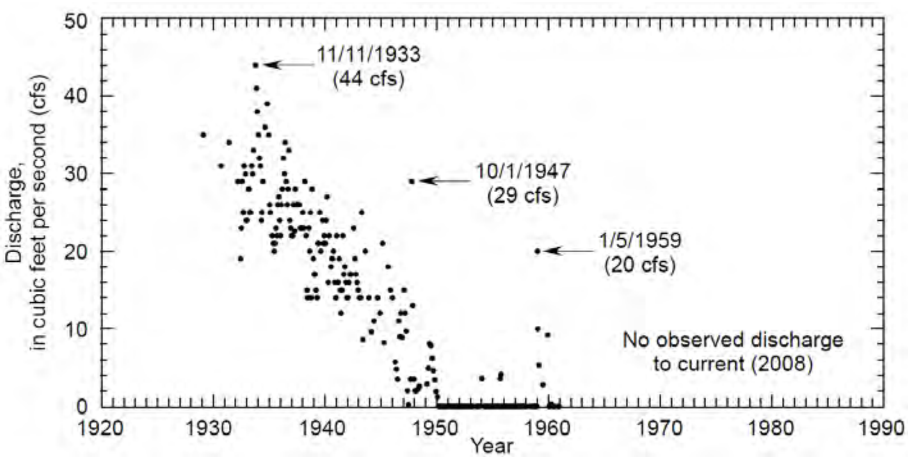

Figure 1.2 *Top*: Periodic discharge measurements at Kissengen Spring in Polk County, central Florida. (modified from Lewelling et al., 1998). *Bottom*: Historic photo of Kissengen Spring which remains dry to the present day after all flow ceased in 1960. (From Peek, 1951.)

As stated in one of numerous scientific publications on Florida's groundwater resources published over many years by USGS, Florida Geologic Survey (FGS), and others, including well before and after the demise of Kissengen Spring:

The Upper Floridan aquifer is of primary importance to the State as a source of water for irrigation and as a source of crystal-clear water that discharges to springs and streams providing recreational and tourist destinations and unique aquatic habitats. The reliance of the region on the Upper Floridan aquifer for drinking water and for the tourism and agricultural economies highlights the importance of long-term management to sustain the availability and quality of these resources.

The following excerpt from Oscar Meinzer's 1927 publication Large Springs in the United States describes Silver Spring (which issues from the Upper Floridan Aquifer), uniformly regarded as the flagship of Florida springs, and often cited as the largest spring in the country or indeed the World:

The deep, cool water of Silver Spring, clear as air, flows in great volume out of immense basins and caverns in the midst of a subtropical forest. Seen through the glass-bottom boats, with the rocks, under-water vegetation, and fish of many varieties swimming below as if suspended in mid-air, the basins and caverns are unsurpassed in beauty. Bright objects in the water catch the sunlight, and the effects are truly magical. The springs form a natural aquarium, with 32 species of fish. The fish are protected and have become so tame that they feed from one's hand. At the call of the guides, hundreds of them, of various glistening colors, gather beneath the glass-bottom boats.

Sometime in 1960s something started to go terribly wrong with Silver Spring and many other beautiful springs in Florida. For one, the population of Florida skyrocketed from about 5 million in 1960 to about 23 million today (end of 2023). The graph in Figure 1.3 shows what has happened to the discharge rate of the main Silver Spring (there are smaller springs in the complex that are not measured) since this unchecked growth started. Interestingly, USGS stopped reporting field measurements of its discharge rate in 2010, after 100 years of doing so, and has been providing only its "gage height" ever since.

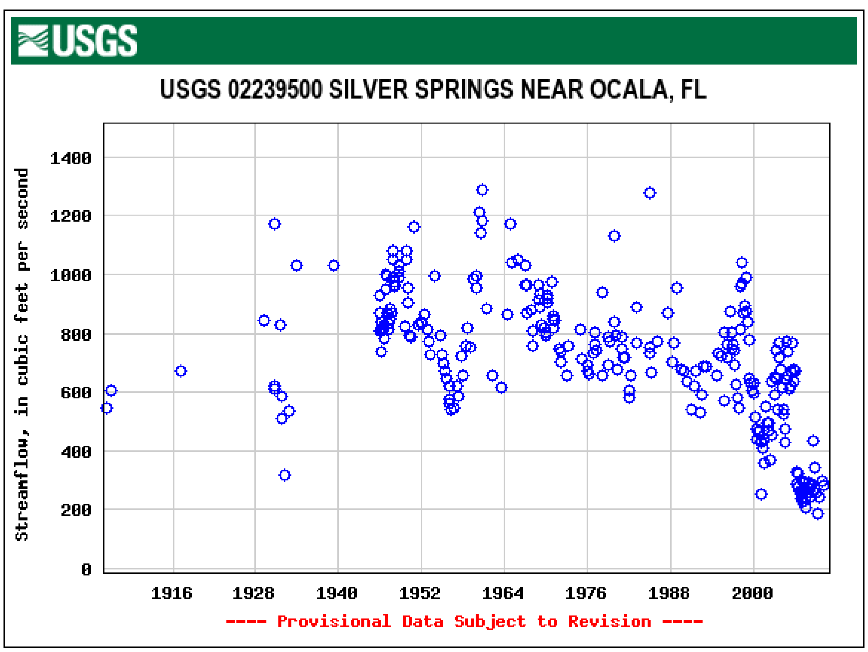

Figure 1.3 Graph of field-measured discharge rate of Silver Springs as provided by the official USGS gaging station, available at https://nwis.waterdata.usgs.gov/. Compare with Figure 2.18, data for Big Spring in Missouri.

Cheerful photographs in Figure 1.4, taken in the 1950s and 1960s, perhaps best illustrate the description of the spring from Meinzer's 1927 publication, water as "clear as air", and the overall magic appeal of this wonder of nature.

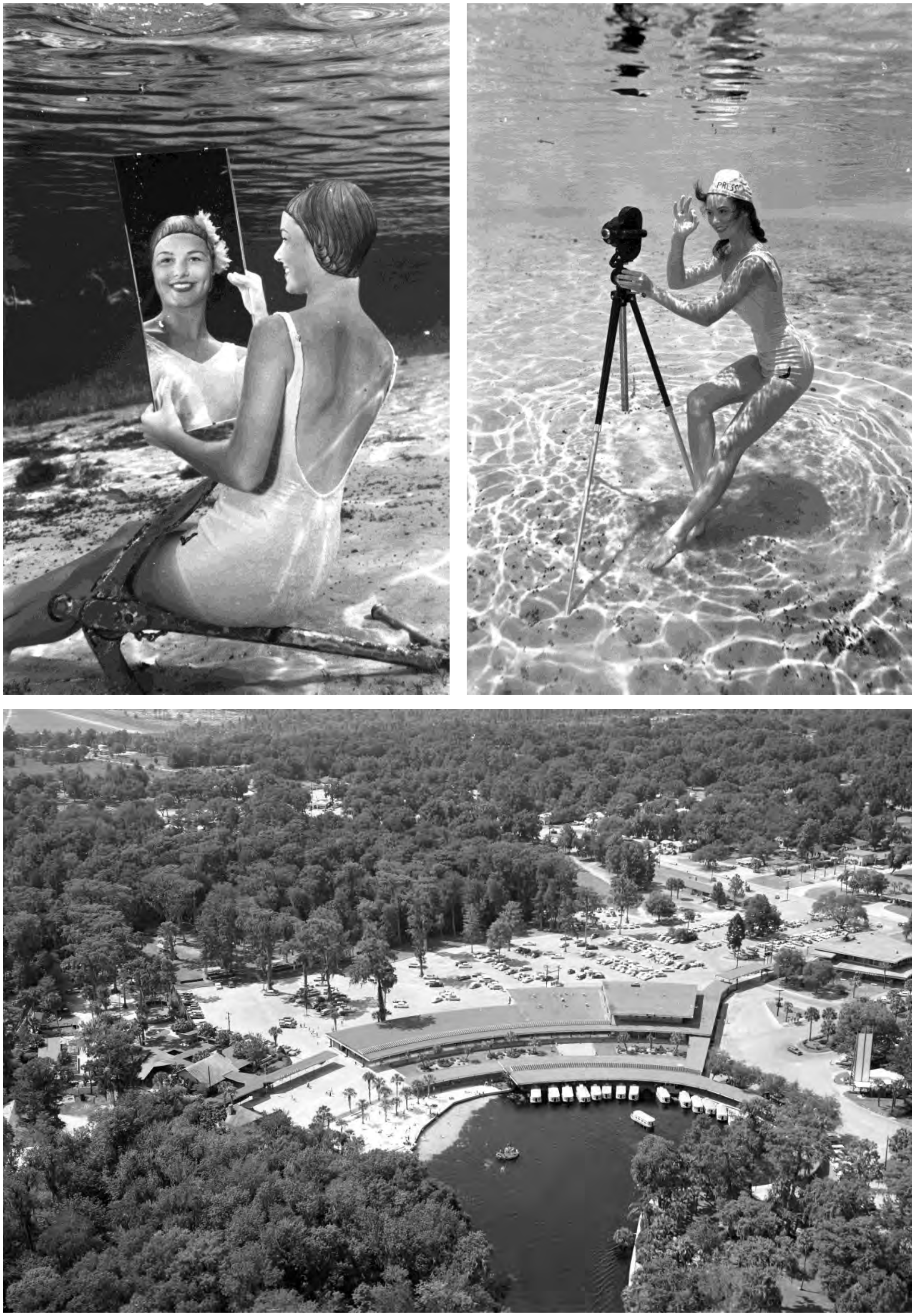

Figure 1.4 *Top left*: A Model's smiling reflection underwater at Silver Springs (circa 1950). *Top right*: Arrilla Jones in a "press" hat with a camera underwater at Silver Springs (circa 1962). Bottom: Aerial view looking northwest over the Silver Springs tourist attraction (circa 1950). Photos by Bruce Mozert, State Library and Archives of Florida. https://www.floridamemory.com/discover/photographs/

Nature photographer John Moran, who graciously provided remarkable photos of Florida springs for this book, also sent the photos below with the following note: "*I've attached a few impaired springs photos. I believe it's important to show that all is not well in Paradise*."

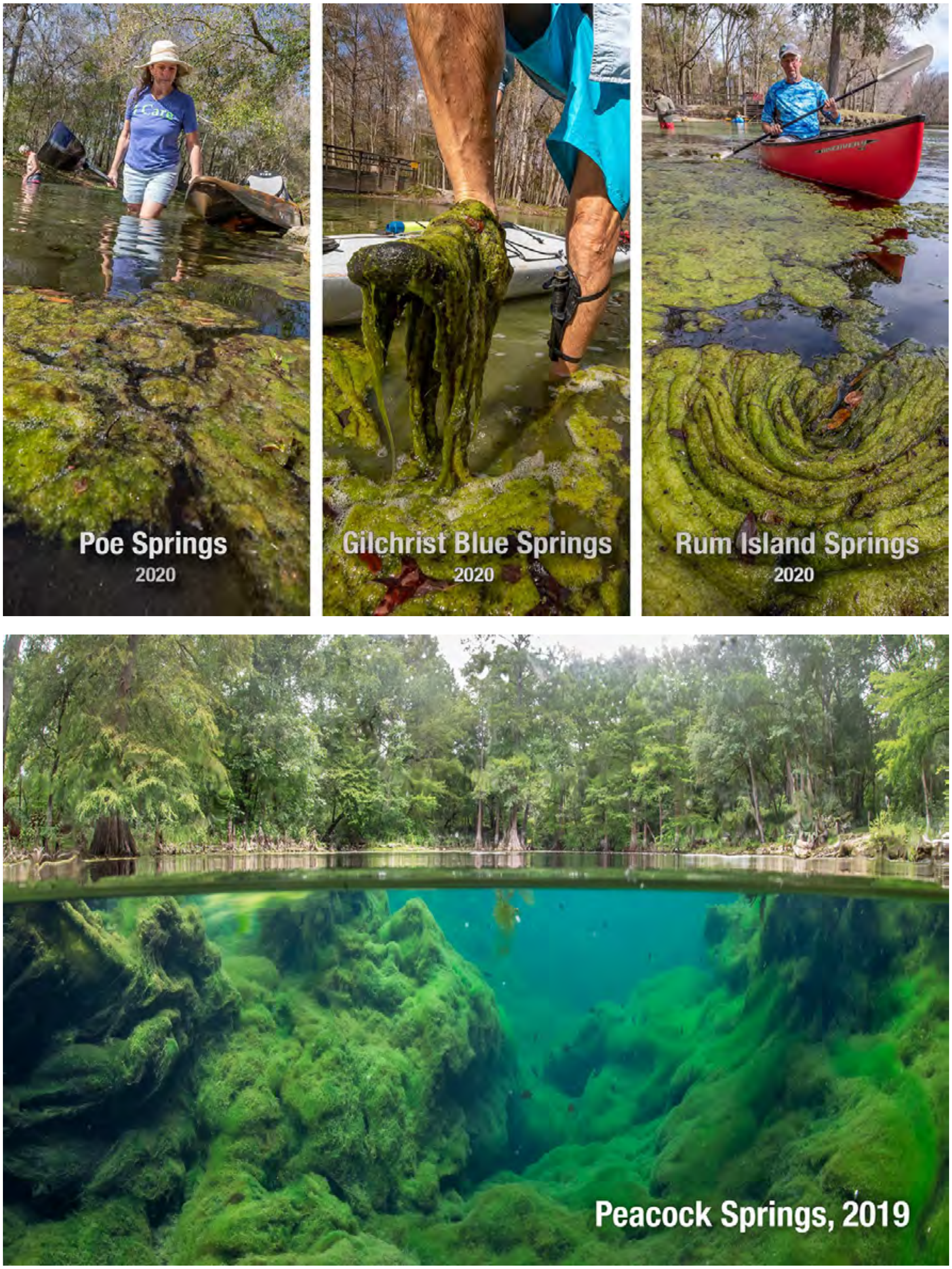

Figure 1.5 Examples of impaired Florida springs. All photographs copyright John Moran; printed with permission.

Figure 1.6 Excessive algae growth and organic slime in the impaired Manatee Springs, one of many degraded springs in Florida, fueled by nutrients and nitrate coming from urban and agricultural runoff loaded with pesticides and fertilizers, application of treated sewage to spray fields, manure applications to cropland, and septic tanks. Photo copyright John Moran; printed with permission.

Under relentless pressure from Florida citizens, activists, and many different organizations concerned with the catastrophes facing beautiful Florida springs, the State Legislature in 2016 enacted Florida Springs and Aquifer Protection Act which specifies 30 "Outstanding Florida Springs". In Statue 373 one can read:

The Legislature finds that the water quantity and water quality in springs may be related. For regulatory purposes, the department has primary responsibility for water quality; the water management districts have primary responsibility for water quantity; and the Department of Agriculture and Consumer Services has primary responsibility for the development and implementation of agricultural best management practices. Local governments have primary responsibility for providing domestic wastewater collection and treatment services and stormwater management. The foregoing responsible entities must coordinate to restore and maintain the water quantity and water quality of the Outstanding Florida Springs.

It remains to be seen if this act will have an effect. In the meantime, those concerned with the destiny of Florida springs remain concerned, some are skeptical, and some are raising their voices disillusioned with what they see happening as illustrated with the following excerpts from a blog by Dr. Robert Knight, Director of The Howard T. Odum Florida Springs Institute (https://floridaspringsinstitute.org/springsblog/) which contains his remarks delivered at a panel discussion held at the University of Florida on April 1, 2023:

But the documented and worsening ecological health of Florida's priceless springs provides ample evidence that Florida's political leadership is not working to fix these problems. Much of the tax dollars being directed to "springs protection" are, in fact, spent on projects that have had no measurable spring benefits. Springs health impairments continue to worsen with every passing year.

This is an unacceptable fate for Florida's most unique and precious natural resources and presents a clear danger for the sustainability of the Floridan Aquifer. The future livability of the Springs Region is not just threatened – it is already substantially diminished.

Everyone I know sees and loves springs differently. But based on what you hear today and what your own eyes tell you, I hope that you will leave with a renewed commitment to act on behalf of your springs and the life they support.

Congress Must Act to Save the Havasupai Tribe from Extinction

This is the title of an opinion piece for Newsweek written by the Havasu Tribe Chairwoman Kissoon in which one can read (https://theofficialhavasupaitribe.com/):

> *We have seen the irreparable damage uranium mining can do. For generations we have been at the forefront, working to permanently protect our homelands from uranium mining, which has disproportionately harmed and sickened Indigenous people across northern Arizona. The Senate has the power to protect not only our Grand Canyon home and our waters, but also the health and safety of our tribe and the people of the Southwest from the life-threatening effects of uranium mining. We urge the Senate to do the right thing and protect the Grand Canyon now and for future generations*.

The blood line of the Havasu Tribe is Havasu Springs and the Havasu Creek which they form, including its spectacular waterfalls (Figure 1.7). Uranium mining in the watershed of the Springs, which are sacred to the Havasu Tribe and other Native Americans, may impair the quality of groundwater, Springs, and surface water, to the point of no return.

Figure 1.7 Havasu Falls on the Havasu Creek which originates at Havasu Springs, all on the Havasu Tribe land in the Grand Canyon area, Arizona. The springs, the falls, and the creek are under constant threat from uranium mining interests. Photo courtesy of the Havasu Tribe. Available at https://www.facebook.com/HavasupaiTribeTourismOfficial

The Little Colorado River, which joins the mainstem Colorado River inside Grand Canyon National Park, is the wrong place to build dams (https://www.grandcanyontrust.org/little-colorado-river-dam-proposals)

This is the title of an article posted on web site of the Grand Canyon Trust in which one can read:

After years of advocacy by Native communities, tribes, the Grand Canyon Trust, and others, in 2022, the federal government cancelled preliminary permits it had issued to a Phoenix-based company for two proposed hydroelectric projects on Navajo Nation lands mere miles from the national park boundary. Both would have flooded a pristine section of the Little Colorado River Gorge, muddied its distinctive turquoise-blue waters, destroyed areas sacred to Native peoples, and threatened the habitat of the already endangered humpback chub.

However, a third application to dam Big Canyon, a nearby tributary canyon adjacent to the Little Colorado River, is still pending.

Public outcry from Grand Canyon advocates defeated the proposed Marble Canyon Dam in the 1960s. It's time we raise our voices again to stop dams from altering the Little Colorado River forever.

What is at stake is flooding and destruction of the most sacred places of the Navajo Nation and many other Native American Tribes, including the largest spring in the Grand Canyon Area, Blue Spring, which contributes most of the flow of the Little Colorado River and creates the most amazing sight one can imagine (photograph in Figure 1.8 can hardly do the justice). One of the proposed projects would have flooded a Hopi sacred site, a place where the Hopi people believe they emerged into this world.

In April 2024, Federal Energy Regulatory Commission (FERC) denied the proposed Big Canyon Dam, citing the Navajo Nation's opposition.

Figure 1.8 Screenshot from a video *Virtual Tour—Grand Canyon, AZ Dams Threaten the Little Colorado River*, produced by EcoFlight in cooperation with the Grand Canyon Trust. Available at https://www.grandcanyontrust.org/little-colorado-river-dam-proposals. Note: the mesmerizing turquoise blue color of the Little Colorado River, before its confluence with the Colorado River, is real; see Chapter 6 for explanation.

Incidentally, one of better-known groundwater scientists in Arizona first agreed to submit proposals for several notable Arizona springs to be included in the MIKAS list, and then declined after months of KC waiting for them. His explanation was somewhat ambiguous, along the lines that National Park Service and the US Forest Service could not endorse these nominations, including for Havasu and Blue Springs, for some unknown reasons. This is of course puzzling since the better-known groundwater scientist teaches at a university and is not a federal employee, neither spring is on Federal lands, and the Native American Tribes need every support they can get to protect these sacred springs as illustrated with the previous examples.

Whatever kept the groundwater scientist from Arizona from nominating these two spectacular and sacred springs for inclusion into the list of most important karst springs in the world, they are now included (see Chapter 6 on Grand Canyon Springs for their detail description). Sadly, however, the Havasu Tribe did not stand a chance in their efforts to protect their sacred spring and lands, as illustrated by the following excerpts from an article by Maanvi Singh published in The Guardian on January 23, 2024 (https://www.theguardian.com/us-news/2024/jan/23/us-uranium-mine-grand-canyon):

One of first US uranium mines opens near Grand Canyon after eight years. Pinyon Plain's start comes amid US's push to boost production, but tribes fear contamination of water and cultural sites

> *A uranium mine in Arizona located just 7 miles south of the Grand Canyon national park has begun operations, one of the first in the US to open in eight years.*
>
> *"It's a very, very sad situation – it's upsetting a lot of tribes in this region," said Carletta Tilousi, a former Havasupai council member who has been leading the tribe's opposition to uranium mining in the south-west. "But I think we all knew this was eventually going to happen."*
>
> *Uranium mining in the region had ceased for years, amid a federal ban on new mining claims around the Grand Canyon. Permitted mines unaffected by the ban sat dormant due to low uranium prices.*
>
> *The company cited rising uranium prices in a statement about its activities, as well as "increased buying interest from US nuclear utilities, US and global government policies supporting nuclear energy to address global climate change, and the need to reduce US reliance on Russian and Russian-controlled uranium and nuclear fuel" among their reasons to ramp-up production. The US still buys uranium from Russia, despite sanctions imposed after Russia's 2022 invasion of Ukraine, but lawmakers have been seeking to divest from the country.*
>
> *Energy Fuels insists that its operations will not affect aquifers in the region, and points out that state regulators have determined that the mine will not impact local water supplies.*

The author hopes that the chapters that follow will inspire future hydrogeologists and others to do what is in their power to help protect springs and prevent their degradation and ultimately, their disappearance. A cautionary tale from Texas shows us what can happen to magnificent springs, first because of ignorance and unrestricted land use, and then because of an overwhelming pressure of population growth and inadequate regulations, as illustrated by the following excerpts from the anthological work by Gunnar Brune.

Springs were vital to the survival of Texas' earliest inhabitants, over 30,000 years ago. At an archeological site near Lewisville in Denton County, radiocarbon analysis has dated the remains of these early new-world men at 37,000+ years old, including crude sculptures, spears, and spear throwers (Newcomb, 1961). These early Americans always made their campgrounds near water, whether it was a spring, spring-fed stream, a river, or a lake. Bedrock mortars or rock mills were worn into the rock by the Indians as they ground stool, acorns, and other nuts, mesquite beans and grain. These mortars can still be seen at many Texas springs. It is also noteworthy that the Pueblo Indians *of west Texas used spring water for irrigation of crops long before the arrival of the Europeans (Taylor, 1902; Hutson, 1898).*

Because the springs were so vital to the life of both the Indians and the white man, it is not surprising that many battles were fought over their possession. In 1650 when Spanish explorers first visited Big Spring in Howard County, they found the Comanche and Pawnee Indians fighting for its possession. When a network of forts was strung across Texas, they were, in nearly all cases, located near springs in order to have a reliable supply of pure water. Later the covered-wagon and stagecoach routes came to rely heavily upon springs. For example, the "Camino Real" or King's Highway, completed by the Spanish colonists about 1697 from Natchitoches, Louisiana, to San Antonio and Mexico, passed 13 major Texas springs and many more minor ones. Most of the springs in West Texas are very small in comparison to those in central and east Texas, because of the very low rainfall and recharge. Nevertheless, they often meant the difference between life and death to the early pioneers.

Nearly all of the larger springs were used for water power by the early settlers. At least 61 were used in this way. Gritsmills, flour mills, sawmills, cotton gins, and later electric generating plants were powered by the flow of spring water.

In the late 1800's, many medicinal or health spas sprang up around the more mineralized springs. At least 25 springs, chiefly in east Texas, were believed to be beneficial in curing various ailments. Most of these waters are high in sulfate, chloride, iron, and manganese.

Many of the early settlements relied entirely on spring water. At least 200 towns were named for the springs at which they were located. About 40 still are shown on the official Texas State Highway Map, but many of the springs have dried up.

Throughout the long period during which various Indian tribes occupied Texas, spring flow remained unchanged except as affected by wet and dry climatic cycles. At the time of Columbus' epic voyages Texas abounded with springs which acted as natural spillways to release the excess storage of underground reservoirs. Early explorers described them as gushing forth in great volume and numbers. The very early accounts usually describe not springs but "fountains". This is an indication of the tremendous force with which these springs spouted forth before they were altered by modern man. As an example, less than 100 years ago Big Boiling Spring, one of the Salado Springs (Bell County) was still described as a fountain rising 5 feet high. Such natural fountains ceased to exist in Texas many years ago.

Probably the first effect upon ground-water tables and spring flow was the result of deforestation by the early white settlers. Deforested land was placed in cultivation or pasture. The deep open structure of the forest soils was altered as the organic matter was consumed and the soils became more impervious. Heavy grazing by introduced stock animals was probably especially harmful. Soon the soils were so compacted that they could take in only a small fraction of the recharge which they formerly conveyed to the underground reservoir.

This reduction of recharge affected larger areas as more and more land was placed in pasture. However, the effect upon water tables and spring flow was probably relatively small in comparison with later developments. In the middle 1800's deep wells began to be drilled. It was found that flowing wells could be brought in nearly everywhere. The "Lunatic Asylum" well in Austin, drilled to the basal Trinity Sands, threw water 40 feet high. Water from a well south of San Antonio reaching the Edwards Limestone rose 84 feet above the surface of the ground (Hill and Vaughn, 1898). Nothing could have had a more disastrous effect upon spring flows than the release of these tremendous artesian pressures through flowing wells. Most of these wells were allowed to flow continuously, wasting great quantities of water, until the piezometric heads were exhausted and the wells stopped flowing.

Although the effects of flowing wells upon spring flow were severe, there was more to come. When the wells ceased flowing, pumping began. Ground-water levels were systematically drawn down, as much as 700 feet in some areas. At first pumping for municipal and industrial use was primarily responsible. In recent years tremendous quantities of *ground water have been withdrawn for irrigation, amounting to about 80 percent of the total ground water used in Texas. As a result, some streams which were formerly "gaining" streams, receiving additional water from streambed seeps and springs, are now "losing", and many streams have ceased flowing. Thousands of small springs have dried up, and the larger springs have generally suffered a decrease in flow.*

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Chapter 2 The Ozarks, Missouri and Arkansas

2.1 Introduction

The following excerpts are from an excellent booklet by Loring Bullard ("Missouri Springs: Power, Purity and Promise", © Watershed Press, available at https://watershedcommittee.org/our-publications/) and serve to set the stage for describing large springs in the Ozarks of Missouri and Arkansas.

The human attraction to springs is extremely durable. Springs guided the habitation patterns and movements of Native Americans, just as they did the later arriving settlers. Indian villages and hunting camps were usually located near perennial springs. One can easily imagine native children squealing in delight with a summertime plunge, just as our own kids would today. Later, European newcomers followed the Indian's lead, building their cabins near springs, their water supplies and refrigerators.

With increasing settlement, business interests eagerly sought perennially flowing springs, particularly to power mills. Unlike streams, springs provided fairly constant flows that in the wintertime were free of machinery-obstructing ice. For decades, springs faithfully turned water wheels or spun metal turbines to grind grain or saw wood. They also supplied feed water for commercial enterprises like tomato canneries, hide tanneries, and distilleries. Thus, springs became the nuclei of a variety of thriving industries, driving the nascent machinery of our prosperity.

Historically, the value of a given spring was largely tied to its capacity to do work. Entrepreneurial zeal led people to assume that the work potential of a spring was its single most important attribute. Scenic and ecological values tended to be ignored or pushed aside.

This fact forever changed the Missouri landscape, because springs became magnets for development. Flows were captured and re-directed, outlets modified, openings blasted or excavated. Wood or rock or concrete dams and flumes and diversions intercepted spring branches or crisscrossed their valleys. Sturdy mills were built on nearby rocky prominences. People began to see undeveloped springs as underutilized resources: "All that water, just going to waste!" was a battle cry for the industrious to get into gear and build something of practical use to society.

It was only natural for people to congregate near these hydro-industrial centers. Many settlements grew around mills and springs, as evidenced by the fact that over sixty-five towns in Missouri contain the word spring in their names. Some towns depended on springs for their first public water supplies. After all, these fortuitous emanations from the earth were considered the purest and most healthful of waters available.

This booklet is in no way meant to diminish our sense of wonder or curiosity about springs. Instead, our intended purpose is to answer some questions commonly asked about them: Why is this spring here? Where does the water come from? Why is it so cool? Why are some springs so blue? You will also learn how our ill-conceived or uncaring manipulations on the land can sometimes have disastrous consequences for springs—the very objects of our affection. Hopefully, a deeper understanding of the workings of springs will help us to more fully honor, preserve and protect these priceless natural assets. That would be our greatest gift to those who follow us to their everlasting waters.

Kimberland Mill at Silver Lake Spring, Stone County. Courtesy of History Museum for Springfield and Greene County.

The Ozarks of Missouri and Arkansas (Figure 2.1), also referred to as the Ozark Plateaus or Ozark Mountains, generally correspond to the Salem Plateau, Springfield Plateau, and Boston Mountains physiographic areas. They include diverse topographic, geologic, soil, and hydrologic conditions that support a broad range of habitat types. The landscape features rugged uplands—some peaks higher than 2,500 feet above sea level—with exposed rock and varying soil depths and includes extensive areas of karst terrain. The Ozark Highlands are characterized by extreme biological diversity and high endemism (uniqueness of species). Vegetation communities are dominated by open oak-hickory and shortleaf pine woodlands and forests. Included in this vegetation matrix is an assemblage of various types of fens, forests, wetlands, fluvial features, and carbonate and siliceous glades.

The Ozarks are the most significant highland region in central North America because of the following (USGS, 2009):

- High levels of terrestrial and aquatic endemism: more than 200 species largely restricted to the Highlands, of which about 160 occur nowhere else in the world.
- More than average rate of growth in human population and agricultural and commercial activity.
- Increasing potential for negative human impacts.
- Competing demands for water resources.
- The three largest single-conduit springs in the United States.
- Important neotropical bird migration and breeding grounds.
- The largest extent of glade communities in North America (historical extent of open woodlands rather than closed forests).
- Home to nearly two-thirds of the 45 federally listed plants and animals in Missouri, Arkansas, and Oklahoma but contain only one-fourth of the land mass in those States.
- The world's largest active lead/zinc mining district (the Viburnum Trend) and several other large inactive districts.
- Valued outdoor recreation and tourism use on private and public lands.

The following description of the Ozark Plateau aquifers (see Figure 2.2), which give rise to some of the largest springs in the United States and the World (Figure 2.3), is based on the information provided by the USGS in Kresse et al., 2014; Hays et al., 2016; Clark et al., 2019; Westerman et al., 2016; and John Van Brahana, 2023.

Figure 2.1 View of the Ozarks from Hasty, Arkansas. Photo courtesy of David Price.

The Ozark Plateau (The Ozarks) is a region of unique and complex hydrogeology and physiography. The Ozark Plateau aquifers are characterized by a predominantly mantled karst terrain where aquifer anisotropy and heterogeneity, and variability in aquifer hydraulic characteristics are the norms. This variability is noted on a small spatial scale where (1) groundwater-flow velocities vary from 10^{-6} ft/s to several feet per second, (2) a well may produce 0.01 gal/min or 1,000 gal/min, (3) surface-derived groundwater contaminants may be effectively ameliorated within a short distance or may travel great distances with little to no attenuation, and (4) a subsurface may be essentially lifeless or home to numerous cave-related species.

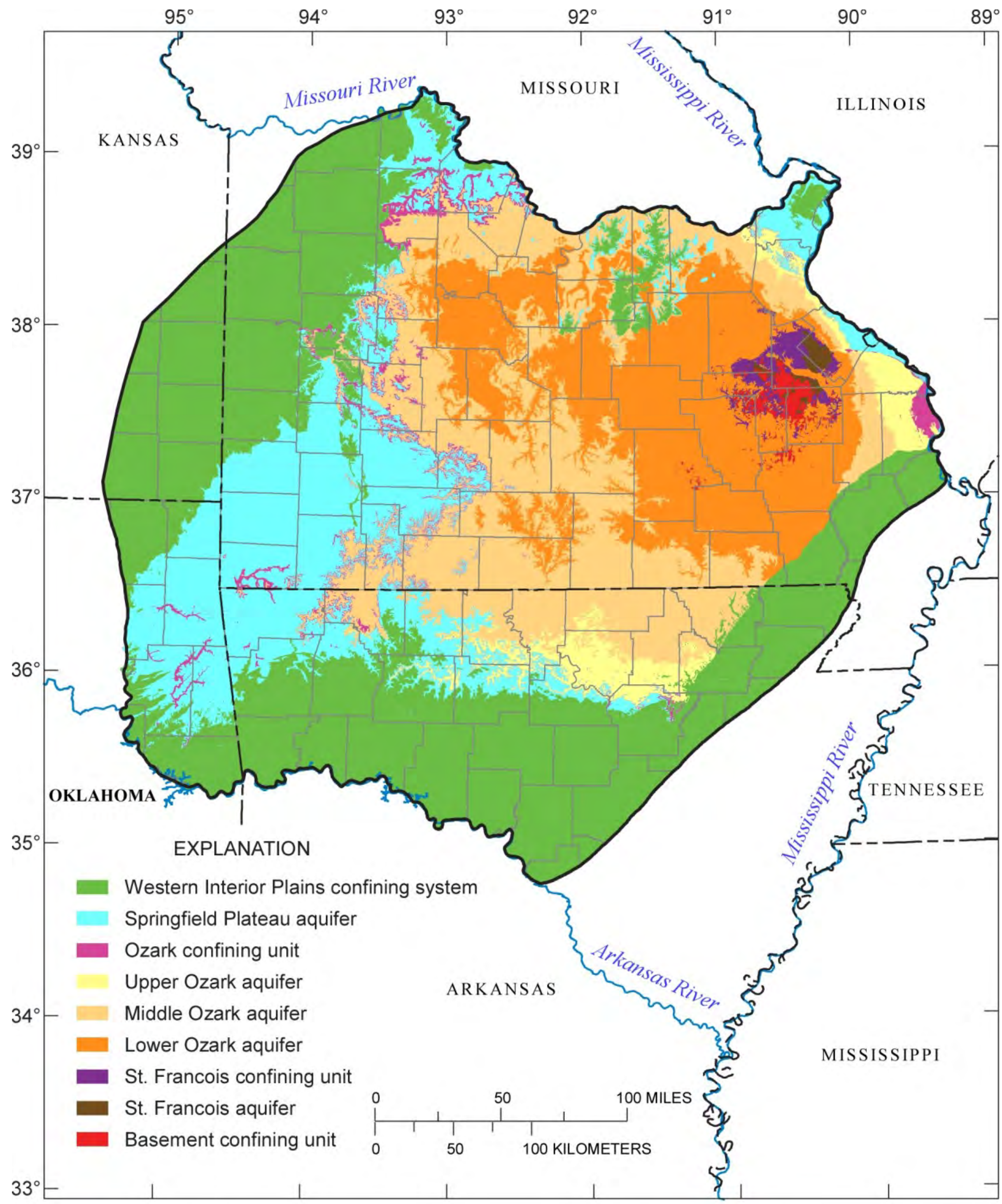


Figure 2.2 Aquifers of The Ozark Plateaus. The extent of the Ozarks Plateaus aquifer system is shown with thick black line. Modified from Westerman et al., 2016; USGS, in public domain.

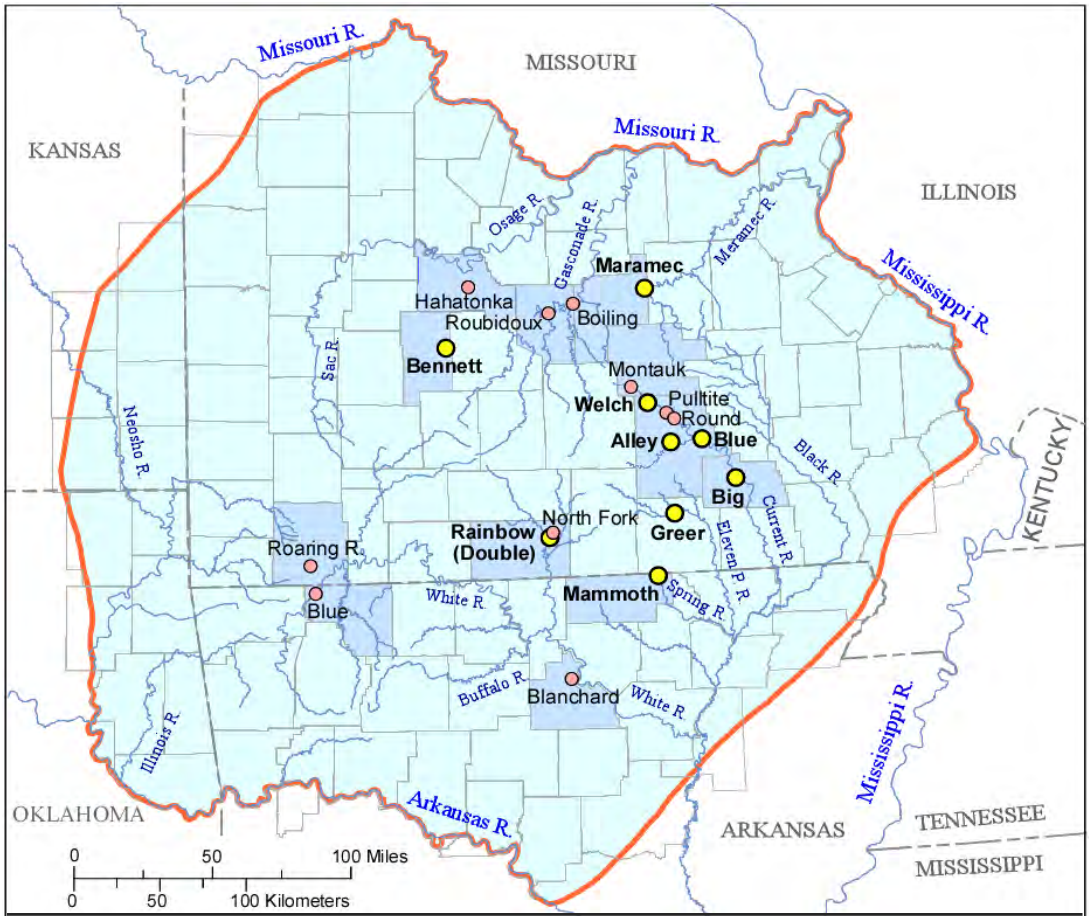


Figure 2.3 Large karst springs in the Ozarks of Missouri and Arkansas. The extent of the Ozarks Plateaus aquifer system shown in red is from Westerman et al., 2016. Yellow circles denote first-magnitude springs, orange circles denote other notable large springs. Darker blue shading shows counties where these springs are located.

The Ozarks were formed by a structural dome that has been uplifted during several periods since Precambrian time. The core of the dome is in southeastern Missouri. Widespread extensional fracturing, jointing, and faulting of Ozarks' rocks occurred with uplift (Hudson and Cox, 2003), creating secondary porosity that has provided key starting points for initiation of dissolution of the carbonate rocks and karst development. The karstic bedrock of the region is overlain by weathered regolith that greatly varies in thickness from near zero in many areas to more than 100 ft.

Bedrock in the Ozarks shows evidence of multiple episodes of water movement and carbonate dissolution defining distinct karst development events through time (Stoffell et al., 2008). Widespread dissolution features associated with the lead and zinc ore-bearing fluids that moved from the Arkoma Basin (Leach and Rowan, 1986) are observed across the Ozarks region. Lead and zinc were mined commercially where faults conveyed mineral-saturated fluids up from depth.

Hypogene indicators such as diagnostic calcite isotopic compositions (Brahana et al., 2009), collapse breccias (McKnight, 1935), and isotopic dating (Brannon et al., 1996) show that this episode of fluid movement and dissolution was a separate occurrence predating recent karst development. Exposure of Mississippian strata associated with the Mississippian-Pennsylvanian unconformity resulted in meteoric diagenesis followed by pedogenesis, regolith formation, and paleokarst development on the Pitkin Limestone (Webb, 1994).

The Ozarks once again showed active karst development as uplift, denudation, and abundant precipitation initiated dissolution of soluble carbonate lithologies. The recent period of dissolution and karst development has had a very visible impact on the modern karst land surface, controlling subsurface flow and ultimately the surface flow in the region. The hydrogeology of the region is typical of karst with focused flow paths that are well connected to the surface and deliver water from input to discharge points at streams and springs at velocities of tens to thousands of feet per day (Funkhouser et al., 1999; Mott et al., 2000; Hudson et al., 2005). Abundant karst features are apparent — ponors (sinks), losing stream reaches, springs, caves, and sinkholes. Recent karst development often reactivated and followed previous dissolution-enhanced flow paths that originally developed during ancient exposure periods (such as at the Ordovician-Mississippian and the Mississippian-Pennsylvanian unconformities; Webb, 1994) or hypogene episodes such as Mississippi Valley Type ore emplacement (Leach and Rowan, 1986; Brannon et al., 1996; Brahana et al., 2009).

Another very important phenomenon caused by karst development is interbasin transfer of water. Dye tracing studies and observations of drainage-area and discharge relations show the abundant occurrence and transfer of groundwater across surface-water drainage-basin divides (Mott et al., 2000). Consideration of interbasin movement of water is an important point for protection and management of groundwater because contributing zones are not apparent at the surface, and contaminants can be introduced into groundwater from unexpected locations. Seeps and springs are the predominant discharge points for the aquifer.

Figure 2.4 Outcrop of the Boone limestone (St. Joe limestone member) at Basin Spring, first spring captured for water supply of Eureka Springs, Arkansas. Native Americans believed that the spring had healing powers.

The Springfield Plateau aquifer (see Figure 2.2) comprises a sequence of limestone and cherty limestone of Mississippian age called the Boone Formation (Figure 2.4) which is exposed across most of the Springfield Plateau. However, outlier remnants of confining clastics are observed in the southern area of the Springfield Plateau where the upper Mississippian section is represented by the Batesville Sandstone and the Fayetteville Shale. These sandstone and shale units typically are well-cemented and exhibit low matrix porosity and permeability but exhibit moderate porosity and permeability when weathered or highly fractured. Owing to the predominance of low-permeable shale and sandstone, the Upper Mississippian and Pennsylvanian strata are included in the Western Interior Plains confining system hydrogeologic unit to the south in the Boston Mountains. The Boone Formation has a thickness of about 200–500 ft but is variably eroded across the plateau.

The basal St. Joe Limestone Member of the Boone Formation is a relatively pure limestone (Figures 2.5 and 2.6). Matrix porosity and permeability of the Boone Formation are low, but where fracturing has occurred, carbonate dissolution has greatly enhanced porosity and permeability. Solutioning of the fractures ultimately created the karst terrain that typifies the area.

Figure 2.5 Bluff on Buffalo River, Arkansas at Grinders Ferry (near highway 65 bridge) made of Mississippian Boone Formation limestone. The Buffalo River National Park Region was established in 1972 to protect one of the few remaining undammed rivers in the nation. Nestled in the northern part of Arkansas, the Buffalo River was recognized by National Geographic as one of America's most underappreciated National Parks. It has more than 500 caves within its boundaries, making it one of the most cave-rich units in the National Parks.

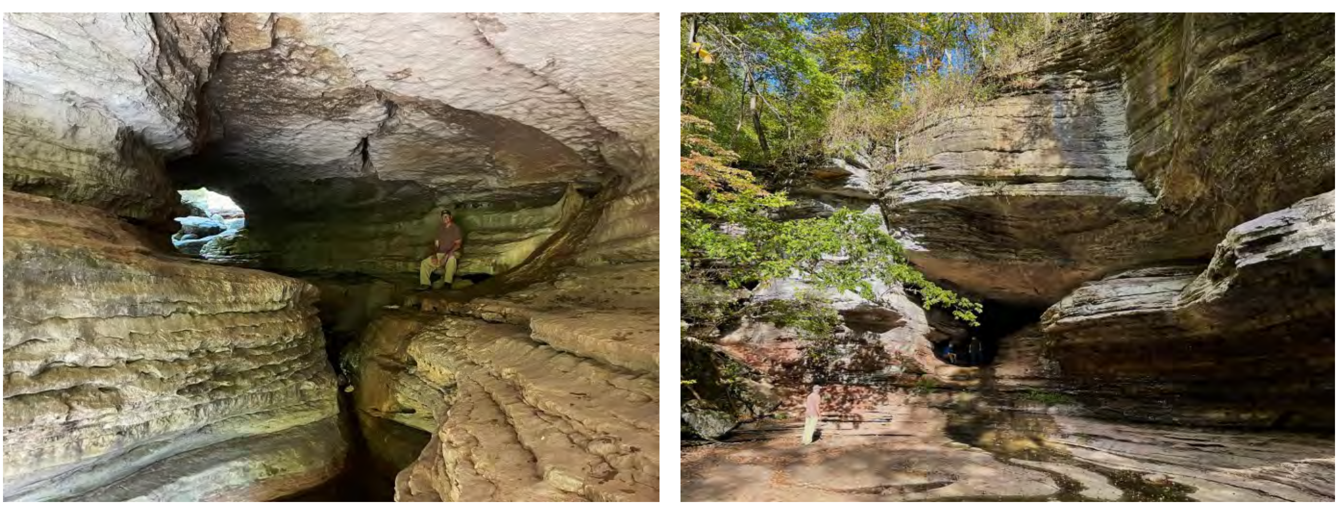


Figure 2.6 *Left*: Lost Valley Cave on Clark Creek, a tributary to the Buffalo National River near Ponca, Northwestern Arkansas. *Right*: Natural Bridge on Clark Creek. The Mississippian St. Joe Limestone Member of the Boone Formation is present in and along the Clark Creek. See also Chandler, 2015.

The Springfield Plateau aquifer generally is unconfined across the Springfield Plateau and confined in the Boston Mountains. The highly soluble nature of carbonate rocks of the Boone Formation has given rise to development of the distinctive karst terrain and pervasive occurrence of karst features, such as caves , springs, and sinkholes. There is hydraulic connection of surface water and groundwater as well as the variable aquifer characteristics that typify the area.

Recharge to the aquifer occurs as diffuse and focused recharge (Alley et al., 2002; Healy, 2010). Diffuse recharge occurs by infiltration of precipitation through the overlying regolith; however, most potential recharge water moving through the soil zone is lost to evapotranspiration, particularly during the growing season (Brahana, 2011b). Diffuse recharge likely amounts to a small percentage of the total recharge compared to focused, rapid recharge through karst features such as sinkholes, fractures, and conduits, and losing stream reaches (Alley et al., 2002; Brahana et al., 2005). Discharge from the Springfield Plateau aquifer is primarily through springs, withdrawals by wells, and inter-aquifer flow to the underlying Ozark aquifer system (Branner, 1937; Harvey, 1980; Brahana and Davis, 1998; Czarnecki et al., 2009; Hudson et al., 2011).

Most recharge to the Springfield Plateau aquifer is by infiltration of precipitation in the aquifer's outcrop area. Where confined, recharge occurs by leakage through overlying units (Adamski et al., 1995).

Springs generally occur near the base of the Boone Formation coincident with structural lows and the underlying Ozark confining unit (Kilpatrick and Ludwig, 1990; Adamski et al., 1995). Where the underlying Ozark confining unit is absent or incompetent, groundwater discharges from the Springfield Plateau aquifer to the underlying Ozark aquifer (Imes and Emmet, 1994).

The Ozark aquifer is exposed and generally unconfined within the Salem Plateau section of the Ozark Plateaus province (shades of yellow and orange on the map in Figure 2.2). The aquifer comprises a sequence of formations predominated by dolostones along with minor limestone, sandstone, and shale intervals of Ordovician age, and dolostones of Cambrian age (Figure 2.7). The main water bearing units of the upper, carbonate-dominated part of the Ozark aquifer, are Cotter Dolomite, and Jefferson City Dolomite.

The middle and lower parts of the Ozark aquifer include the Roubidoux Formation (Figure 2.8), Gunter Member of the Gasconade Dolomite, Van Buren Formation, Eminence Dolomite, and Potosi Dolomite.

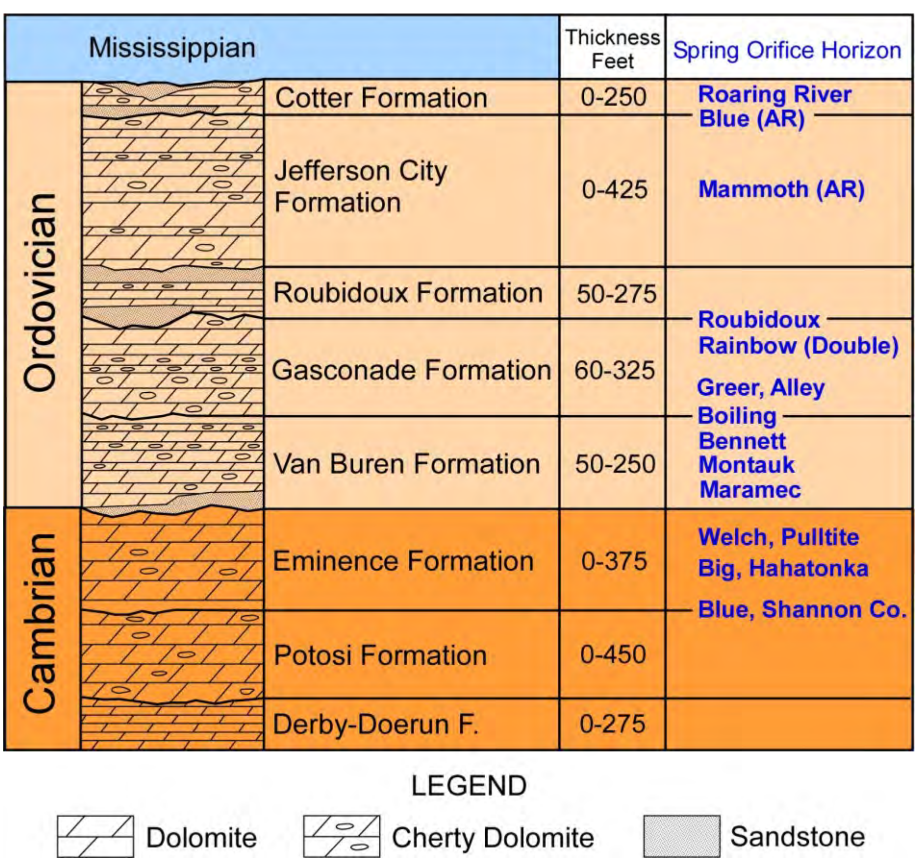


Figure 2.7 Principal geologic units of the Ozark Aquifer, with the horizons of orifices of large karst springs shown in Figure 2.3. Modified from Beckman and Hinchey, 1944.

Figure 2.8 Dolomite of the Roubidoux Formation, Missouri State Rt. 19 near the bridge over the Eleven Point River.

The topographic relief of the Ozark Plateaus resulted primarily from erosional dissection (Figures 2.9 and 2.10) rather than from intense folding and faulting. This erosion has been controlled to a degree by structural features such as faults and fracture zones as well as by lithology.

Figure 2.9 One of the most photogenic bluffs on the entire Buffalo National River called Roark Bluff. Middle Ordovician Everton Formation sandstone and dolostone are the major rock types along this section of the river. See also Chandler, 2015.

Figure 2.10 Gorge of the Greer Spring Branch, tributary of Spring Creek, incised in the Ordovician Gasconade Dolomite between two outlets of the Greer Spring, the second largest spring in the Missouri Ozarks.

Evidence provided by Palmer (2011) has shown that deep-seated dissolution has occurred within the Ozarks. Orndorff et al. (2006) also provided evidence of karst development at depth in confined aquifers. This deep karstification, the large extent, and the great thickness of the Ozark Plateaus aquifer system (Table 2.1), are the key reasons for the existence of some of the largest, permanent, ascending karst springs in the United States and the World.

Table 2.1 Summary statistics for the interpreted hydrogeologic units within the Ozark Plateaus aquifer system. [NAVD 88, North American Vertical Datum of 1988]. From Westerman et al., 2016.

Hydrogeologic unit	Mean altitude (feet above NAVD 88)	Median altitude (feet above NAVD 88)	Mean depth below land surface (feet)	Median depth below land surface (feet)	Minimum thickness (feet)	Maximum thickness (feet)	Mean thickness (feet)	Median thickness (feet)
Western Interior Plains confining system	809	818	--[1]	--[1]	<1	11,392	1,420	542
Springfield Plateau aquifer	-84	631	1,024	216	<1	1,840	227	237
Ozark confining unit	-268	448	1,207	437	<1	1,609	59	42
Upper Ozark aquifer	-841	255	1,686	648	<1	1,999	649	590
Middle Ozark aquifer	-224	446	1,106	390	<1	2,197	504	416
Lower Ozark aquifer	-429	222	1,309	672	<1	2,687	1,006	885
St. Francois confining unit	-1,420	-581	2,301	1,502	<1	973	235	228
St. Francois aquifer	-1,646	-755	2,526	1,698	<1	1,196	316	291
Basement confining unit	-1,939	-1,005	2,820	1,996	--[1]	--[1]	--[1]	--[1]

[1]Thickness values were not calculated for this hydrogeologic unit.

In karst systems, large, cavernous conduits allow for deep and rapid circulation of recharge. Conduits and dissolution-enhanced fracturing help integrate flow to spring resurgences. As a result, springs are common throughout the exposed sections of the Ozark aquifer. The Roubidoux Formation, Gasconade Dolomite, Eminence Dolomite, and Potosi Dolomite form aquifers of generally high yield (Harvey, 1980). Where these units are exposed in Missouri, multiple studies have been conducted using dye traces and other approaches (Figures 2.11 and 2.12). Results indicate a complex karst hydrologic system having long, interwoven flow paths that change drastically in terms of basin boundary extents and dominant flow paths with changing hydrologic condition (Mesko and Imes, 1995).

As discussed by Weary and Orndorff (2016), large springs occur in the Ozark aquifer because: (1) It is chiefly dolomite affected by solution via various processes over a long time period, (2) Paleozoic hypogenic fluid migration through these rocks exploited and enhanced flow-paths, (3) a consistent and low regional dip of the rocks off of the Salem Plateau (less than 2 degrees to the southeast) allows integration of flow into large groundwater basins with a few discreet outlets, (4) the springs are located where the rivers have cut down into structural highs, allowing access to water from stratigraphic units deeper in the aquifer thus allowing development of springsheds that have volumetrically larger storage than smaller springs higher in the section, and (5) quartz sandstone and bedded chert in the carbonate stratigraphic succession that are locally to regionally continuous, serve as aquitards that locally confine groundwater up dip of the springs creating artesian conditions. This subhorizontal partitioning of the Ozark aquifer allows contributing areas for different springs to overlap, as evidenced by dye traces that cross adjacent groundwater basin boundaries, and possibly contributes to alternate flow routes under different groundwater flow regimes.

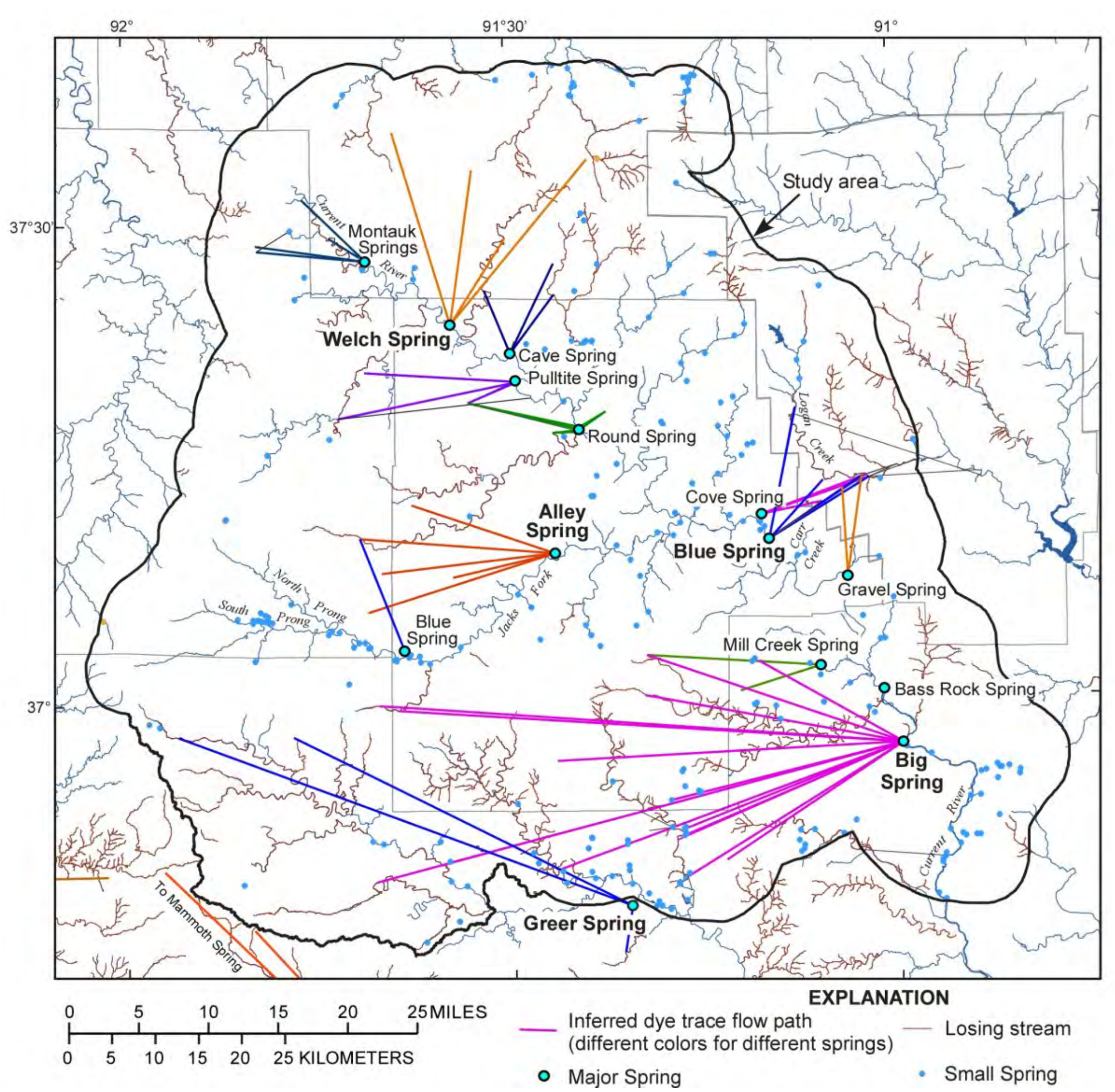


Figure 2.11 Locations of dye traces in the basin of the Current River, Missouri. Modified from Aley and Aley, 1987; Missouri Department of Natural Resources, 2007; and Imes et al., 2007. Modified from Mugel et al., 2009; USGS, in public domain.

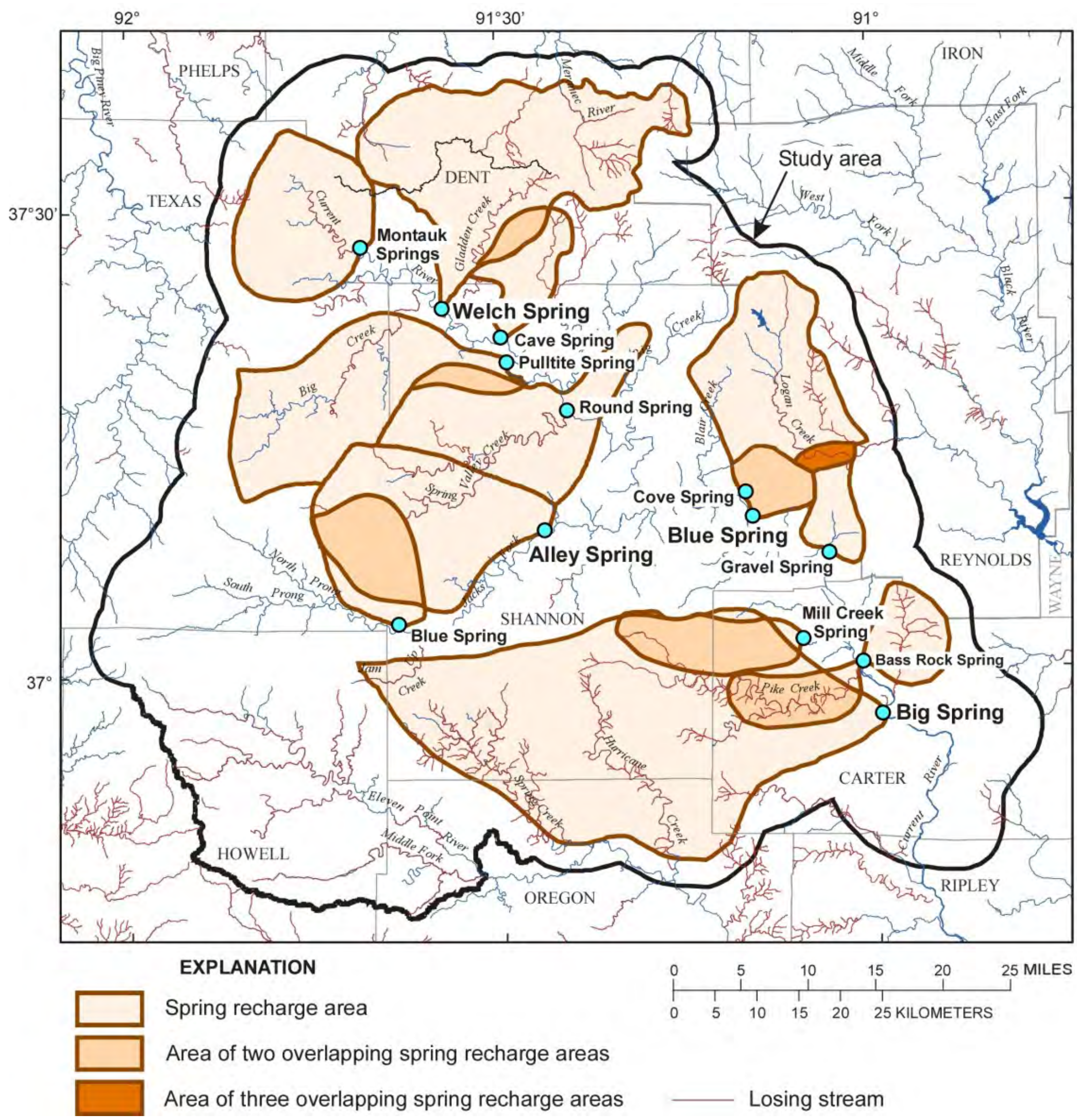


Figure 2.12 Recharge areas of springs in the surface-water basin of the Current River, Missouri reproduced or modified from Aley and Aley, 1987; Imes et al., 2007; Keller, 2000; and Vandike, 1997, using potentiometric surface maps and dye traces. Losing streams modified from Missouri Department of Natural Resources. First magnitude springs are denoted with larger bold font. From Mugel et al., 2009; USGS, in public domain

2.2 The Ozark National Scenic Riverways

Ozark National Scenic Riverways (ONSR) located in south central Missouri, is part of the National Park Service, within the Department of the Interior. The 134 miles of scenic and wild riverways are composed of two rivers, the Current and Jacks Fork (Figure 2.13). ONSR was the first national park to protect a river system in its wild, undammed state. The movement for the park started as a grassroots reaction to plans to build a series of dams on the Current and Jacks Fork rivers. While local residents and conservation groups in nearby cities disagreed on how the rivers should be preserved, most agreed the rivers should not be dammed but should be kept free-flowing. In 1964, after much debate and compromise, Congress officially established Ozark National Scenic

Riverways. The State of Missouri donated three state parks—Alley, Big Spring, and Round Spring—to the National Park Service as a gift from Missouri to the American people. Land along the rivers between the former state parks was purchased, and the whole area knitted together as America's first national river park. The successful effort to preserve these rivers was the prototype for the Wild and Scenic Rivers Act of 1968, which protects many of America's free-flowing rivers.

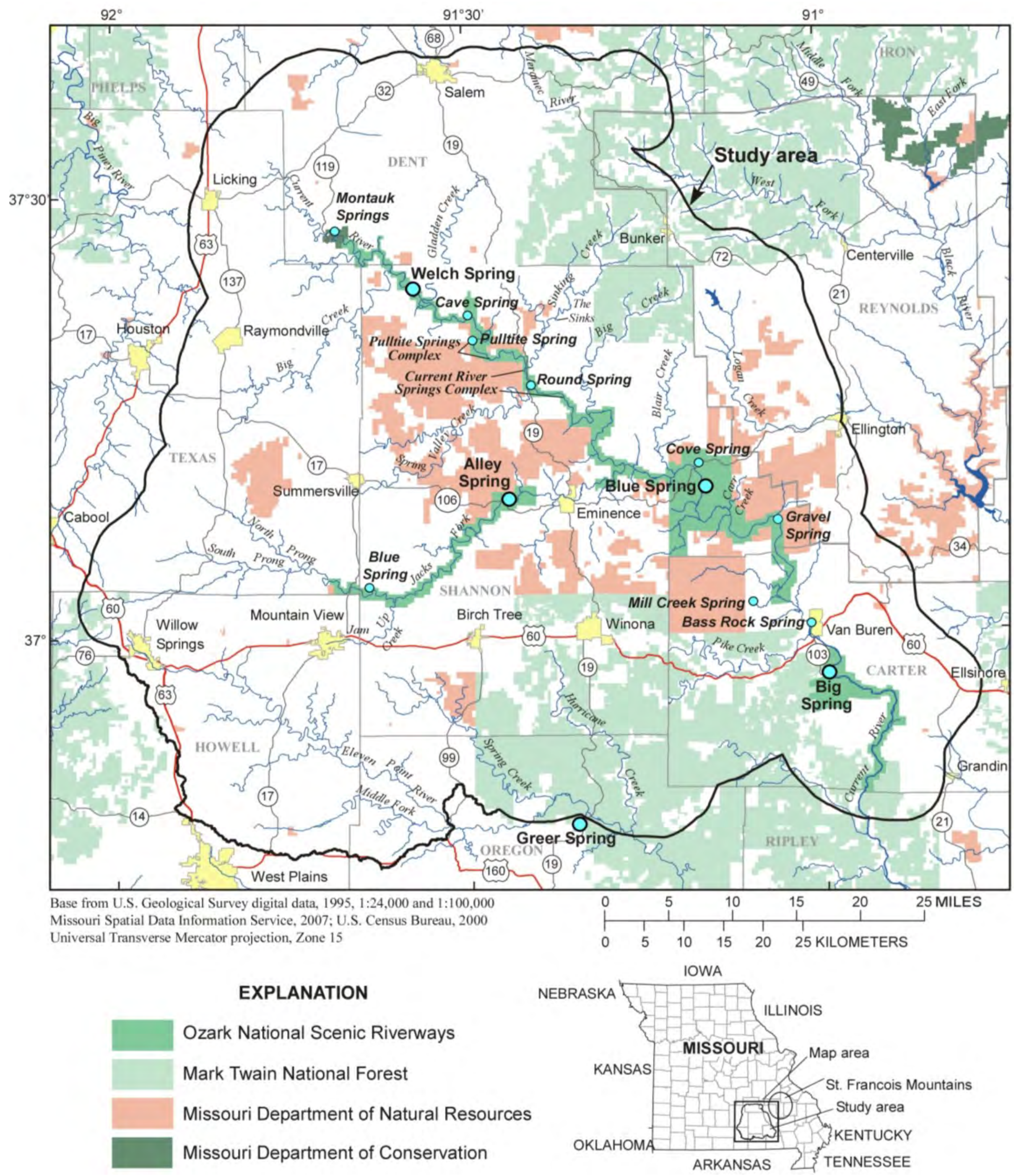


Figure 2.13 ONSR area showing locations of streams, selected springs, and public land ownership. Larger blue circles mark first-magnitude springs. Modified from Mugel et al., 2009; USGS, in public domain.

Since 1964 millions of people have come to ONSR to enjoy the rivers' beauty and their many recreational opportunities. Canoeing and water sports are popular, as are hiking, camping, and birdwatching. Spring wildflowers and autumn tree colors here are spectacular. Today the park continues to protect the rivers and the watershed to ensure enjoyment of these natural and cultural resources for generations to come. The park is home to more first magnitude springs (springs with daily flows of over 65 million gallons of water) and second magnitude springs (daily flows of over 6.5 million gallons) in one area than anywhere else on Earth (Figure 2.13; see also Tables 2.2 and 2.3). These springs offer people beauty and respite, and they supply most of the Current and Jacks Fork rivers' flow. It is virtually certain that, without the protection of the National Park status, all of them would have disappeared because of the trend of river damming at the time.

Figure 2.14 Blue Spring on Jacks Fork near Mountain View, Missouri is a popular swimming hole.

As noted by the NPS (https://www.nps.gov/ozar/learn/nature/spring-laws.htm)

The first paragraph of the enabling legislation for Ozark Riverways reads: Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled, That, for the purpose of conserving and interpreting unique scenic and other natural values and objects of historic interest, including preservation of portions of the Current River and the Jacks Fork River in Missouri as free-flowing streams, preservation of springs and caves, management of wildlife, and provisions for use and enjoyment of the outdoor recreation resources thereof by the people of the United States,..............

*The second specific purpose listed for the establishment of the park is "*preservation of springs*", out ranked only by "preservation of portions of the Current River and the Jacks Fork River". The word preservation was chosen here and not the weaker term conservation. It is clear that the springs must be protected to the highest standard. Big Spring is certainly by virtue of its magnitude alone one of, if not the most, valuable single resource* *feature in the park. It is clear therefore that actions and activities that affect Big Spring must be judged using the highest standard.*

Springs are unique ecosystems. Their stable thermal regime and water chemistry characteristics provide a unique environment for a variety of flora and fauna not commonly found in the main channel of their receiving stream. By definition springs are small systems, which makes them more sensitive to disturbances than the main river channel.

Watercress and other aquatic macrophytes play a key role in the spring ecosystem by providing organic input, habitat for macro invertebrates and substrate for periphyton growth (Converse 1994). Watercress grows mainly in shallow areas and is easily dislodged by wading activities. Wading activities by large numbers of visitors in the spring branch would significantly reduce the watercress biomass in the spring ecosystem. This biomass reduction would negatively affect the thermal regime present in these springs. At least one species of caddisfly is known to occur only in Big Spring and Greer Spring. Small changes in small sensitive systems like springs can have large effects. In addition, the export of large amounts of macrophyte material to the receiving river is significant (Converse 1991). No less than 38 animal species are restricted in distribution to Ozark springs and subterranean waters (Vineyard and Feder 1974). Several aquatic invertebrate species are known from as few as two Ozark springs including springs within Ozark National Scenic Riverways.

The scenic values of our large springs are probably the most obvious values to park visitors. The number of publications using photographs of these springs on their cover or in the body every year evidences this. Tens of thousands of people come to Big and Alley Springs every year just to look at these jewels of the Ozarks.

2.3 Discharge Rates of Large Springs in The Ozarks

As discussed by Jerry Vineyard and Gerald Feder in their anthological publication *Springs of Missouri* (first published in 1974, revised in 1982, and available at https://dnr.mo.gov/land-geology/geology/karst-missouri/springs)

> *Through the years records of the rate of flow of the large springs of the Ozark region of Missouri have been collected. Daily records are available from 1921 to present (1972) for Big Spring in Carter County and Greer Spring in Oregon County. Records for several years are also available for other large springs. Occasional measurements of discharge are available at most springs. From these continuous and occasional measurements it is possible to determine only an approximation of the relative size of the springs. Table 1 shows the relative size of the large springs in the Ozarks. This order of magnitude has been revised from that given by Beckman and Hinchey (1944, p. 16) because of the availability of longer records.*
>
> *During periods of high water many springs are flooded by nearby streams making discharge measurements difficult or impossible. For this reason the maximum discharges of many springs are not accurately known. Estimates of spring discharge during floods can be made by measuring the discharge of the receiving stream above and below the spring inflow, and using the difference as the estimate.*
>
> *Spring discharge measurements are given in this report in terms of gallons per day (gpd) or cubic feet per second (cfs). Discharge measurements are routinely made in terms of cfs. then converted to gpd when considered desirable. One cfs is a measure of volume and means one cubic foot of water passing a fixed point in one second.*
>
> *One cfs is equivalent to 646,000 gallons per day (gpd). Thus, to convert measurements in cfs to gpd, one simply multiplies the cfs figure by 646,000. Occasionally discharge measurements are needed in other terms. Conversion factors to other units of volume are:*

1 cfs = 449 gallons per minute = 646,000 gallons per day = 1.98 acre-feet per day = 28.3 liters per second.

Table 2.2 includes discharge rates for all first magnitude springs (average flow is greater than 100 cfs) and some second magnitude springs (10-100 cfs) in the Missouri Ozarks as listed by Vineyard and Feder. The only first magnitude spring in Arkansas, Mammoth Spring in Fulton County, is included by Vineyard and Feder because virtually its entire drainage area is in Missouri. For comparison, the table also includes average flow rates, in million gallons per day, for all first magnitude springs as provided by the Missouri Department of Natural Resources (DNR) in July 2021. DNR maintains a comprehensive GIS (Geographic Information System) database online for more than 4,400 springs, including bedrock geology and other useful information (see Figure 2.15). Minimum and maximum flow rates for quite a few springs are provided but without the period of record. Notably, there are no average flow rates, and it is not clear how were the reported values derived (e.g., from a few manual measurements, based on continuous monitoring for a specific period, etc.) All springs shown on the map in Figure 2.3, except for two second magnitude springs in Arkansas—Blue Spring in Carroll County, and Blanchard Spring in Stone County—are included in Table 2.2.

Table 2.3 is developed for this book from the official record by the United States Geological Survey (USGS) available online at https://waterdata.usgs.gov/ as of September-October 2023. Hydrographs for the individual springs were created from the downloaded USGS data and are provided further in the text.

In general, different sources including various web pages may give differing values for average daily flow of the same spring, often not citing where the original information came from. It is therefore important to understand the methodology of deriving an average flow rate value even when a longer period of record is available.

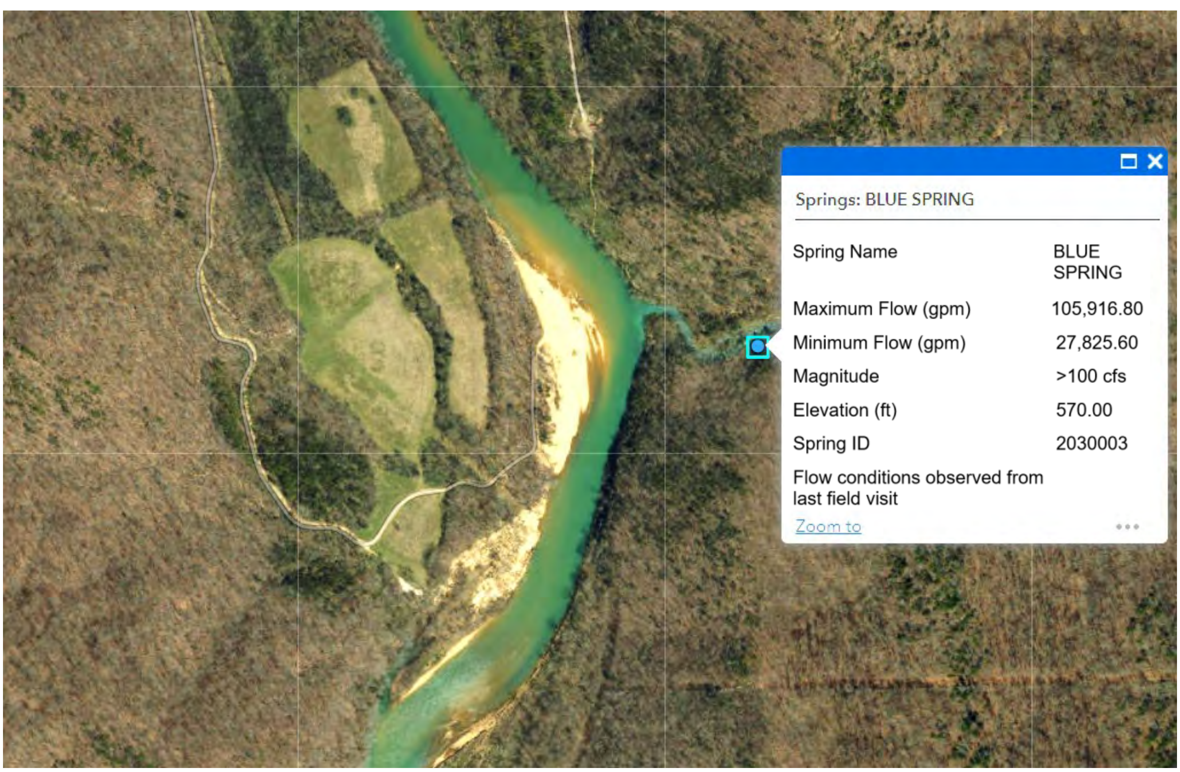


Figure 2.15 Screenshot of the Missouri DNR GIS database with spring data for over 4,000 springs. State of Missouri, Maxar | Esri Community Maps Contributors, Missouri Dept. of Conservation, Missouri DNR, © OpenStreetMap, Microsoft, Esri, HERE, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA.

Table 2.2 Flow rates of large karst springs in The Ozarks of Missouri and Arkansas (AR); Missouri Department of Natural Resources (DNR)

Name	County	Latitude	Longitude	Vyneard and Fedder, 1982; average, million gallons per day; MGD	Missouri DNR GIS		Missouri DNR[1] average; cubic feet per second cfs	Missouri DNR[1] average; million gallons per day MGD
					Qmin (gallons per minute)	Qmax (gallons per minute)		
Big Spring	Carter	36°57'08.31" N	90°59'38.98" W	276 MGD	105,917	583,440	470 cfs	304 MGD
Greer Spring	Oregon	36°47'11.47" N	91°20'56.14" W	214 MGD	46,675	405,266	360 cfs	233 MGD
Mammoth Spring	Fulton (AR)	36°29'52.23" N	91°32'09.52" W	155-278 MGD**	107,712	193,433	347 cfs	224 MGD
Bennet Spring	Dallas	37°42'59.64" N	92°51'24.24" W	100 MGD	39,943	77,642	185 cfs	120 MGD
Rainbow Spring***	Ozark	36°43'10.95" N	92°11'14.40" W	100 MGD*	21,094	104,122	155 cfs	100 MGD
Maramec Spring	Phelps	37°57'13.48" N	91°31'58.74" W	96 MGD	25,133	291,720	149 cfs	96 MGD
Blue Spring	Shannon	37°09'57.73" N	91°09'44.09" W	90 MGD*	27,825	105,917	139 cfs	90 MGD
Alley Spring	Shannon	37°09'17.15" N	91°26'29.66" W	81 MGD	24,235	475,728	125 cfs	81 MGD
Welch Spring	Shannon	37°23'38.20" N	92°34'27.44" W	75 MGD*	31,416	148,553	116 cfs	75 MGD
Boiling Spring	Pulaski	37°53'22.71" N	92°02'06.70" W	68 MGD*	25,133	31,506	105 cfs	68 MGD
Montauk Springs	Dent	37°27'36.91" N	91°40'59.67" W	53 MGD*	17,144	55,202		
Hahatonka Spring	Camden	37°58'26.67" N	92°46'01.50" W	48 MGD	44,027	44,027		
North Fork Springs	Ozark	36°43'28.29" N	92°11'13.30" W	43-49 MGD**	29,711	33,795		
Roubidoux Springs	Pulaski	37°49'31.24" N	92°12'05.55" W	38 MGD	2,091	86,170		
Pulltite Spring	Shannon	37°20'06.05" N	91°29'24.54" W	0.4-92 MGD**	2,648	63,730		
Round Spring	Shannon	37°16'49.61" N	91°24'40.57" W	26.5 MGD	4,488	233,376		
Roaring River Spring	Barry	36°35'30.00" N	93°49'56.95" W	20 MGD	3,608	79,438		

Notes: [1]Value from: Missouri Geological Survey, July 26, 2021. *Follow the Water. Understanding Springs in the Missouri Ozarks*. Accessed at https://storymaps.arcgis.com/stories/b046232085004488a24ec12e2631e793
** Average flow not given; range of several measurements
*** Previously known as Double Spring

Table 2.3 Annual mean discharge of large springs in the Ozarks of Missouri and Arkansas (AR) based on the analysis of officially reported measurements for USGS gaging stations as of October 2023. Available at https://waterdata.usgs.gov/. Notes: *Last two periods used. ** No USGS gaging station data publicly available; values are from Mugel et al., 2009 (USGS)

Spring	USGS Station ID	Annual mean discharge		USGS Period of Record
		Cubic feet per second	Million gallons per day	
Big Spring	07067500 Big Spring near Van Buren	454	293	10/1921 to 09/1996 02/2000 to 10/2023
Mammoth Spring (AR)	07069190 Mammoth Spring at Mammoth Spring	355.2	230	2/1981 to 10/2023
Greer Spring	07071000 Greer Spring at Greer	355.1	230	10/1921 to 10/2023
Bennett Spring*	06923500 Bennett Spring at Bennett Spring	198	128	10/1928 to 9/1941; 10/1965 to 01/1996; 02/2007 to 10/2023
Maramec Spring	07010500 Maramec Spring near St. James	153	99	10/1921 to 10/1929 10/1965 to 03/1986
Alley Spring	07065500 Alley Spring at Alley	134	87	10/1928 to 09/1939 08/1965 to 12/1979
Blue Spring**	N/A	107.8	70	1971
Hahatonka Spring	06924500 Ha Ha Tonka at Ha Ha Tonka State Park	74	48	10/1922 to 10/1926
Montauk Springs**	N/A	72.3	47	1965, 1967-68
Round Spring	07065000 Round Spring at Round Spring	47	30	10/1928 to 09/1939 08/1965 to 12/1979

2.4 Big Spring

As stated by the National Park Service (NPS) on its website for the Ozark National Scenic Riverways (ONSR), *The Big Spring is sometimes called America's biggest spring. In reality there are three contenders for that title: Big Spring, Idaho's Snake River Springs Complex and Florida's Silver Springs complex. Since the flow from springs varies with local rainfall, any of these three might be biggest on any given day depending on the weather in Missouri, Idaho, and Florida! The truth is they are all about the same size.*

Nevertheless, the publicly available official USGS records of the flow rates at these springs confirm that the Big Spring (Figures 2.16 and 2.17) is the largest individual spring in the United States based on its average discharge rate of 454 cfs for the period of record, October 1921–September 2023 (Figure 2.18). The Malad Canyon Springs and The Thousand Springs in Idaho are the two largest groups of closely spaced springs with the average discharge rate of 1,229 and 1,198 cfs respectively (see Chapter 4.2), whereas the main spring at the Silver Springs group, sometimes referred to as Mammoth Spring, has experienced a dramatic decline over the last several decades due to anthropogenic influences such that its average flow rate is significantly lower than that of Big Spring (see Chapter 1, Figure 1.3). On the other hand, Wakulla Spring in Florida has experienced a notable increase in discharge over the last decade, apparently due to saltwater intrusion from the Gulf of Mexico and may overtake Big Spring as the largest single spring in the country if the measurements are confirmed to be accurate (see Chapter 3.7).

Big Spring was one of Missouri's first state parks. It was a state park from 1924 until 1969 when the people of Missouri donated it, along with Alley and Round Spring State Parks, to the National Park Service to become a part of the ONSR. It is located four miles south of Van Buren at the end of State Route 103 (See Figure 2.13.)

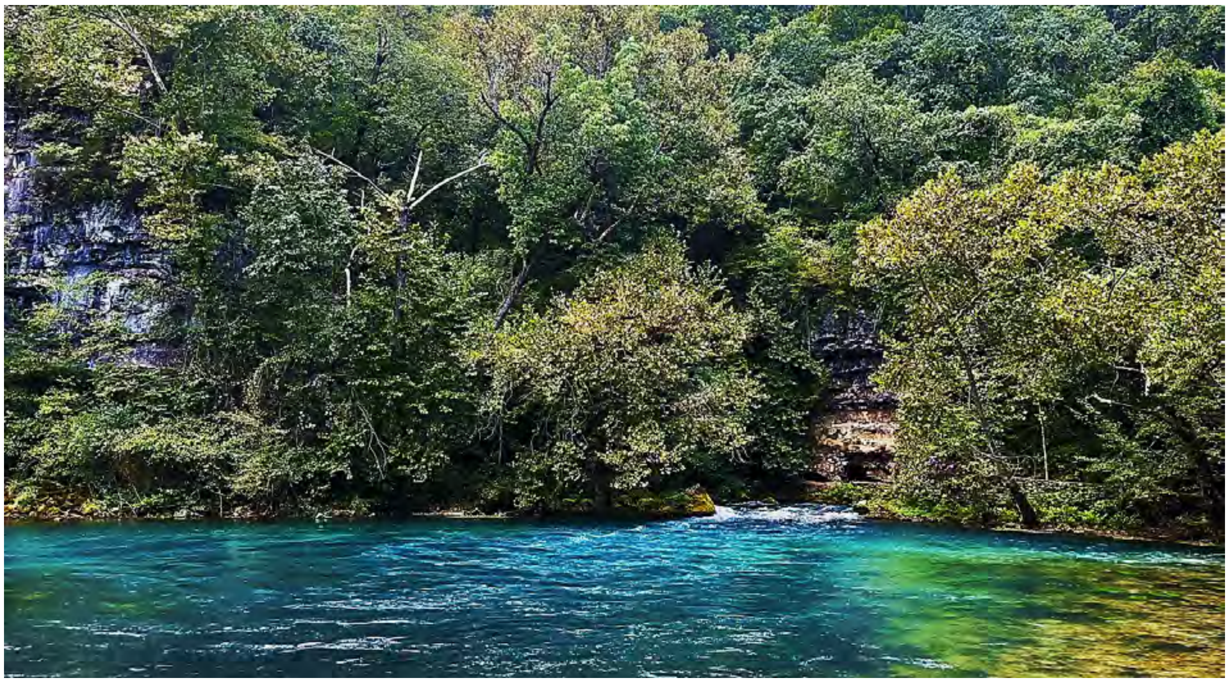


Figure 2.16 Big Spring in Carter County, Missouri, the largest individual spring in the United States, with the average flow rate of 454 cfs (293 MGD) for the entire period of record, October 1921—September 2023. For the February 2000—September 2023 period, the average flow is 477 cfs (308 MGD; see Figure 2.18).

Figure 2.17 Big Spring in Carter County, Missouri, the largest individual spring in the United States.

Big Spring rises at the base of a cliff formed in the Eminence Dolomite through a jumble of giant boulders that forces the water to flow through the openings between the rocks, thus causing the dramatic "boil" at the spring orifice (Figure 2.17). As described by Vineyard and Feder (1982), about one-third of the way up the slope, amidst large breakdown boulders, is the entrance to a small pit cave (closed to visitors) that can be entered with the aid of ropes giving access to a small room through which part of the Big Spring water flows. Here the water is quiet, but it moves swiftly toward the orifice. Divers of the St. Louis Underwater Recovery Team entered Big Spring through this relatively quiet pool to explore the conduit system channeling water to the spring orifice. They also descended into the main boil area of the spring, searching carefully for "dead spots" in the powerful current. Neither effort was successful in getting past the breakdown into the undisturbed conduit system of the spring, though one diver reported a tantalizing glimpse of immense caverns beyond. Since then, research dives showed the spring is at least 80 feet deep (Missouri Department of Conservation, 2023a).

The water and air-filled caves beyond the spring orifice must be very large. Grawe (1945, p. 181) calculated that, during an average day, Big Spring removes in solution about 175 tons of calcium carbonate, the chemical constituent of limestone (actually, it is calcium-magnesium carbonate, the main constituent of dolomite – author's remark). Therefore, in a year's time enough bedrock (640,000 tons) is removed to form a cave passage 30 feet high by 50 feet wide and 1 mile long. Of course, this material is not removed as a unit, but is distributed throughout the ramifying system of solution channels that feed the spring. The Big Spring system is continuously getting larger simply because each year the feeder system grows larger by the removal of rock by groundwater solution and, each year, more rock is exposed to the dissolving action of groundwater.

The maximum possible instantaneous flow from Big Spring has not been adequately defined because of backwater effects from the Current River during high-flow conditions. Notably, the graphs in Figure 2.18 show that the recorded peak flows were often truncated at 1,000 and 1,200 cfs, which means they were likely higher and could not be estimated. In 1983 and 1985 the flow exceeded 2,000 cfs couple of times each year.

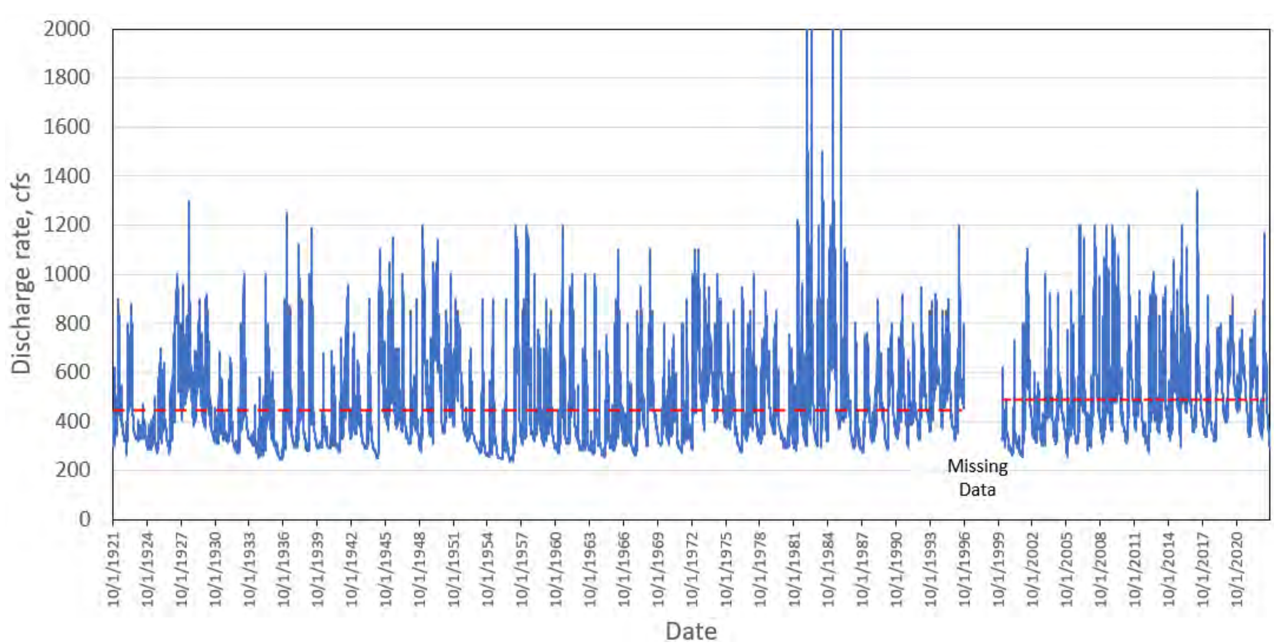


Figure 2.18a Hydrograph of the Big Spring discharge rate recorded at the USGS gaging station 07067500 Big Spring near Van Buren, MO for the period of record. For October 1921-September 1996 period the average is 447 cfs; for the February 2000 to September 2023 period the average is 477 cfs. The average rate for the entire period of record is 454 cfs or 293 million gallons per day (MGD).

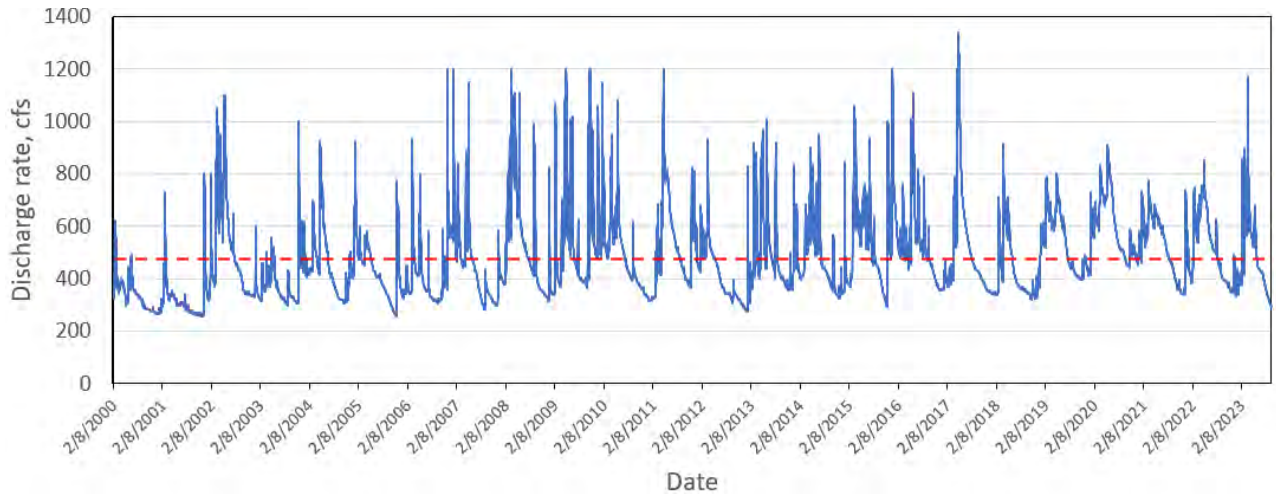


Figure 2.18b Hydrograph of the Big Spring discharge rate recorded at the USGS gaging station 07067500 Big Spring near Van Buren, MO for the February 2000 to September 2023 period; the average is 477 cfs. Note a number of peak flows truncated at 1200 cfs which suggests the flow rate exceeded this value and could not be reliably estimated

Big Spring is the most famous attraction in the Ozark National Scenic Riverways (ONSR) where thousands of visitors each year are educated by numerous panels such as the one shown in Figure 2.19. The National Park Service has produced a variety of pamphlets that can be found at the Visitors Center and at other locations throughout ONSR. The visitors are also informed that over 300 caves have been identified within the boundaries of ONSR, ranging from not much more than a rock overhang to one cave with almost seven miles of identified passages. Eight caves, including an open sinkhole, have been designated as outstanding natural features.

Most importantly, the visitors are alerted that cave ecosystems are unique and delicately balanced, with major changes possibly occurring from relatively slight disturbances. Geologic formations in some caves are quite fragile, easily damaged by vandalism or visitor overuse. Their formation is extremely slow, and physical damage may remain in evidence for generations. Some caves have been used by humans and animals since prehistoric times, and evidence of this use and artifacts may be easily obliterated.

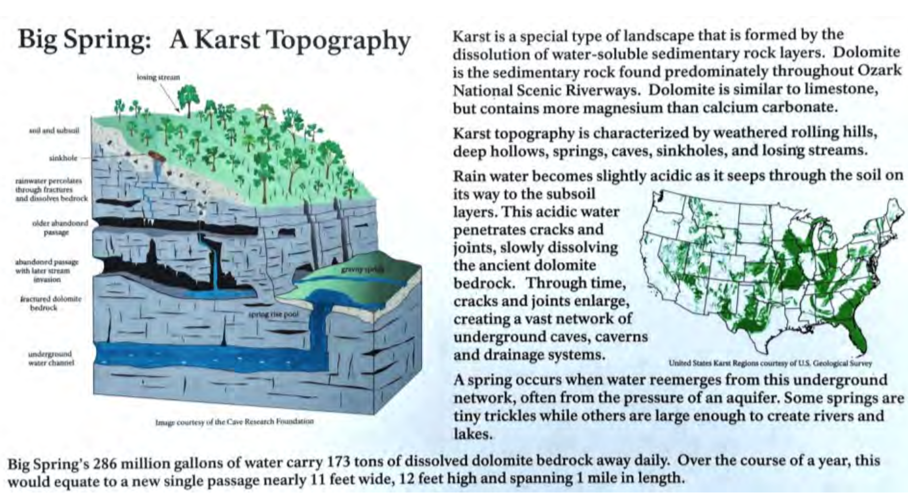


Figure 2.19 One of educational panels lining trails to Big Spring.

Some Ozark caves, which are better known or more easily reached, have received considerable visitation, and more damage and site deterioration have occurred. Caves may contain unsuspected hazards to visitors unfamiliar to such alien environments, and the threat of serious injury or death from falls or drowning is always present.

Several caves serve as habitat for the endangered Indiana and gray bats. As of October 2023, "***All park caves are now closed to visitation. This includes all caves along the Current and Jacks Fork Rivers. Please respect these closures."***

The reason for the cave closure is a serious disease of bats called White Nose Syndrome that has been killing bats, including the Federally Endangered gray bat. The disease may be spread by humans.

Both the Federal Government and the State of Missouri take protecting caves very seriously. Review of the applicable state and federal laws can be found at: https://www.law.cornell.edu/uscode/text/16/chapter-63.

2.5 Greer Spring

Greer Spring, one of the most significant natural features in Missouri, is located 18 miles south of Winona on the right side of Missouri Highway 19. It is the second largest spring in the state with a mean daily discharge of 355.1 cfs or 230 million gallons per day (Figure 2.22). The spring and the surrounding area, designated as a protected natural area in 2021, are in Mark Twain National Forest and owned and operated by the USDA Forest Service. Greer Spring was designated a National Natural Landmark in 1980.

Greer Spring flows from two openings – an upper cave outlet (Figure 2.20) and a lower orifice in the bed of the gorge (Figure 2.21) some 250 feet from the cave. The spring cave may be explored for several hundred feet, past a waterfall and plunge pool into a low-ceilinged passage in which the air space above water level gradually decreases until the wide, bedding-plane opening becomes completely water-filled, the rise of an underground stream. The lower orifice is a powerful streambed boil that obscures the conduit in the Gasconade Dolomite that feeds the spring. Divers have been successful in penetrating this opening to a depth of more than 100 feet, despite the powerful current (William Cate, oral comm., 1972; from Vineyard and Feder, 1982).

Greer Spring has the longest spring branch of all the first magnitude springs in Missouri, flowing just over a mile before entering the Eleven Point River where it more than doubles its flow. In addition to hydrogeologic significance, Greer Spring is an important aquatic natural community supporting a diverse assemblage of native fish species and aquatic invertebrates, including some species of conservation concern such as the cold-water crayfish (*Faxonius eupunctus*). The flora of the spring branch and associated Ozark fens is diverse as well. Greer Spring is critically important to the hydrology of the Eleven Point River, a National Wild and Scenic River (Missouri Department of Conservation, 2023b).

Figure 2.20 Panoramic photograph of the Greer Spring Cave outlet. Vertical gorge walls are in the Ordovician Gasconade Dolomite

Figure 2.21 Boil of the Greer Spring about 250 feet downstream from the spring's cave outlet.

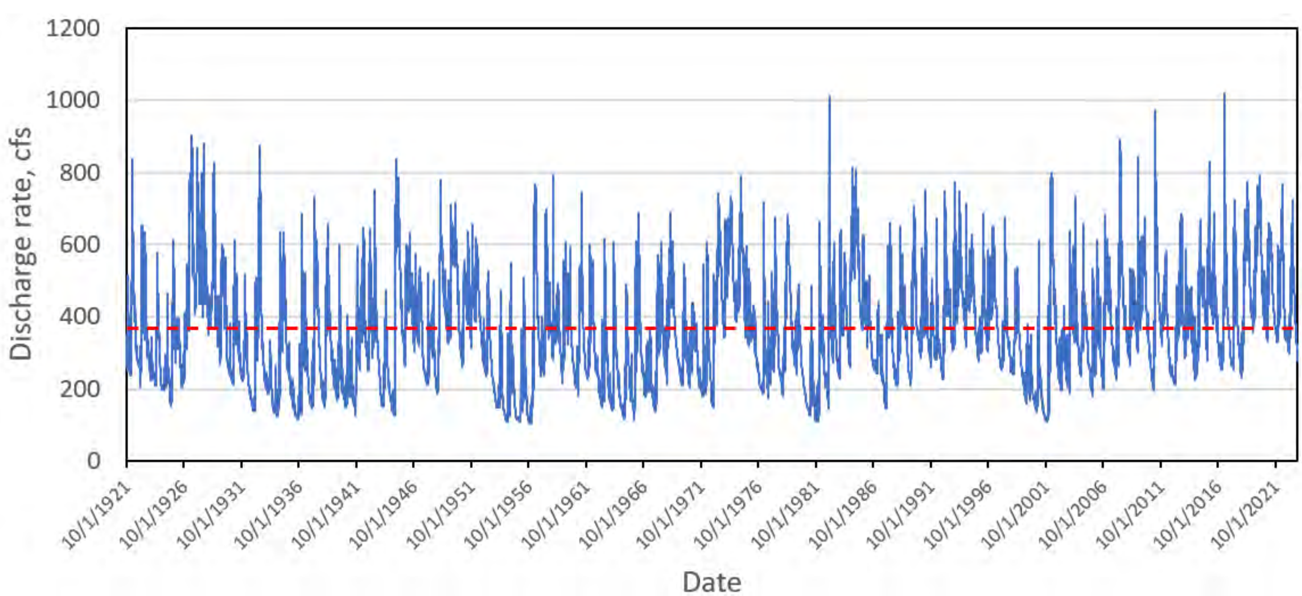


Figure 2.22 Hydrograph of the Greer Spring discharge rate recorded at the USGS gaging station 07071000 Greer Spring at Greer, MO. The average rate for the entire period of record (102 years) is 355.1 cfs (230 MGD). It appears that the overall spring discharge has had an upward trend since about 2011, which is a longer period than during previous long-term cycles. A similar trend can be seen on the hydrograph for Big Spring (Figure 2.18) indicating possible effects of climate change (?) in this part of the country.

As explained by Sony Hocklander in a Springfield Daily Citizen's backstory on the historic Greer Spring Mill (available at https://sgfcitizen.org/springfield-culture/greer-spring-mill-history/), Greer Spring is named for Samuel Greer, an early settler who moved his family to Missouri in 1859. He and his father, John Greer, purchased land that included the spring and built a mill the following year. That mill burned to the ground during the Civil War, according to historic records, and by 1870 Samuel Greer had constructed a new three-story mill, dam, and water wheel near the spring. In 1883 he began construction on a third mill — this time a roller mill (new technology) at the top of a hill above the spring in partnership with George Mainprize. Tragically, Greer's 23-year-old son Lewis was killed in 1884 during construction.

This third mill — the only one still standing — began operating in 1899. That mill was built 1,140 feet above its water source of power, conducted to the mill through a turbine and pulley system, making it a rare operation.

A catalyst for social interaction and commerce, the mill changed hands twice until operation ceased around 1920. About this time the land changed hands twice again, with ownership held by the Louis E. Denning family until the late 1980s. That's when St. Louis resident Leo Drey purchased the property to preserve it until an eventual sale to the United States Forest Service of the USDA added the mill and spring to the Eleven Point National Scenic River Area and Mark Twain National Forest.

Figure 2.23. Historic photos of the old mill operation like the one shown here can be found on the Friends of the Eleven Point River Facebook page at: https://www.facebook.com/media/set/?set=oa.454870931289175&type=3

Vineyard and Feder in their publication on the Missouri springs (1974) provide this inspiring tale of the lucky destiny of Greer Spring:

> Missouri's second largest spring may be unsurpassed in the beauty of its wilderness setting, so colorfully described by Owen (1898, p. 82-93) and little changed in 75 years. In the days when water power was the wave of the future, engineers dreamed of taming the wild Greer Spring branch, with a flow said to be " ... *two hundred and eighty yards per minute, With no appreciable variation,"* by building a dam across the precipitous gorge carved by the spring branch. However, Miss Owen showed foresight far in advance of her time when she said, *"The high walls of Greer Spring gorge will, of course, far more than double the value it would otherwise possess, when it becomes desirable to control and turn to practical account the power now going so cheerily to waste, but the artistic loss will be proportionately severe."* Fortunately for this generation and others to come, those who have owned the spring since it was named for Captain Greer nearly a hundred years ago, appreciated its beauty and no dam was ever built in the gorge. Greer Spring is as wild and beautiful today as it was in the 1880's.

2.6 Mammoth Spring, Arkansas

The orifice of Mammoth Spring is a short distance across the Missouri-Arkansas line at the head of the Spring River in the town of Mammoth Spring, Arkansas, east of state highway 63 (Figure 2.24). Mammoth Spring is a permanent spring that ascends upward under pressure along a major northwest-trending basement lineation (fault) and forms a pool which has two natural outlets (Figures 2.25 and 2.26). The springs resurges from the Jefferson City Dolomite (Figure 2.27), a low-yielding aquifer that is not capable of such large discharge, hence the source of the flow is attributed to deeper dolomitic formations which include Potosi, Eminence, Gasconade, and Roubidoux Formations, ranging in age from Upper Cambrian through Lower Ordovician (Brahana, 2023).

Figure 2.24 Google Earth map of the Mammoth Spring area. The Spring pool (shown with dark blue arrow) is in the upper center-left, with two outlets (shown with yellow arrows) discharging into a marshy lake. Dam for the historic Arkansas Missouri Power Company electric power plant is in bottom center. Spring is in the Mammoth Spring State Park. Imagery ©2023 Maxar Technologies, State of Arkansas, USDA/FPAC/GEO, Map data ©2023.

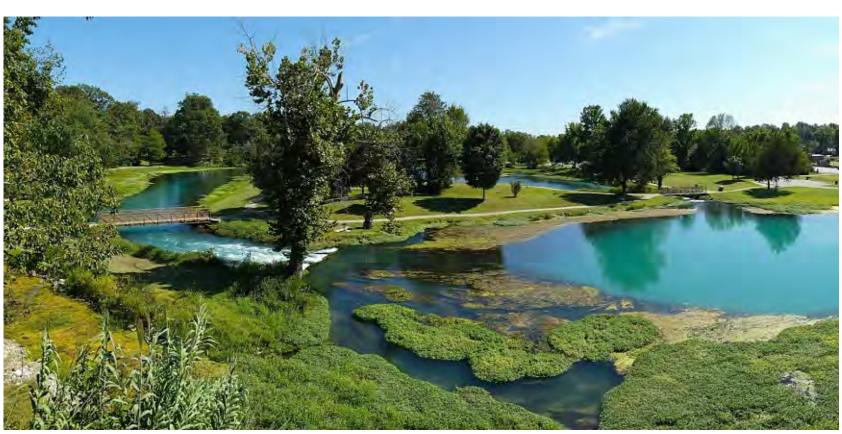


Figure 2.25 View of the Mammoth Spring pool from the viewing platform. Northeastern outlet is in the center-left, and southern outlet is in the center-right.

Figure 2.26 *Left*: Northeastern outlet of the Mammoth Spring pool. *Right*: Southern outlet of the Mammoth Spring pool.

Vineyard and Feder (1974) detail the quest to establish drainage area of the Mammoth Spring including various dye tracing tests. Here is an interesting excerpt:

*"Beckman and Hinchey discussed the probable recharge area of Mammoth Spring and recounted local stories of water tracing by cornstalks and straw dumped into Grand Gulf near Thayer, Missouri. In 1966 fluorescein dye was traced from Grand Gulf to Mammoth Spring by Toney Aid in a test monitored by Vineyard (Aid, unpublished report, 1966). Subsequently Aley (written comm., 1972) also traced water from a Missouri locality into Mammoth Spring. Grand Gulf (*Figure 2.28 in this book*) is one of the most spectacular surface karst features of the Ozark region; it was recently (1972) acquired by a private foundation for eventual donation to a state or federal agency for the enjoyment of the public. Owen (1898; 1970, p. 95-101) gave a colorful description of Grand Gulf as it was in the mid-1880's. At that time it was possible to enter and explore a large underground stream by boat – the same stream that emerges some 9 miles away as Mammoth Spring. Always a careful observer, geologist Owen mentioned (p. 100) the blind white fish in the stream: "The small eyeless fish had been noticeable in the water everywhere but now came swimming about the boat in an astonishing multitude, and as unconscious of any possible danger as bees in a flower garden."*

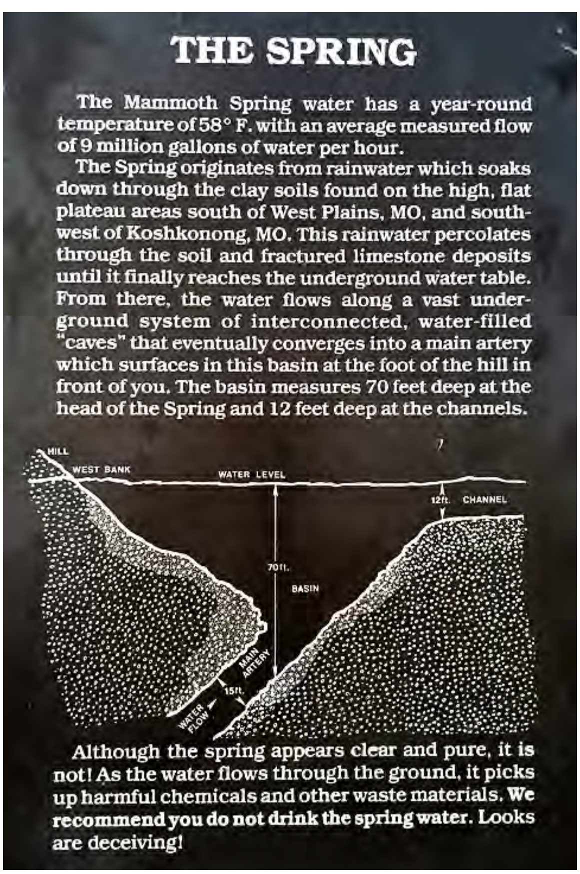


Figure 2.27 One of many panels that inform visitors of the Mammoth Spring State Park about various natural and cultural features in the park. This panel states that "...water has a year-round temperature of 58 ^{O}F, with an average measured flow of 9 million gallons of water per hour (the updated number is 9.5 or 355 cfs – see Figure 2.28). And that "the water flows along a vast underground system of interconnected, water filled "caves" that eventually converges into a main artery which surfaces in this basin at the foot of the hill in front of you. The basin measures 70 feet deep at the head of the Spring and 12 feet deep at the channels."

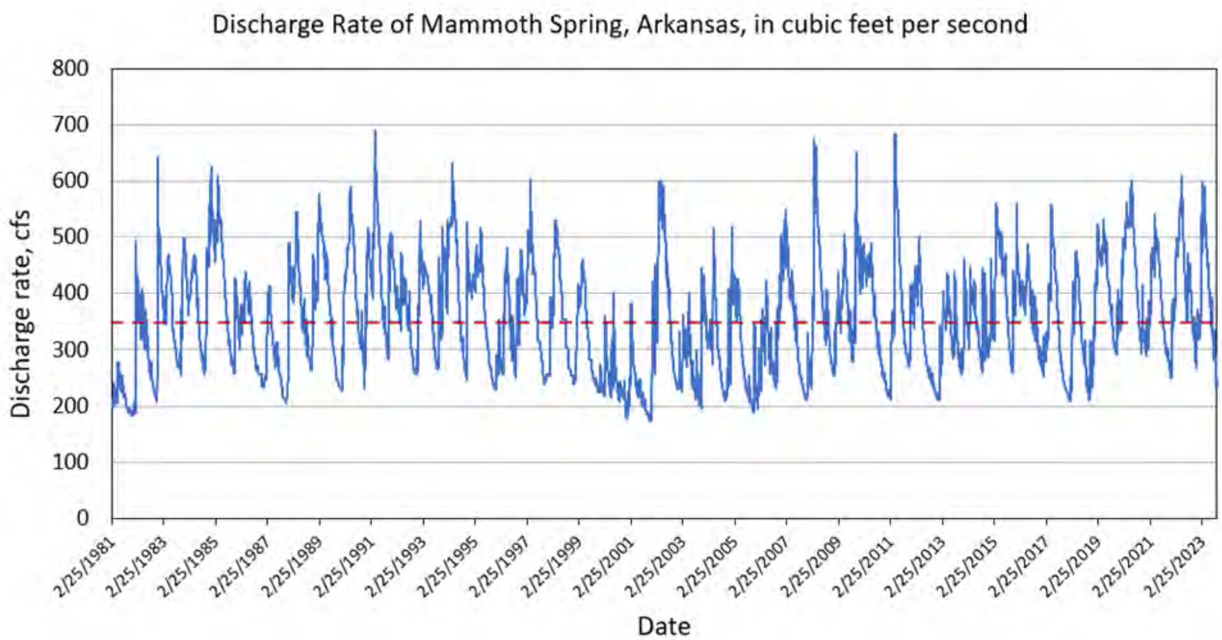


Figure 2.28 Hydrograph of the Mammoth Spring discharge rate recorded at the USGS gaging station 07069190 Mammoth Spring at Mammoth Spring, Arkansas. The average rate for the period of record (42 years) is 355.2 cfs (230 MGD), which is virtually the same as the rate of Greer Spring in Missouri (see Figure 2.22).

The state of Missouri established Grand Gulf State Park in 1988. Some people call it the “Little Grand Canyon.” Some just call it breathtaking (Figure 2.29). The park is one of the exceptional natural wonders, presenting the most spectacular collapsed cave system in the Ozarks. The Grand Gulf stretches for about three-quarters of a mile between 130-foot-high walls. Visitors can view the gulf from trails on top or from the floor where they can walk under the natural bridge, which spans 250 feet with a 75-foot-high opening. There is no official trail leading to the bottom, so visitors should use extreme caution when attempting to access the bottom. Interpretive signs detail the formation of the gulf.

Visitors of the Mammoth Spring State Park can also learn that the Spring’s water forms the scenic Spring River, one of Arkansas’s most popular trout rivers. In addition to the rainbow trout found in its upper stretches and the walleye and bass in its lower reaches, the Spring River is rated one of the state’s best float streams. White-water shoals and rushing falls challenge canoe and kayak paddlers from its origins to Williford, 31 miles away.

Early 19th century settlers in the Mammoth Spring area formed a village known as “Head of the River.” The town prospered due to a grist mill powered by the spring’s water. In 1886, the Kansas City, Fort Scott & Memphis Railroad built lines into the area and constructed one of its first train depots in the town, now called Mammoth Spring. In 1901, the "Frisco Railroad" acquired the line. With the coming of the railroad and the addition of the dam by the Mammoth Spring Milling Company (wheat mill) in the 1880s, the town flourished. The Arkansas-Missouri Power Company bought rights to the dam in 1925 and constructed a hydroelectric plant which provided electricity to the area until 1972 (Figure 2.30). In 1957, legislation established Mammoth Spring State Park (https://www.arkansasstateparks.com/parks/mammoth-spring-state-park). Mammoth Spring was declared a National Natural Landmark by the Department of the Interior in June 1972.

Figure 2.29 Two photographs from the Grand Gulf State Park in Missouri, about 9 miles northwest of Mammoth Spring. Courtesy of Missouri State Parks.

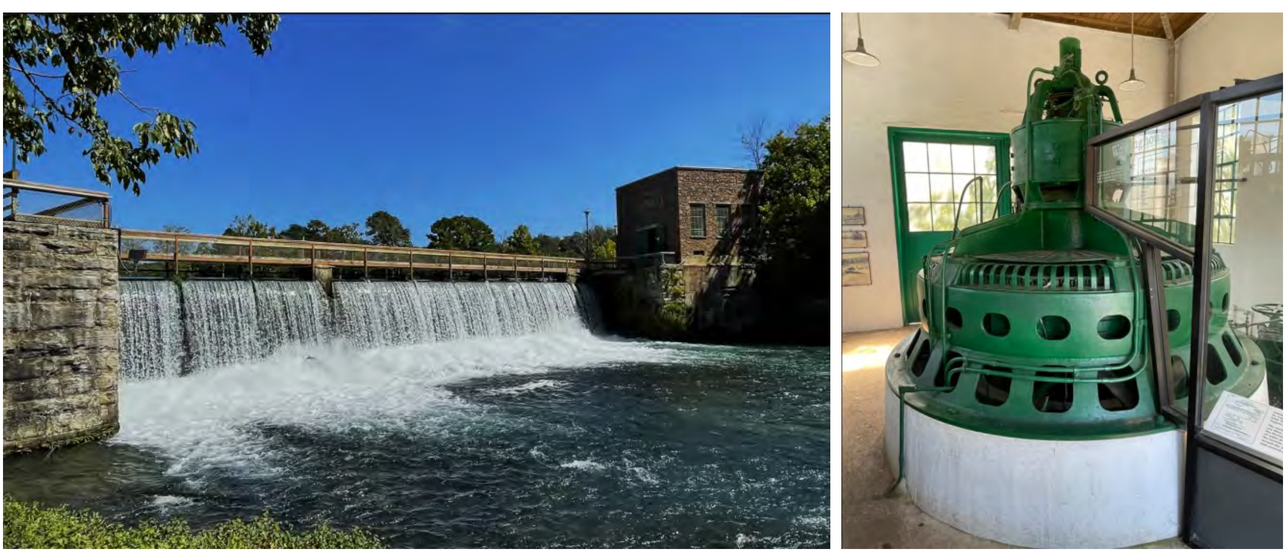


Figure 2.30 *Left*: Dam, headwater of the Spring River, built by the Mammoth Spring Milling Company in 1888, and hydroelectric plant built by the Arkansas-Missouri Power Company in 1925-1926. *Right*: Original generator on display in the power plant building.

2.7 Bennett Spring

As explained by James E. Vandike in a very comprehensive hydrogeologic report with excellent visuals ("The hydrogeology of the Bennett Spring area, Laclede, Dallas, Webster, and Wright Counties, Missouri", 1992) Bennett Spring, less than a mile west of the Laclede County line in Dallas County, is considered the third largest spring in Missouri and the largest spring in the Niangua River basin. The spring rises from a steeply inclined water-filled cave passage developed in the Gasconade Dolomite on the east side of Spring Hollow about 1.3 miles upstream from its confluence with the Niangua River. Divers have explored and mapped the inclined spring conduit to a depth of about 80 feet and a horizontal distance of about 130 feet (Figure 2.31). The passage continues, but gravel chokes most of it. Higher velocity of the water resulting from the decrease in cross-sectional area has halted exploration (Porter, 1986).

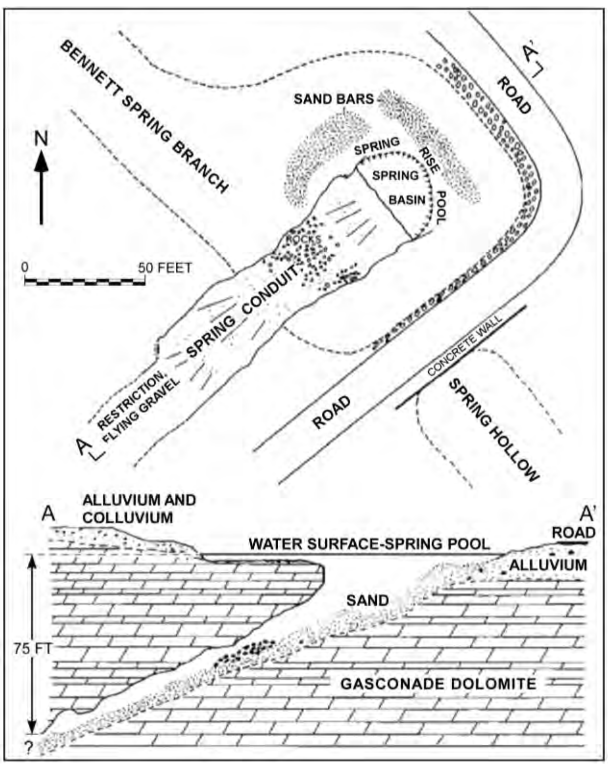


Figure 2.31 *Left*: Plan view and cross-section of Bennett Spring. Modified from a map by Porter and Brown, 1984 (in Porter, 1986). From Vandike, 1992. *Right*: aerial photograph of Bennett Spring. Courtesy of Missouri Department of Natural Resources; available at: https://dnr.mo.gov/land-geology/geology/karst-missouri/springs

Vandike's analysis shows that, as of 1990, forty-one years of discharge records were available from the U.S. Geological Survey (1916-1919, 1928-1941, 1965-1990), and the average discharge was 170 ft^3/sec (cfs), or about 110 million gallons per day. Figure 2.32 includes additional flow data available as of October 2023 and shows a higher average discharge based on the last two continuous monitoring periods: 1996 cfs for 10/1965 to 1/1996, and 200 cfs for 2/2007 to 9/2023.

Bennett Spring is the principal groundwater outlet for an extensive karst area in south-central Missouri. A hydrologic reconnaissance in the Bennett Spring area of Laclede, Dallas, Wright, and Webster counties, which includes the upper Niangua River, Osage Fork of the Gasconade River, and Dry Auglaize Creek, identified nearly 40 streams that lose significant volumes of surface flow into the karst groundwater system. The Bennett Spring recharge area, based on water tracing and existing potentiometric map data, consists of a 265 mi^2 area east, south, and southwest of the spring. Precipitation, discharge, and specific conductivity data show that the discharge of

Bennett Spring begins increasing generally within a few hours after precipitation due to pressure-head increase in the recharge area, but the water introduced into the aquifer from a precipitation event does not reach the spring for several days. The magnitude of flow increase depends greatly on soil moisture conditions; greater flow increases occur after precipitation when soils are wet than during relatively dry conditions (Vandike, 1992).

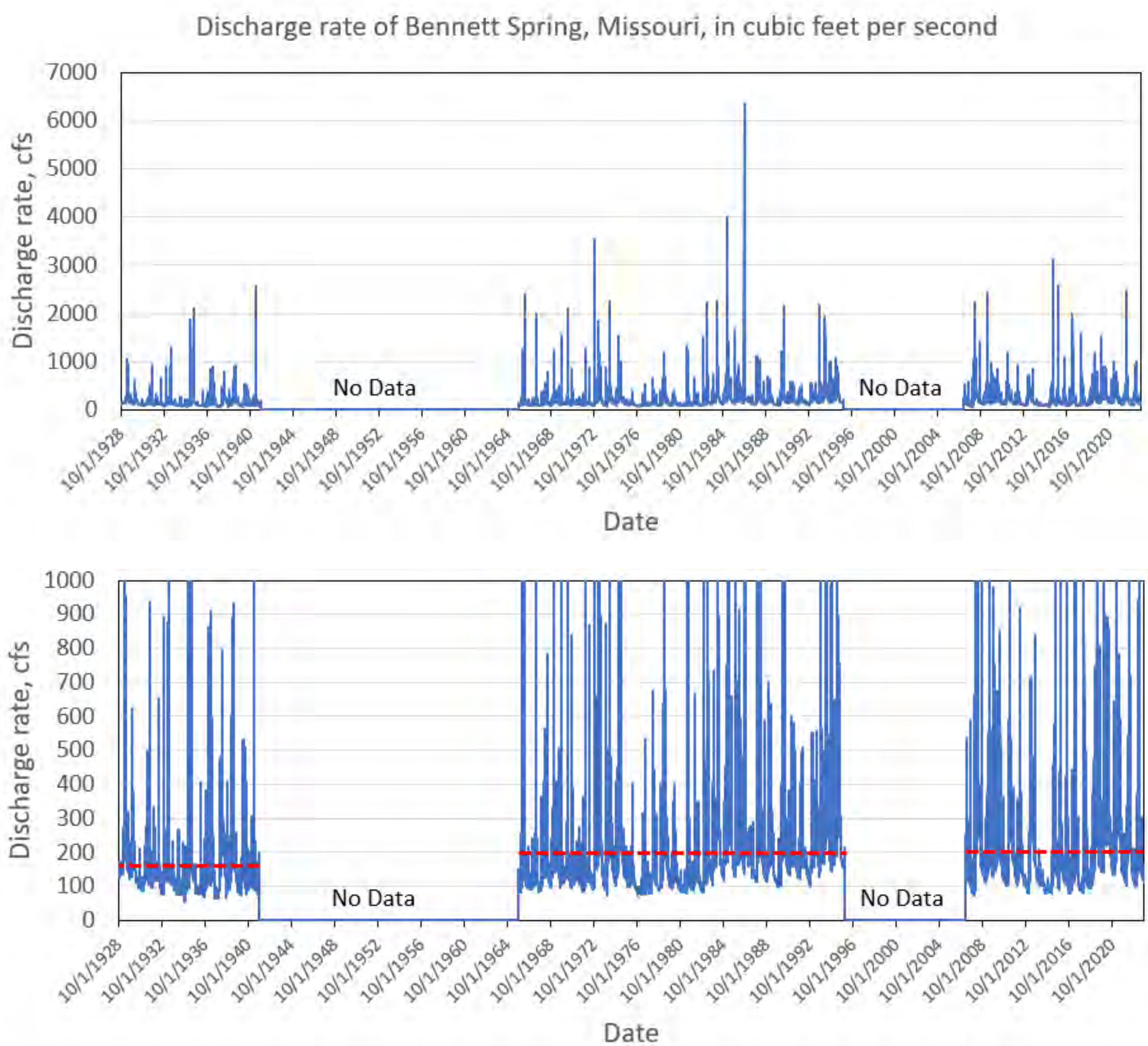


Figure 2.32 Hydrographs of the Bennett Springs discharge rate recorded at the USGS gaging station 06923500 Bennett Spring at Bennett Springs, Missouri. Average for the first period 10/1928 to 9/1941 is 152 cfs; Average for the last two periods is 196 cfs for 10/1965 to 1/1996; and 200 cfs for 2/2007 to 9/2023. Bottom graph is with a different vertical scale (truncated at 1000 cfs) to better show variations in minimum flows.

Bennet Spring is in a Missouri state park of the same name. The park features a nature center, a pool, dining, a store, trails, float trips, lodging, and campsites. Like the other three public trout parks in Missouri—Roaring River, Montauk State Park, and Maramec Spring Park—the Bennet Spring Park has high-quality fishing in a cold-water spring (Figure 2.33) with specific trout fishing seasons. The stream formed by the spring is stocked daily from March 1 to Oct 31.

Figure 2.33 Bennet Spring is part of the Bennet Spring State Park renowned for its excellent trout fishing.

2.8 Rainbow (Double) Spring, and North Fork Springs

Rainbow Spring, also known as Double Spring, is located 30 miles west of West Plains, Missouri and accessible via Route CC (west), State Highway 181 (south), and County Road 374 (east). It boils up around large blocks of dolomite and sandstone at the western base of a wooded bluff on the right bank of the North Fork River (Figures 2.34 and 2.35). Spring is in the uppermost Gasconade Dolomite. Ledges of sandstone of the Roubidoux Formation are exposed in the bluffs upstream and downstream from the spring, and in the bed of the North Fork at North Fork Springs (Vineyard and Feder, 1982). The water bursts from the base of a wooded bluff with a boil that rises one to two feet above the surface in a rocky grotto green with ferns, mosses, and watercress.

The outflow from Rainbow Spring divides into two branches as it leaves the pool, one leading north and the other south, forming a long island between the spring branch and the North Fork (Figure 2.35). This is the reason why Rainbow Springs originally was called Double Spring. The south branch carries 70 to 80 percent of the flow. Dams are built across both ends of the island to connect it with the mainland.

Rainbow Spring has been measured 27 times between 1919 and 1966, with the average discharge rate of 127 cfs. The maximum flow of 232 cfs was measured in April 1965 and the minimum flow of 47 cfs was measured in November 1964 (Vineyard and Feder, 1982; Table 13, page 128). It is therefore not entirely clear why Vineyard and Feder give an estimated value of 100 million gallons per day (155 cfs) for the average flow of the spring in Table 1 of the same publication.

The spring, and thousands of wooded acres around it, has been privately owned and preserved by Carpenter's St. Louis-based family for more than a century. Rainbow Springs is still the best-kept secret among Missouri's natural wonders.

Figure 2.34 Rainbow Spring (formerly better known as Double Spring) has an estimated average discharge rate of 127 cfs based on 27 measurements between 1919 and 1966. Left photo Courtesy of Missouri Department of Natural Resources; available at https://dnr.mo.gov/land-geology/geology/karst-issouri/springs. Right photo by W.H. Pohl, from Beckman and Hinchey, 1944.

Figure 2.35 Screenshot of the Missouri DNR GIS database with satellite image of the area of Rainbow and North Fork Springs in Missouri. Esri, NASA, NGA, USGS, FEMA|Esri Community Maps Contributors, Ozark County, Missouri Dept. of Conservation, Missouri DNR, © OpenStreetMap, Microsoft, Esri, HERE, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA.

North Fork Springs are about 750 to 1,000 feet upstream from Rainbow Spring. They consist of numerous openings on the left bank of the river, in the bed of the river, and in the gravel bar toward the right bank. The openings on the left bank and in the bed of the river are along joints and those in the river form lines of boils extending from the shore to the gravel bar; they are aligned with the joint system in the bank and bed of the river. The rises comprising North Fork Springs extend about 100 feet along the river. North Fork Springs were first measured in November 1964 and three measurements of the spring flow have been made since that time. North Fork River flows over a bedrock floor in much of the reach from North Fork Spring to Rainbow Spring.

As noted by Vineyard and Feder (1982), it is difficult to explain the correlative measurements of the outflow of Rainbow and North Fork Springs. Listed below are these measurements of the two springs:

	Nov 16, 1964	April 8, 1966	July 6, 1966	Oct 6, 1966
North Fork Springs	75.9 cfs	66 cfs	75.3 cfs	68.4 cfs
Rainbow Spring	47 cfs	180 cfs	150 cfs	132 cfs

If the two springs are hydraulically connected, there should be closer correlation between the outflows of the two springs. It is suggested that if the two are hydraulically connected, North Fork Springs have a constricted outlet opening allowing little variation in flow. Rainbow Spring, on the other hand, can discharge the greater volumes of water available in the spring supply system during the winter and spring months. The similarity of the water from North Fork and Double Springs also suggests a common supply system. In April 1966 the springs were sampled, and the results show that their water is chemically almost identical (Vineyard and Feder, 1982).

Fed by springs and protected by national forest for the top two-thirds of its 50 miles, the North Fork has one of the largest self-sustaining wild rainbow trout populations in the Midwest. Resident bald eagles live in the valley, and the river was chosen by wildlife researchers for a restocking program of endangered Ozark hellbenders, a large, aquatic salamander.

2.9 Maramec Spring

Maramec spring (Figure 2.36) is located approximately 8 miles south of St. James in Phelps County, Missouri. The spring issues from within Maramec Spring Park which is privately owned by The James Foundation (http://maramecspringpark.com/). The spring's average discharge is 153 cfs or 99 million gallons per day (see Table 2.3 and Figure 2.37).

Waters of the spring rise in a circular basin beneath a high bluff of Gasconade Dolomite which is above the Eminence Dolomite, the main water-bearing unit for the spring. The Eminence is a gray, medium- to coarsely-crystalline gray dolomite and contains very little chert. The unit hosts most of the 10 largest springs in the Ozark region. To date, the submerged channel of spring has been explored out to 3,800 ft in length and to a depth of 280 ft. The seven-minute video entitled "The Hidden World Beneath Maramec Spring Park," is on display inside the Maramec Spring Park Museum (OCDA, 2023).

Three Ordovician-age bedrock formations are exposed in the Maramec Spring area. The Gasconade Dolomite, from which the spring discharges, is about 350 ft thick, and is the basal Ordovician bedrock unit. It overlies the Eminence Dolomite and is exposed at Maramec Spring as well as along the parts of the valleys of Dry Fork Norman Creek, and the Meramec River. An artificial lake has been created by the damming of the spring branch downstream from the spring orifice. The dam, which raises the water level 8 to 10 feet, was built in the early 1800's to provide waterpower for a charcoal iron-making industry. Vineyard and Feder (1982).

As explained by Vineyard and Feder (1982), Maramec Spring played an important role in the early development of Missouri. Near the great spring were deposits of the red iron mineral hematite, brown limonite, and iron pyrites. Thomas James, an ironmonger from Ohio, came to Missouri in 1826 and began to build the

Maramec Iron Works at Maramec Spring. The spring was used for waterpower for the Maramec Works, the largest and sometimes the only local supplier of iron products in the Missouri economy. Maramec iron was shipped to markets across Missouri over primitive "iron roads" that later became routes of Missouri's highway system.

Figure 2.36. Maramec Springs, discharging beneath a high bluff of Gasconade Dolomite. Courtesy of Maramec Spring Park. Photo by Tammie Leigh. Available at http://www.maramecspringpark.com/spring/

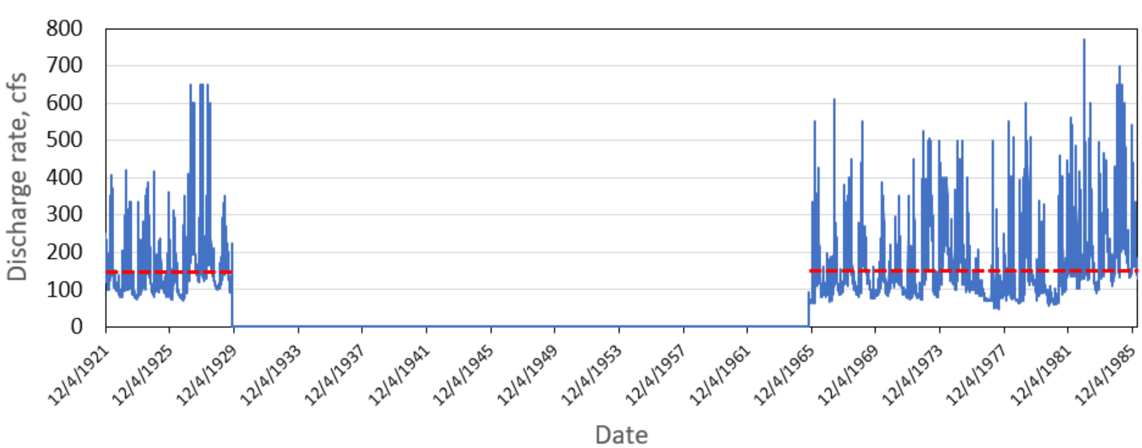


Figure 2.37 Hydrographs of the Maramec Spring discharge rate recorded at the USGS gaging station 07010500 Maramec Spring near St. James, Missouri. Average for the first period 12/1921 to 10/1929 is 150 cfs; for the second period 10/1965 to 3/1986 it is 156 cfs. For the entire period of record the average discharge is 153 cfs.

Maramec Spring powered the undershot water wheels (Figure 2.35) of the iron works for half a century, from 1826 to 1876, when advancing technology made the charcoal iron-making industry obsolete. Today the spring and what remains of the Maramec Iron Works are part of the privately-owned public park, operated by the James Foundation of New York, which offers trout fishing, playgrounds, and an excellent museum.

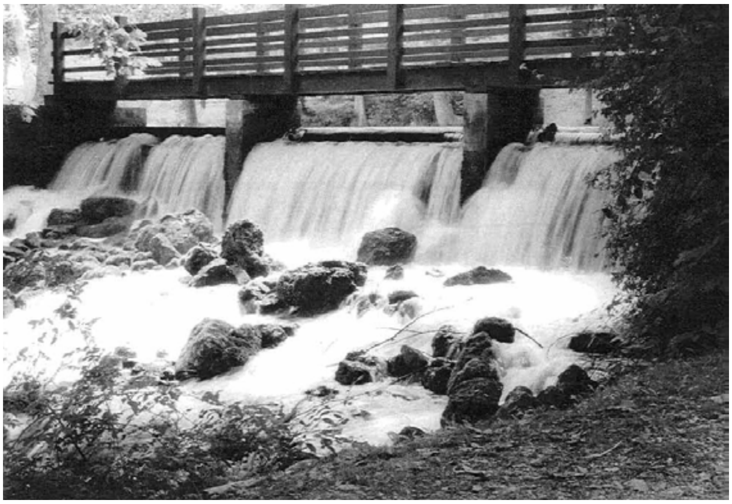


Figure 2.35 This scenic waterfall at Maramec Spring was the site of an undershot water wheel that helped power the Maramec Iron Works. Photo by Jim Vandike.

Figure 2.36 Maramec Spring is filled with rainbow trout, stocked daily by the Missouri Department of Conservation. Trout season starts March 1st until October 31. Catch and release fishing runs from November through February. Courtesy of Maramec Spring Park. Photo by Tammie Leigh. Available at http://www.maramecspringpark.com/spring/

Figure 2.37 Young people enjoy an outing at Maramec Spring, circa 1903. From left to right: Lena Gorman, Austin Gunter, Laura Morrison, Ethel Worthand, Elsie Pinto. Photo courtesy of the Lucy Wortham James Memorial Library and the James Foundation. Photographer unknown. From Vandike, 1996.

In 1843 Thomas James sent his son, William, to manage the Maramec Iron Works with furnaces powered by the rushing spring water. He remained there until operations ceased and the Iron Works closed in 1876. At its peak, the company town had an estimated population of over 500.

Following the death of William James in 1912, his granddaughter, Lucy Wortham James, acquired ownership of Maramec Spring along with the forest and farmlands surrounding it in 1920. Upon her death in 1938, she made her residuary estate a part of a Trust and authorized creation of the James Foundation.

To her executors, Lucy Wortham James wrote, “As this is considered to be the most beautiful spot in Missouri, it is my great hope that you will arrange that it may ever be in private, considerate control, and ever open to the enjoyment of the people.”

2.10 Blue Spring on Current River

Blue Spring is located 14 miles east of Eminence or 14 miles west of Ellington off State Route 106. A long dirt road leads to the parking area from the state highway, and it is very steep. It is not recommended for large RVs or buses, although in most weather a normal passenger car can make it quite well. From the parking lot it is about 1/4 mile walk down a pleasant trail.

Blue Spring rises quietly beneath a bluff of Eminence Dolomite (Figures 2.38 and 2.39) from a very deep cave shaft and flows swiftly toward the Current River about 1/4-mile away. The spring’s average discharge rate is 108 cfs (70 MGD) based on limited record (see Table 2.3). Schumacher (2008) summarized data for 115 discharge measurements made by the USGS from 1923 through 2006, including some measurements that had not previously been compiled. The discharge measurements ranged from 59.3 to 290 ft^3/s with a mean of 127 ft^3/s.

The Blue Spring Natural Area is managed by the Missouri Department of Conservation, while the Current River and surrounding area are administered by the National Park Service, as part of Ozark National Scenic Riverways.

Many divers, notably members of the St. Louis Underwater Recovery Team and more recently of The Ozark Cave Diving Alliance (OCDA), have explored Blue Spring. The tubular orifice of the spring plunges at a steep angle beneath the bluff. It is this steep angle and extremely deep water that heightens the deep blue color of the spring. The maximum depth reached by divers (currently 278 feet) may not represent the total depth of the spring; divers report that only the technical problems of descending to such depths prevent further exploration of the conduit system that feeds Blue Spring. A map of progressive diving attempts is shown in Figure 2.40 and can be found at the web site of OCDA together with the accompanying narrative (note that dive access is limited to those who obtain a research permit) https://www.ocda.org/exploration/projects/photo-of-the-month/.

The following description of the Spring is from Missouri Department of Conservation, 2023c: “A large, beautiful, undisturbed spring and spring branch with associated aquatic plants and animals surrounded by forest in the Current River Hills region of the Ozarks. The Osage Indians reportedly called this spring “Spring of the Summer Sky” (“Do-Ge-Ke-Thabo-Bthi”). Spring water is actively dissolving away limestone and or dolomite as it moves through the earth. Springs are actually excavating new caves through this process. This dissolved limestone and or dolomite, along with the influence of the spring's depth and the blue of the sky, impart the blue color of the spring. The recharge area for the spring includes the headwaters of Logan Creek which is nearly 10 miles away. This part of the recharge area lies in the topographic watershed of the Black River despite the fact that the spring itself is feeding the Current River. In the spring pool star duckweed, American bur-reed, and water starwort occur. Giant cane, grass-of-Parnassus, and blue boneset grow along the banks of the spring run. Southern redbelly dace, Ozark sculpin, and rainbow darter inhabit the spring run. The rare Swainson's warbler has been found in giant cane stands along the Current River just upstream from the spring run. Other birds to look for include American redstart, northern parula, kingfisher, Kentucky warbler, red-shouldered hawk, ovenbird, wood thrush, and yellow-throated warbler.

Figure 2.38 Blue Spring in Shannon County, Missouri, the gem of Ozark National Scenic Riverways.

The surrounding area was used for a lodge and retreat until 1960 when it was sold to the Conservation Department. Just upstream on the Current River is Owls Bend. This area historically supported a mill that produced gunpowder and a river ferry which was the only way across the Current River here until 1975."

The area first came into possession of a logging company in the 1800's but was later purchased by Richard G. Hager in 1925. After passing down the family Blue Spring became a sportsmen's retreat and lodge. It is mentioned by Leonard Hall in his famous float book, *Stars Upstream*. The Missouri Department of Conservation came into possession of the property in 1960.

Figure 2.39 Cave diving photograph from Blue Spring in Shannon County, Missouri. Copyright Jennifer Idol, printed with permission.

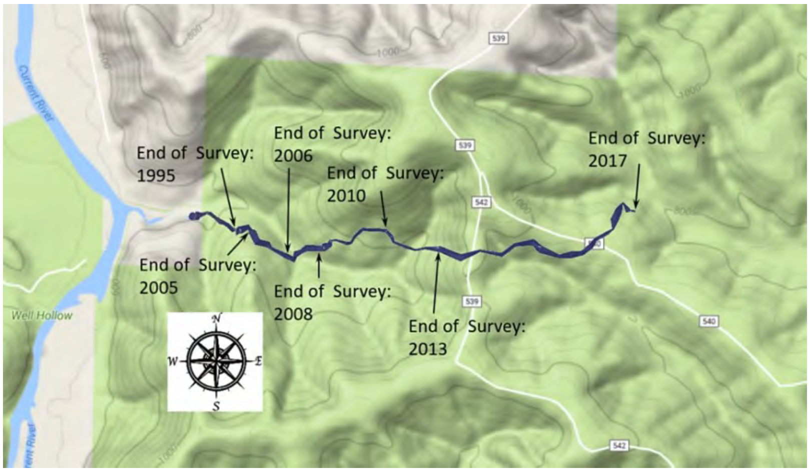


Figure 2.40 Mapped submerged passages of the Blue Spring cave. Courtesy of The Ozark Cave Diving Alliance; available at https://www.ocda.org/wp-content/uploads/2021/10/Blue-Spring-Progression.png

If hard pressed to pick one favorite spring out of all fascinating springs featured in this book, the author would select this one. Blue Spring in Shannon County is simply mesmerizing, and no words or photographs can describe it. One simply must see it to believe a natural beauty like this exists.

2.11 Alley Spring

Alley Spring is located six miles west of Eminence, Missouri on State Route 106. The grounds of the famous red Alley Mill powered by the Spring (Figures 2.41 and 2.42) and the wider Spring area are part of the Ozark National Scenic Riverways operated by the National Park Service. Spring has an average daily flow of 134 cfs or 87 million gallons (see Table 2.3 and Figure 2.43). During most times the water is a placid azure blue, gently welling up from below, but after a storm has swelled the underground conduits feeding the spring, it can gush forth in angry swells and splashes of brown.

Alley Spring discharges at the foot of a picturesque limestone bluff of Eminence Dolomite and flows past the Alley Mill before discharging into Jacks Fork, about 1/2-mile away.

Alley was home, farm, and school for people who lived there a century ago. Dances, baseball games, and roller skating were all part of Alley's busier days. John Knotts purchased the 80-acre site in 1902 and diversified the enterprises to include a well-stocked store and blacksmith shop. The mill was vital to community life, where grain was ground to provide the daily bread. It was also used for grinding cattle feed, operating a sawmill, and furnishing electrical power for nearby houses. The present building was constructed during 1893-1894 by George Washington McCaskill as a merchant mill. It was larger than most mills in the Jacks Fork area and replaced an earlier mill on this same site that was built by 1868. Originally unpainted, it was first painted white with green trim, then later the famous red color associated with Alley Mill today.

In 2001 the United States Geological Survey requested the assistance of The Ozark Cave Diving Alliance (OCDA) to obtain scientific data from within Alley Spring. To date the team has surveyed/mapped several thousand feet of passage, collected rock and sediment samples, and taken video and photographs within the system. Just under 3000 feet of the system has been surveyed with an average depth of 155 feet. This system is normally affected by poor visibility and high flow. A map is on display inside the Red Mill that was created by the survey information gathered by the OCDA (OCDA, 2023).

Figure 2.41 Beautifull red Alley Mill located on the Spring's bank utilized perennial flow of water to operate its turbine powered flour mills. A control wheel on the porch allowed the miller to control how much water entered the turbine and thereby control its speed. This ability to control the speed was one of the innovations that made turbines preferable to the old water wheels. The Spring pool (see Figure 2.42) and the bluff of Eminence Dolomite are visible in the center right. Seen here is one of the two outlets from the spring basin.

Figure 2.42 Alley Spring basin behind Alley Mill.

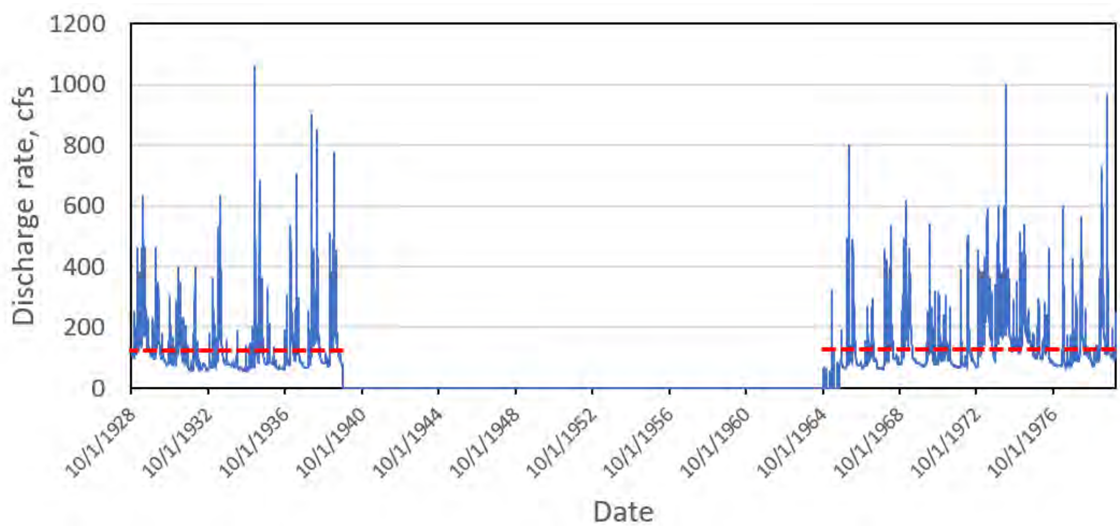


Figure 2.43 Hydrograph of the Alley Spring discharge rate recorded at the USGS gaging station 0706550 Alley Spring at Alley, Missouri. Average for the first period 10/1928 to 9/1939 is 124 cfs; for the second period 8/1965 to 12/1979 it is 141 cfs. For the entire period of record the average discharge is 134 cfs.

An interesting note is provided by Vineyard and Feder (1982) illustrating a textbook example of the mature classic karst nature of the Ozark aquifer: "Bridge (1930) reported that the spring was once observed to cease flowing for about 12 hours. The water level decreased rapidly and sank to about 5 feet below normal pool level. After about 12 hours the water level rose and flow resumed, but the spring was quite muddy for several days thereafter. At approximately the same time a large sink formed in the upland about 15 miles northwest of the spring. Bridge does not record the date of the temporary interruption of the flow, nor the location of the sink, but it was generally supposed that the problem was caused by temporary blockage of the spring supply channel by the sinkhole collapse."

Figure 2.44 Intensely karstified dolomite on a trail around Alley Spring.

As described by the Missouri Department of Conservation (2023d), despite the historic use of the spring to power a mill, Alley Spring has retained its biological integrity. The cool waters issuing forth from Alley Spring flow through a spring branch for a half-mile before entering the Jacks Fork River. The spring branch cool water

(58 degrees Fahrenheit) provides habitat for colorful Ozark fishes including the southern redbelly dace, the Ozark sculpin, and the bleeding shiner.

On the dry rocky ridges of this natural area are some of the highest quality old growth stands of white oak and shortleaf pine woodland known in the Ozarks. These stands were spared the heavy, indiscriminate timber cutting of the Ozarks that occurred from 1880-1920. Looking up at the sentinel pines found on the ridges one can get a glimpse of what the six million acres of shortleaf pine woodlands that were in Missouri in 1860 looked like. Today only about 600,000 acres of shortleaf pine remain in the state. At one time the nation's largest sawmill was at Grandin, Missouri, where lumber production peaked at the beginning of the 20th century. In 1910 the mill was moved to West Eminence, just 4 miles from Alley, but by 1920 the woods were cut over and the mill was sold.

Also protected is Branson Cave, one of the most biologically diverse caves known in Missouri. The natural area conserves five species of conservation concern dependent on spring and cave natural communities. A wide spectrum of Ozark natural communities typical of the Current River Hills region can be explored from springs and associated mesic upland forests to cherty dry woodlands and dolomite glades. Visitors can see plants such as wild hydrangea and walking fern near the spring and then ascend the hill to see shortleaf pine and low bush blueberry on dry cherty slopes. Birds to look for in the woods include ovenbird, summer tanager, red-eyed vireo, and black-and-white warbler. Deep below the trails are cave passageways which support at least seven cave-adapted animals or "troglobites" including the grotto salamander, a species of conservation concern.

2.12 Welch Spring

Welch Spring is located approximately 2 miles north of Akers on Highway K. The spring flows from the base of a wooded dolomite hill near the historic Welch Hospital, and then flows to the Current River over a rock impoundment (Figure 2.45). The spring is part of Ozark National Scenic Riverways.

Figure 2.45 Panoramic photograph of Welch Spring which flows into the Current River seen in the distance. Visible are numerous patches of watercress (Nasturtium officinale) a species of aquatic flowering plant in the cabbage family Brassicaceae. It is one of the oldest known leaf vegetables consumed by humans; it was a favorite of Native Americans.

Vineyard and Feder (1982) estimated that the spring's annual mean discharge was 116 cfs. Aley (1976) estimated an annual mean discharge of 140 cfs, whereas Keller (2000) estimated an annual mean discharge of 229 cfs and suggested that a flood in 1985 changed the character of the spring channel such that some of the flow that had gone through the alluvial gravel before 1985 could now be measured, resulting in larger discharge measurements. This would rank Welch Spring as the third largest spring in Missouri and the second largest spring in the Current River Basin.

The OCDA was given the opportunity to explore Welch Spring in 2007. Inside the gated entrance is an underground lake 10-18 ft deep, and there is living cave on the ceiling. There is dry passage which extends into the bluff from this lake area which has been mapped in the past. The spring then descends to 149 ft and gently ascends to the 100 ft area at the current end of the line. The rather poor visibility in this system is typical of Missouri springs and varies with weather. Exploration of this system will hopefully continue in the future (https://www.ocda.org/exploration/projects/welch-spring/).

The area around Welch Spring was settled in 1855 by Thomas Welch whose family ran a gristmill for fifty years after the Civil War. The spring and 40 acres were sold in 1913 to Dr. Chrisian Diehl of Roxana, Illinois, who spent the next 30 years alternately practicing medicine in Illinois in the winter and building and promoting a sanitarium for asthma sufferers in the spring.

As described by NPS, "Dr Diehl believed that the spring water had healing properties and that cool, pollen free air coming from the adjacent cave would be beneficial for people with asthma, emphysema, and tuberculosis, which together were called "consumption" at the time. He said that it worked for him, helping him with a chronic case of hay fever. To tap this clean air resource, Dr Diehl built a hospital over the mouth of the cave. Welch Spring, which flowed from the cave, was dammed up so that water would close off the entrance. This was to force more air out through the cave opening into the hospital. In today's terms, it might be better called a "health spa" since there wasn't much in the way of formal medical treatment, just an invitation to breathe the fresh air of the cave.

Dr Diehl was not blind to the scenic values of the region either. He hoped to run a thriving campground resort to supplement his medical fees with tourist dollars. In time his healing resort expanded to a few small cabins, a campground, a show cave, and he even had an electric generator running off the spring. Visitors came from the local area and from as far off as Oklahoma and Illinois, but times were hard and travel to such remote places still difficult.

Unfortunately, the hospital and resort were not a big success. Roads in the Ozarks were rough and unpaved, making it difficult to get into the Current River Country. Few tourists were willing to make the trip. The good doctor died in 1940, and his family did not have much interest in keeping up the resort afterwards, which soon fell into ruin.

Figure 2.46 Ruins of Welch hospital standing next to the beautiful Welch Spring. Courtesy of NPS.

Was Dr Diehl just a man ahead of his time? In time, tourists did discover the Current River, over a million come to canoe, camp, hike, and fish every year. As for his medical ideas, he wasn't out of step with his times. Many people at the time believed in the healing qualities of cave air and spring water. It was almost a cliché for people to take a vacation to "take the waters" at one spring centered resort or another. This was the heyday of the healing spas at Hot Springs, Arkansas among others. Years earlier a tuberculosis sanitarium had been built in Mammoth Cave, some three hundred feet underground."

2.13 Boiling Spring

As described by Vineyard and Feder (1982) Boiling Spring, near Powellvile, Missouri on interstate highway 44, is the largest in the Gasconade basin. It rises in the channel of the Gasconade River near the right bank, beneath a high bluff of Gasconade Dolomite. On the surface of the river the spring appears as a very pronounced boil whose height above the surface depends upon the discharge of the spring and that of the river. Unlike the water in some resurgences, where flow lost in upstream reaches reappears downstream, the water in this spring has a bright blue color and its source is in the upland areas east and south of the spring. It is reported that it has been turbid only once in 30 years (Bretz, 1956, p. 412). At low river stage, when the bottom of the pool can be seen, it is filled with gravel continually churned by the rising current.

The Missouri Department of Natural Resources (DNR) lists the discharge rate of Boling Spring of 105 cfs (68 MGD) on one of their web sites where there is a GIS-based visual story titled "Follow the Water" (Table 2.2). Vineyard and Feder (1982) provide the same number as an estimate but also list the maximum measured discharge rate of only 45.3 MGD (70.2 cfs; Table 9, page 92). Incidentally, the official Missouri DNR GIS web site for all springs in Missouri lists the minimum and maximum discharge rates as 25,133 and 31,506 gallons per minute respectively (56 cfs and 70 cfs respectively). Because of these discrepancies Boling Spring is not shown as a first magnitude spring on the map in Figure 2.3 of this book.

The spring can be reached by a private road from county drive 8541; at the time, the owner charged a small admission fee for using the road and viewing the spring. Another private road leads to a lookout point on the bluff where the spring can be viewed from above. Years ago, the spring was used as a water supply for a bluff-edge lodge and cabins above the spring. A cable was stretched from the bluff to a point above the spring, and a bucket could be lowered into the spring and water drawn upward to the lodge (Vineyard and Feder, 1982)

On the other side of the river is a nearby Boiling Spring Campground (18700 Cliff Road, Dixon) from where kayakers often visit the spring nowadays.

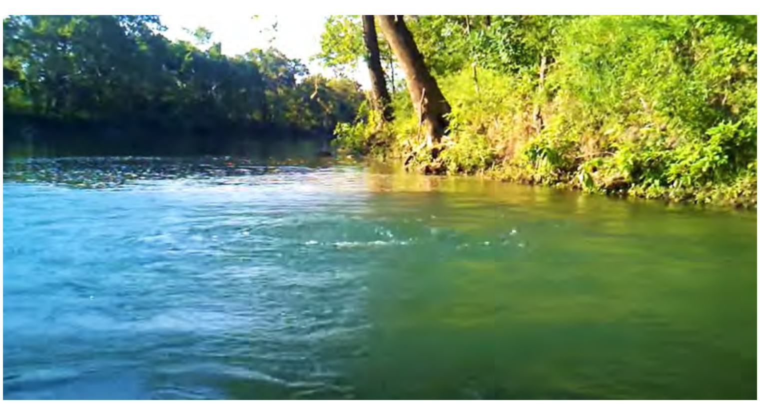


Figure 2.47 Screenshot from a YouTube video Boiling Spring @SterlingB2122 available at https://www.youtube.com/watch?v=F8AuC19oLgs

2.14 Montauk Springs

Montauk Springs is in the Montauk Springs State Park (established in 1926), 15 miles southwest of Salem, Missouri via state roads 39 and 19. Montauk Springs was a single spring with a bedrock opening that became filled with gravel following a flood in the early twentieth century, causing the spring discharge to rise in several pools, gravel bars, and creek beds in the flood-plain alluvium (Vandike, 1997).

Figure 2.48 Screenshot from GeoSTRAT GIS by Missouri Geological Survey, State of Missouri, Maxar|Esri Community Maps Contributors, County of Dent, Texas County, Missouri Dept. of Conservation, Missouri DNR, © OpenStreetMap, Microsoft, Esri, HERE, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA

A dam on the southwest branch submerges the springs which feed it and forms Spring Lake, which is used to supply water to fish rearing ponds. The northeast branch is composed of the flow from a number of spring outlets, usually about seven in all, which emerge from gravel beds or from rocks at the base of a hill of Lower Gasconade dolomite. The flow of this latter branch is augmented by the smaller flow from Pigeon Creek above. The two branches unite near the park headquarters to form the headwaters of Current River.

The spring outlets are inconspicuous if compared with those of some other large springs in the State, but their combined flow (constituting the headwaters of Current River) forms an excellent stream for trout fishing. Montauk State Park is best known for being one of the three “trout parks” in the Missouri state park system. The Missouri Department of Conservation manages and operates the trout hatchery, and offers tours as well.

The annual mean discharge for the 3 years the USGS maintained a gage at Montauk Springs was 58 cfs in 1965, 73 cfs in 1967, and 86 cfs in 1968, but no longer term annual mean discharge value is available (Mugel et al., 2009). The average of 28 discharge measurements made from 1980 through 1994 was 87.6 cfs (Vandike, 1997). Aley (1976) estimated the annual mean discharge from Montauk Springs at 100 cfs, whereas based on 17 measurements between 1923 and 1965 Vineyard and Feder (1982) give value of 63.3 cfs for the average discharge rate.

The valley surrounding the springs that form the Current River attracted settlers in the early 1800s. Early residents came to the area from New York and named their first post office after Montauk in Suffolk County, Long Island. Because of its proximity to the springs and its abundant supply of water power, the village of Montauk proved to be an excellent spot for milling. Four mills were constructed to serve the community. The last one, a gristmill built in 1896, still stands today and retains much of its original machinery. It is open seasonally for tours.

The next big step in the park’s history was in 1926 when it became a Missouri state park. Members of the Civilian Conservation Corps built many of the amenities and structures in the park in the 1930s. Many of these structures still stand today, a testament to the craftsmanship of this era.

Anglers wanting to try their luck for rainbow trout flock to the clear, spring waters and go away happy with their catch. The Current River is also known as one of the finest canoeing rivers in the Midwest. Canoe access is located just outside the park’s southeast border, making Montauk State Park the perfect place to stay during a river adventure.

Figure 2.49 *Left*: Montauk Springs and Pigeon Creek form headwaters of the Current River shown here flowing over a dam. Photo courtesy of Missouri State Parks (https://www.flickr.com/photos/mostateparks/albums/.) *Right*: Montauk Fish Hatchery, courtesy of Missouri Department of Conservation.

2.15 Hahatonka Spring

Hahatonka Spring (Figure 2.50) is in Ha Ha Tonka State Park which is located about 6 miles south of Camdenton, Missouri, on State Road D.

With an average discharge of about 74 cfs (Figure 2.51), it is the largest spring in Camden County. The spring discharges from a phreatic cave developed in the upper part of the Eminence Dolomite. Lower Gasconade Dolomite and the Gunter Sandstone member crop out in the valley walls around the spring branch. The spring rises at the head of a narrow, deep valley that is likely developed by collapse rather than by surface erosion (Vandike, 1992). A bedrock island, containing several caves and heavily weathered bedrock, divides the spring branch a few hundred feet downstream of the spring. Beyond the island, spring flow enters the Niangua arm of Lake of the Ozarks. Two dams were constructed below the spring and a mill was built on the south branch from the spring. When Bagnell Dam was built and the Lake of the Ozarks was created, water backed up the Niangua arm to inundate the lake.

Figure 2.50 Hahatonka Spring in Ha Ha Tonka State Park. Left photo courtesy of Missouri State Parks. Right photo by Noel Hunnarf, from Beckman and Hinchey, 1944.

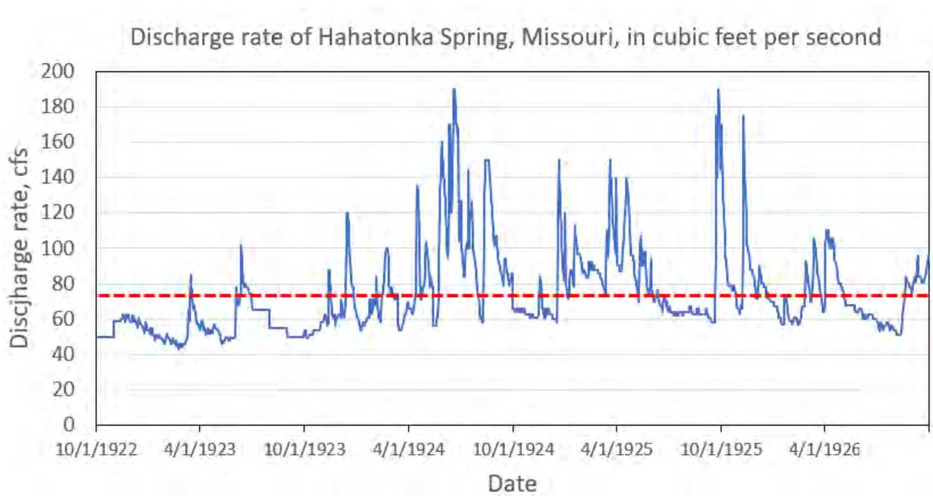


Figure 2.51 Hydrograph of discharge rate of Hahatonka Spring in Ha Ha Tonka State Park recorded at the USGS gaging station 06924500. Average discharge is 73 cfs.

Hahatonka Spring is one of many karst features occurring in the immediate area. Several major sinkholes, one containing a large natural bridge, lie within a few hundred yards east of the spring. River Cave, which pirates flow from surface drainage and channels it into the Hahatonka Spring conduit system, is 2,000 feet to the northeast. Divers entering the spring have made the underwater connection with River Cave (Porter, 1990; personal communication; from Vandike, 1992). The abundance of solution features in the area is of interest because of the many indications of strong structural disturbance. Faulting is prominent in the area. Certain stream alinements and the offsetting of other streams suggest additional faulting or intense jointing, much of it still unmapped. Together, these features suggest the development of a large underground storage reservoir that keeps the flow of the spring at a high level (Vineyard and Feder, 1974).

Figure 2.52 Natural bridge in Ha Ha Tonka State Park. Photo courtesy of Missouri State Parks.

As described by the Missouri Department of Conservation, Ha Ha Tonka State Park is one of the best open oak woodland landscapes in Missouri that has been restored and managed with prescribed fire by State Parks staff. Gnarled old-age (150+ years) post, white and chinkapin oaks grow scattered over an open understory with a lush ground cover of native grasses, sedges, and forbs. In 1819 Henry Rowe Schoolcraft toured portions of the Missouri Ozarks and described a landscape of open oak woodlands as: “A tall, thick, and rank growth of wild grass, covers the whole country, in which the oaks are standing interspersed, like fruit trees in some well cultivated orchard, and giving to the scenery the most novel, pleasing and picturesque appearance.” A similar scene can be found today at Ha Ha Tonka Oak Woodland Natural Area (https://mdc.mo.gov/discover-nature/places/natural-areas/ha-ha-tonka-oak-woodland).

Dotting this landscape of cherty dry woodlands are openings in the woods – dolomite glades – that provide a panoply of wildflower blooms throughout the season: reds of Indian paintbrush in the spring, yellow coneflowers in early summer, pinks of blazing stars in summer, and yellows and purples of prairie dock and aromatic aster in fall. Steep north facing slopes and sinkholes provide habitat for more moisture loving trees such as northern red oak, slippery elm, and basswood. Conspicuous dry woodland wildflowers include pale purple coneflower, a variety of asters (e.g., blue, spreading, prairie, and flax-leaved), rough blazing star, many goldenrods (e.g., downy, rigid, elm-leaved, and white) and lots of legumes (e.g., goat’s rue, lead plant, wild indigo, purple prairie clover, and slender lespedeza) that provide excellent food for turkeys and other wildlife. On deeper soils white oak dominated dry-mesic woodlands occur with bristly sunflower, whorled milkweed, bee balm, and bare-stemmed and small-leaved tick trefoils. All told 500 native plant species have been documented growing in the park. The natural area protects three rare plant species and the Ozark endemic, ringed salamander, as well as a characteristic landscape of the Osage River Hills region.

2.16 Roubidoux Spring

Roubidoux Spring (in the past also known as Big Spring and Waynesville Spring) flows from a rocky basin at the base of a high bluff of Gasconade Dolomite along Roubidoux Creek within the city limits in the southern part of Waynesville, Missouri. A county road passes between the spring and the bluff and is protected by a concrete retaining wall (Figure 2.53) which prevents undermining of the road by the spring during periods of high discharge. The spring is easily reached from Interstate 44, 3/4 mile south of the spring, and from Business Route 66 north of the spring.

When Roubidoux Creek is in flood, the spring may be covered with 8 to 10 feet of water, but even when this occurs the discharge of the spring increases accordingly and is sufficient to produce a mound or boil of water that rises above the level of flood waters in Roubidoux Creek.

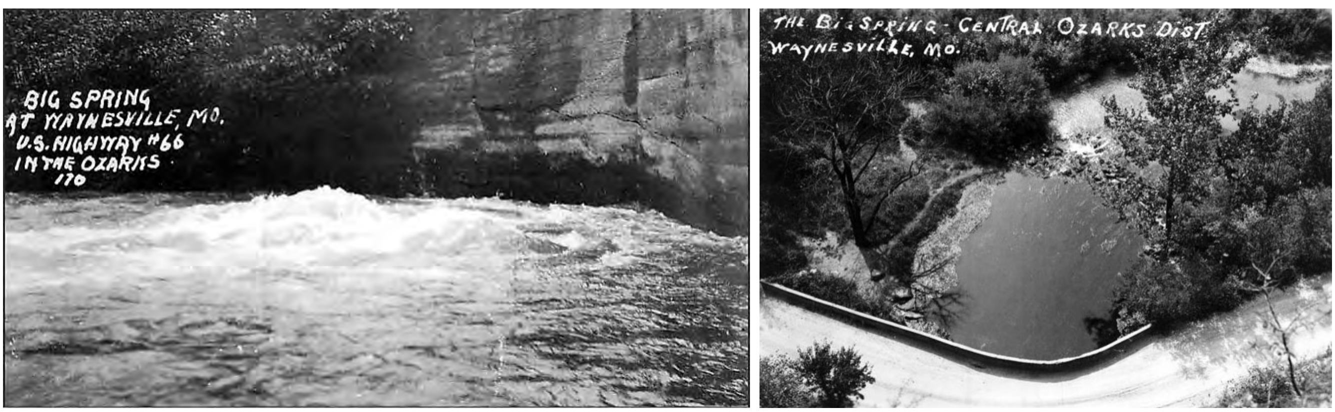


Figure 2.53. Historic photographs of Roubidoux Spring. During periods of high discharge, the flow coming from the underwater opening can boil three feet above the surface of the pool. The view at right, taken from the top of the bluff, shows the road above the retaining wall and the spring rise pool. The rock dam at the bottom of the pool serves to raise the level about two feet to protect it from the creek. Photographs courtesy of Jan and Terry Primas. From "The Big Spring" by Terry Primas, Old Settler Gazette, 2008. Available at https://clients.municipalimpact.com/documents/355/TheBigSpring.pdf.

Rubidoux Spring has never been measured in periods of peak flow. During high flow, spring water is usually much clearer than Roubidoux Creek water. It is interesting to note that the maximum measured flow of Roubidoux Spring is greater than that of Boiling Spring in Pulaski County, but the minimum flow of Roubidoux Spring is far less than the lowest measurement of Boiling Spring. Based on 14 measurements from 1924 to 1970, the average discharge rate is 58.3 cfs; the minimum and maximum are 4.7 cfs and 192 cfs respectively (Vineyard and Feder (1982).

Recharge for Roubidoux Spring comes from the dry valley of Roubidoux Creek extending south and west for approximately 10 miles from Roubidoux Spring. Permanent flow begins in Roubidoux Creek about 1 mile southeast of Roubidoux Spring. From this point toward the headwaters of the creek, Roubidoux Creek sinks into a wide gravel bed, and the stream is dry most of the year for approximately 15 river miles (Vineyard and Feder (1982).

"The spring lies at the south end of Roy Laughlin Park on City of Waynesville property. It hasn't always been so. In the early part of the 20th century, the spring belonged to Frank O. Gray. In October, 1909, J. W. Wheeler, Administrator of the estate of Frank O. Gray, deceased, posted a notice in the *Democrat* that all of Gray's belongings, including a parcel of land containing the Big Spring, would be auctioned off on the south steps of the Pulaski County Courthouse. The *Democrat* reported on the impending sale, noting with some vision that "This is a remarkable piece of property and the citizens realizing the fact that it should belong to the town, have raised a fund to buy the tract of land on which it is situated. It may prove to be of great value to the city." (From *The Big Spring* by Terry Primas, Old Settler Gazette, 2008, p. 20-21.)

The following text by Terry Primas, which accompanies the photograph in Figure 2.54, attests to a wise decision of the City to acquire the property: "Ninety-eight degrees in the shade and where to have a picnic? The Big Spring in Waynesville was a favorite public place on a sweltering day for local town dwellers. Folks from neighboring villages came to enjoy a stream-side lunch, too. The Big Spring (also known as Waynesville and Roubidoux Spring) boils out of an underwater cave (see Figure 2.56) with a water temperature of 58 degrees. The cool temperature moderates the heat around the spring."

Figure 2.54 A very early photograph of the Roubidoux Spring (known as Big Spring at the time) with citizens in their Sunday finery stairstepped up the bluff. Courtesy of Pulaski County Historical Society.

Figure 2.55 1960's era photograph of Roubidoux Spring. Courtesy of Jo Schaper. Available at https://www.ocda.org/exploration/projects/roubidoux-spring/

During the 1837-1839 Trail of Tears forced relocation of the Cherokee Nation, the area was used as an encampment along the 2,200-mile-long route from the southeastern part of the country to Oklahoma. The city of Waynesville erected memorial boards along the Roubidoux Walking Trail in Laughlin Park along with a Wayside Exhibit that can be found on the bank of the Roubidoux.

Figure 2.56 Cave diving photograph from Roubidoux Spring. Copyright Jennifer Idol, printed with permission.

In the 1960's, Don Rimbach and John Viper cleared the spring opening and were the first divers to enter the cave. Since then, Roubidoux Spring and Cave system has become a hot spot on the spelunking tour of every certified cave diver.

Waynesville was home to the 2015 National Speleological Society (NSS) Convention which showcased the Roubidoux Spring cave along with other cave systems in Missouri. For over 60 years, divers have braved the dark passages to a depth of 350+ feet. Depending on the rate of flow and temperature, which averages between 55-60° Fahrenheit most divers experience a beautiful and breathtaking experience. As reported by The Ozark Cave Diving Alliance, with improved conditions and some real long weekends the system has now been pushed out to 11,528 feet at a relatively modest depth of 145 feet (https://www.ocda.org/exploration/projects/roubidoux-spring/).

2.17 Pulltite Spring

Pulltite Spring is located close to Pulltite campground, about 14 miles north of Eminence, Missouri off highway EE. It emerges from the rock structures at the bottom of a dolomite cliff forming a small pool and its branch flows into the Current River (Figure 2.57). Pulltite Spring gained its name from the "tight pull" of the horse drawn teams down a steep hill next to the mills that were positioned on the spring-branch. The spring was purchased by St Louis businessmen in 1911 and was run as a fishing resort, until the area was acquired by the National Park Service in 1967 when it became part of the Ozark National Scenic Riverways.

Figure 2.57 Panoramic photograph of Pulltite Spring. Courtesy of the town of Eminence. Available at https://visiteminence.com/area-attractions/springs-caves-and-historic-sites/pulltite-spring-and-cabin/

Based on six measurements between 1923 and 1964 reported by Vineyard and Feder (1974), the average discharge rate of the Pulltite Springs is 36 cfs or 23.3 MGD (maximum was 142 cfs on October 3, 1923, and minimum was 5.09 cfs on November 30, 1964). No other flow measurements for the spring are publicly available.

2.18 Round Spring

Located approximately 13 miles north of Eminence on Highway 19 is Round Spring, one of the major attractions of the Ozark National Scenic Riverways (ONSR). The spring rises quietly in a nearly circular basin (Figure 2.58) formed by the collapse of a cavern roof. Part of the roof remains intact as a natural bridge (Figure 2.59) beneath which the waters of the spring flow toward nearby Current River. Boulders from the collapse of the cavern roof effectively block the tubular conduit of the spring, limiting divers to a depth of about 55 feet and preventing their access to the water-filled spring supply channels that are accessible in some other springs. Based on 20 years of record (Figure 2.60), the average discharge rate of Round Spring is 47 cfs or 30.4 MGD.

According to a NPS pamphlet on Round Spring, it is believed that a portion of the spring's recharge area is to the northeast of Spring Valley, which means that the water would have to flow under the Current River to reach the spring. Round Spring was one of the first parks in the Missouri state park system (1932).

The water temperature in the spring remains between 55- and 58-degrees Fahrenheit year around. Watercress abounds in the cold water, providing shelter for aquatic life including periwinkle snails, insect larvae, and a variety of fish species. Large number of birds, deer and small mammals visit the spring. People, however, are prohibited from swimming in it.

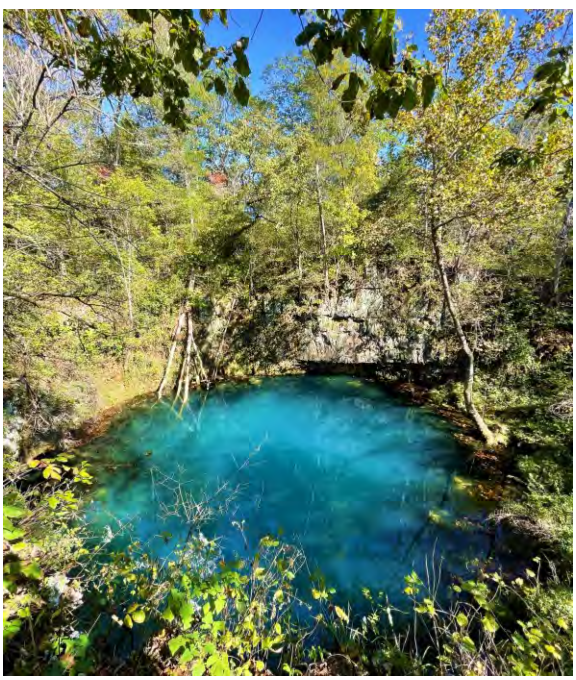


Figure 2.58 Round Spring rises from the wreckage of a cavern in the Eminence Dolomite. Part of the former cave roof remains as a rock tunnel about 100 feet long (center of the picture) through which waters of the spring flow toward the nearby Current River.

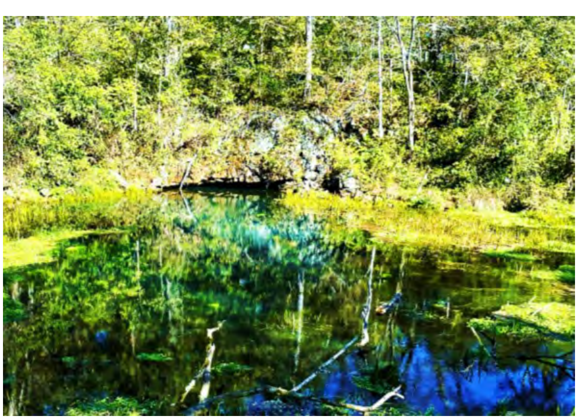


Figure 2.59 The other side of the rock tunnel (former cave passage) through which Round Spring flows into the spring branch shown here. The course of the branch is approximately 1,450 feet long before it empties into the Current River.

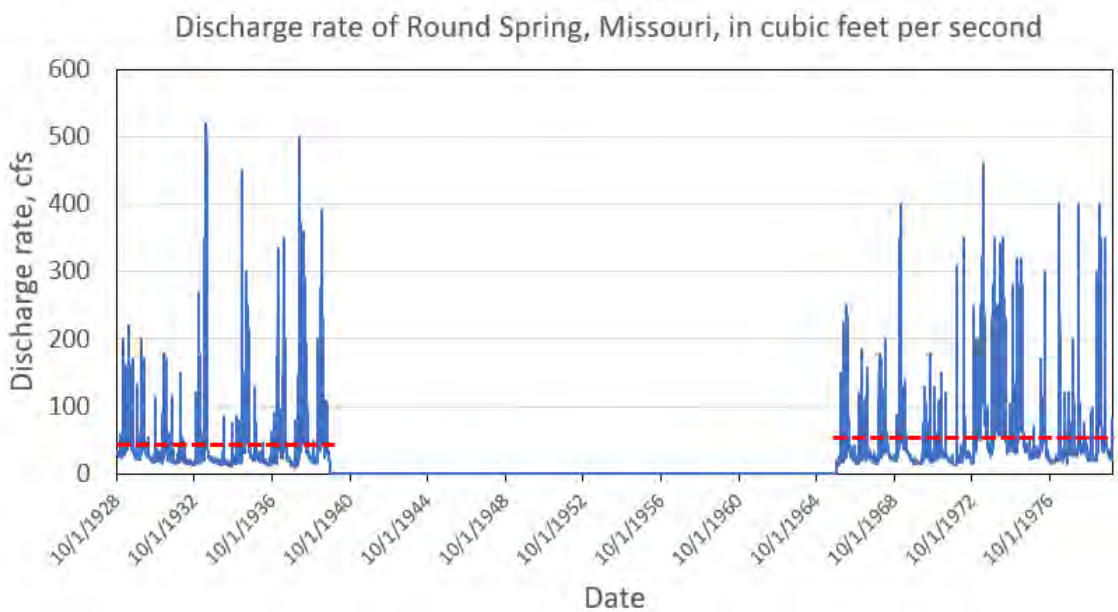


Figure 2.60 Hydrograph of Round Spring discharge rate recorded at the USGS gaging station 07065000 Round Spring at Round Spring, Missouri. Average for the first period 10/1928 to 9/1939 is 41 cfs; for the second period 10/1965 to 12/1979 it is 51 cfs. For the entire period of record the average discharge is 47 cfs.

2.19 Roaring River Spring

Roaring River Spring is in the Roaring River State Park, about 10 miles south of Cassville via State Highway 112. The park is surrounded by Mark Twain National Forest in the southwestern corner of Missouri.

Roaring River Spring flows from a pool at the base of a high bluff of Cotter Dolomite (Figures 2.61 and 2.62) in a narrow, canyon-like valley and forms the head of Roaring River. A prominent vertical joint crevice, which has been slightly enlarged by solution work and which extends upward in the face of the bluff above the spring outlet, suggests that the underground flow at this point may be directed in part by the pattern of jointing in the rocks.

As emphasized by Beckman and Hinchey (1944), a small spring is located about 90 feet directly above the Roaring River Spring. This upper spring flows out of a small, cavernous solution channel at the base of the St. Joe (Mississippian) limestone formation at its contact with underlying Kinderhook (Mississippian) shales.

Figure 2.61 Roaring River Spring in Roaring River State Park. Courtesy of Missouri State Parks. Available at https://mostateparks.com/park/roaring-river-state-park

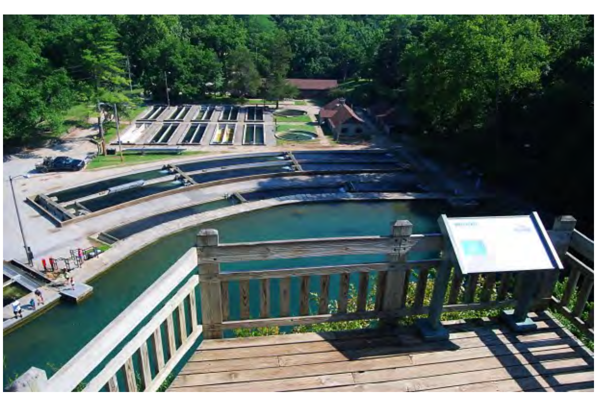
Apparently this small spring has its source in the overlying limestone and cherty limestone strata of Mississippian age and discharges water which has percolated from the surface downward through joints, crevices, and openings in those limestones. Its further downward movement has been checked by the relatively impervious shales, upon which it has followed a lateral course along the top of the shale beds to emerge in the crevice above the big Roaring River Spring. Thus, the smaller flow is "perched" upon the impervious shale strata.

According to Vineyard and Feder (1982), the water quality data of Roaring River Spring indicate that much of the recharge area is in uplands underlain by Mississippian limestone.

Roaring River Spring has been used for many years as a source of water for one of the large state fish hatcheries (Figure 2.63). 216 measurements of the spring discharge rate were made between 1923 and 1966 with the average of 31.6 cfs. The maximum discharge was measured on April 6, 1965, when the spring flowed at a rate of 177 cfs. The minimum measured discharge was 8 cfs on October 31, 1963 (Vineyard and Feder, 1982).

When the flow of the spring declined in the late summer and fall it was frequently necessary to reuse the water, so pumping facilities were installed when the production of the hatchery increased to the level at which more water was needed.

2.62 Photo of Roaring Spring in early 1940s taken by W.H. Pohl; from Beckman and Hinchey, 1944.



The spring serves as the nucleus of a resort with dining and lodging facilities that are popular with fishermen who come to fish in the spring branch and lake below the hatchery. Trout are sent throughout the state for stocking lakes and reservoirs. Roaring River State Park consistently ranks high in the number of visitors in the Missouri State Park system.

Figure 2.63 State trout hatchery at Roaring Springs State Park. Courtesy of Missouri State Parks.

As of fall 2023, Roaring Springs holds the record for the deepest explored spring in the United States thanks to divers of the KISS (Keep It Super Simple) team (Figure 2.64). The previous record was 462 set in 2013 at Phantom Spring Cave in west Texas. The following excerpts from article *Down deep at 472 feet* by Flip Putthoff, published September 13, 2022, in NWA Democrat-Gazette, illustrate this quest.

CASSVILLE, Mo. -- Scores of visitors admire the beautiful flow of turquoise water that emerges from Roaring River Spring at the heart of Roaring River State Park cradled in an Ozarks canyon south of Cassville, Mo.

From a sidewalk at the spring's outflow, it's easy to tell the clear water comes from deep in the Earth, but how deep? That's one fact a team of highly trained cave divers hopes to find out during extremely deep dives into the spring's dark, mysterious and dangerous depths.

These elite divers have reached a depth of 472 feet in the spring, but there's more cave below that, said chief diver Mike Young of Fort Smith. Their dive to 472 feet in November 2021 set the record for the deepest explored spring in the United States. The previous record was 462 set in 2013 at Phantom Spring Cave in west Texas.

Professional divers have explored the spring before -- two in the spring of 1979. A team in the early 1990s reached a depth of 225 feet. At that depth, there's a tight squeeze through a restriction that leads to more of the spring's cave. Bulky conventional scuba tanks prevented those divers from penetrating beyond the restriction.

Rebreather scuba technology the current team uses was developed in the late 1990s. Rebreathers are smaller than conventional scuba air tanks. They work by removing the carbon dioxide from a diver's exhaled breath so the diver rebreathes the oxygen.

The KISS (Keep It Super Simple) brand of rebreathers are manufactured in Fort Smith, Arkansas at Young's business, which builds several rebreather models. Special training is required before a diver can purchase a rebreather.

The smaller rebreathers allowed the divers to go through the restriction. Still, the squeeze is tight, said Randall Purdy of Kearney, Neb., the team's underwater photographer. Gesturing with his arms, he formed an opening about the diameter of a 55-gallon barrel. Wonders never before seen by humans unfolded when the divers emerged. They encountered a colossal water-filled cave room so large it could contain the 550-foot tall Washington Monument, according to Young.

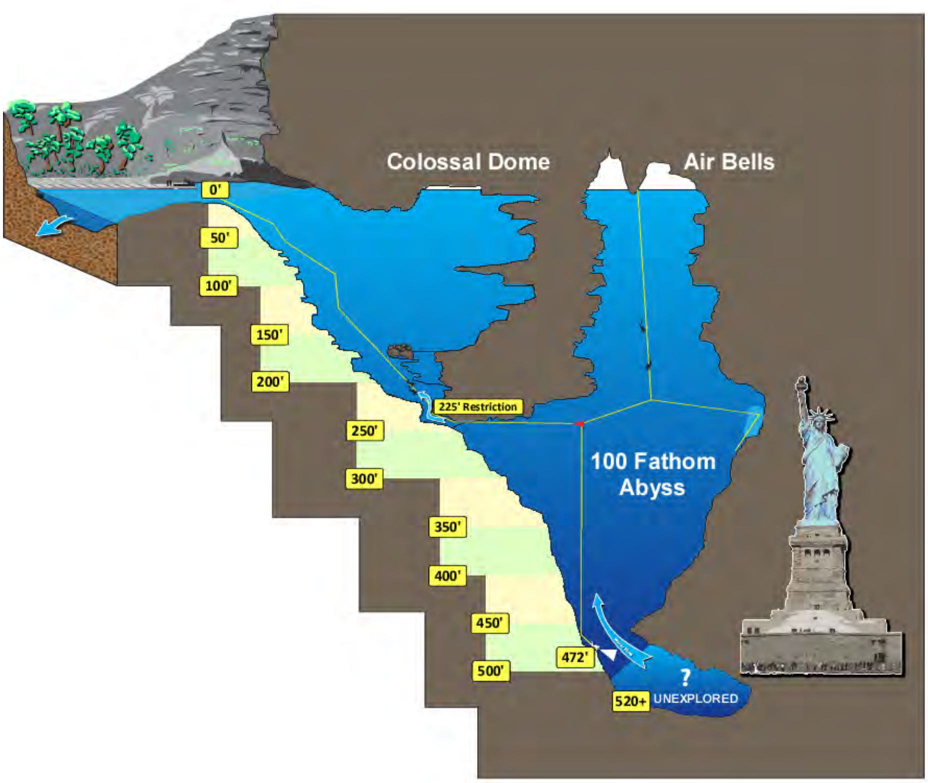


Figure 2.64 Profile of Roaring River Spring, at least 520 feet deep, based on most recent information from the KISS team divers (2021-2023). Participating divers: Gayle Orner, Fernando Gutierrez, Jon Lillestolen, Randall Purdy, Neil Brownlow, Mike Henry, Greg Abels, Charles Walker, Bob Dankert, Eric Hahn, Charles Jay, Mike Young (Chief Diver), Tim Bass, Joseph Heinrichs, Matthew Westpheling. Surface surface: Colonel (Ret)Tony Bryant, Tom Creason, Adam McDowell, Tana Henry. Moral support: Sheri Young, Jennifer Ables, Angela Brownlow, Paige Purdy. Illustration by Curt Bowen. Courtesy of Mike Young and the KISS Dive Team www.kissrebreathers.com/

The rugged hills and valleys of Roaring River State Park tell a fascinating geologic story about the southwestern Ozarks of Missouri. The park is located on the edge of the Ozark Plateau where it is dissected by the White River. This natural erosion process over thousands of years has created an abrupt change in the landscape, from the flat plains of the plateau to deep valleys and steep hills. Visitors driving to the park are often surprised to find themselves going down and down into the park. The last mile of the drive into the valley drops 400 feet in elevation.

Roaring River is a tributary of the White River, which has cut into the flat plateau, creating deep valleys and revealing an unusual variety of rock formations. As the river cuts through the plateau, it exposes the different layers of sediment, including shale, limestone, dolomite, and chert. Roaring River State Park is one of only a few places in Missouri where visitors can see such a variety of rock formations within such a small area.

2.20 Blanchard Springs, Arkansas

Blanchard Springs (Figure 2.65) is in the Sylamore Ranger District of the Ozark–St. Francis National Forest, fifteen miles northwest of Mountain View (Stone County), Arkansas. As a natural outlet of the subterranean stream that formed the Blanchard Springs Cavern, the spring emerges from the mountainside in a waterfall and flows into a trout pond called Mirror Lake. According to the Office of State Geologist (www.geology.arkansas.gov/), discharge rate can vary between 1,000 to 103,000 gallons per minute (1.44–148 MGD) depending on local rainfall.

The spring was named for John H. Blanchard, who left his family's plantation in Kentucky and fought for the Confederacy, enlisting in the Kentucky Volunteers in 1861. Following bitter conflict at such battles as Chickamauga, where he was wounded, Blanchard sought peace after the war ended by homesteading 160 acres in the tranquil Ozarks. There, he built a gristmill powered by the falling spring which now bears his name.

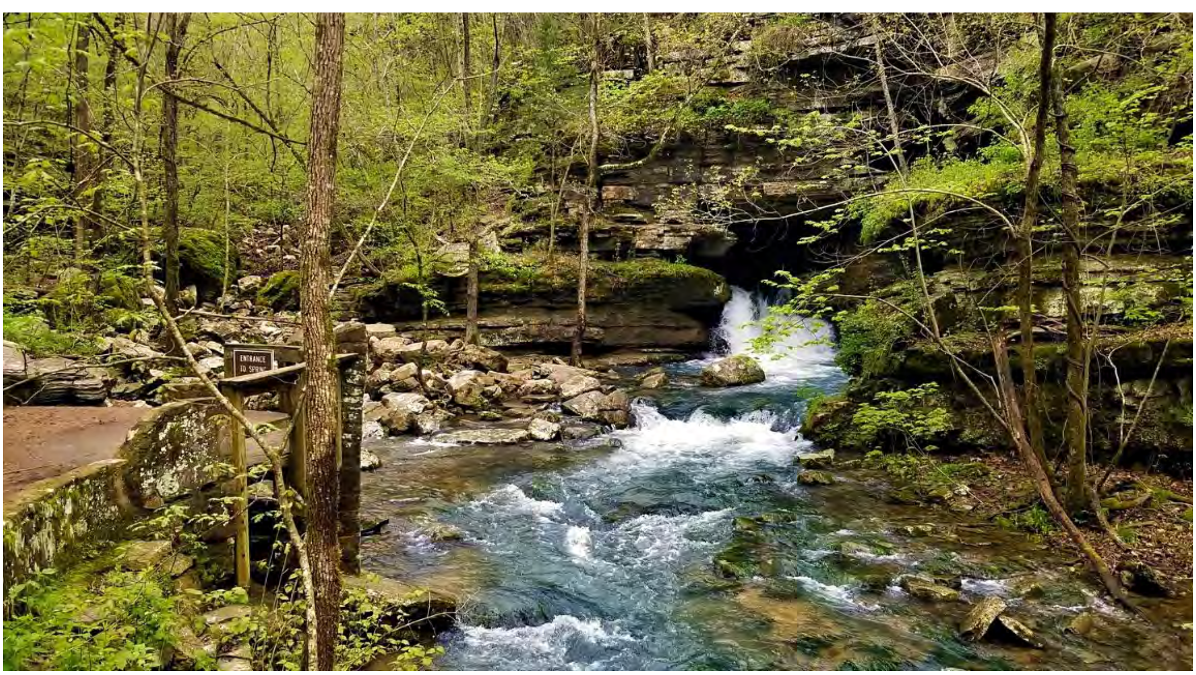


Figure 2.65 Blanchard Springs in Stone County, Arkansas. Courtesy of USDA, Forest Service; available at https://www.recreation.gov/camping/campgrounds/250010

Blanchard Springs Caverns (BCS) is one of the most spectacular and carefully developed caves in the United States. The active cave, with its glistening formations, stalactites, stalagmites, and flowstones is constantly changing, providing return visitors something new to see each time. Beautifully lighted rooms (Figure 2.66), that accentuate the cave's features, are equipped with handrails and paved trails for comfortable walking. An undeveloped section of the cavern allows visitors an opportunity to climb over rocks, crawl through tight spaces and slide on red clay mudslides. (https://www.recreation.gov/ticket/facility/233266)

BCS is a cavity formed primarily in layers of limestone with thin layers of shale and sandstone which collapsed (https://www.blanchardsprings.org/geology-of-blanchard-caverns/). The cavern cavity zone lies between Boone Formations, which are mostly bedded chert, an insoluble siliceous rock, and St. Peter Sandstone, which is also insoluble.

As described in the Encyclopedia of Arkansas (https://encyclopediaofarkansas.net/), “BSC is a magnificent limestone cave system starting more than 200 feet underground. It is the only cave administered by the U.S. Forest Service. Three guided tours through the caves are open to the public: the Dripstone Trail (open all year), the Discovery Trail (open during the summer), and the Wild Cave (open by special reservation).

The limestone rock from which the cave developed was formed by fossilized sediment from sea creatures at the bottom of an ancient inland sea estimated to exist about 350–500 million years ago. When prehistoric land masses shifted, the seabed was uplifted about 300 million years ago to form the Ozark Plateau. The exposed land was shaped by the elements, such as wind and rain, into mountains and rivers. When the slightly acidic rainfall penetrated cracks and crevices in the limestone, cavities were formed. Water entered, enlarging the cavities as it flowed through and filled them. As the water cut its way downward, seeking lower levels, it left hollow, air-filled caves. Dripping water from above then deposited calcium carbonate and other minerals to form the cave features and formations, called speleothems, which continue to change as long as water continues to drip.”

The first documented visit to the cavern was in 1934, by Civilian Conservation Corps (CCC) planner Willard Hadley (https://encyclopediaofarkansas.net/). Signs of earlier human exploration discovered in the caves, such as cane and wooden torch remains, have been scientifically dated to a period encompassing AD 215–1155. The first professional exploration was in 1960 by Hugh Shell and Hail Bryant. In 1971, scuba divers entered through the spring entrance and followed its course. The divers followed 4,000 feet of underwater passages and also mapped five caverns filled with air but inaccessible at that time. They photographed the cave formations and noted forms of cave life. They estimated that it takes about twenty-four hours for water to flow through the cave, a journey of less than a mile.

Figure2.66 One of the lighted rooms in Blanchard Springs Caverns that can be seen on a guided tour called the Dripstone Trail, open to the public all year. Courtesy of USDA, Forest Service; available at https://www.recreation.gov/ticket/facility/233266

2.21 Blue Spring, Arkansas

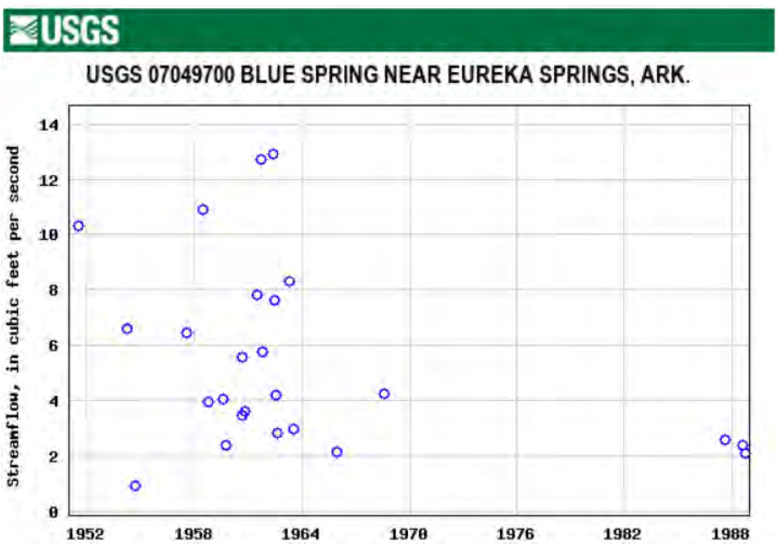
Blue Spring (Figure 2.67) in Carroll County, Arkansas lies in a large incised meander (Figure 2.68) of the White River seven miles northeast of Eureka Springs via highway US-62W and County Road 210. This permanent ascending spring discharges from Cotter Dolomite through a near-vertical submerged narrow cave passage which extends deep into the underlying Jefferson City Dolomite of Lower Ordovician. The total depth of 229 feet below the spring pool level was reached by cave diving team of Mike Young, Kendall Hopkins, and Mike Wright (the video of this cave diving exploration by T.L. Bass productions is available on YouTube). Although the diving results questioned previous information on the spring's depth (560 feet according to Sam Leath's article published in The Ozark Mountaineer in May 1955; or 510 feet as displayed on the information panel by the spring pool), Blue Spring is still one of the deepest and most notable in The Ozarks, with challenging narrow passages and depths yet to be fully explored.

Figure 2.67 Blue Spring in Carroll County, Arkansas.

Figure 2.68 Google Map of the Blue Spring area. Imagery ©2023 Arkansas GIS, Maxar Technologies, State of Arkansas, USDA/FPAC/GEO, Map data ©2023

Although the spring is located in an incised meander of the White River (Figure 2.68) it apparently has no hydraulic connection with the river: the flow rate and physical characteristics of the spring (temperature is constant at 54 degrees) are reportedly not affected by the river stage or changes in the river water characteristics.

The spring flow originates beyond the White River valley, and the drainage area is unknown but must be of significant extent based on the spring's large average flow rate of 5.5 cubic feet per second (Figure 2.69). Curiously, the information panel at the spring states that "water from Blue Spring originates in the Pacific NW". Staff of the Blue Spring Heritage Center where the spring is located could not reference where this information came from, and were somewhat skeptical when told that, if true, this would constitute one of the most incredible hydrogeologic and natural phenomena known to mankind. Nevertheless, Blue Spring does present a puzzle given that it is surrounded by the White River and the depth of its explored submerged vertical feeder conduit is well over 250 feet below the river level which means that the water discharging at the spring must flow even deeper beneath the river.



Crystal clear water pours from the Blue Spring circular pool into a trout-filled lagoon formed behind a wooden dam. The lagoon overflows into the White River, "replenishing the area with some of the purest water in the region according to a recent study."

Figure 2.69 Officially available period of record for measured discharge rate at Blue Spring is 1951-1988. Based on 25 measurements, the average is 5.5 cfs or 3.5 million gallons per day (MGD). Official brochure of the Blue Spring Heritage Center states that the average daily flow of the spring is 38 MGD, without citing source of data.

Figure 2.70 *Left*: View of Blue Spring before construction of a round concrete pool cap; circa 1905 (courtesy of T.L. Bass productions). *Right*: Blue Spring today.

Unlike other springs near and in Eureka Springs, Blue Spring has become a garden setting, with the deep blue spring pool circled by a garden wall. A tourist attraction in some manner since 1920s, in 1993 the spring area was transformed into the Eureka Springs Gardens, which, in 2003, were blended with the area's historical aspects to become the Heritage Center it is today.

For thousands of years, Native American elders have told stories of visits to Blue Spring and the important ceremonies held in the bluff shelter that served not only as a refuge, but also a sacred place for ritual. Osage Indians claimed the Blue Spring as their trading post. Early settlers nicknamed them "Strongboat Indians" and used their boats to float furs, bear oil, and beeswax down the old trade route of the White River to New Orleans.

In March 1839, Blue Spring became a respite and stopover on the Trail of Tears for the Cherokee people during their forced march from Echota, Georgia. They knew of stories long told about the Spring and spent time there in hope of healing on a journey with impossible odds. Cherokee are said to have camped under a rocky overhang called Bluff Shelter (Figure 2.71) for several days on their march west toward Oklahoma. The shelter, which has Native American markings and pictographs, is now listed on the National Register of Historic Places.

In the early 1840's, Blue Spring Mill was built 300 feet downstream from the Spring, powered by the water to grind corn. In 1903, a new mill was built combining a saw, grist and flour mill three stories high and also powered by water. Although most of the building was removed in 1943, the turbine remains as a reminder of days past.

Figure 2.71 Bluff Shelter at Blue Spring listed on the National Register of Historic Places.

In 1971, Robert G. Chenall and his students from the University of Arkansas conducted an archeological dig of the Bluff Shelter next to Blue Spring. They found prehistoric artifacts, shellfish and the bones of deer, turtle, and other fauna. Some date back as far as 8000 BC. Chenall also uncovered fire pits, and evidence of life such as small arrow points and Woodward Plain pottery, confirming the presence of American Indians dating back as far as 1700 AD. Many of the arrowheads found from the dig are displayed in an on-site museum (Figure 2.72).

Figure 2.72 Native American arrowheads found on grounds of Blue Spring, on display at the Heritage Museum.

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Chapter 3 The Floridan Aquifer

3.1 Introduction

The information presented in this chapter is based primarily on materials and publications by the following agencies and institutions:

- United States Geological Survey (USGS) including Ground Water Atlas of the United States, HA 730-G (Miller, 1990; available at https://pubs.usgs.gov/ha/ha730/ch_g/G-text6.html), Berndt et al., 2014; and Williams and Kuniansky, 2016; as well as the USGS monitoring data on Florida springs available at https://dashboard.waterdata.usgs.gov/
- Florida Geological Survey (https://floridadep.gov/fgs) including four successive reports specifically on Florida springs (Ferguson et al., 1947; Rosenau et al., 1977; Scott et al., 2002; Scott et al., 2004).
- Various Florida agencies including
  Northwest Florida Water Management District (http://www.nwfwater.com/)
  Suwannee River Water Management District (http://www.mysuwanneeriver.com/)
  Southwest Florida Water Management District (http://www.sjrwmd.com/)
  St. Johns River Water Management District (http://www.sjrwmd.com/)
  Florida Department of Environmental Protection (https://floridadep.gov/springs/visit)

Most of the springs described in this chapter are in Florida state parks or local parks named after the springs; the web sites of these parks were sources of additional information including photographs.

Invaluable were educational materials, numerous downloadable publications, and information provided by The Howard T. Odum Florida Springs Institute which, in the opinion of this author, maintains one of the most comprehensive and visually pleasing websites dedicated to springs and many related environmental issues (https://floridaspringsinstitute.org/).

Details of springs and insightful discussions of them are provided by Joe Follman and Richard Buchanan in their on-line publication entitled "Springs Fever: A Field & Recreation Guide to 500 Florida Springs", 3rd Edition (accessed in December 2023 at http://thespringsfever.com/index.html).

The Floridan aquifer system is one of the most productive aquifers in the world. It underlies an area of about 100,000 square miles in southern Alabama, southeastern Georgia, southern South Carolina, and all of Florida (Figure 3.1) and provides water for numerous small and several large cities, including Savannah and Brunswick in Georgia; and Jacksonville, Tallahassee, Orlando, and St. Petersburg in Florida, to name a few. In addition, the Floridan (often used synonym) provides water for many individual households, smaller communities, and rural areas. Locally, it is intensively pumped for industrial and irrigation supplies.

A thick sequence of carbonate rocks (limestone and dolomite) of Tertiary age comprises the Floridan aquifer system. The thickest and most productive formations of the system are the Avon Park Formation and the Ocala Limestone of Eocene age. The Suwannee Limestone (Oligocene age) also is a principal source of water, but it is thinner and less extensive than the Eocene formations. The Tampa Limestone of Miocene age is part of the Floridan in only a few places where it is sufficiently permeable to be an aquifer. Both the Suwannee and the Tampa Limestones are discontinuous. The lower part of the Avon Park Formation, the Oldsmar Formation of early Eocene age, and the upper part of the Cedar Keys Formation of Paleocene age also are included in the Floridan where they are highly permeable. Limestone beds in the lower part of the Hawthorn Formation of Miocene age are considered part of the Floridan by some but are excluded from the USGS Groundwater Atlas because the permeability of these beds is thought to be minimal. The base of the aquifer system in much of Florida consists of nearly impermeable anhydrite beds in the Cedar Keys Formation.

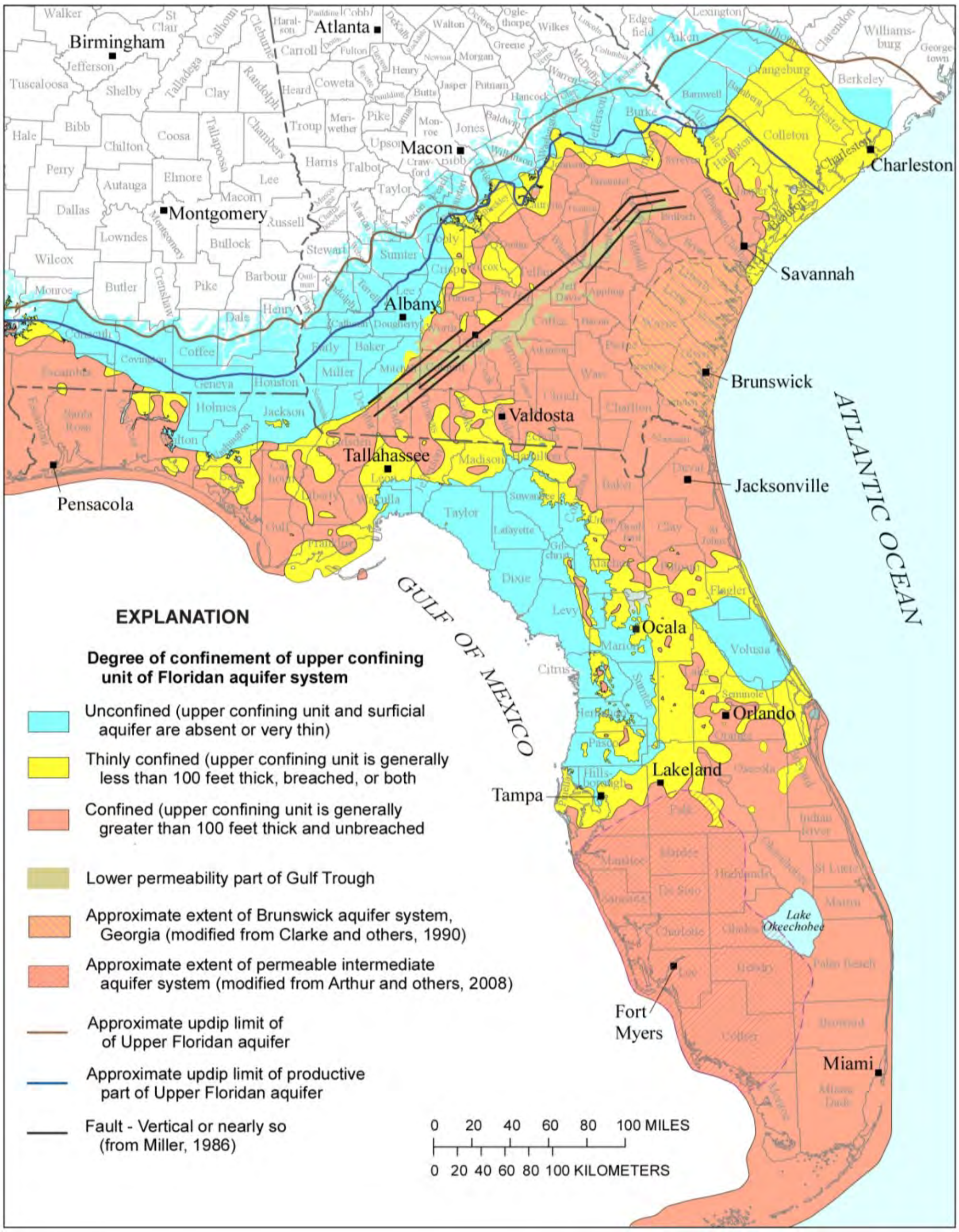


Figure 3.1 Relative degree of confinement of the upper confining unit of the Floridan aquifer system and approximate limit of the Upper Floridan Aquifer. Modified from Williams and Kuniansky, 2016.

Aquifers and Confining Units

The Floridan aquifer system has been defined based on permeability. In general, the system is at least ten times more permeable than its bounding upper and lower confining units. In most places, as shown by the idealized layers in Figure 3.2, the system can be divided into the Upper and Lower Floridan aquifers, separated by a less-permeable confining unit.

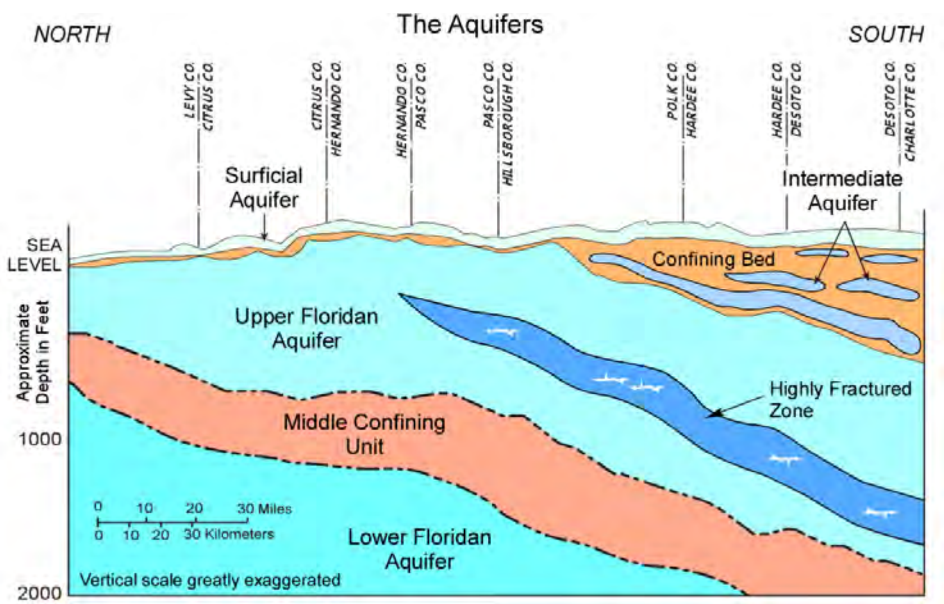


Figure 3.2 Generalized division of West-Central Florida's Aquifers. From SWFWMD, 2017c.

The geology and hydraulic properties of the Upper Floridan aquifer have been extensively studied, and this is the part of the system described by most reports. The Upper Floridan is highly permeable in most places and includes the Suwannee and Ocala Limestones, and the upper part of the Avon Park Formation. Where the Tampa Limestone is highly permeable, it also is included in the Upper Floridan.

In most places, the Upper Floridan aquifer yields sufficient water supplies for most purposes, and there is no need to drill into the deeper Lower Floridan aquifer. The confining unit separating the Upper and Lower Floridan aquifers, informally called the middle confining unit (or semiconfining unit where it allows water to leak through it more easily), is present at different altitudes and consists of different rock types depending on changes in location. The confining unit consists of seven separate, discrete units that are idealized into a single layer in Figure 3.2. At some locations, the confining unit consists of clay; at others, it is a very fine-grained (micritic) limestone; at still other places, it is a dolomite containing pore spaces filled with anhydrite. Regardless of rock type, wherever the middle confining unit is present, it restricts the movement of groundwater between the Upper and Lower Floridan aquifers.

A series of small faults bounds downdropped, trough-like crustal blocks (grabens) in southern Georgia and southwestern Alabama (Figure 3.1). Within these grabens, respectively called the Gulf Trough and Mobile graben, clayey sediments have been downdropped opposite permeable limestone of the Floridan aquifer system. This juxtaposition creates a damming effect that restricts the flow of groundwater across the grabens.

A detailed description of the hydrogeological units of Florida is provided in the Florida Geological Survey's Special Publication No. 28 (Copeland et al., 2009).

The carbonate rocks of the Floridan aquifer system are readily dissolved where they are exposed at land surface or are overlain by only a thin layer of confining material. Precipitation absorbs some carbon dioxide from the atmosphere as it falls and absorbs much more carbon dioxide from organic matter in soil as the precipitation percolates downward through the soil, thus forming weak carbonic acid. This acidic water dissolves the limestone and dolomite of the Floridan aquifer system, initially by enlarging pre-existing openings such as pores between grains of limestone or fractures (joints) in the rock. These small solution openings become larger as more of the acidic water moves through the aquifer, creating the “rock sponge” seen in Figure 3.3. This is the main reason for the extraordinary groundwater storage capacity of the Upper Floridan Aquifer. Eventually, these openings may grow to form “karst conduits” (cave channels) that can be tens of feet in diameter (Figure 3.4), as well as networks of conduits that can be thousands of feet long (Figure 3.5). The result of the dissolution of carbonate rocks is a type of topography called karst, named for the Karst Plateau in Slovenia, which is characterized by caves, sinkholes, and other types of openings caused by dissolution, and by numerous sinking streams, a few large permanent surface streams, and very large karst springs. This process of karstification is responsible for the occurrence of all large springs in Florida, The Ozarks (Chapter 2), Texas (Chapter 5) and many other notable springs described in this book.

Figure 3.3 Ocala limestone at Gainer Springs. Photo copyright John Moran. All rights reserved.

Figure 3.4 One of submerged channels in the Weeki Wachee Cave System. Photo courtesy of Andrew Pitkin, Karst Underwater Research (KUR). From SWFWMD, 2017b.

Dissolution of carbonate rocks is greatest where groundwater circulation is most vigorous. Water can enter, move through, and discharge from the Floridan aquifer system more readily and rapidly where it is unconfined or where the upper confining unit is thin. Such areas are shown in Figure 3.1. In these unconfined areas, the aquifer is either exposed or, more commonly, is covered by a thin layer of sand or by clayey residual soil. In adjacent areas, the Floridan is confined, but the upper confining unit is less than 100 feet thick. In these areas, sinkholes that locally breach the confining unit and allow precipitation to move quickly downward into the aquifer are common (Figure 3.6). Where the confining unit is thick and unbreached, there has been less dissolution of the aquifer system except in deeply buried zones of paleokarst, such as the Fernandina permeable zone of southeastern Georgia and northeastern Florida, and the Boulder Zone of southern Florida. However, these deeply buried zones were chiefly formed in the geologic past, when the rocks comprising the zones were at or near the land surface and are not the result of the modern groundwater flow system.

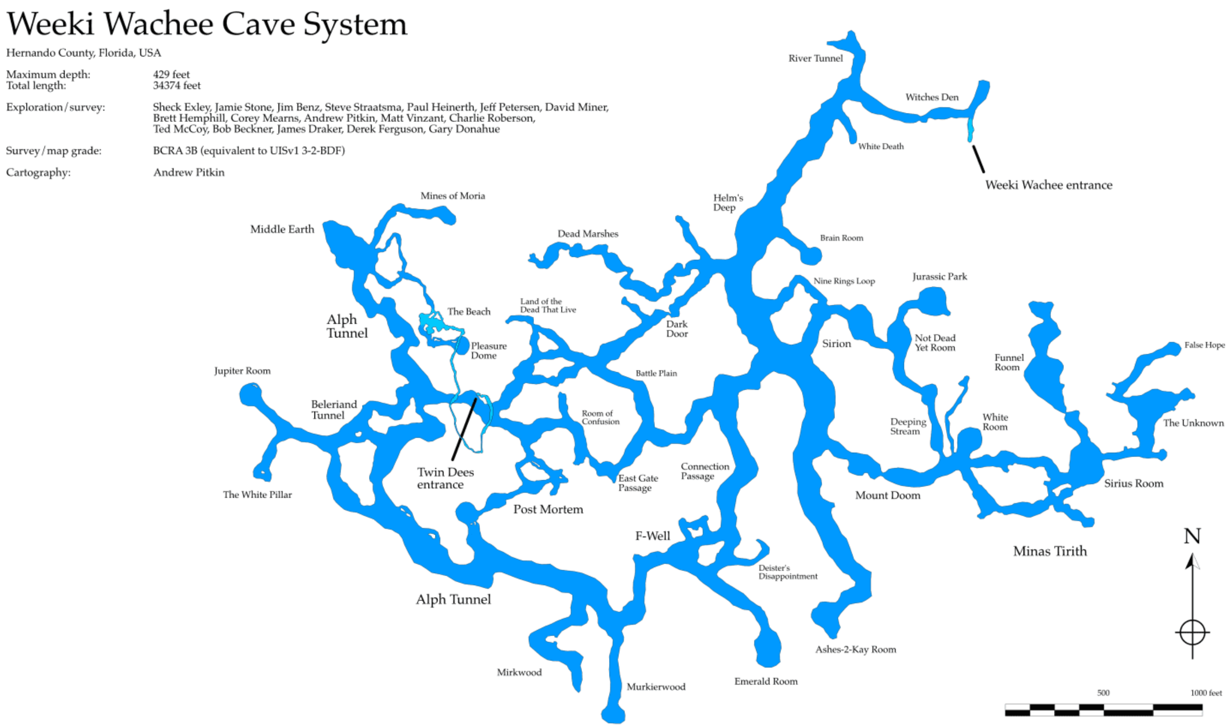


Figure 3.5 Map of the Weeki Wachee Cave System. Courtesy of Karst Underwater Research (KUR). Available at https://gue.com/blog/exploration-of-weeki-wachee-2019-20-the-search-for-the-source-continues/

Figure 3.6 New sinkholes frequently open in Florida, often triggered by anthropogenic factors such as groundwater pumping for irrigation (*photo on the left*) and water supply, modified surface drainage controls, failing/leaky water and sewer pipelines, mining, and other activities which interrupt a delicate balance between the surficial and Upper Floridan aquifers separated by a thin confining layer. *Right*: The infamous Winter Park sinkhole that suddenly opened in 1981, causing serious damage. Both photos by Professor George Sowers, courtesy of Francis Sowers.

Florida has quite a few first-magnitude springs (springs with an average flow of 100 cubic feet per second (cfs) or more) and many second- and third-magnitude springs (average flow 10-100 cfs, and 1-10 cfs respectively). The location of these springs is shown in Figure 3.7. All of them issue from the Upper Floridan aquifer, and practically all of them are in areas where the upper confining unit of the Floridan aquifer system either is less than 100 feet thick or is absent (compare Figures 3.1 and 3.7).

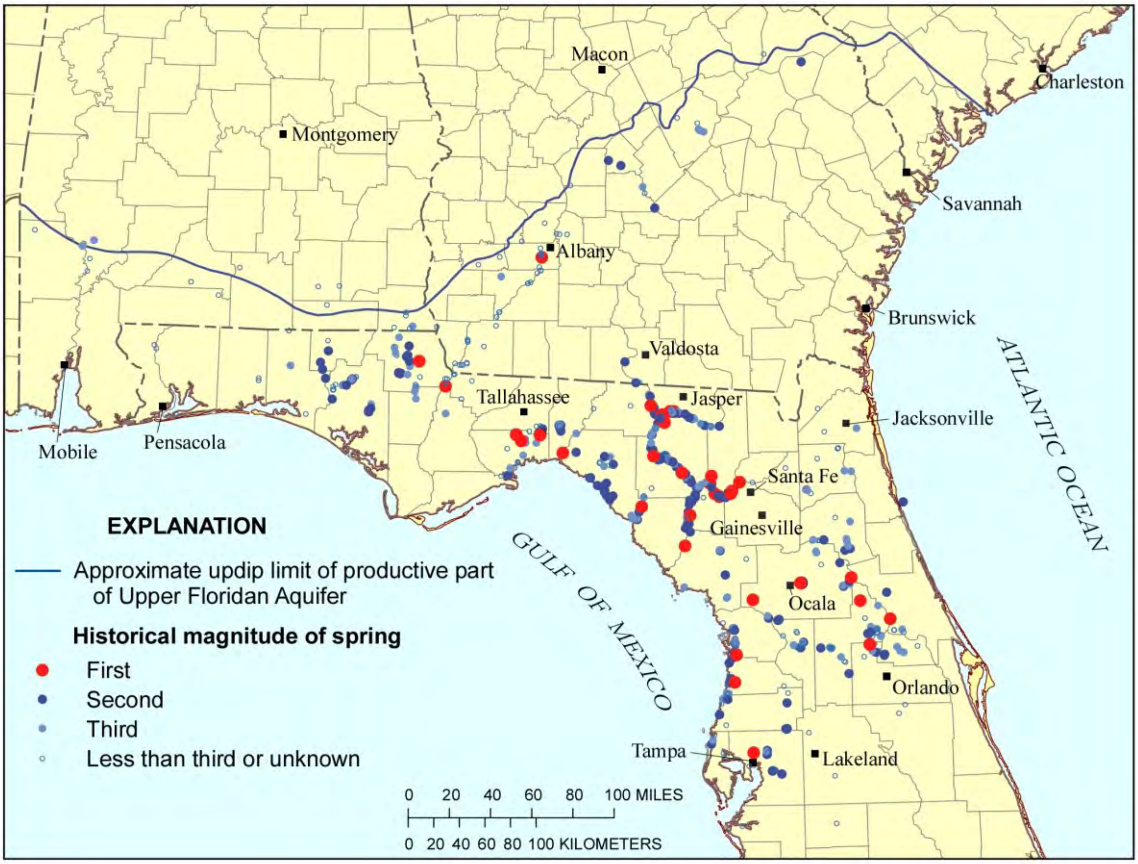


Figure 3.7 Major springs of the Floridan aquifer system (FAS), southeastern United States, based on assessment of the USGS. Modified from Williams and Kuniansky, 2016.

Most notable are linear distributions of springs in the Suwanee River watershed (Figure 3.8) where major surface streams have incised into the limestones and dolomites of Upper Floridan aquifer and act as linear discharge zones for groundwater stored and flowing in the aquifer. This discharge of groundwater takes place both via karst conduits—orifices of springs (Figure 3.9), and via so-called diffuse discharge from the "rock sponge" directly into the surface water.

Figure 3.8 With more than 300 documented springs, the Suwannee River Water Management District (SRWMD) has one of the highest concentrations of freshwater springs in the United States. Modified from SRWMD, available at https://www.mysuwanneeriver.com/267/Springs

Figure 3.9 Panoramic photograph of Telford Spring and its short run to the Suwannee River. One can dive below a limestone ledge in and out of the spring's eye. The spring, a popular stop for kayakers on the Suwannee, is in Luraville, on the left bank of the river. Shown here are Andrew Park and Yuset Cueto enjoying a weekend in mid-December 2023.

Sadly, many Florida springs including the largest and most famous are experiencing a dramatic decline in discharge rate (magnitude) and water quality. This is illustrated with the following excerpts from a report prepared by The Howard T. Odum Florida Springs Institute (2020):

Human activities, including agriculture, industry, and urban development have been responsible for the ongoing depletion and pollution of the Floridan Aquifer. Groundwater extractions from the Floridan Aquifer average nearly 4 billion gallons each day (Bellino 2017). Compared to estimated pre-development conditions, aquifer levels have declined, resulting in an average decline in Florida spring flows by about one third (Knight and Clarke 2016). Agricultural and urban nitrogen fertilizer loading to the surface of the vulnerable lands overlying the aquifer exceed 340 million pounds per year (Knight 2015). As a result of these substantial loads, nitrate nitrogen concentrations in the Floridan Aquifer and springs have risen from a natural background of about 0.05 mg/L to an average of nearly 1 mg/L, an average increase of 1,900 percent. Over 80 percent of Florida's 1,000+ springs are impaired by elevated concentrations of nitrate nitrogen as determined by FDEP's spring standard of 0.35 mg/L.

Unfortunately, the springs feeding the Santa Fe River are no exception to this decline in Florida's aquatic resources and environment. During this study, additional priority pollutants were tested and found to be present in the Santa Fe River and springs in low concentrations, including salts, metals, and pesticides. Along with the effects of groundwater withdrawals and nitrogen and trace pollutant loading, human use in the form of recreation and structural modifications has impacted many of the state's springs.

Florida's springs attract over 30 million visitors each year, resulting in direct annual revenues of $1 billion which is equivalent to a natural annual income-providing endowment equal to $30 million (Knight 2015). A university study of the economic importance of springs in the Santa Fe River Basin alone indicated that about 1 million people visit these springs annually with a resulting economic impact of about $94 million (Borosova et al. 2014).

Florida's springs have a very large economic value, both for recreation and resource conservation and studies show that people who benefit from Florida springs place a high value on them (Wynn et al 2014).

Long-term reductions in spring flows throughout the state have been caused by excessive groundwater pumping that ultimately impact the levels and potentiometric surface of the Floridan Aquifer. Groundwater in the Floridan Aquifer is finite and is also the most pristine natural source of water available for human and natural systems. Through analysis of all available spring flow data Knight and Clarke (2016) estimated that fully a third of average spring flow is captured by wells. Long-term flow declines have been documented in all spring systems with adequate historic data. As documented in this report and by others (Intera 2012), spring flow declines have also been documented at the springs along the Santa Fe and Ichetucknee rivers, with increasing frequencies of zero flow and flow reversals recorded at Santa Fe Spring, River Rise, Hornsby Spring and Poe Spring during periods of low rainfall. Significant flow declines are also documented in downstream springs, including Gilchrist Blue, Ginnie Springs, and the Ichetucknee Springs System.

As mentioned in Chapter 1-Introduction, recognizing the undeniable evidence of the ongoing demise of Florida springs, the Florida Legislature, in 2016, enacted the Florida Springs and Aquifer Protection Act (the Act) and identified 30 Outstanding Florida Springs (OFSs) that require additional protections to ensure their conservation and restoration for future generations (see https://www.flsenate.gov/Laws/Statutes/2021/373.802).

OFSs are defined by statute and include all *historic* (emphasis added) first magnitude springs, including their associated spring runs, as determined by DEP using the most recent Florida Geological Survey springs bulletin (#66), and the following additional springs, including their associated spring runs: De Leon Springs; Peacock Springs; Poe Springs; Rock Springs; Wekiwa Springs; and Gemini Springs. The term does not include submarine springs or river rises. (Section 373.802(4), F.S.).

The Act requires Florida Department of Environmental Protection (DEP) to assess the water quality in the OFSs. Based on these assessments, DEP determined that most of these springs are impaired. For these impaired springs, DEP must adopt (or re-adopt) a basin management action plan (BMAP) to implement all the protections of the Act, including:

- Prioritized lists of restoration projects along with planning level estimates for cost, schedule, and nutrient load reduction;
- Phased milestones (5-year, 10-year, and 15-year) to achieve water quality restoration targets in 20 years;
- Estimated nutrient pollutant loads, allocated to each source or category of sources;
- Completed remediation plans for onsite sewage treatment and disposal systems (OSTDS), commonly referred to as "septic systems," where septic loading accounts for at least 20 percent of the estimated nutrient input; and
- Delineated "priority focus areas" where certain activities are prohibited.

Since the enactment of the Act, BMAPs for the thirty OFSs were developed by various agencies including water management districts. These reports can be found on websites of the districts (see the beginning of Chapter 3). An example of various analyses of available historic data for the OFS springs is shown in Figure 3.10.

There are at least two puzzling things about regulatory business related to the protection of Florida springs in general, and OFSs in particular.

1. Use of word "historic". Do the State of Florida and other PRPs (Potentially Responsible Parties – a term used routinely in the environmental and groundwater remediation industry) know something that the public does not? All listed first-magnitude OFSs are still alive, anyone can see them including many

thousands of out-of-state and international visitors which come to Florida specifically because of the famous spring tourism industry. They all are referred to as first-magnitude springs (not as "historic") on many maps, web pages, and in various brochures and documents published by many different entities. They certainly do not look anything like the real historic springs such as the unfortunate Kissingen Spring or Worthington Spring in the town of Worthington Springs which stopped flowing decades ago (more on the dead Kissingen Spring is provided at the end of this Chapter). Is the term chosen preemptively?

2. Are hundreds of springs that did not make it to the OFSs list doomed? Or, to put it more bluntly, are we going to be complicit in watching the ongoing, slow-motion, mass murder of Florida springs?

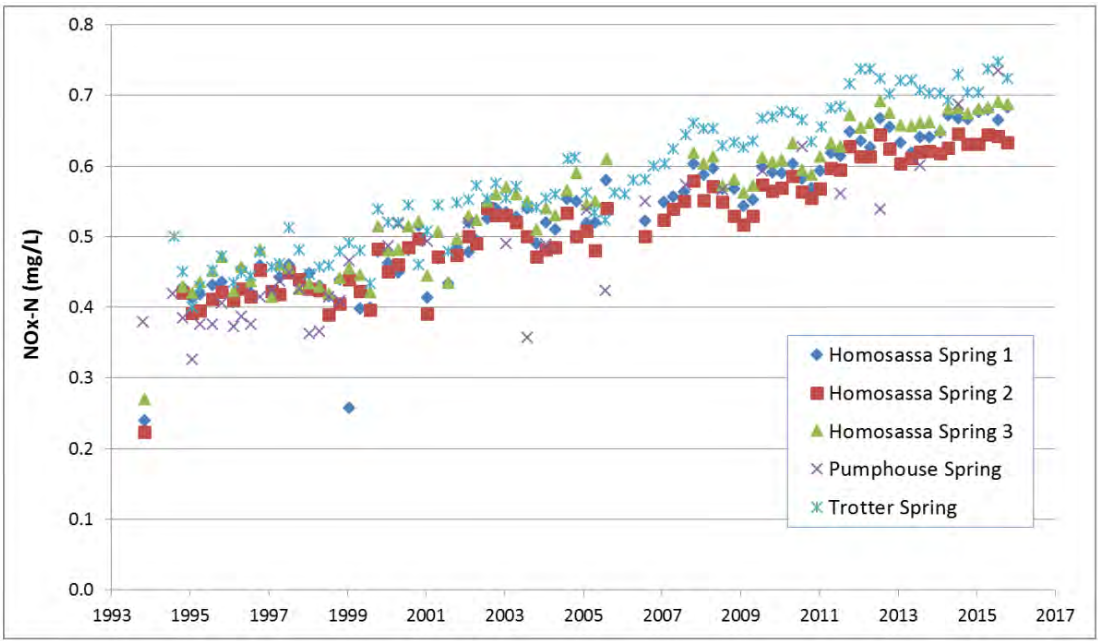


Figure 3.10 Nitrate Changes in Several Homosassa River Springs. From SWFWMD, 2017a.

Note to the reader: If you already are unnerved by these questions, please jump to Section 3.4 where you can start reading usual, upbeat descriptions of notable Florida springs, accompanied by nice color photographs including some historic black-and-white.

As for the nice color photographs—here are few quotes from an enlightening article by Jennifer Adler titled "Lenses and Love: The Art of Saving Florida's Springs" available at https://stateofwater.org/highlight/lenses-and-love-the-art-of-saving-floridas-springs/, part of the *State of Water, State of Change* project which showcases the work of students enrolled in Environmental Journalism courses at the University of Florida's College of Journalism and Communications.

Tolbert feels similarly conflicted when people think a degraded spring is magnificent. "I don't really say that much… I might show them the old pictures," she says. "It's hard to stand there and say 'well, it used to look better'…" It's challenging to get across the idea that many springs are only greenish shades of their former selves.

Nature photographer Mac Stone, who has seen the splendor and suffering of the Everglades firsthand, says it's a fine line: "You've got to show the beauty of it but you've also got to show the maybe not so pleasing side. If you're constantly shooting to put photos up on people's walls, then you're not telling a story… it's not all sunshine *and rainbows," he explained. "But you've got to have a balance of both or you won't get people on board to listen to you."*

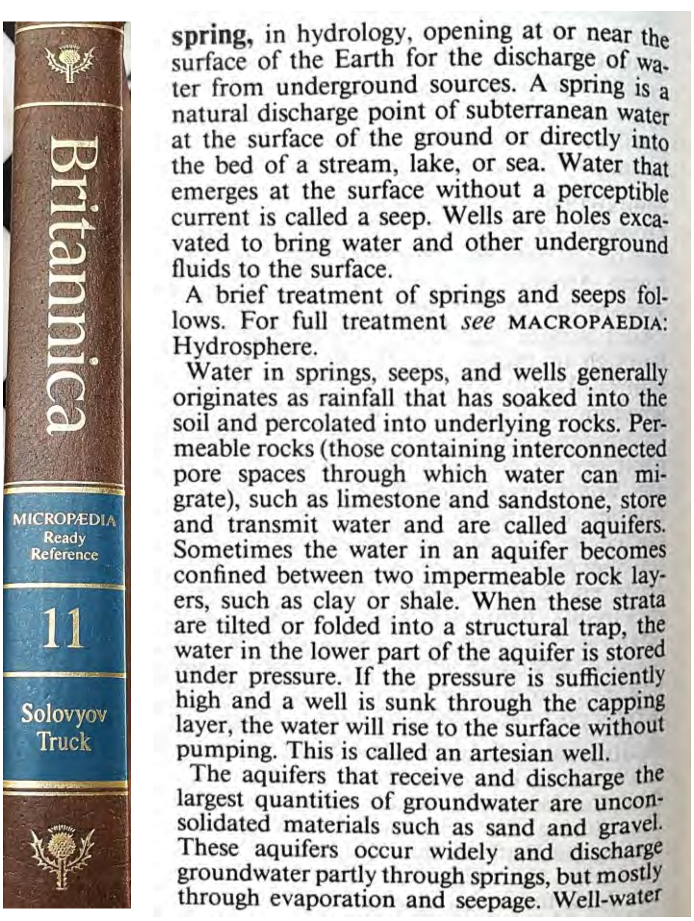
And despite the sad state of some springs and parts of the Everglades, Stone says there are still a lot of pretty photos to be taken: "... you have to give them reason to celebrate too, and there is plenty of reason to celebrate."

Gamble agrees: "We need to enjoy what we do have, honor and celebrate the springs as unique and truly 'wondrous.'" But there's a caveat: "The additional pressure with springs issues is that we're short on time," she added. So where do we go from here?

For those that are willing to stick with the following two sections for a while, here is a warning: What you are about to read and see may be disturbing.

3.2 Spring vs. Spring Group vs. River Rise

This section is the first part of an explanation regarding an improbable increase of the number of first-magnitude springs in Florida between years 1927 and 2004. The second part of the explanation is provided in section 3.3 Discharge Rates of Large Springs in Florida.



spring, in hydrology, opening at or near the surface of the Earth for the discharge of water from underground sources. A spring is a natural discharge point of subterranean water at the surface of the ground or directly into the bed of a stream, lake, or sea. Water that emerges at the surface without a perceptible current is called a seep. Wells are holes excavated to bring water and other underground fluids to the surface.

A brief treatment of springs and seeps follows. For full treatment *see* MACROPAEDIA: Hydrosphere.

Water in springs, seeps, and wells generally originates as rainfall that has soaked into the soil and percolated into underlying rocks. Permeable rocks (those containing interconnected pore spaces through which water can migrate), such as limestone and sandstone, store and transmit water and are called aquifers. Sometimes the water in an aquifer becomes confined between two impermeable rock layers, such as clay or shale. When these strata are tilted or folded into a structural trap, the water in the lower part of the aquifer is stored under pressure. If the pressure is sufficiently high and a well is sunk through the capping layer, the water will rise to the surface without pumping. This is called an artesian well.

The aquifers that receive and discharge the largest quantities of groundwater are unconsolidated materials such as sand and gravel. These aquifers occur widely and discharge groundwater partly through springs, but mostly through evaporation and seepage. Well-water

The definition of a spring according to Encyclopedia Britannica is shown in Figure 3.11. Many similar definitions and explanations abound on the web and in various textbooks. Common to all of them is that water discharged at a spring comes from groundwater stored and flowing in an aquifer (where there are interconnected pore spaces).

The definition of a spring group is more convoluted. Oscar Meinzer in his famous publication *Large Springs in the United States* (Meinzer, 1927) provides the following discussion:

When an attempt is made to compare the large springs in the United States with respect to their size, or the quantity of water that they discharge, serious difficulties are at once encountered. First of all, it is very difficult to determine what constitutes a unit for comparison.

Figure 3.11 Definition of spring in Encyclopedia Britannica.

The water seldom issues from a single opening and may issue from a great many openings, which may be close together or scattered over a considerable area. What is called a single spring in one locality may be equivalent to what in another locality is regarded as a group of springs, each of which has an individual name.

This difficulty is made especially perplexing by the present lack of detailed maps or other data regarding most of the large springs. Some units are designated in the singular and some in the plural for example, "Silver Spring" and "Thousand Springs." The idea that underlies this usage is that if the water issues from a single opening or from several openings that are close together it forms a "spring," whereas if it issues from a number of openings that are farther apart it forms " springs." In fact, however, local usage is so variable in this respect that there is no consistent distinction between "a spring" and "springs," and often there is no uniformity in usage even for the same group of openings.

In the case of Florida, Wilson and Skiles (1989) believe that classification of first-magnitude springs by FGS in its Bulletin No. 66 published in 2004 has created some confusion due to the grouping of hydrogeologically unrelated springs into groups and the inclusion of river rises and karst windows. Often, individual springs comprising a group do not have the same water source region or spring recharge basin (springshed) and are not hydrogeologically related. Nevertheless, FGS chose to include groups of springs with combined discharge greater than 100 cfs in the 2004 list, as well as on its current (as of December 2023) maps of first-magnitude springs.

Perhaps the main reason behind this decision is the following statement by FGS: "*The individual spring vents within a group may not discharge enough water to be classed as first magnitude*." (page 9 of Bulletin No. 66).

Apparently, FGS has always had some doubts as to what should and should not be treated as a first-magnitude spring. For example, in the 1947 report by Ferguson et al. Table 4 shows that some springs at the time were not lumped into a first-magnitude spring such as Wacissa Springs where three individual springs are listed and not lumped and shown as one first-magnitude spring on the accompanying map.

NAME	LOCATION	APPROXIMATE WATER TEMPERATURE °F	DETERMINATION OF FLOW DATE	C.F.S.	M.G.D.	G P.M.	FACILITIES AVAILABLE, 1947 DEVELOPMENT OR USE, 1947
HILLSBOROUGH COUNTY							
Buckhorn Spring	2.8 mi. N.E. of Riverview	76	a	11.0	7.1		Swimming, private
Eureka Springs	3 mi. E. of Tampa	74	a	3.9	2.5		Aquarium of tropical fish
Lithia Springs	3 mi. W. of Lithia	76	a	50.2	32.4		Undeveloped, swimming
Messer Spring	3 mi. N.E. of Riverview	77	5- 1-46	.32	.21		House supply, hydraulic ram
Palma Ceia Springs	Bayshore Blvd., Barcelona St.		5- 1-46			42	Abandoned swimming pool
Purity Spring	0.5 mi. W. of Sulphur Spgs.		a			350-850	Public supply, bottled
Spring (no name)	0.1 mi. E. of Buckhorn Spg.		5- 1-46	1.27	.82		Water for stock
Spring (no name)	0.5 mi. W. of Buckhorn Spg.	75	5- 1-46	.09	.06		Water for stock
Sulphur Springs	At Sulphur Springs		ab	52.6	34		Resort, swimming
HOLMES COUNTY							
Ponce de Leon Spgs.	1 mi. S. of Ponce de Leon	68	ab	19.4	13		Resort, bath houses
JACKSON COUNTY							
Blue Springs	5 mi. N.E. of Marianna	70	ab	163	105		Resort, swimming, fishing
JEFFERSON COUNTY							
Wacissa Spgs. group	1 mi. S. of Wacissa		a				Fishing, boating, hunting
Big Spring			7-16-42	69.4	45		
Blue Spring			7-16-42	9.4	6.1		
Garner Spring			7-16-42	17.0	11		

Figure 3.12 Part of Table 4 starting on page 180 of the FGS 1947 report by Ferguson et al. entitled Springs of Florida. Wacissa Springs group has 3 individual springs, and it is not shown as one first-magnitude spring on the accompanying map.

Silver Springs is often called the largest freshwater spring in Florida, the United States, and even the world. However, as noted in both the 1947 and 1977 editions of *Springs of Florida*, only about half of this total is from the main spring vent at the headwaters of Silver River (Figure 3.13). The rest of the flow is from other springs as far as 3,500 feet below the headspring (Rosenau et al., 1977, pp. 276-79). These various vents have water with different temperatures, which means the waters come from different depths or directions and are, in essence, different springs.

Follman and Buchanan (2023) argue that individual springs within spring groups should be measured separately. Doing so will give a clearer picture of the flow of individual springs of Florida, their fluctuations, sources, flow patterns, chemical components, and impacts on them. A perfect example is Silver Springs. Flow of the head spring (3 spring vents about 50 feet apart – Figure 3.13) was measured for 100 years before the PRPs stopped reporting it (Figure 3.14). From the available monitoring record, it is painfully obvious that something started being terribly wrong with the very heart of the Silver Springs group. It is not clear why the PRPs stopped reporting the heartbeat of this mighty spring, once the strongest in the Nation. Perhaps not to spread panic?

Figure 3.13 Head spring of the Silver River is comprised of three closely spaced vents (1) Silver Spring Mammoth West Vent A, (2) Silver Spring Mammoth East Vent B, and (3) Silver Spring Main. (compare to Figure 3.47 for some inconsistencies between different agencies in Florida). All three were measured together in the field by USGS for more than 100 years, until 2010. First downstream springs in the Silver River, Oscar Spring and Mastodon Bone Spring are shown here, with a dozen more springs in the river further downstream for about 3,500 feet. From Florida Department of Environmental Protection GIS database. https://ca.dep.state.fl.us/mapdirect/?webmap=07f160c92ea94770ae3a892539e61a83. *Marion County Property Appraiser, FDEP, Esri, HERE, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, USDA | This data has been collected, compiled, and maintained by the Florida Department of Environmental Protection's Florida Geological Survey and Division of Environmental Assessment and Restoration. The Florida Geological Survey currently manages and updates the dataset. Springs data has also been collected, revised, and provided by the Northwest Florida Water Management District, the St. Johns River Water Management District, the South Florida Water Management District, the Florida Fish and Wildlife Conservation Commission, the United States Geological Survey, and local governments of Florida.*

Whatever the case may be, the question remains which doctor or Concilium of doctors will be able to help, not knowing what the patient's heart is even doing?

Some other examples include springs of King's Bay, Rainbow River, and Wacissa River. The total flow from King's Bay (Crystal River) represents the combined output of several dozen, some say as many as 100 submerged springs.

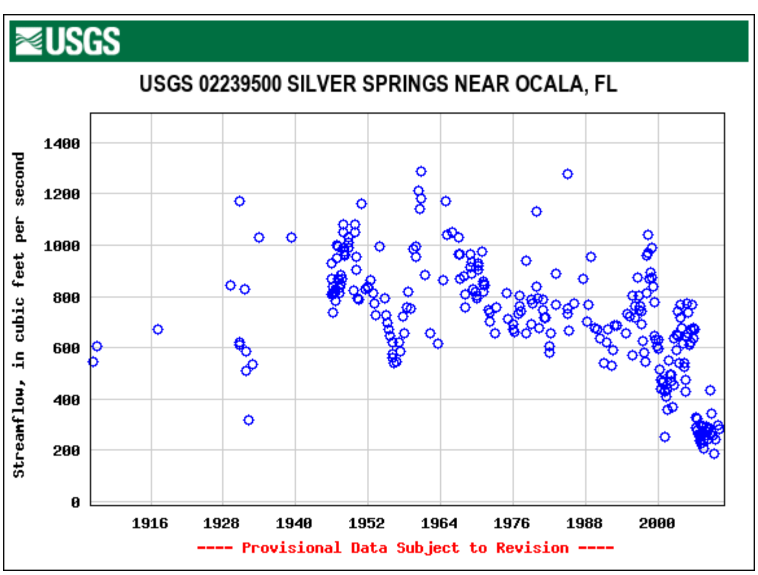
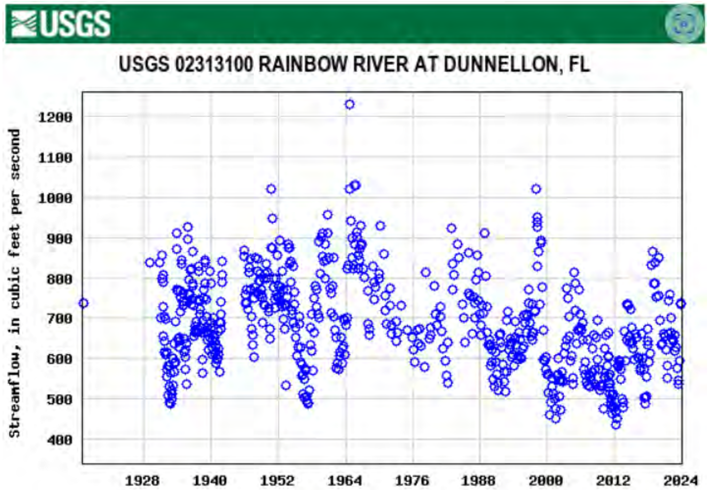


Figure 3.14 Graph of field-measured discharge rate of head springs of Silver River as provided by the official USGS gaging station (see https://nwis.waterdata.usgs.gov/.) There are no officially reported discharge (flow) rates since 2010.



Rainbow Springs form the Rainbow River which is gaged by USGS as such (the station is named Rainbow River—see Figure 3.14) and has an average flow of 685 cfs for the entire period of record. This flow must be divided by at least a dozen springs stretched over 1.5 miles.

Figure 3.14 Hydrograph of field measurements of flow rates of the Rainbow River which is formed by at least dozen springs stretched over 1.5 miles.

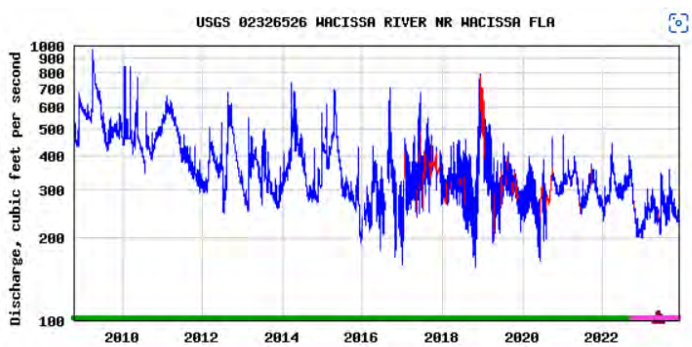


Figure 3.15 Combined flow from at least 12 springs which form the Wacissa River is measured daily by USGS. Several springs are located at the head of the river near the county park. The rest are scattered along the upper 2 miles of the river. All of them are grouped together as one first-magnitude spring by FGS. The hydrograph shows a dramatic decline in discharge rate of the river since 2008 when the monitoring started (note the semi-log scale of the vertical axis).

River rise is the resurgence of river water that descended underground through a sink some distance away. Wilson and Skiles (1989) state that the resurging water may contain a significant portion of aquifer water but is primarily river water and therefore should not be classified as a spring. However, as argued by FGS "*Due to the inclusion of a significant addition of groundwater, river rises have continued to be considered as springs*."

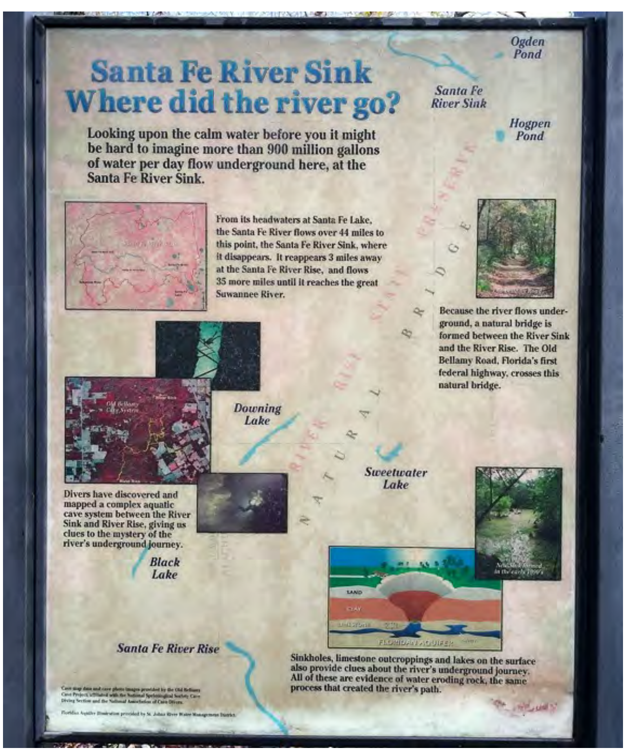
Follman and Buchanan (2023) accept that river rises may meet the technical definition of a spring, but state that this acceptance is a little begrudging: "*Lacking the filtration and clear water of other springs, river rises simply do not have the aesthetic, personal, or visual appeal of "traditional" springs*." The author of this book could not agree more but also feels very sorry for the river rises as explained further.

In 2016 something unfortunate happened to the first-magnitude river rises and karst windows in Florida. A State Legislator decided that they cannot join the very prestigious group of newly designated 30 Outstanding Florida Springs. They are not special, not worth taking care of, they are now on their own. They can still be called first-magnitude springs, but that is about it. One can imagine the devastating effect this cruel decision had on poor river rises and karst windows. And then the Suwannee River Water Management District (SRWMD) doubled down:

Holton Creek Rise (Figure 3.16) *is not an artesian spring that draws from the Floridan Aquifer, but a resurgence of the Alapaha River. Most of its water comes from swallets in the Dead River Sink, where the Alapaha River disappears. Holton Creek Rise serves as an overflow for the Alapaha River, and when river levels are low or high, the spring flow fluctuates*. (https://map.mysuwanneeriver.com/district-springs/holton-creek-rise-25/)

Figure 3.16 Holton Creek Rise, designated by FGS as first-magnitude spring. It is not one of 30 Outstanding Florida Springs. SRWMD does not consider it to be a spring. Its water is dark due to presence of naturally occurring substance in rivers called tannin which gives brown color to wood. The tannin is released during the decomposition of wood. Courtesy of SRWMD.

Or consider the sad case of Nutall Rise, designated as a first-magnitude spring by FGS. It is the largest and last one of more than 30 disappearances and appearances of the Aucilla River until it reaches the Gulf of Mexico. As it is a resurgence of the Aucilla River, the Nutall Rise's waters are dark and tannic. It is not entirely clear why FGS did not classify at least some of the other 30+ resurgences of the Aucilla River as first-magnitude springs. In any case, after what happened in 2016, Nutall Rise could not care anymore why there will not be brothers and sisters that would make its existence happier.



Nothing, however, can compare with the cruel destiny of Santa Fe River Rise. Santa Fe River Sink, located in O'Leno State Park, and Santa Fe River Rise, located in River Rise State Park are only 3 miles apart. As described on an information panel shown in Figure 3.17 "*From its headwaters at Santa Fe Lake, the Santa Fe River flows to this point, the Santa Fe Sink, where it disappears. It reappears 3 miles away at the Santa Fe River Rise, and flows 35 more miles until it reaches the great Suwannee River.*"

Figure 3.17 Information panel by the Santa Fe River Sink. "*Santa Fe River Sink; Where did the river go*? *Divers have discovered and mapped a complex aquatic cave system between the River Sink and River Rise, giving us clues to the mystery of the river's underground journey*."

Photographs shown in Figures 3.18 and 3.19 were taken in December 2023. The Sink was gasping for oxygen, choking and green from anger and despair. The whole organism was terribly ill, not just its heart, the Sink, which was pumping water to the Rise and the remaining 35 miles of the organism's body and limbs. The heart was pumping as hard as ever, terribly exhausted and begging for some help from someone, any help from anyone.

Figure 3.18 Foam floating on the Santa Fe River in December 2023, just yards away from the Sink pool. Foam commonly occurs in waters with high organic content such as productive lakes, bog lakes, and in streams that originate from bog lakes, wetlands, or woody areas. When the plants die and decompose, the oils contained in the plant cells are released and float to the surface. The concentration of the oil changes the physical nature of the water, making foam formation easier. The turbulence at river rapids and wave action introduce air into the organically enriched water, which forms the bubbles. It is quite common to find foam in dark-colored streams (the dark brown tint is caused by the presence of tannin that gives wood its brown color), especially during late fall and winter, when plant materials are decomposing in the water. From EGLE, 2023; Foam: A Naturally Occurring Phenomenon (michigan.gov). Foam can also be caused by substances released by the textile industry, paper production facilities, oil industries, agricultural and lawn application of pesticides, herbicides, and fertilizers, failing sewer systems and domestic septic tanks, household cleaning products that contain synthetic surfactants, and firefighting activities. In addition, the presence of silt in water, such as from construction sites, can cause foam. Although one should never touch it, human-made foam is sticky and usually a pure white color. Natural foam is more persistent, light, not slimy to the touch. However, if there is suspicion it may be a spill or pollution, the foam and water should not be touched, and the authorities should be contacted. See also https://www.ausableriver.org/blog/what-causes-foam-rivers

Figure 3.19 In December 2023 Santa Fe Sink was choked with green algae, other organisms, white foam, and various debris including pieces of construction lumber and other human-made objects.

As discussed by The Howard T. Odum Florida Springs Institute (2020):

In 1983, the Suwannee River Coalition described the Santa Fe River as one of Florida's "most valuable rivers ecologically" as it was in excellent condition. Although they reported problems with exotic vegetation like hydrilla or water hyacinths, it was still classified as "one of the cleanest, healthiest, and least disturbed rivers of its size *in the southeastern United States." In the past the Suwannee River Coalition similarly described the St. Johns River as a popular place for Floridians to fish, sail, and swim before pollution had gotten so bad and the dissolved oxygen content so low that fish populations diminished, and the unappealing aesthetics drove visitors away. The 1983 coalition report included an eerie warning to avoid the degradation of the Santa Fe River: "To permit a similar fate for the Santa Fe River would be an irresponsibility of the first magnitude. We must protect this river and it is essential that we designate the Santa Fe River system an Outstanding Florida Water so that it will be enjoyed by generations to come."*

And yet, State of Florida, PRPs, and indeed the citizens of Florida all failed terribly. They let down the Santa Fe River, its Sink, and its Rise, as attested by the photographs taken exactly 40 years after the eerie warning.

Karst windows form when the roof of a cave collapses exposing an underground stream for a short distance. Four karst windows are included in the FGS No. 66 Bulletin (2002, page 9) and two of them are designated as first-magnitude springs. This inclusion of the karst windows into the prestigious group of first-magnitude springs is despite the following definition, just a year earlier, in the FGS' own Special Publication No. 52 (Copeland, 2003; page 9) where it is stated:

Note that the FSNC believes that flow through an exposed conduit in an aquifer is different from flow onto the earth's surface. For this reason, the FSNC does not consider a karst window to be a spring. It is an exception to the definition of a spring.

As explained by Follman and Buchanan (2023), formerly called "spring-sink combinations," karst windows are characterized by water that rises from underground, flows a short distance (typically between 100 and 300 yards), and then drains back underground again into a sinkhole. Karst windows have also been described as "long sinkholes"—sites where the surface collapsed above a several-hundred-foot section of the Floridan Aquifer instead of over a pinpointed spot. Rhodes Springs (Leon County), Double Spring (Jackson County), and Owens Spring (Lafayette County) have similar characteristics and should more properly be called karst windows.

In any case, the inconsistencies regarding spring groups, river rises, and karst windows became two of the four guiding principles of the FGS' classification of first-magnitude springs (detail explanations of the other two principles, including the term *double trifecta*, are provided in section 3.3 on discharge rates of large Florida springs):

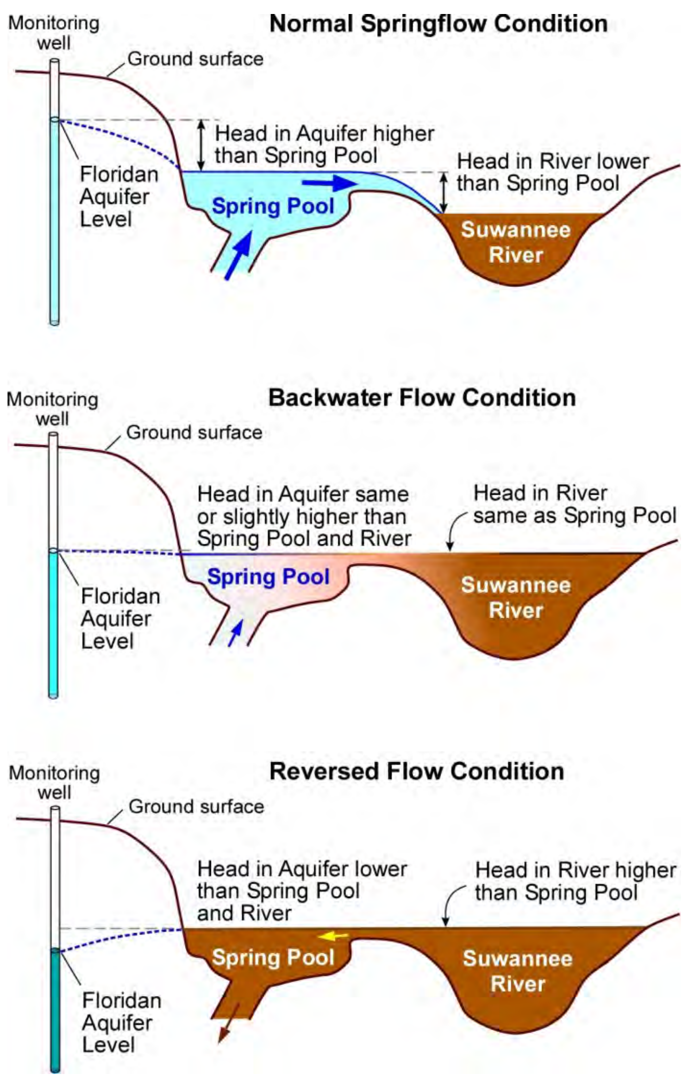
The individual spring vents within a group may not discharge enough water to be classed as first magnitude. Decide, at will, where and how many individual springs are needed to create one first-magnitude spring.

River rises and karst windows are not springs but are first-magnitude springs for the double trifecta purposes.

What happens with springs when there is overpumping of groundwater?

Answer to this important question is provided by Suwannee River Water Management District (SRWMD) on their web page https://www.mysuwanneeriver.com/418/Discharge and illustrated with three schematic drawings included here in Figure 3.20. As explained by SRWMD "*Typically groundwater flows out of a spring, down a spring run, into a river, and eventually ends up in the ocean. However, the springs found within the Suwannee*

River Water Management District (SRWMD) have very dynamic flows that can be greatly affected by both the level of the river into which it flows, and the groundwater levels within the springshed. During high river stages, river water pushes back against the groundwater, slowing stopping, or even reversing a spring's flow. On the other hand, low river levels can produce large differences between groundwater and surface levels, resulting in high spring flows. Some of the District's highest recorded spring flow measurements were conducted in 1998 when river levels dropped during a drought that occurred after a wet winter, which had raised groundwater levels."



Typically, groundwater levels are higher than river levels and the flow is out of a spring, down a spring run, into a river, and eventually ends up in the ocean.

When the river stage is equal to groundwater level, the river will act like a temporary "dam," slowing or stopping a spring's flow.

When the river stage becomes higher than groundwater levels, a reversing of a spring's flow can occur. Reversals result in the river water flowing back into the spring and aquifer, providing an important groundwater recharge point (see Figure 3.21 for an example).

Figure 3.20 Sketches illustrating what happens to a spring near a river when there is overpumping of groundwater in the adjacent aquifer. All captions are by SRWMD. Sketches and annotations are modified by the author for clarity and accuracy. From https://www.mysuwanneeriver.com/418/Discharge

An increasing number of springs next to Florida rivers are experiencing flow reversal more frequently. Today, one can only try to imagine the majestic sight described by William Bartram in 1774 (Figure 3.22). The sight must have been similar at many other Florida springs.

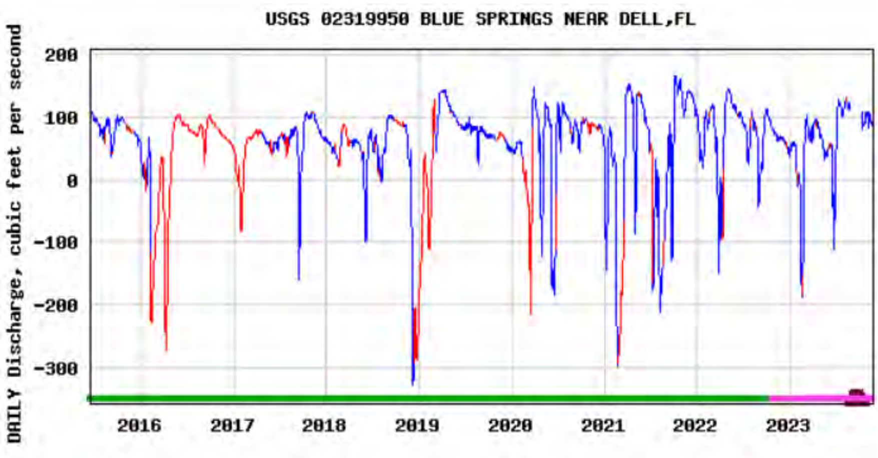


Figure 3.21 Hydrograph of Lafayette Blue Spring near Dell, Lafayette County. For the last 8 years the discharge rate rarely exceeded 100 cfs (average is 52.2 cfs). The spring acted as a sink 14% of time—negative discharge value means that flow is from the Suwannee River into the spring.

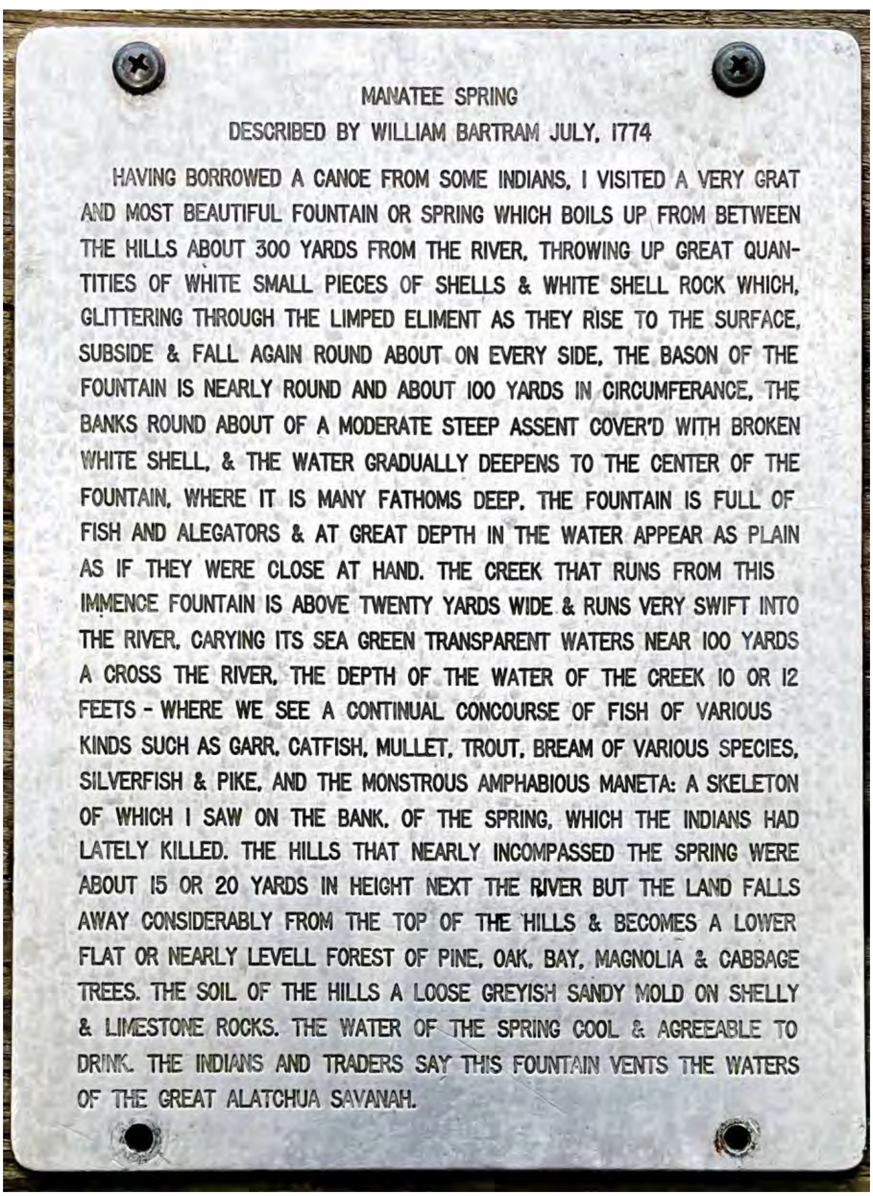


Figure 3.22 Metal plaque by Manatee Spring in Manatee Springs State Park.

Old Timers who swam in Ichetucknee Spring in the 1920s called it "the Boil". They remember that the spring flowed at a much higher rate than today. Many of the Old Timers remember that you could see the boil was at least 3 inches higher than the water surface. The boil was so strong you could not swim across it. According to several Old Timers you could hear the water boiling out of the spring before you could see it. One said that you could hear it about 300 feet away. No one hears the Ichetucknee Head Spring today. It is silent now as are so many springs in Florida.

From *Silenced Springs* by Robert L. Knight

North of Gainesville, a church camp once attracted thousands of visitors because it was built around the gushing waters of Hornsby Springs. Then the spring stopped flowing and the camp had to spend more than $1 million to build a water park to replace it. The old spring site is now so stagnant that it's frequently declared unfit for humans to swim in.

From *Florida's vanishing springs* by Craig Pittman

3.3 Discharge Rates of Large Springs in Florida

According to the FGS Bulletin No. 66 published in 2004, which is the basis for all regulatory dealings with Florida springs:

Springs are most often classified based upon the average discharge of water. Individual springs exhibit variable discharge depending upon rainfall, recharge and groundwater withdrawals within their recharge areas. One discharge measurement is enough to place a spring into one of the eight magnitude categories (emphasis added). *However, springs have dynamic flows. A spring categorized as being a first-magnitude spring at one moment in time may not continue to remain in the same category. This can result in a spring being classified as a first magnitude spring at one point in time and a second magnitude at another. A spring assigned a magnitude when it was first described continued with that magnitude designation even though the discharge may have changed considerably through time* (emphasis added).

Put in a more straightforward manner, the statement may look like this:

One flow measurement >100 cfs is sufficient to classify spring as being of first magnitude forever.

As demonstrated further in this section, this statement is the key guiding principle of FGS and it has secured a leading position for the State of Florida in surreal race towards the largest number of first-magnitude springs in the Nation, and indeed the world. The statement also defies common sense, the principles of the sciences of hydrology and hydrogeology, and key principles of statistics. Sadly, it and some examples of its application play right into the hands of those cynical people that like to use the following sentence "There is a lie, a big lie, and then the statistics."

But let's start from the beginning. It is not unlikely that this mad, self-imposed race about which state has the most first-magnitude springs started back in 1947 when Ferguson et al. published a table on page 37 of their Bulletin No. 31 entitled *Springs of Florida* (see Figure 3.23 in this book). Text describing the table reads:

Based on this tabulation, Florida has the greatest number of first magnitude springs in the United States. It also has approximately 49 springs of second magnitude, or springs having an average flow of 10 to 100 second-feet. The primary vents of both Silver and Rainbow Springs are believed to have larger average flows than any limestone spring in the United States and possibly in the world. Certainly the total average flows down Silver Springs Run and Rainbow River, 808 and 699 second-feet respectively, will rank these springs among the largest in the world.

SPRINGS OF FLORIDA—DISCHARGE 37

NUMBER OF SPRINGS OF FIRST MAGNITUDE IN THE UNITED STATES

(Average flow of 100 second-feet or more)

REGION	NUMBER OF SPRINGS
Florida	17
Snake River Basin in Idaho	15
Ozark region of Missouri (including Mammoth Spring just south of Missouri-Arkansas State line)	12
Deschutes River Basin, Oregon	8
Sacramento River Basin, California	7
Willamette and Umpqua River Basin, Oregon	5
Balcones fault belt in Texas	4
Montana	3
Klamath River Basin, Oregon	2
Northern Alabama and adjacent areas	1
Interior basins of Oregon	1
Total in the United States	75

Figure 3.23 Table on page 37 of the FGS Bulletin No. 31 entitled Springs of Florida (Ferguson et al., 1947)

As one can see from Figure 3.23, the race was tight in 1947.

It is not entirely inconceivable that someone at the State of Florida, or at various PRPs (this acronym stands for Potentially Responsible Parties, term commonly used in the environmental and groundwater remediation industries), or at Florida Council of Tourism Leaders (or some equivalent organization at the time), decided that this race must be won decidedly, at any cost. This is, possibly, how the FGS' 1977 groundbreaking Bulletin No. 31 (Revised) by Rosenau et al. came about. Exactly 30 years after the first comprehensive report on Florida Springs, there are now 10 more champions! Florida has 27 first-magnitude springs, far more than any other state in the Nation!

This accomplishment was achieved by a combination of innovative approaches to statistics, treatment of spring groups, and other methods unfamiliar to hydrogeologists and hydrologists practicing their respective sciences outside Florida. Figure 3.24 includes two screenshots from the groundbreaking 1977 Bulletin No. 31 (Revised) that show one of the equally groundbreaking new methods applied. Admittedly, the method is a clear forerunner of the first key guiding principle by FGS. It reads like this

The average value of one measurement equals that same measurement.

It is possible that the person(s) responsible for this groundbreaking new principle of statistics did not have any intention to become famous and simply forgot to remove word "average" from column 3 of their Table 2 in Bulletin No. 31 (Revised). However, this is also unlikely because all FGS spring bulletins, including No. 31 and No. 31 (Revised), and any other publications dealing with the classification of springs based on their discharge rates clearly cite where this method came from: Oscar Meinzer's 1927 publication entitled *Large Springs in The United States*. Figure 3.25 is a photograph of the Meinzer's original publication showing the famous table every state geological survey in the United States and the USGS have been referring to ever since. In that table it is very clear that a spring's magnitude should be determined based on its average discharge rate. It is that plain and simple.

TABLE 2-- The 27 first-magnitude springs and spring groups of Florida--with period of record, discharge and representative temperatures and dissolved solids--known through December 1976.

Spring and number by county (refer to figs. 11-15, and 17)	Period of record	Average (ft^3/s)	Discharge Range (ft^3/s)	Number of measure-ments	Average Water temperature C	Average Water temperature F	Average Dissolved solids (mg/L)
Alachua County							
9. Hornsby Spring	1972-75	163	76- 250	2	22.5	73	230
Wakulla County							
2. Kini Spring	1972	176	-	1	20.0	68	110
5. River Sink Spring	1942-73	164	102- 215	6	20.0	68	110
6. Wakulla Springs	1907-74	390	25-1,910	276	21.0	70	153
13. Spring Creek Springs (1,4)	1972-74	2,003	(1)	1	19.5	67	2,400

Figure 3.24 Screenshots of two portions of Table 2 on page 7 of the FGS Bulletin No. 31 (Revised) which lists 27 first-magnitude springs and spring groups of Florida. Note that Kini Spring and Spring Creek Springs have one measurement each and the average discharge rate is that same measurement. Notes 1 and 4 for the Spring Creek Springs are: (1) tidal affected. (4) see Figure 17 (this is unclear since Figure 17 shows location map of Gainer Spring)

Proposed classification of springs according to discharge

Magnitude	Average discharge
First	100 second-feet or more.
Second	10 to 100 second-feet.
Third	1 to 10 second-feet.
Fourth	100 gallons a minute to 1 second-foot (448 gallons a minute).
Fifth	10 to 100 gallons a minute.
Sixth	1 to 10 gallons a minute.
Seventh	1 pint to 1 gallon a minute. About 200 to 1,500 gallons, or 5 to 40 barrels, a day.
Eighth	Less than 1 pint a minute. Less than about 200 gallons, or 5 barrels, a day.

Figure 3.25 Oscar Meinzer's table on page 3 of the USGS's Water Supply Paper 557 published in 1927.

Below are some telling excerpts from the Meinzer publication (on page 2) which every student of hydrology, hydrogeology, and similar sciences should learn very early on, and every practicing professional in these scientific and engineering fields should know by heart even when awakened in the middle of the night including, for example, due to some natural disaster such as a category 3-5 hurricane which, from time to time, will hit Florida and may increase flows of some springs by many orders of magnitude, albeit for a short time.

Thus the discharge of a spring can be determined with fair accuracy only by establishing a gaging station and obtaining a continuous record over a period of years. To compare a single measurement of one spring with a single measurement of another spring made at an entirely different time may give a result that is almost as incorrect as would be obtained by a similar comparison of surface streams. The question also arises as to whether a comparison is made according to the minimum, maximum, or average discharge. Thus, if the average discharge of a nearly constant spring is about the same as that of a spring which fluctuates greatly, the constant spring will rank higher with respect to minimum discharge and the fluctuating spring higher with respect to maximum discharge. There is some popular interest in the maximum discharge, but the value of a spring, whether it is used for a public supply, irrigation, power, or other purpose, generally depends more nearly on its minimum discharge, or on its discharge at the time when the most water is needed. In so far as comparisons are attempted in the following discussion, they are based on the average discharge.

Why FGS and/or PRPs (Potentially Responsible Parties) in Florida failed to follow these simple, logical rules that all hydrogeologists and hydrologists follow in just about any foreign country and every other state in the United States, is beyond mystifying.

In 2004, the brand new, definitive publication on Florida springs has just been published. FGS Bulletin No. 66, with a very nice front cover (see Figure 3.26 in this book) and many color photographs of beautiful Florida springs tells the world that Florida has 33 first-magnitude springs, reaffirming what the FGS Open File Report No. 85 announced 2 years earlier (Figure 3.27). In less than 80 years, Florida went from having 11 such springs (the number given by Meinzer in 1927 on page 4 of his seminal work entitled *Large Springs in the United States*) to having 33 such springs. Three times more first-magnitude springs! Far more than any other state in the United States and any other country in the world as declared by FGS. In an equivalent horse race and associated gambling practices this, perhaps, would be called a **<u>double trifecta</u>**!

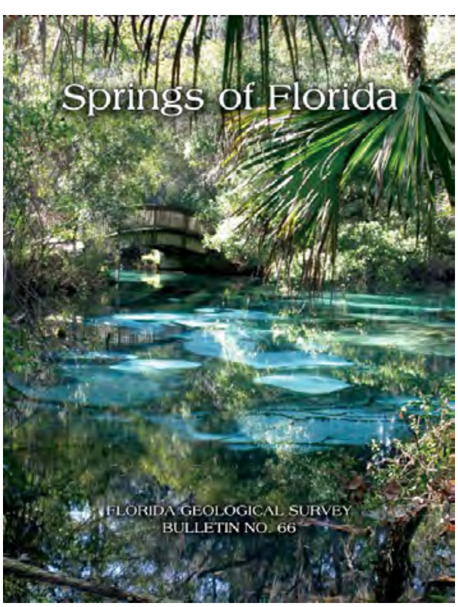
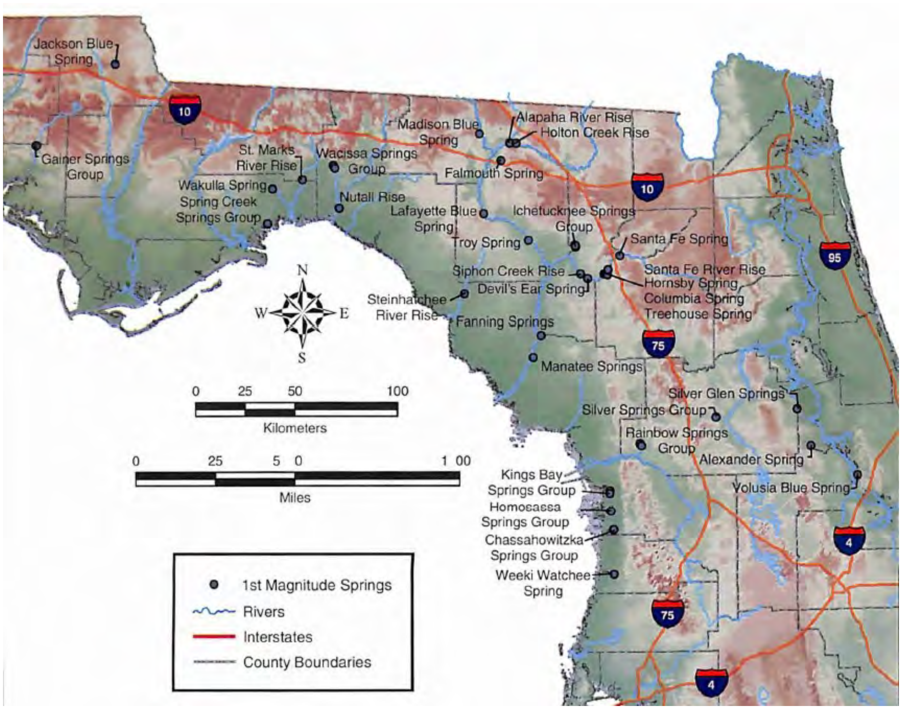


Figure 3.26 Front cover of Florida Geological Survey Bulletin No. 66.



Thanks to some good press releases by public relations and marketing departments at various Florida agencies, tourism entities, and similar, this incredible news quickly spread and has been immortalized. Today, everyone can find out by searching the web, or by reading brochures handed out by various national and international tourist agencies, tour operators, Florida State Parks, and others, or simply by word of mouth, that Florida has 33 first-magnitude springs, far more than anyone else, anywhere in the world.

Figure 3.27 Locations of 33 first-order magnitude springs in Florida as designated by FGS. From Scott et al., 2002.

The recipients of this information would not know how this incredible achievement came about. And why should they care? The number has been verified and promulgated by official Florida government agencies and entities, so, what is there to discuss?

Nevertheless, for those that are curious, and especially for the benefit of hydrogeologists, hydrologists and young scientists of any kind, here is a brief explanation that sheds some light on the double trifecta. The following four FGS guiding principles sum it all up:

One flow measurement >100 cfs is sufficient to classify spring as being of first magnitude forever.

The average value of one measurement equals that same measurement.

The individual spring vents within a group may not discharge enough water to be classed as first magnitude. Decide, at will, where and how many individual springs are needed to create one first-magnitude spring.

River rises and karst windows are not springs but are first-magnitude springs for the double trifecta purposes.

3.3.1 Coastal Springs

Two groups of coastal submarine springs were classified as first-magnitude freshwater springs in the FGS Bulletin No. 31 (Revised) authored by Rosenau et al. (1977): Spring Creek Springs in Wakulla County and Crystal River/Kings Bay Springs in Citrus County (see Figures 3.27 and 3.31). In the case of Spring Creek Springs, this classification was based on a single flow measurement as shown in Figure 3.24 (Table 2 of the FGS Bulletin (Revised), and an unknown number of dissolved solids analyses expressed in mg/L. In the same Bulletin No. 31 (Revised) the authors emphasize, on page 5, that "*Of the 78 first magnitude springs in the United States, Florida has 27, the most for a single slate. Florida seems to have the largest number of springs and also the largest spring in terms of average flow: a submarine spring* (emphasis added*) at Spring Creek in Wakulla County yields about 2,000 cubic feet per second*."

Despite of glaring inconsistencies in the FGS Bulletin No. 31 (Revised) when using word *spring* (singular; in the text—"a submarine spring") and *springs* (plural; in Table 2—"Spring Creek Springs"; see Figure 3.24), this statement stood the test of time and was reinforced by the U.S. Geological Survey in Fact Sheet FS-151-95 (USGS, 1995). This is illustrated by the screenshot of the top part of the Fact Sheet's Table 2 shown here as Figure 3.28.

Table 2. Summary of discharge and water-quality data collected at Florida's 27 first-magnitude springs
[Map number refers to figure 1. All values are averages. ft^3/s, cubic feet per second; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter]

Map Number	Name	County	Average discharge ft^3/s	Specific conductance (µS/cm)	Chloride (mg/L)	Sulfate (mg/L)
1	Spring Creek Springs	Wakulla	2,000	4,300	1,200	280
2	Crystal River Springs	Citrus	878	4,300	1,400	200
3	Silver Springs	Marion	799	410	9.5	42

Figure 3.28 Top part of Table 2 of the USGS' Fact Sheet entitled *Springs of Florida* (USGS, 1995)

Figure 3.29 USGS gaging station on Spring Creek. Photo courtesy of USGS.

In 2007, a year after first reporting that springs in Spring Creek have ceased flowing, USGS established a gaging station there (Figure 3.29) and started systematic measurements of streamflow, salinity, specific conductance, water temperature, and several other parameters (Figures 3.29 through 3.33).

Based on the USGS data, the Spring Creek Spring Group, consisting of 9 springs identified by the Florida Department of Environmental Protection (Figure 3.30), did not flow 42% of time during the period of record. During such times, the flow was reversed – the springs collectively acted as a sink for saline/sea water and this saltwater intrusion propagated 12 miles inland (north) to Wakulla Spring (see Section 3.6 Wakulla Spring).

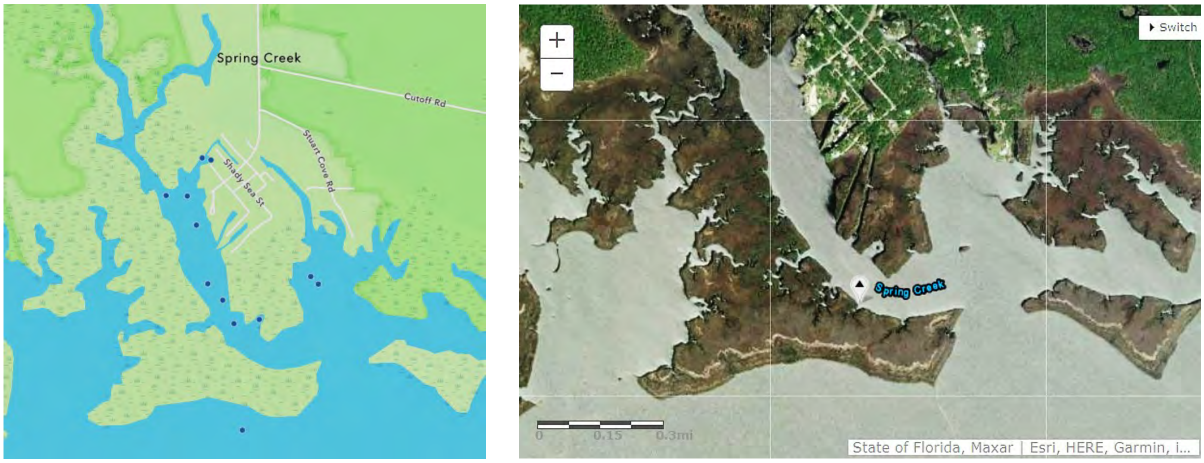
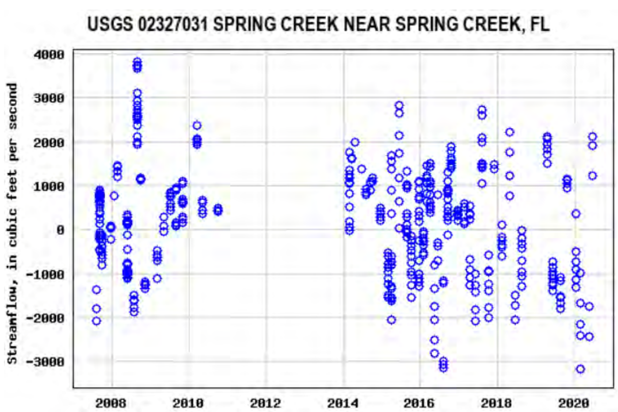
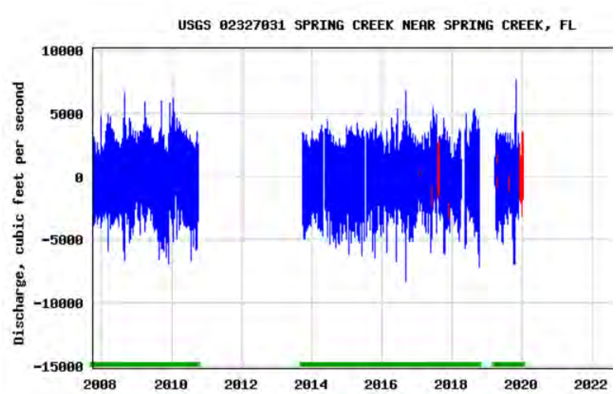


Figure 3.30 *Left*: Springs of the Spring Creek Group identified by Florida Department of Environmental Protection. Available at [Florida Springs | Florida Springs | Florida Department of Environmental Protection Geospatial Open Data (state.fl.us)](). Most individual springs shown have the same general accompanying text: *Submarine spring discharging below sea level in coastal saltwater. FGS Nov 1997*. Map courtesy of Esri Community Maps Contributors, Florida State University, FDEP, Esri, TomTom, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA, USFWS. *Right*: Location of the USGS gaging station USGS 02327031 SPRING CREEK NEAR SPRING CREEK, FL Latitude 30°04'21", Longitude 84°19'39" NAD27 Gage datum 0.00 feet above NAVD88. Base map courtesy of State of Florida, Maxar |Esri, HERE, Garmin. Available at USGS Site Map for USGS 02327031 SPRING CREEK NEAR SPRING CREEK, FL.





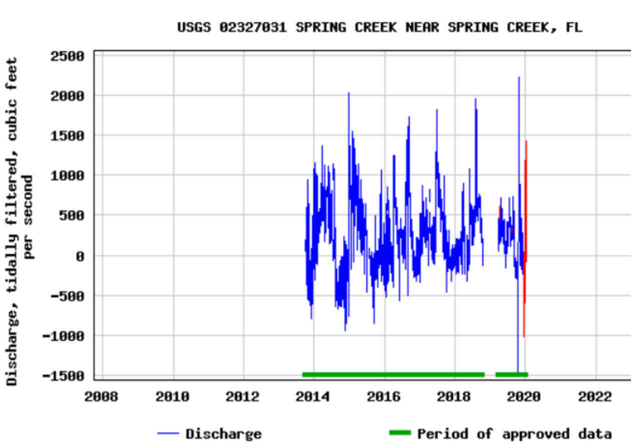


Figure 3.31 *Upper Left*: Hydrograph of field-measured Spring Creek streamflow (in cubic feet per second) not filtered for tidal influence. Discharge data is not reported after January 15, 2020. *Upper Right*: Hydrograph of continuous discharge measurements not filtered for tidal influence. *Lower Left*: Hydrograph of continuous discharge measurements tidally filtered. Available at USGS Current Conditions for USGS 02327031 SPRING CREEK NEAR SPRING CREEK, FL

The average flow rate of the intermittent Spring Creek Spring Group, when it is discharging a mixture of sea water and brackish groundwater, is 258 cfs after filtering for tidal influence. This is roughly eight times less than the reported value of 2,003 cfs in Rosenau et al. (1977).

While it has not been reported exactly where, how, and what was measured when Spring Creek Spring Group was classified as a first-magnitude spring in 1977 based on one single measurement, this group cannot be classified as such: there is no flow 42% of the time, and the water exceeds specific conductance of 10,000 microsiemens per centimeter (µSi/cm) 91% of the time, and it exceeds 3,000 µSi/cm 99.8% of the time (Figure 3.32). Note that specific conductance of fresh groundwater typically ranges between 200 and 3,000 µSi/cm, although water that is higher than 1,500 µSi/cm is not considered potable water. Sea water is typically about 53,000 µSi/cm but it can vary somewhat from sea to sea (location).

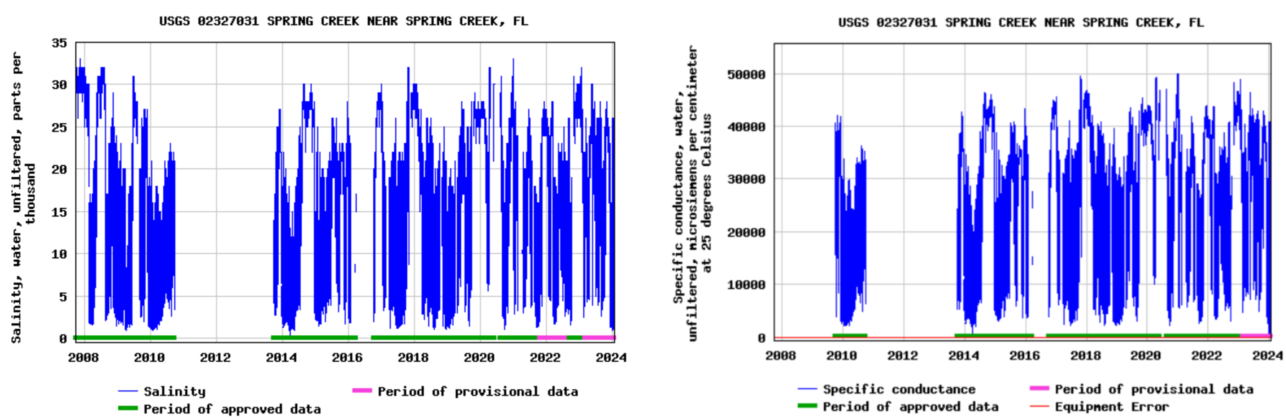


Figure 3.32 Graphs of salinity (left) and specific conductance (right) of the Spring Creek water measured continuously by USGS. Fresh potable water has salinity of less than 1 parts per thousand (ppt); by convention, sea water has salinity of 35 ppt which equals 53,000 microsiemens per centimeter (µSi/cm). The wide cyclic range of salinity and specific conductance unmistakably demonstrates that the Spring Creek springs do not discharge real groundwater like virtually all other first-magnitude and outstanding Florida Springs do. Instead, they discharge a mixture of brackish groundwater and sea water reflecting changes caused by the varying interactions between the two waters of different density.

Although there is no continuous or even sporadic record (except for one single measurement as mentioned earlier) on the flow rates or any historic salinity trends for the Spring Creek Spring Group prior to the 2007-2024 time period, it has been argued that a rising sea level since 1930s has had the crucial influence on the reduced freshwater flow of these submarine springs, and an increasing flow of Wakulla Spring (Davis and Verdi, 2014; see Section 3.6 Wakulla Spring for more detail.)

Perhaps the best, unbiased judge of the dilemma if the springs of the Spring Creek are real groundwater springs, let alone one lumped “first-magnitude spring”, are the beloved manatees, the most iconic Florida creatures. The best time to see manatees in Florida is from November through February. Cooler sea temperatures during these months entice these gentle mammals to warm-water havens such as natural Florida springs and power plant outlets. Throughout the winter, manatees congregate in large numbers at these shelters, making it easier to spot them.

Florida wildlife officials explain that manatees can face health problems if they remain for too long in water colder than 68 degrees Fahrenheit (20 degrees Celsius), and cold stress can lead to death for the mammals (https://myfwc.com/education/wildlife/manatee/). This is why manatees avoid the cold Spring Creek water in winter (Figure 3.33) and are finding their sanctuary at real springs discharging groundwater of very comfortable and steady temperature such as at Homosassa Springs shown in Figure 3.34 as an example.

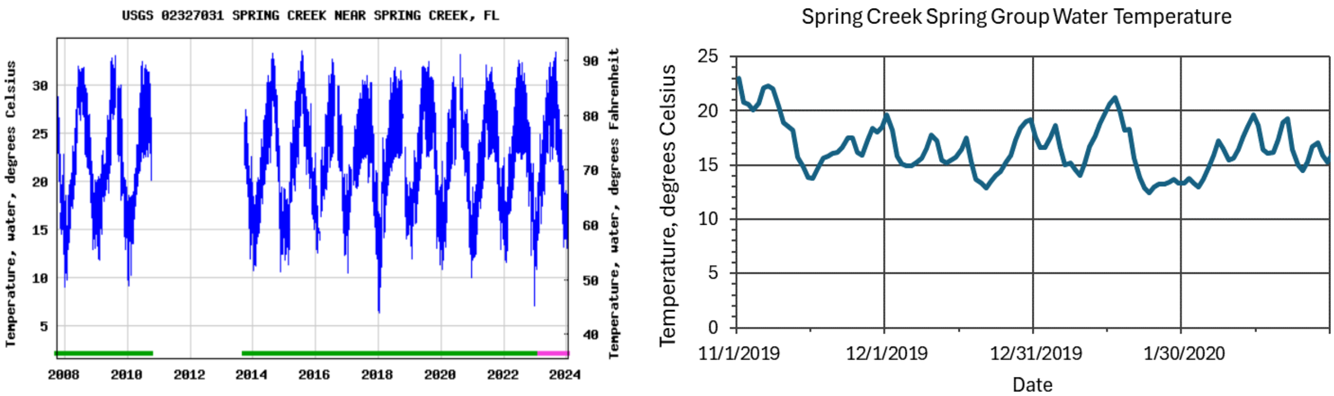


Figure 3.33 *Left*: Daily water temperature of Spring Creek, years 2008 through 2024. *Right*: Example of daily water temperature during time of typical cold-season congregation of manatees at Florida springs which offer warm water shelters to these iconic sea mammals. Manatees do not shelter in Spring Creek because they cannot survive for long in water colder than 20 degrees Celsius. The wide cyclic range of temperature unmistakably demonstrates that the Spring Creek springs do not discharge real groundwater like virtually all other first-magnitude and outstanding Florida Springs do. Instead, they discharge a mixture of brackish groundwater and sea water reflecting seasonal changes caused by the varying interactions between the two waters of different temperature.

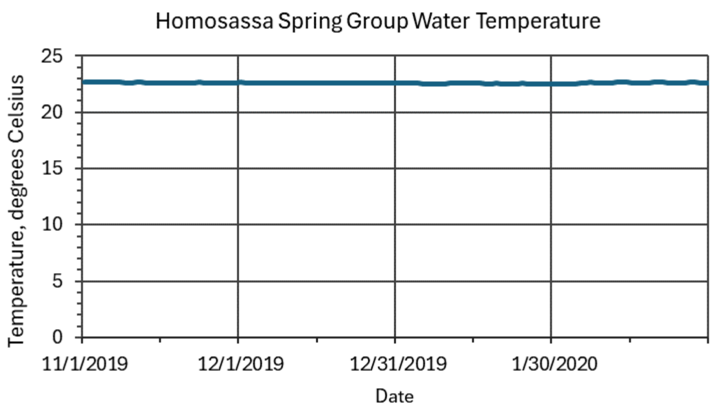


Figure 3.34 Daily water temperature of Homosassa Spring Group during time of typical cold-season congregation of manatees at this well-known warm water shelter for the iconic sea mammals. The average water temperature is a very comfortable and steady 22.6 degrees Celsius or 72.7 degrees Fahrenheit.

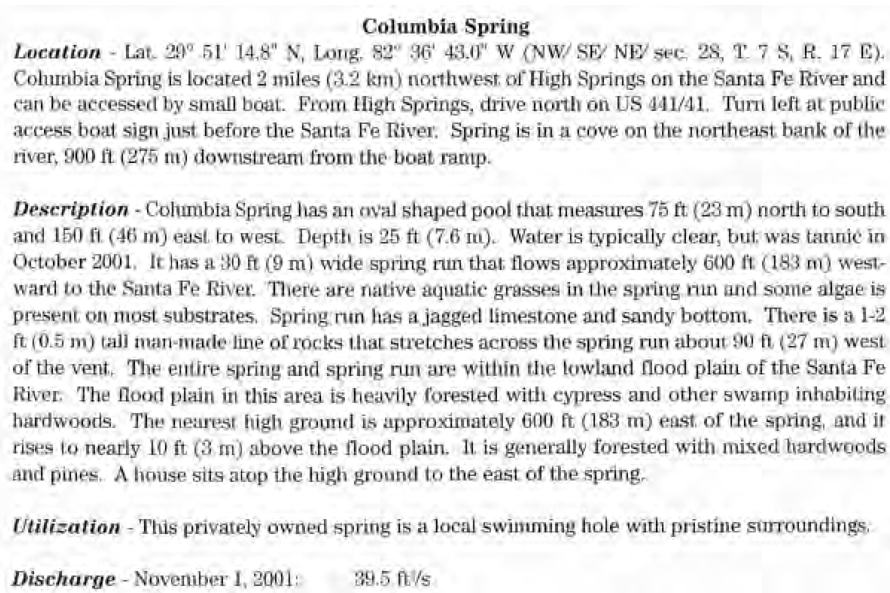
3.3.2 Independent Analysis

As one of those alleged *purists* (perhaps an adequate, contemptuous synonym would be *unreasonable people*), i.e., a practicing professional hydrogeologist for more than four decades, and not agreeing with the four guiding principles of FGS, I became quite skeptical about the accuracy of other facts presented in the infamous Bulletin No. 66. I therefore decided to carefully read what is written about the 33 champion springs. I also looked for additional sources of information including publicly available records of discharge (flow) rates of the alleged first-magnitude springs and spring-fed rivers ("spring groups") in Florida measured by USGS.

One of the first things that jumped out at me was this weird error regarding one of the newest additions to the exclusive club of first-magnitude springs, Columbia Spring near High Springs. Figure 3.35 illustrates the error.

It is not entirely clear if this whole thing about Columbia Spring is simply an honest mistake and why no one discovered it during the last 20-22 years since the publication of the two milestone reports on Florida Springs by FGS. In any case, I have yet again learned an old truth that nothing or no one is perfect, including public agencies.

It is very interesting that two newly discovered first-magnitude springs in FGS Bulletin No. 66—Treehouse Spring, and Columbia Spring—may not even be real springs after all. Namely, on an information panel by the Santa Fe River Rise these two "springs" are marked as rises of the Santa Fe River as well, together with their associated swallets (Figure 3.36). It is puzzling that Bulletin No. 66 lists these two river rises as springs without mentioning the possibility that they may, in fact, be river rises. At the same time, it appears that only the visitors to the River Rise State Park are informed about their true nature. Finally, in addition to the Columbia Spring's unexplainable error in classification (only one measurement of 39.5 cfs shown in the FGS Bulletin No. 66), Treehouse Spring does not have a USGS gaging station, and has only 2 discharge measurements listed on page 47 of Bulletin No. 66. This, of course, would be insufficient for any classification of a spring outside Florida.



Columbia Spring

Location - Lat. 29° 51' 14.8" N, Long. 82° 36' 43.0" W (NW/ SE/ NE/ sec. 28, T. 7 S, R. 17 E). Columbia Spring is located 2 miles (3.2 km) northwest of High Springs on the Santa Fe River and can be accessed by small boat. From High Springs, drive north on US 441/41. Turn left at public access boat sign just before the Santa Fe River. Spring is in a cove on the northeast bank of the river, 900 ft (275 m) downstream from the boat ramp.

Description - Columbia Spring has an oval shaped pool that measures 75 ft (23 m) north to south and 150 ft (46 m) east to west. Depth is 25 ft (7.6 m). Water is typically clear, but was tannic in October 2001. It has a 30 ft (9 m) wide spring run that flows approximately 600 ft (183 m) westward to the Santa Fe River. There are native aquatic grasses in the spring run and some algae is present on most substrates. Spring run has a jagged limestone and sandy bottom. There is a 1-2 ft (0.5 m) tall man-made line of rocks that stretches across the spring run about 90 ft (27 m) west of the vent. The entire spring and spring run are within the lowland flood plain of the Santa Fe River. The flood plain in this area is heavily forested with cypress and other swamp inhabiting hardwoods. The nearest high ground is approximately 600 ft (183 m) east of the spring, and it rises to nearly 10 ft (3 m) above the flood plain. It is generally forested with mixed hardwoods and pines. A house sits atop the high ground to the east of the spring.

Utilization - This privately owned spring is a local swimming hole with pristine surroundings.

Discharge - November 1, 2001: 39.5 ft^3/s

Figure 3.35 Description of Columbia Spring in the 2002 FGS Open File Report 85 by Scott et al. entitled *First Magnitude Springs of Florida* (on page 43). The exact same value is given on page 73 of the 2004 FGS report by Scott et al. entitled *Springs of Florida*. Based on this single value (39.5 cubic feet per second), Columbia Spring is declared a first-magnitude spring with the average discharge rate greater than 100 cfs. As such, it is featured on various FGS maps and their derivatives, including the most current one (as of December 2023) available on the official FGS web page floridadep.gov/fgs/fgs/content/springs

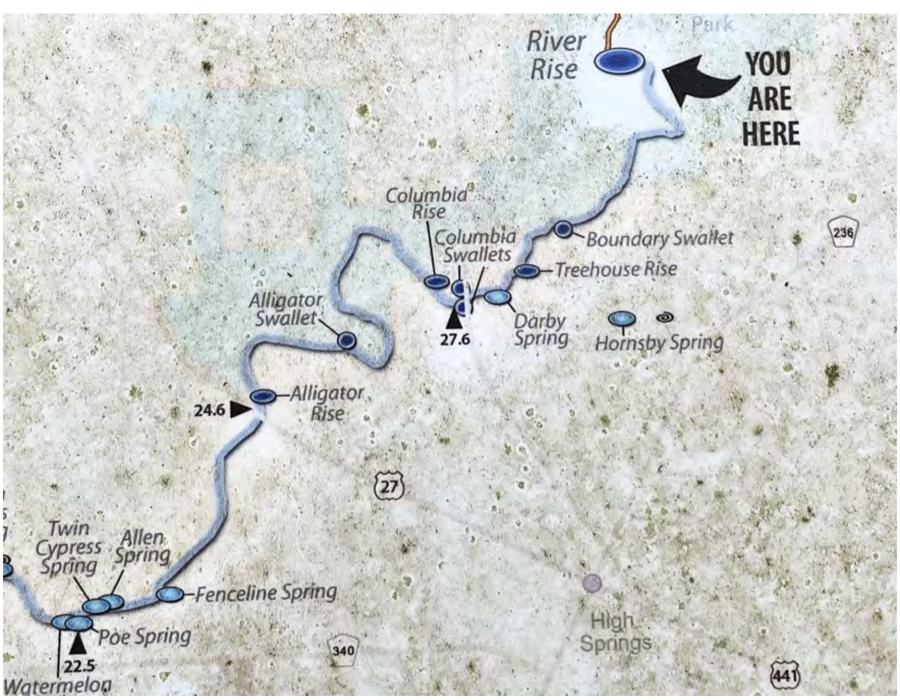


Figure 3.36 Part of the information panel at the Santa Fe River Rise in River Rise State Park near High Springs, Florida. The panel clearly indicates that Columbia Rise and Treehouse Rise are Santa Fe River rises and not springs as listed in the FGS Bulletin No. 66. They both have their swallets upstream where waters of the Santa Fe River sink and then reappear downstream at the two river rises.

The result of my cursory analysis more than surprised me – when everything was said and done, seven springs and three "spring groups" (in reality, spring-fed rivers) are not first-magnitude freshwater springs. When one excludes eight river rises and karst windows from the double trifecta number of 33, there are nine springs and six spring-fed rivers with the average discharge rate greater than 100 cfs left in Florida. This conclusion is based on publicly available long-term records of the Florida springs' discharge measured by USGS as of December 2023. The number of 15 reigning champion springs and spring-fed rivers is two less than in the 1947 report by Ferguson et al. which, one must admit, is rather intriguing if not amusing to those who like betting on which state has the most first-magnitude springs. The map in Figure 3.37 and graphs in Figures 3.38 through 3.43 present the results of this independent analysis. It is possible that additional, not publicly available, and/or non-USGS data on the long-term discharge rates of certain springs exist, and this may change the results of the analysis.

In any case, I understand that the analysis and the accompanying figures cannot change much when it comes to the FGS' interpretation of what constitutes a first-magnitude spring. The reader may also ask why I spent all this effort to discover something that is not all that important. I completely agree – it is somewhat irrelevant if Florida has 9, 11, 15, 17, 27, or 33 first-magnitude springs. It is infinitely more important what is happening not only to these springs but also to all other beautiful springs in Florida.

Many Florida springs are clearly in trouble, and some are seriously ill. It will take lots of courage from Florida politicians and other bureaucrats, as well as its citizens, to heal their springs. It also will require thinking out of the box because, based on my professional judgment, the current "Best Management Action Plans" for restoring the damaged Outstanding Florida Springs is just window-dressing. There is no bite behind these plans, no real funding for their full implementation, no clearly specified milestones and deadlines, no enforcement mechanisms, and no serious fines or other consequences for failures to implement them and achieve visible results. None.

I, of course, am not the only one expressing such an opinion having only recently learned about the egregious neglect and catastrophe of Florida springs. Below excerpts are from an article entitled *FDEP Continues to Fail Florida Springs* published March 24, 2022 on the web page of Sierra Club Florida Chapter (https://www.sierraclub.org/florida/blog/2022/03/fdep-continues-fail-florida-springs)

> *OCALA, FL—On Monday, March 21, 2022, the Florida Department of Environmental Protection (FDEP) held its first public workshop in more than five years related to* ***proposed rules 62-41.400, 62-41.401, and 62-41.402*** *to implement* ***373.219(3) F.S.****, preventing groundwater withdrawals that are harmful to Outstanding Florida Springs. Since 2016, FDEP has ignored a requirement in state law to adopt new rules to protect Outstanding Florida Springs, but completed rulemaking to benefit large water users and developers.*
>
> *For the past five years FDEP has delayed rulemaking by filing a "notice of extension" claiming that, "The Department needs additional time to further develop and solicit public comment on the rules associated with this rulemaking effort." However, at Monday's workshop FDEP representatives were unable to name even one person or group they spoke to during those five years.*
>
> *Cris Costello, Sierra Club Senior Organizing Manager, said: "Sierra Club Florida fully endorses both the FSC letter and the FSC draft rule." Costello added: "Per statute requirements FDEP needs to make a new rule to protect Outstanding Florida Springs, but the Department has no intention of actually doing anything to protect them, so they copy and paste everything that has never worked in the past and call it a new rule. It is a prime example of DeSantis greenwashing, but with exponentially more dangerous implications. In this case it isn't 'let's talk about the problem but never do anything about it,' rather it is 'let's make a rule to kill the state's most endangered springs and call it protection.''*

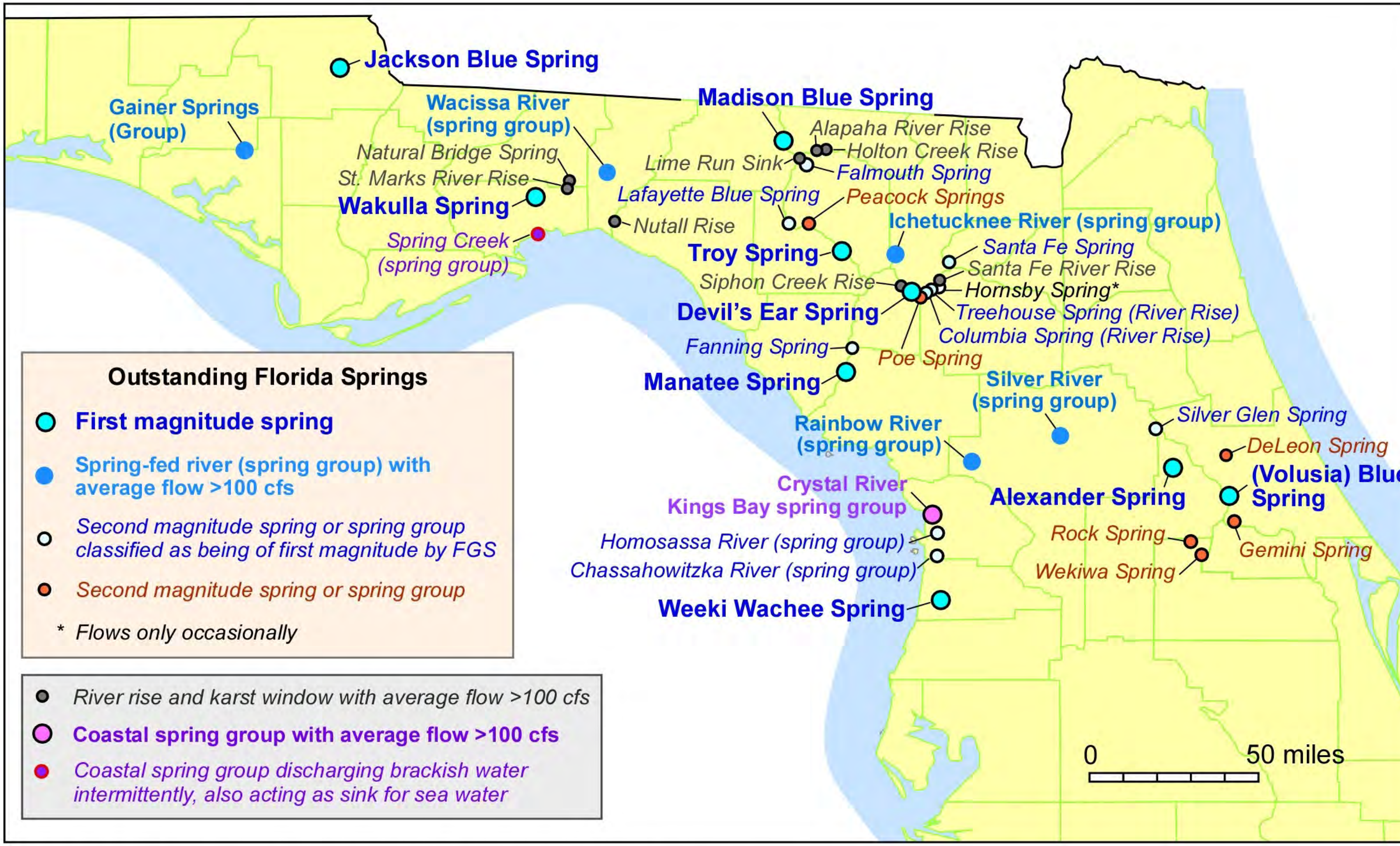


Figure 3.37 Nine first magnitude springs and six spring-fed rivers ("spring groups") in Florida with average discharge rate >100 cubic feet per second (cfs), and other large springs with discharge rates <100 cfs based on long-term record as of December 2023. Thirty Outstanding Florida Springs, as specified in Florida Statute 373.802, include "all historic first magnitude springs and their associated spring runs, as determined by the department using the most recent Florida Geological Survey springs bulletin (No. 66), and the following additional springs, including their associated spring runs: De Leon Spring, Peacock Spring, Poe Spring, Rock Spring, Wekiwa Spring, and Gemini Spring." River rises, karst windows, and costal springs are not included in Outstanding Florida Springs.

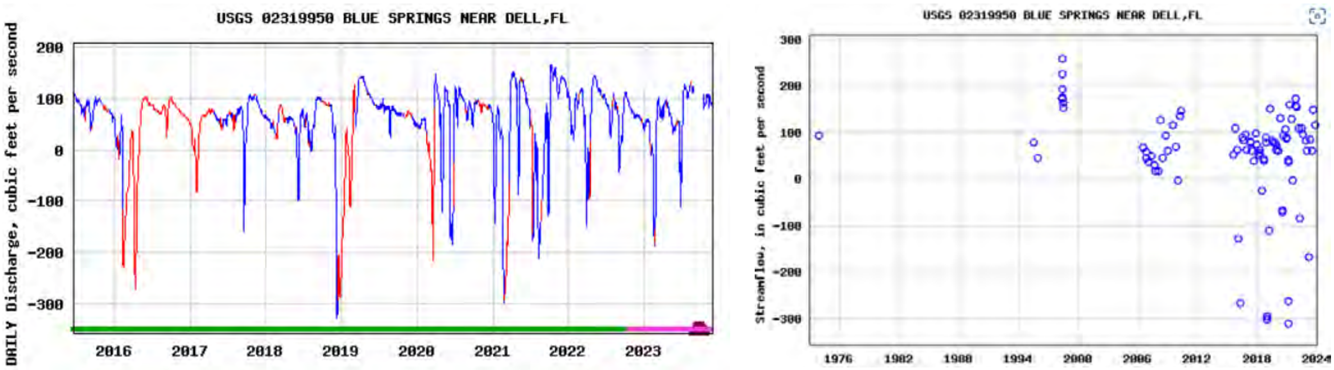


Figure 3.38 Lafayette Blue Spring discharge measurements for the period of record. *Left*: Continuous daily measurements based on rating curve; average is 52.2 cfs including flow reversal. *Right*: Field measurements; average is 66.4 cfs including flow reversal.

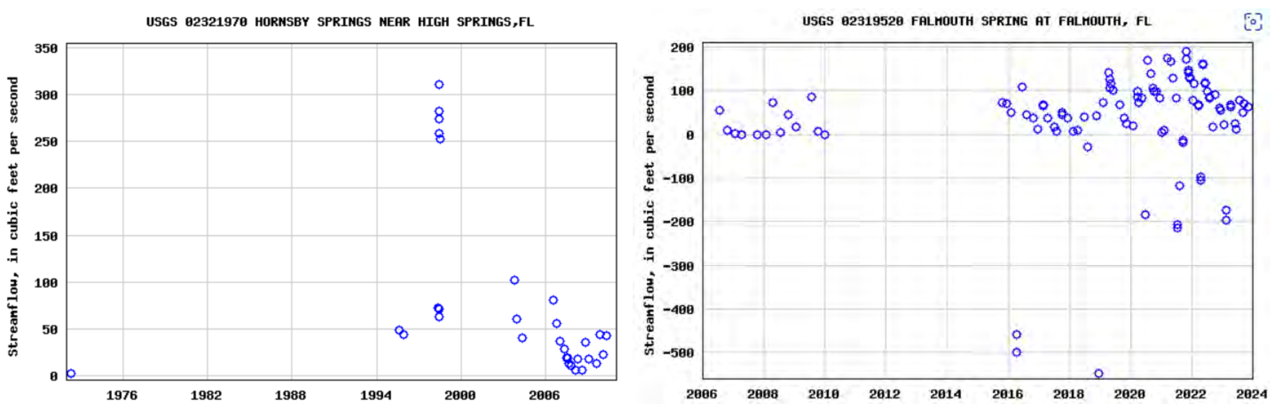


Figure 3.39 Field measurements of Hornby and Falmouth springs discharge rates for the period of record. *Left*: Historic average for Hornsby Springs is 76.1 cfs. Hornsby Spring was once a beautiful spring, and one of the strongest springs in Florida. Today Hornsby Spring is not flowing most of the time because of damage caused by over-pumping of the Floridan Aquifer. *Right*: Average for Falmouth Spring is 33.5 cfs including flow reversal (negative values).

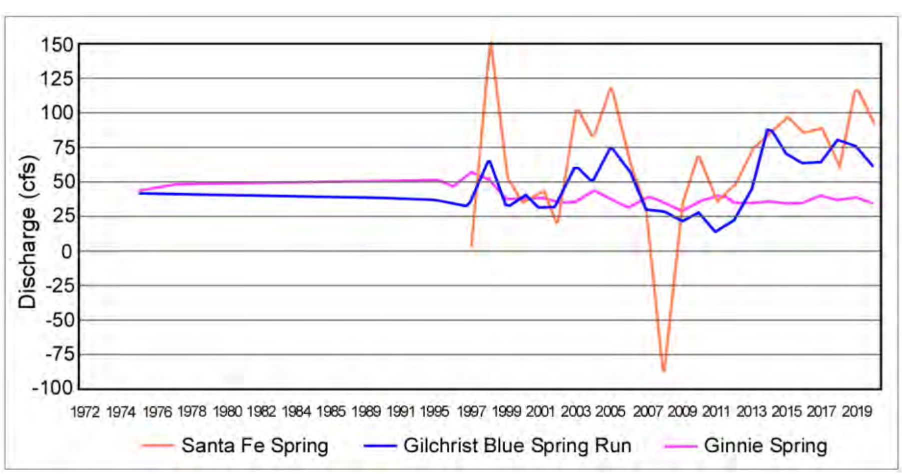


Figure 3.40 Field measurements of springs' discharge rates for the period of record. Orange line is for Santa Fe Spring; average is approximately 62 cfs. There are no publicly available measurements by USGS for these three springs. From The Howard T. Odum Florida Springs Institute, 2020. Modified for clarity.

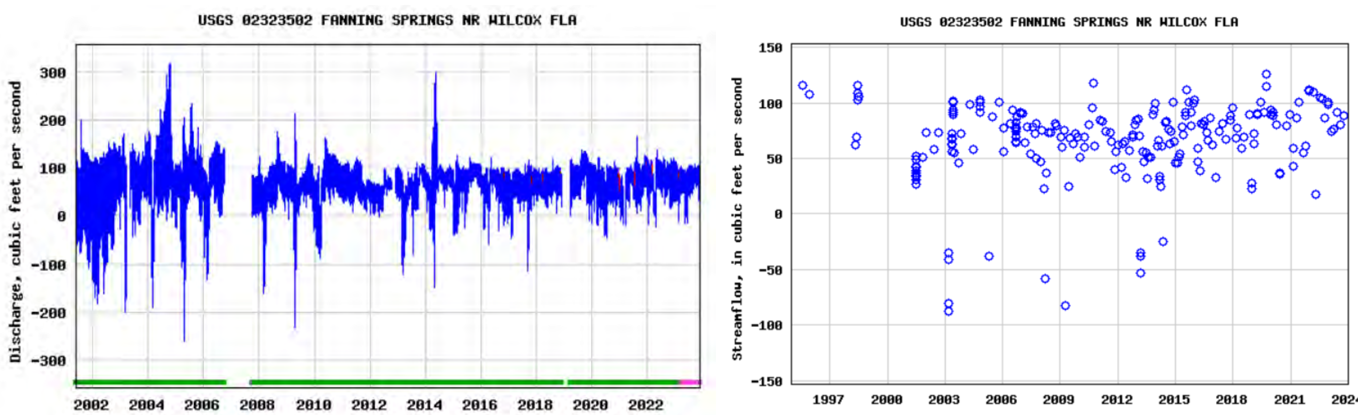


Figure 3.41 Fanning Springs discharge rate. *Left*: continuous measurements based on rating curve; average is 70.6 cfs including flow reversal. *Right*: field measurements, average is 66.4 cfs including flow reversal.

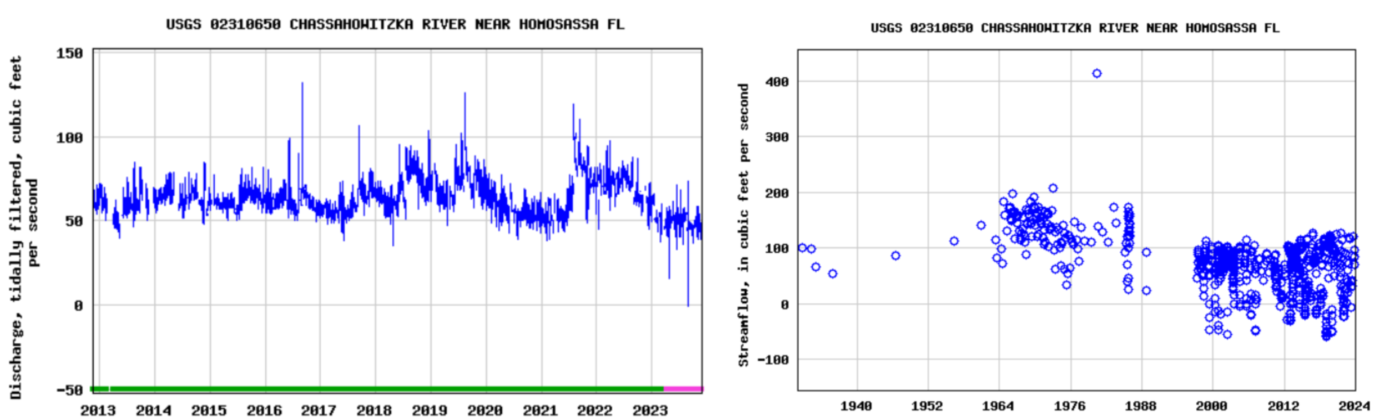


Figure 3.42 *Left*: Chassahowitzka River discharge rate measurements for the period of record. *Left*: Continuous measurements filtered for tide; average is 63.2 cfs. *Right*: Field measurements; average is 73.6 cfs including flow reversal.

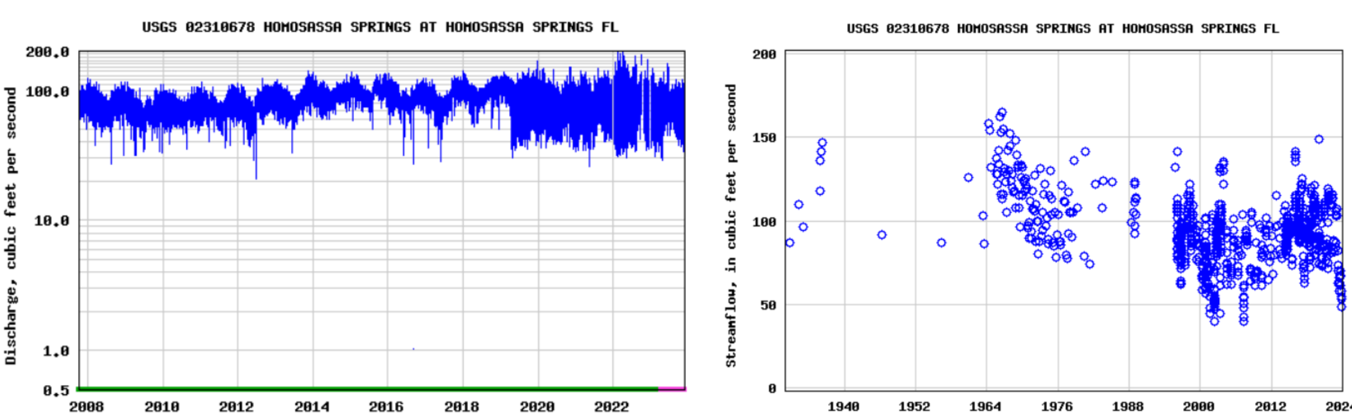


Figure 3.43 Homosassa Springs discharge measurements for the period of record. *Left*: Continuous measurements; average is 84.9 cfs. *Right*: Field measurements; average is 94 cfs for the entire period of record.

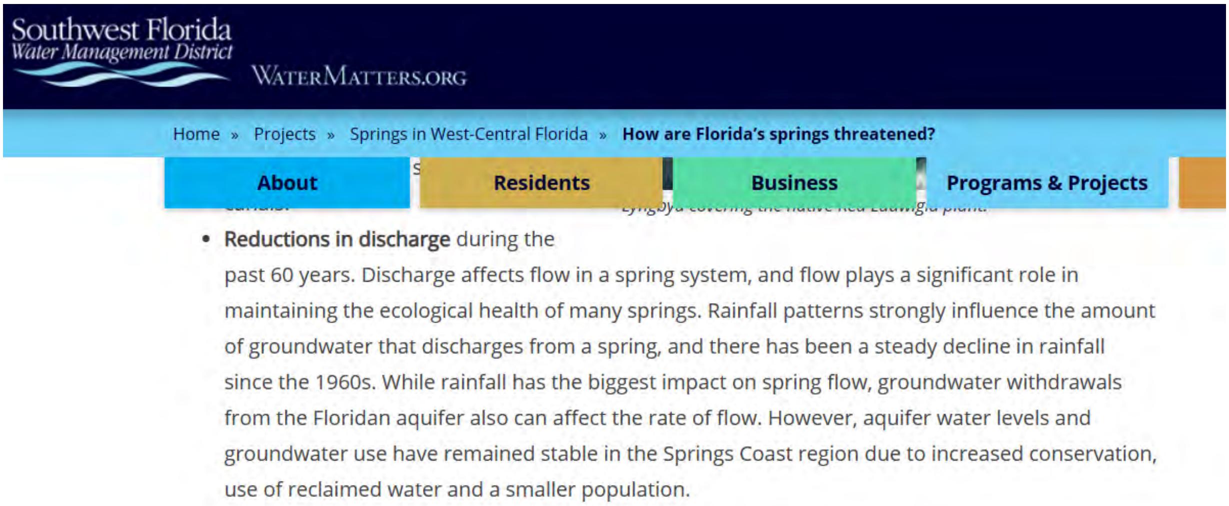
Perhaps the main reason why I went into all this trouble of decoding the unfortunate and misguided classification of Florida's first-magnitude springs is to help young scientists and professionals avoid falling into a deadly trap of groupthink. Here are some excerpts describing the term as applied to the profession of hydrogeology, and many other human activities (modified from Kresic and Mikszewski, 2013; and Kresic, 2023):

> *The above example illustrates that one should never accept previously published, peer reviewed information at face value without independent, critical analysis. While the Agency produces many useful and accurate reports, the institution is not infallible. It is often desirable for a hydrogeologist to directly cite public agencies such as USGS or United States Environmental Protection Agency as there will generally be less resistance from stakeholders in accepting the related concepts and conclusions. However, if the assumptions and results of the study in question are wrong, it can lead to the rapid propagation of conceptual errors that can become entrenched in professional practice.*
>
> *The widespread endorsement of a report with apparent conceptual and other problems could be construed as an example of groupthink, when group pressures lead to a breakdown in independent thought and result in flawed decision making (Irving Janis, 1971, 1972, 1982). Groupthink favors anecdotal assumptions over scientific evidence, avoids criticism and controversy to achieve "consensus," and rationalizes bad decisions made in the past rather than exploring new solutions. To avoid groupthink, group members should remain as impartial as possible and consult independent, evidence-based opinion from third parties removed from the impacts and political pressures of the decision to be made.*
>
> *The symptoms of groupthink arise when the members of decision-making groups become motivated to avoid being too harsh on their judgments of their leaders, or their colleagues' ideas. They adopt a soft line of criticism, even in their own thinking. At their meetings, all the members are amiable and seek complete concurrence on every important issue, with no bickering or conflict to spoil the cozy, "we-feeling" atmosphere (Janis, 1971).*

Admittedly, the State of Florida and PRPs (Potentially Responsible Parties) are now, unfortunately, between a rock and a hard place. Namely, who would dare to distribute a press release that starts something like this: "Once upon time, Florida had 33 first-magnitude, beautiful springs, more than any other state and any other country on Earth...."?

All maps currently floating on the web, including on official web pages of PRPs, that show how Florida has (not had) 33 first-magnitude springs (not "historic" first-magnitude springs) would have to be replaced by updated versions. And all descriptions by unsuspecting national and international travel agencies, tour operators, hotels, motels, state parks, and others that benefit from the double trifecta would have to be replaced. Who would even dare to undertake this monumental effort that could potentially hurt everyone involved?

Before we start visiting notable Florida springs, I also must admit that, more than once, I felt I was in a parallel universe while doing my research. The universe where there are alternative facts, laws of statistics, principles of hydrogeology/hydrology, and an unknown common sense. There were also plenty of wormholes inviting me to travel, instantaneously, to this parallel universe. The last one I saw was on the web page of the Southwest Florida Water Management District https://www.swfwmd.state.fl.us/projects/springs/how-are-floridas-springs-threatened accessed on December 22, 2023. On it there is a bullet stating that one of the threats to Florida springs is reduction in discharge.


Southwest Florida Water Management District

WaterMatters.org

Home » Projects » Springs in West-Central Florida » **How are Florida's springs threatened?**

About | Residents | Business | Programs & Projects

- **Reductions in discharge** during the past 60 years. Discharge affects flow in a spring system, and flow plays a significant role in maintaining the ecological health of many springs. Rainfall patterns strongly influence the amount of groundwater that discharges from a spring, and there has been a steady decline in rainfall since the 1960s. While rainfall has the biggest impact on spring flow, groundwater withdrawals from the Floridan aquifer also can affect the rate of flow. However, aquifer water levels and groundwater use have remained stable in the Springs Coast region due to increased conservation, use of reclaimed water and a smaller population.

Clearly, according to SWFWMD, the steady decrease in rainfall since the 1960s is solely to blame for the reduction in discharge of their springs because all other factors are under control and are not responsible for this reduction. Nevertheless, before I enter this inviting wormhole to the parallel universe, I better install some cable behind, I thought to myself, so I can find my way back if needed. And I did. I looked for the long-term record of rainfall at two closest major rain gaging stations, Ocala and Tampa, between which the springsheds of the SWFWMD's springs are located. This record is publicly available, anyone can see the graphs of long-term rainfall for Ocala and Tampa on their computer screens (or screens of other electronic devices) when they visit Climate Data & Visualization web page of Florida Climate Center at Florida State University.

One can also download the data and play with it, including looking at possible trends, perhaps using some simple functions in Microsoft Excel (no need for "fancy" mathematical/statistical analyses). Curious readers not inclined to practice quantitative analyses of data can simply trust their own eyes and common sense applicable to this universe.

Graphs of long-term daily and annual rainfall for Tampa and Ocala are shown in Figures 3.44 through 3.46 Data are from https://climatecenter.fsu.edu/climate-data-access-tools/climate-data-visualization.

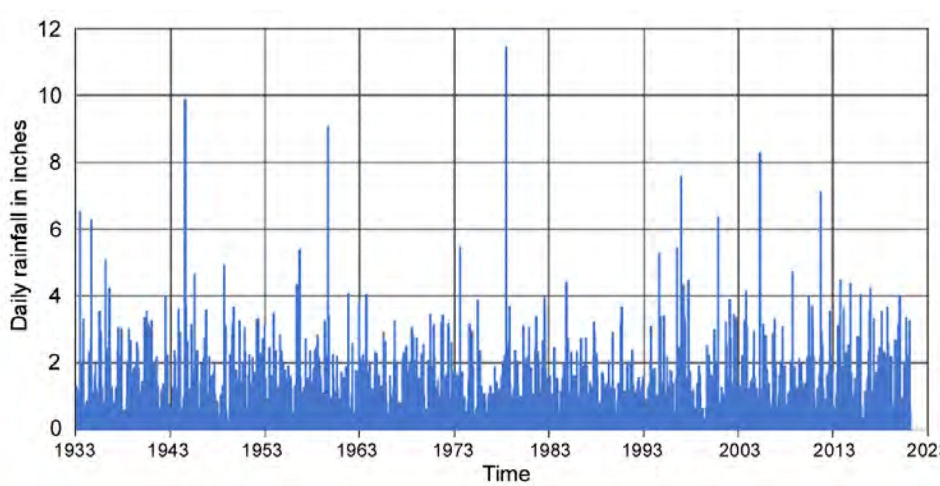


Figure 3.44 Daily rainfall recorded at Tampa Airport since 1933.

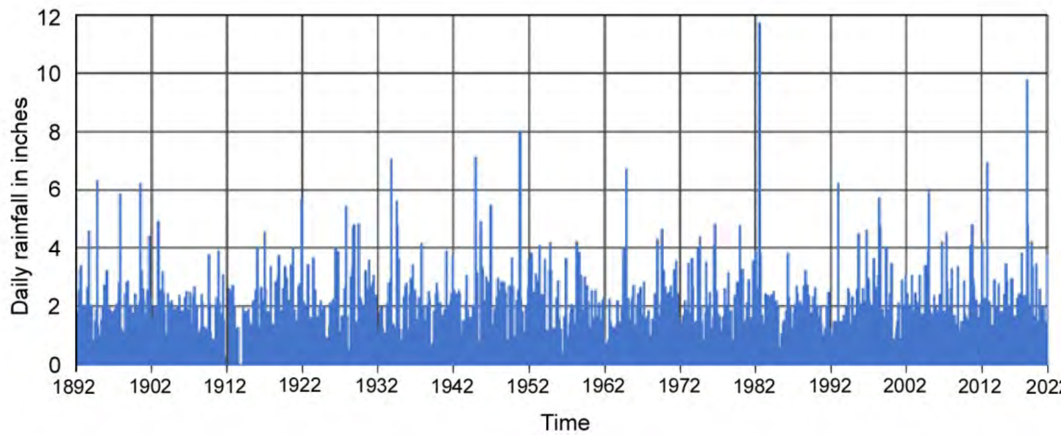


Figure 3.45 Daily rainfall recorded at Ocala since 1892.

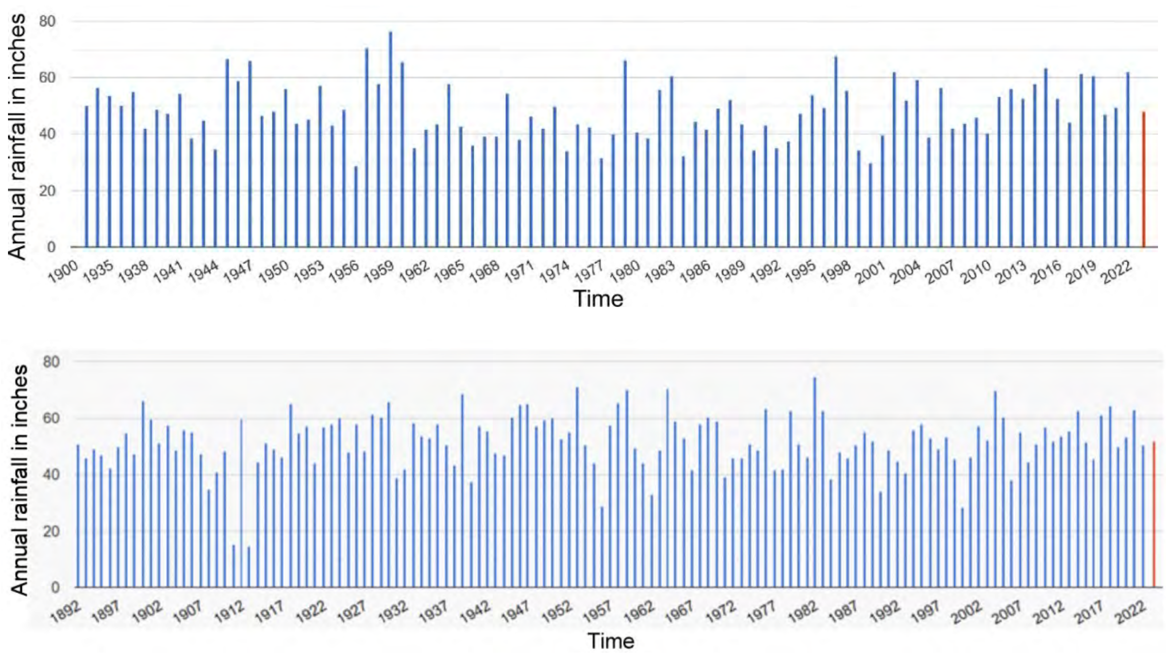
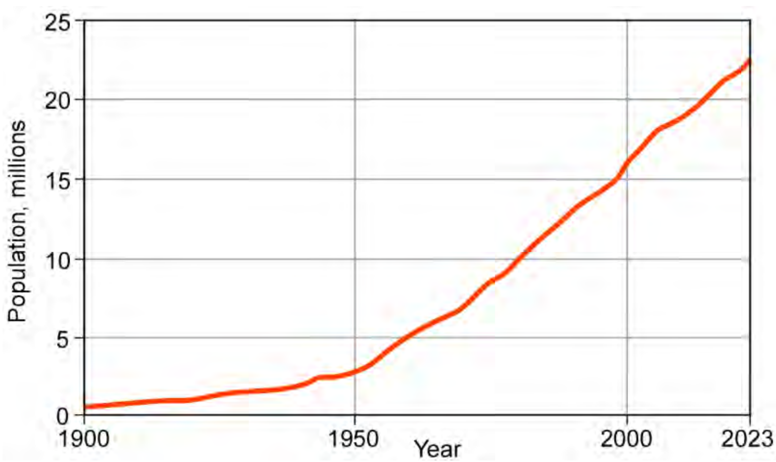


Figure 3.46 *Top*: Annual rainfall recorded at Tampa International Airport. *Bottom*: Annual rainfall recorded in Ocala. Available at https://climatecenter.fsu.edu/climate-data-access-tools/climate-data-visualization

I will let the readers make their own conclusion as to what they see and if they believe there has been a steady decline in rainfall since the 1960s, the main reason for the decline of springs' discharge rates as alleged by SWFWMD. For my own sanity, and not fully trusting my own eyes and common sense, I did perform a simple trend analysis in Excel and completed several quantitative time-series modeling exercises, but I will not bother the readers about details of the models and such.

3.4 The Deadly Combination

More people, more pumping of groundwater for water supply, more sewage, more irrigation with pumped groundwater, more pesticides and fertilizers, more food based on domestic animals, more manure, more land application with human and animal excreta, more contamination of groundwater, and more of political weakness and groupthink = death of Florida springs.



Population growth in Florida. Data from US Census Bureau. Available at https://www.census.gov/

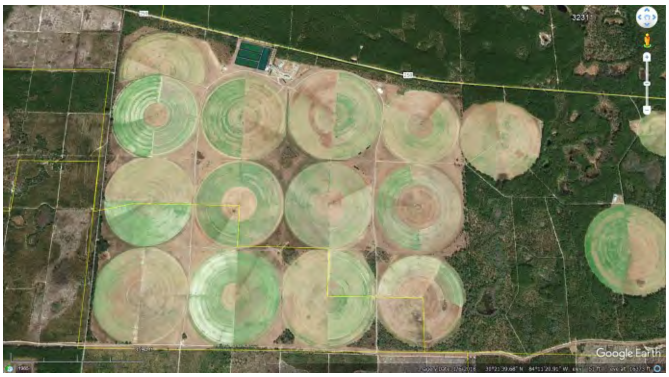
Excerpts from: ***Opinion. Florida's booming population. 7 charts tell the hidden story***
People love the Sunshine State. But the influx of millions of people poses challenges.

This article represents the opinion of the Tampa Bay Times Editorial Board. Published May 11, 2023|Updated May 12, 2023. https://www.tampabay.com/opinion/2023/05/11/floridas-population-is-booming-some-surprising-ways-editorial/

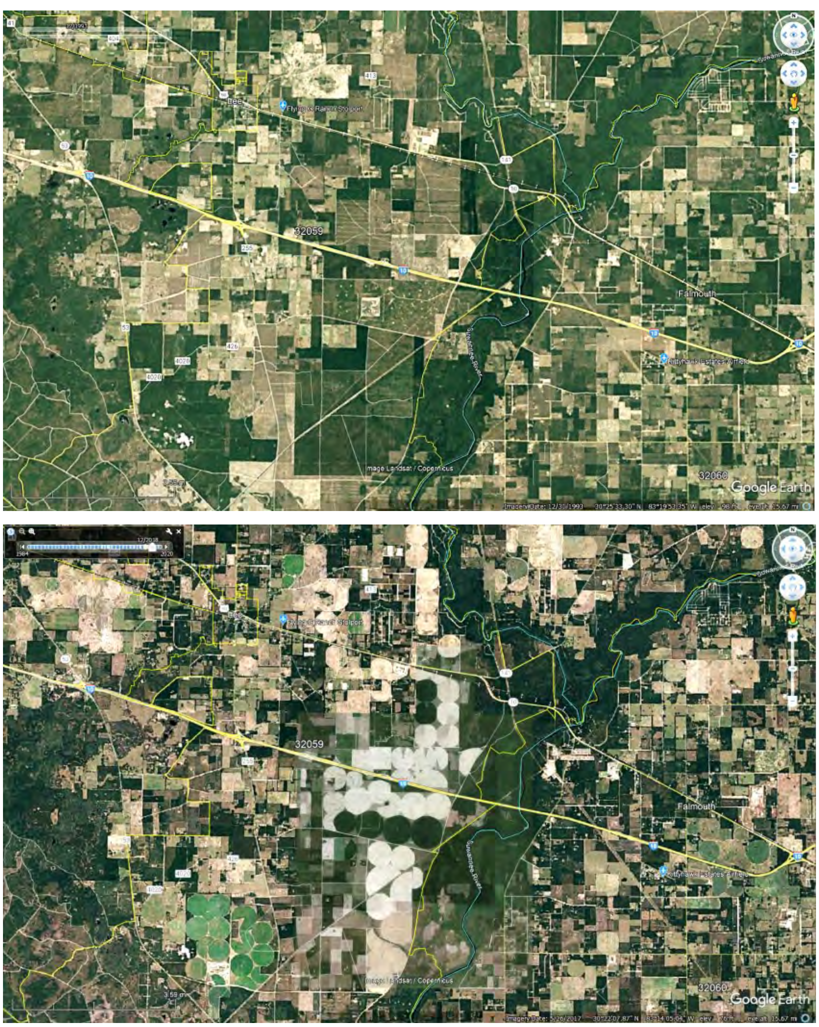
New housing development sprawls outward from Orlando, near where the toll road 429 branches north from Interstate 4. [by Carlton Ward Jr.]

"Our waterways and springs are already too polluted, walking in many of our cities is too dangerous, too many people live on the streets, and we have too many people in prison. Some of our neighborhoods are flooding more often, even on sunny days. Our electricity rates keep rising, many of our sewer systems are aging, and our interstates are often either a logjam or something out of a "Mad Max" movie.

"How many more housing developments do we want to carve out of Florida's limited wilderness or ranch land? At its most basic, that's the choice: With so many more people coming to Florida, we either build smarter by promoting more density in already developed areas or we tear up what's left of Florida's pristine lands to build more single-family homes on oversized lots. The decision should be clear, but we don't act like it is."



Google Earth map showing center-pivot irrigation with pumped groundwater southeast of Tallahassee, Florida. Satellite image by Landsat/Copernicus, January 6, 2018.



Google Map showing general area of the confluence of the Suwannee and Withlacoochee Rivers in north Florida. Satellite images by Landsat/Copernicus. *Top*: Image acquired on 12/30/1993; virtually no center-pivots ("large circles") are present. *Bottom*: Image acquired on 5/26/2018. Center-pivots are visible throughout, not only in the center of the image where they are most obvious.

There are quite a few organizations, most of which are run entirely by volunteers, that advocate and fight for the protection of Florida springs. Their names and links to their web pages can be found at https://www.floridaspringscouncil.org/springs-organizations.

The Florida Springs Council is a 501c3 organization based in Gainesville and focused on the protection and restoration of Florida's springs and spring-fed rivers through education, advocacy, and litigation. The only state-wide advocacy group focused solely on springs, the Florida Springs Council serves as a state-wide umbrella organization, bringing together experts from across the state in science, policy, law, and advocacy to address both local concerns and state-wide issues more effectively (https://www.floridaspringscouncil.org/).

The Florida Springs Institute (FSI) is a 501c3 scientific and educational organization located in High Springs. FSI focuses on gathering data, conducting research, and publishing their findings about the health of Florida's springs (https://floridaspringsinstitute.org/).

A Personal Note

I visited some of the beautiful Florida springs for the first time in summer of 1989. I joined an extended field trip organized by Karst Commission (KC) of the International Association of Hydrogeologists (IAH) and its Chair at the time, Dr. William (Bill) Back of USGS. The trip took place after 28th World Geological Congress in Washington, D.C. Before leaving for Yucatan, Mexico, we experienced the crystal clear waters of a few Florida springs and enjoyed watching both children and adults screaming in delight as they were tubing down the cool runs of the springs, in the heat of the summer. None of us on that trip heard that some of these springs were in any trouble. And none of us even thought of engaging in any discussions about which country or a state in a country, or a region of the world had most first magnitude springs. It was simply not the topic on anyone’s mind. Instead, we all enjoyed every single moment of looking at the beautiful Florida springs and learning about their hydrogeology from the knowledgeable and friendly hosts.

I visited some of the Florida springs again twenty years later, in February 2009, this time as Co-chair of KC and member of the Scientific Advisory Committee of the National Ground Water Association’s (NGWA) 5th Conference on Hydrogeology, Ecology, Monitoring, and Management of Ground Water in Karst Terrains. The main organizer of the conference, Robert Masters of NGWA, kindly asked me to also help with a workshop entitled *Karst Aquifer Characterization and Restoration*, which I gladly accepted and presented at.

This time around, we did hear about emerging concerns regarding some of the Florida springs, but nothing seemed alarming, and no one made any substantial deal about it. It was all more in passing so to speak. One presentation, however, did leave a lasting impression on me. It was a talk on the unfortunate destiny of Kissingen Spring given by Thomas Jackson. “Big Tom”, as everyone called him, and I hit it off right away. Big Tom also joined me at a dinner I had with dear friends visiting from former Yugoslavia.

Incidentally, the classic Dinaric Karst region of former Yugoslavia, smaller than the State of Florida, has the most first-magnitude karst springs, with the average discharge exceeding 100 cfs, in the world. This includes two largest individual springs in the world, Ombla Spring near Dubrovnik, Croatia, and Buna Spring near Mostar, Bosnia and Herzegovina which have long-term average discharge rates of 862 and 837 cubic feet per second (cfs) respectively.

During dinner, Big Tom told us he quit his job with an agency and started his own company, disillusioned (disgusted would perhaps be too strong of a word) with the agency’s inability or unwillingness to do something concrete about the demise of Florida Springs. I promised Big Tom I will include the example of Kissingen Spring in my upcoming book and do whatever I could to spread the word about the looming demise of more springs in Florida. Not that this would make any difference, I thought to myself, but Big Tom was full of energy and hope that having more people learn about what was happening would make a difference, so I kept my promise.

The Gentle Giant passed away a day after Christmas that same year. Below is the official abstract of his presentation about the Kissengen Spring. We all owe it to him.

Prospects for Restoration of Flow at Historic Kissengen Spring Located near Bartow in Polk County, Florida. Thomas E. Jackson, P.G., Jackson Geological Solutions. 5th Conference on Hydrogeology, Ecology, Monitoring, and Management of Ground Water in Karst Terrains. February 23-24, 2009, Safety Harbor Resort and Spa, Florida. National Ground Water Association.

Abstract

When historic Kissengen Spring ceased continuous flow in February 1950, it was reportedly (Peek, 1951) the first largest spring in Florida to cease flow as the result of man's activities. Peek clearly documented the capture of springflow by overpumpage of the underlying aquifer system as the primary reason for the cessation of flow. It is commonly thought by many that prospects for restoration of flow at Kissengen Spring are virtually non-existent.

However, groundwater pumpage in the vicinity of the spring has been greatly reduced in recent years as mining activities concluded in the area. Recent water level data from new monitor wells adjacent to the spring suggests that artesian water could have risen into the spring basin if only the spring vent had not been plugged (since 1962). Flow was observed in January 2006 from Otter Sink, a sinkhole that recently opened up adjacent to the historic spring pool area. A window of opportunity currently exists for restoring at least part-time flow, but this may not last if significant new withdrawals of groundwater near the spring site are permitted. With improved characterization of the local hydrogeology and flow system, innovative management of the springshed, and implementation of a gradual long-term recovery strategy, reasonable prospects exist for restoration of spring flow in an economically viable manner. This could benefit both the public and the ecological health of the natural system in the area. In a fundamental sense, the fate of Kissengen Spring is iconic of how we choose to manage and protect our springs and serves as an environmental indicator of the overall health of our water-dependent natural systems. Restoration of Kissengen Spring could provide both hope and a model to follow for the restoration and protection of our precious springs, and the management of water resources in a sustainable manner.

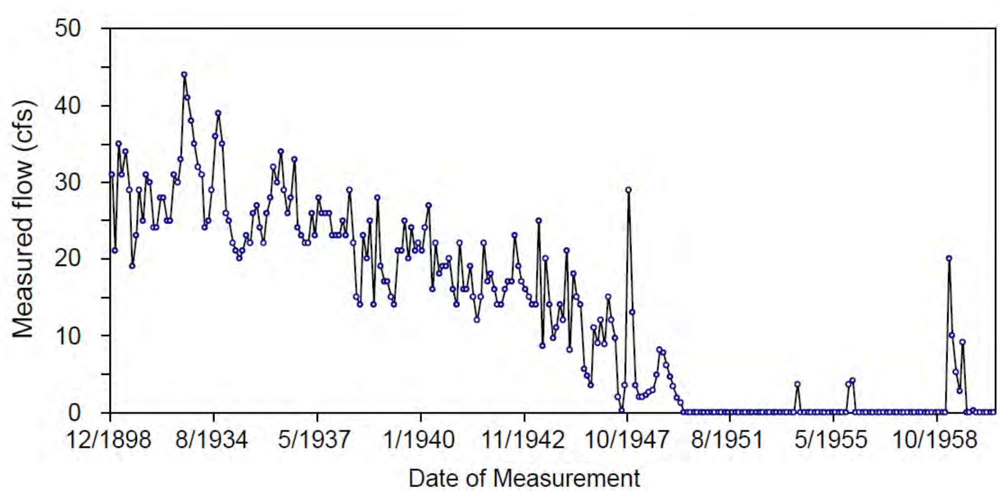


Figure 3.47 Hydrograph of the Historic Kissengen Spring, Polk County, central Florida. Courtesy of Thomas Jackson. From Kresic, 2009.

Fountain of Sorrow; The Deplorable Fate of Kissengen Springs

From People for Protecting Peace River Inc.—3PR; https://protectpeaceriver.org/ accessed 26 December 2023

No one person is responsible for the loss of Kissengen Springs, but all signs point to the culpability of an industry and a kind of mass hypnosis that not only allowed the destruction of the springs, but has never held the perpetrators accountable for what happened. On the contrary they accepted their blood money. It's obvious, isn't it? When you walk through miles of useless degraded land, overgrown with invasive vegetation where there are still old cast-off rusty pipes and wires strewn around and huge mine pits gouging the earth a stone's throw from where the springs once prospered, it's obvious what happened to the springs. Yet just down the road, there lies "Mosaic Peace River Park" with its historical brass plaque that says, "The spring ceased to be a tourist destination after the groundwater was captured for other uses." The historical society obviously dared not utter the word "phosphate" since it was the mother of all phosphate mines and fertilizer production that donated the land to the public. The industry mined it and effectively destroyed the natural order that had prevailed there since the dawn of time, and then returned it to the public as a gift, and people bowed their heads and expressed their gratitude.

Figure 3.48 *Left*: Kissengen Spring in 2006. Courtesy of United States Geological Survey. The spring is surrounded by private property and land access is restricted. *Right*: Group enjoying the water at Kissengen Spring; 1930 (circa). State Archives of Florida, Florida Memory, accessed December 26, 2023.

Thomas (Tom) Earl Jackson

Thomas (Tom) Earl Jackson, a long-time resident of Lakeland, Florida died peacefully December 26th, 2009, at the age of 60 of heart failure.

Tom was born in Lakeland on January 22, 1949, at Morrell Memorial Hospital. Though he traveled widely, he spent most of his life residing in Lakeland. He grew up playing baseball, football, basketball and waterskiing on Lake Parker. He enjoyed himself most by spending time with his family and his many close, long-standing friends. Tom was also an extraordinary and self-taught master woodworker and craftsman. He was a loyal friend with a huge heart. Tom was always up for a laugh and had a grateful attitude towards life. He had a lifelong interest in the great outdoors, natural science, and history. He received both his undergraduate and master's degrees in geology from the University of South Florida and worked for 20 years as a Professional Hydrogeologist. He actively volunteered for many not-for-profit organizations committed to the preservation and restoration of our natural resources. He organized and led many geology field trips for the Southeastern Geological Society and served as its 2009 President. Tom founded and worked tirelessly with Friends of Historic Kissengen Spring. He was an active member of the Nature Conservancy, the Sierra Club, and numerous other professional environmental and geological organizations.

3.5 Visiting Florida Springs

Florida springs were the state's first and biggest tourist destination before Disney and the beaches became major draws. They continue to attract about 30 million visitors every year. For example, Silver Springs alone, the flagship of Florida springs, had more than 489,000 visitors during the 2021/2022 fiscal year with a direct economic impact of $61.5 million a year (Toeppen-Sprigg, 2023). Since the 1870s, visitors have viewed their splendor through glass-bottom boats, accentuated in 1932 with the use of electric motors to provide a peaceful experience.

There are currently 27 Florida State Parks developed around springs (https://www.floridastateparks.org/ and https://www.floridastateparks.org/learn/springs-florida-state-parks), and more parks are managed by counties, cities, and private businesses offering places to swim, dive, snorkel, picnic, camp, kayak or otherwise enjoy the magic of some of the most beautiful springs anywhere in the world (Figure 3.41). Their nearly constant water temperatures year-round (on average about 72 degrees Fahrenheit or 22.2 degrees Celsius) provide for a welcoming escape from the summer heat and the chilly winter air.

Detail descriptions of many springs including all thirty Outstanding Florida Springs (Table 3.1; see also Figure 3.30) are provided by the official Florida government agencies on their websites listed at the beginning of Chapter 3. The most comprehensive source is FGS' Bulettin No. 66 *Springs of Florida* which is full of color photographs and available for free download at http://publicfiles.dep.state.fl.us/FGS/

Figure 3.41 A small sample of printed informational materials and pamphlets on Florida springs available to visitors.

Particularly informative and visually pleasing are presentations and photographs on the web page of The Howard T. Odum Florida Springs Institute (https://floridaspringsinstitute.org/). A Field & Recreation Guide to 500 Florida Springs by Joe Follman and Richard Buchanan including photographs is another excellent source available online at http://thespringsfever.com/index.html.

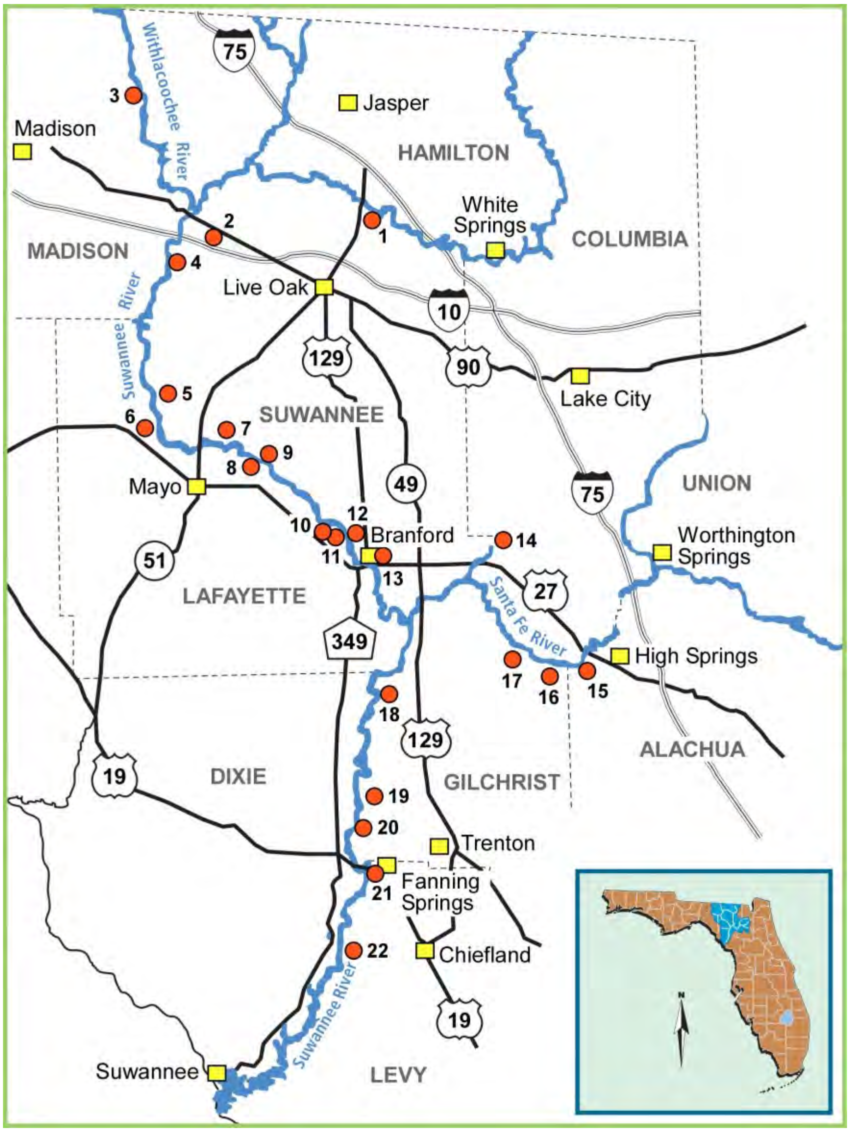
Many Internet web pages and blogs have been created by Florida springs enthusiasts. One can spend hours browsing them while preparing for a visit. This author's favorite is a blog by Frank Moore, a native Floridian. Frank was taken to visit many of Florida's springs growing up, with his family often returning to Wakulla and Ichetucknee. Having lived in the Peruvian desert for a little over two years, he has a strong appreciation for the best that Florida has to offer: water. This blog is pure pleasure for the reader. A few of Frank's outstanding photographs of the most famous Florida springs, including taken by drone, are presented in this book and many more are available at https://firstmagflorida.com/.

Melissa Watson's book, *Touring the Springs of Florida. A Guide to the States' Best Springs*, is full of useful details and features excellent maps with the locations of the springs. It includes GPS coordinates, descriptions of recreational options, and photographs. It is highly recommended to those who like holding books in their hands.

Table 3.1 Outstanding Florida Springs. *Managed by concessionaire company Naventure. **GPS coordinates are for Three Sisters Springs. SWFWMD: Southwest Florida Water Management District. USFWS: United States Fish and Wildlife Service. SRWMD: Suwannee River Water Management District.

Spring Name	County	GPS Coordinates	Management
Alexander Spring	Lake	29 04 53.15 N / 81 34 33.01 W	US Forest Service*
Chassahowitzka Spring Group	Citrus	28 42 55.60 N / 82 34 34.65 W	Citrus County
Columbia Spring	Columbia	29 51 15.01 N / 82 36 43.74 W	Private
Crystal River / Kings Bay Springs**	Citrus	28 53 18.10 N / 82 35 20.11 W	SWFWMD; USFWS; City of Crystal River
DeLeon Spring	Volusia	29 08 03.34 N / 81 21 46.24 W	Florida State Park
Devil's Ear Spring	Gilchrist	29 50 06.83N / 82 41 47.78 W	Private
Falmouth Spring	Suwannee	30 21 39.85 N / 83 08 05.95 W	SRWMD
Fanning Springs	Gilchrist	29 35 15.61 N / 82 56 07.50 W	Florida State Park
Gainer Spring Group	Bay	30 25 44.17 N / 85 32 56.11 W	Private
Gemini Spring	Volusia	28 51 45.72 N / 81 18 37.51 W	Private
Homossassa Spring Group	Citrus	28 47 57.38 N / 82 35 17.73 W	Florida State Park
Hornsby Spring	Alachua	29 51 01.30 N / 82 35 35.50 W	Private
Ichetucknee Spring Group	Columbia	29 59 02.89 N / 82 45 42.32 W	Florida State Park
Jackson Blue Spring	Jackson	30 47 25.05 N / 85 08 24.51 W	Jackson County
Lafayette Blue Spring	Lafayette	30 07 33.23 N / 83 13 34.21 W	Florida State Park
Madison Blue Spring	Madison	30 28 49.93 N / 83 14 39.81 W	Florida State Park
Manatee Spring	Levy	29 29 22.60 N / 82 58 36.75 W	Florida State Park
Peacock Springs	Suwannee	30 07 21.06 N / 83 07 57.03 W	Florida State Park
Poe Springs	Alachua	29 49 32.58 N / 82 38 56.30 W	Alachua County
Rainbow Spring Group	Marion	29 06 09.03 N / 82 26 15.41 W	Florida State Park
Rock Springs	Orange	28 45 23.20 N / 81 30 06.25 W	Orange County
Silver Glen Springs	Marion	29 14 45.04 N / 81 38 36.50 W	US Forest Service*
Silver Springs	Marion	29 12 58.54 N / 82 03 10.09 W	Florida State Park
Treehouse Spring	Alachua	29 51 17.73 N / 82 36 10.31 W	Private
Troy Spring	Lafayette	30 00 21.69 N / 82 59 51.01 W	Florida State Park
Volusia Blue Spring	Volusia	28 56 50.94 N / 81 20 22.52 W	Florida State Park
Wacissa Spring Group	Jefferson	30 20 23.59 N / 83 59 29.34 W	Jefferson County
Wakulla Spring	Wakulla	30 14 06.70 N / 84 18 09.30 W	Florida State Park
Weeki Wachee Spring Group	Hernando	28 31 01.89 N / 82 34 23.40 W	Florida State Park
Wekiwa Spring	Orange	28 31 02.30 N / 82 34 24.26 W	Florida State Park

The Suwannee River Water Management District (SRWMD), which hosts many of the largest Florida springs, provides information on recreational options (Table 3.2). The lovely little town of High Springs (see Figures 3.42 and 3.43) is a natural base for exploring these springs, all less than an hour's drive away. The town is considered the world capital of spring scuba diving.



No.	Spring Name
1	Suwannee
2	Falmouth
3	Madison Blue
4	Anderson
5	Charles
6	Lafayette Blue
7	Peacock
8	Convict
9	Royal
10	Troy
11	Ruth
12	Little River
13	Branford
14	Ichetucknee
15	Poe
16	Gilchrist Blue
17	Ginnie
18	Rock Bluff
19	Hart
20	Otter
21	Fanning
22	Manatee

	Florida State Park
	Owned by SRWMD
	County or City Park
	Privately Owned

Figure 3.42 Notable springs in the Suwannee River Water Management District (SRWMD). Map based on information provided by SRWMD at https://mysuwanneeriver.com/271/Enjoying-Our-Springs and by Suwannee County at https://visitsuwannee.com/explore-freshwater-springs

Figure 3.43 Town of High Springs is natural base for visiting many of Florida's finest springs, a fact fully embraced and promoted by local businesses and citizens. Blue Gem Motel is a favorite of scuba divers.

An important part of visiting springs along and close to the Suwannee and Santa Fe Rivers is to consider the possibility that some of them may be impacted by a high river stage and not open for swimming due to "brownout" (see Figures 3.20 and 3.44). Such conditions are less likely to occur during the dry season and in the summer (except after hurricanes), but there are no guarantees. Those interested should check with the springs' managing entities while planning a visit. Two springs spared from the brownout and offering guaranteed swimming and diving experiences are Head Spring and Blue Spring of the Ichetucknee Spring Group which forms the Ichetucknee River, a short tributary of the Santa Fe River. Gilchrist Blue Spring and Ginnie Springs, although right next to the Santa Fe River, are similar in that respect thanks to the favorable elevation difference and their high discharge rates.

No.	Spring Name	Fee	Swimming	Scuba Diving	Canoeing	Camping	Picnic
1	Suwannee		✓				✓
2	Falmouth		✓				✓
3	Madison Blue	✓	✓	✓	✓		✓
4	Anderson		✓		✓		
5	Charles		✓		✓		✓
6	Lafayette Blue	✓	✓		✓	✓	✓
7	Peacock	✓	✓	✓			✓
8	Convict	✓	✓	✓	✓	✓	
9	Royal		✓	✓	✓		✓
10	Troy		✓		✓		
11	Ruth		✓				
12	Little River		✓	✓	✓		✓
13	Branford		✓		✓		✓
14	Ichetucknee	✓	✓	✓	✓		✓
15	Poe	✓	✓		✓	✓	✓
16	Gilchrist Blue	✓	✓		✓	✓	✓
17	Ginnie	✓	✓	✓	✓	✓	✓
18	Rock Bluff	✓	✓				✓
19	Hart	✓	✓	✓	✓	✓	✓
20	Otter	✓	✓			✓	✓
21	Fanning	✓	✓			✓	✓
22	Manatee	✓	✓	✓		✓	✓

Florida State Park | Owned by SRWMD | County or City Park | Privately Owned

Table 3.2 Recreational activities at the SRWMD's springs shown in Figure 3.42.

Figure 3.44 Troy Spring (left) and Peacock Spring (center and right) were closed for swimming in mid and late December 2023 respectively. The "brownout" conditions were caused by high river stages and reversed flow from the Suwannee to the springs. Although the presence of alligators at Florida springs is always a concern, it is especially worrisome when water transparency (visibility) is minimal to non-existent during a brownout.

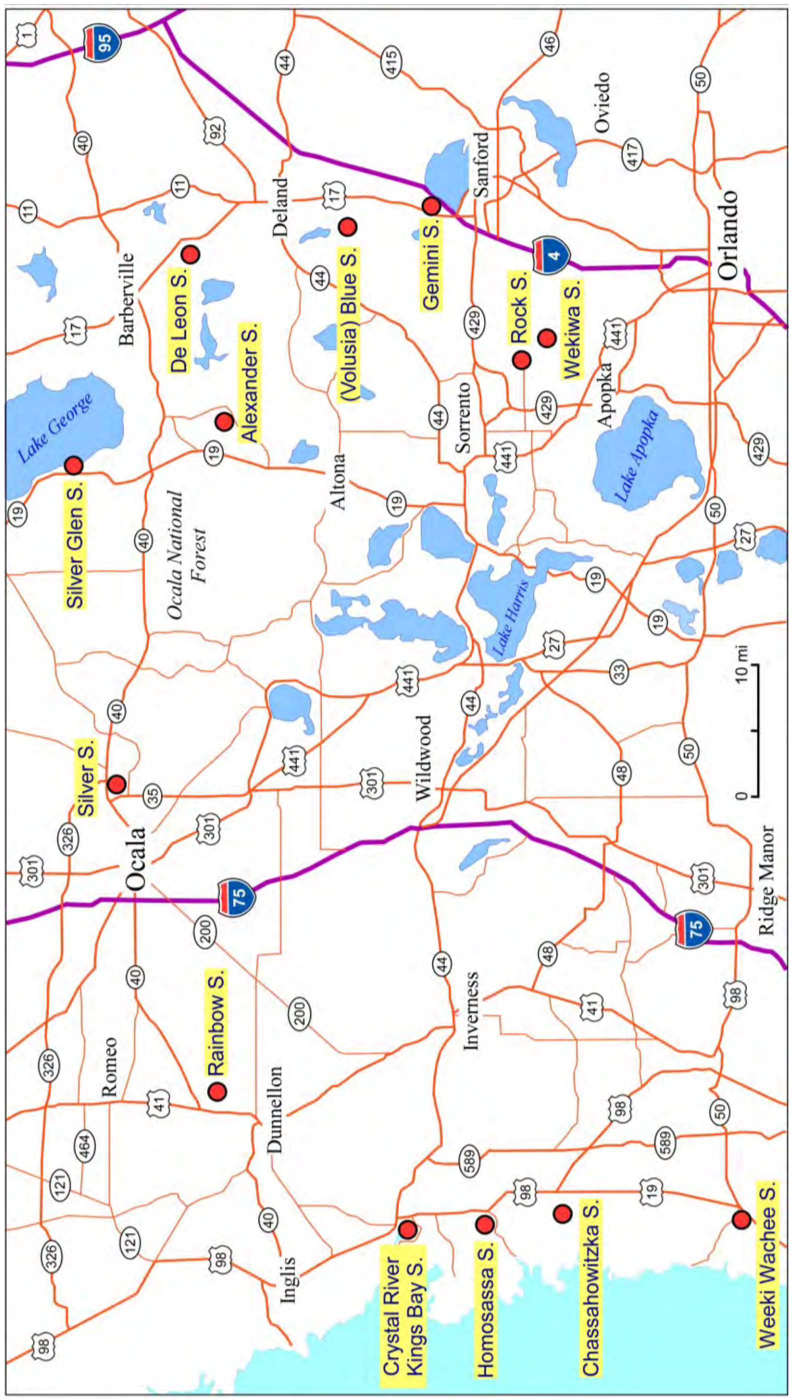


Figure 3.45 Outstanding Florida Springs an easy drive from Ocala.

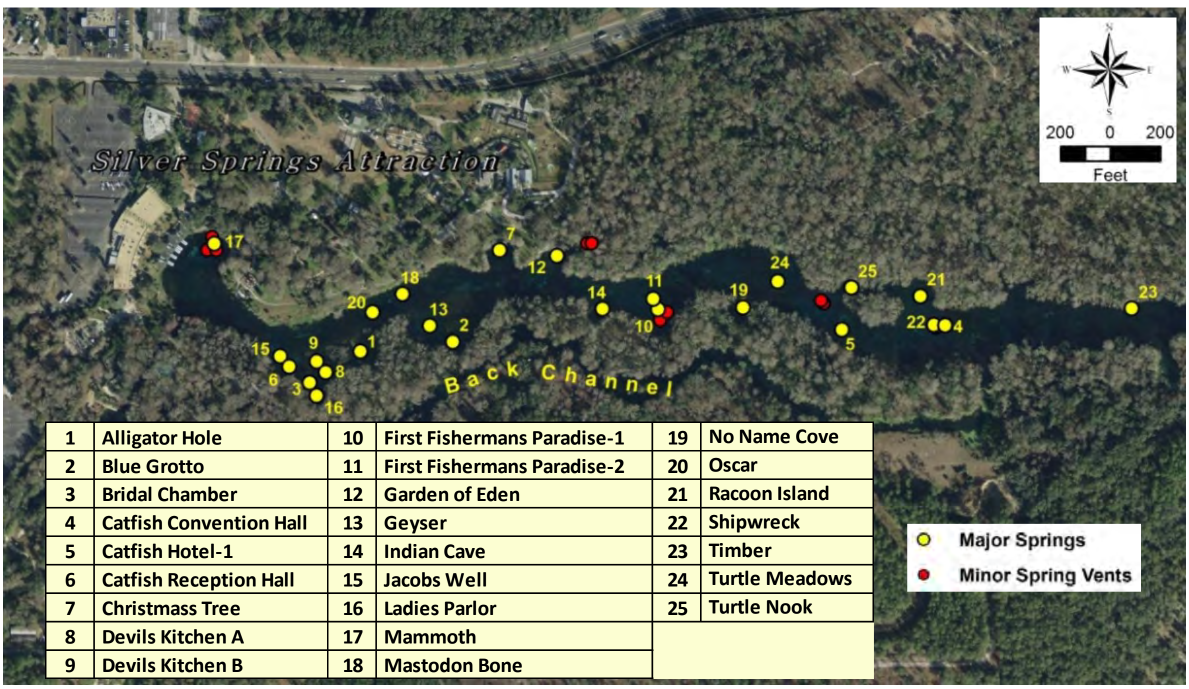
Ocala is a natural hub for visiting 12 Outstanding Florida Springs shown on the map in Figure 3.45 including Silver Springs, the most famous of them all, and only 6.4–mile drive from downtown.

Visitors to springs located in Florida State Parks are asked to speak up for the springs (Figure 3.46). It is the hope of this author and all advocates for Florida's springs that the citizens of Florida will, sooner rather than later, be fully informed about the ongoing catastrophic demise of their beautiful springs and work to put an end to it together with their elected representatives at every level of government.

Figure 3.46 This panel asks visitors at all Florida State Parks featuring springs to do the right thing.

3.6 Silver Springs Group

The Silver Springs Group, flowing from numerous vents, forms the headwaters of the Silver River, a major tributary of the Oklawaha River. There are around 30 springs in the group (25 springs are named; see Figure 3.47). The largest is Mammoth Spring which is developed in a steep-walled depression in limestone, the headspring pool. It has two vents the largest of which is located approximately 100 feet east of the glass-bottom boat loading area (Figure 3.48). The vent is a horizontal, oval-shaped opening about 5 feet high and 135 feet wide beneath a limestone ledge on the northeast side of the spring pool (Figure 3.49). The depth of water measured over the vent opening is about 30 feet. The second vent is in the northwestern part of the main pool near the boat loading area.



1	Alligator Hole	10	First Fishermans Paradise-1	19	No Name Cove
2	Blue Grotto	11	First Fishermans Paradise-2	20	Oscar
3	Bridal Chamber	12	Garden of Eden	21	Racoon Island
4	Catfish Convention Hall	13	Geyser	22	Shipwreck
5	Catfish Hotel-1	14	Indian Cave	23	Timber
6	Catfish Reception Hall	15	Jacobs Well	24	Turtle Meadows
7	Christmass Tree	16	Ladies Parlor	25	Turtle Nook
8	Devils Kitchen A	17	Mammoth		
9	Devils Kitchen B	18	Mastodon Bone		

Figure 3.47 Springs of the Silver Springs Group. Modified from Sutherland et al., 2017.

Figure 3.48 Two views of the headspring pool of the Silver River. Closeup of the Mammoth Spring is on the right photo, courtesy of Silver Springs State Park (https://silversprings.com/gallery/). Left photo courtesy of St. Johns River Water Management District.

The spring pool measures about 300 feet north to south and 200 feet east to west. The water is clear and blue, with aquatic vegetation and algae across the sandy spring bottom and limestone substrate. The spring run is also usually clear and the bottom at all locations is easily visible.

Figure 3.49 The main vent opening of Mammoth Spring with exposed Ocala Limestone. The Ocala limestone is a white, chalky, highly fossiliferous limestone that was deposited in a warm, shallow marine environment more than 35 million years ago. Photo courtesy of St. Johns River Water Management District.

The Silver River flows from its headspring pool eastward for approximately 5 miles through a dense mixed hardwood and cypress swamp to the Oklawaha River. The Oklawaha River flows northward and is a tributary to the St. Johns River. Higher sandy terrain with pine and the Silver Springs community lie to the west of the springs.

There are three entrances to Silver Springs State Park. The main entrance is located on SR 40 at 5656 East Silver Springs Boulevard, Silver Springs, FL 34488. The camping and Silver River Museum entrance is located on SR 35 at 1425 N.E. 58th Ave., Ocala, FL 34470. The equestrian entrance is located approximately 1.3 miles east of the Main Entrance on SR 40.

As described on the Park's website (https://silversprings.com/park-history/), in the 1820s, following Florida's annexation into the United States, the Springs became an attraction for adventurous travelers. They poled their way up the narrow Ocklawaha River from its intersection with the St. Johns River to the Silver River, through thick overhanging cypress and Spanish moss.

By 1850, Silver Springs had become a commercial distribution center for Central Florida. Pole barges and later, steamships plied back and forth on the Silver and Ocklawaha Rivers, moving supplies and crops. Plantations growing vegetables, tobacco and oranges sprang up along the banks as nearby Ocala grew.

In the years right after the American Civil War, Silver Springs began to attract tourists from the North via steamboats up the Silver River. Hart Line and Lucas Line steamboat companies competed for the privilege of transporting visitors to the headwaters of the Silver River, to the point of holding passenger-laden races upriver to the Springs. Railroads also entered service bringing ever-growing numbers of admirers. Silver Springs had become a mandatory stop on the "grand tour" of Florida.

Then, in the late 1870s, Hullam Jones and Phillip Morrell fixed a piece of glass to the bottom of a rowboat. History was made and a new enterprise was born. Silver Springs' Glass Bottom Boat tours began their more than century and a half-long reign of world fame (Figure 3.50).

Entrepreneurs soon took notice of Silver Springs' popularity, and began to improve accommodations for visitors. But none did more than Col. W.M Davidson and Carl Ray, who acquired rights to the Springs in 1924 and later introduced an electric-powered version of the Glass Bottom Boat. Other attractions on the property followed, including zoological displays and demonstrations, notably those by famed herpetologist Ross Allen. All this transformed Silver Springs into Florida's first bona fide attraction (Figure 3.51).

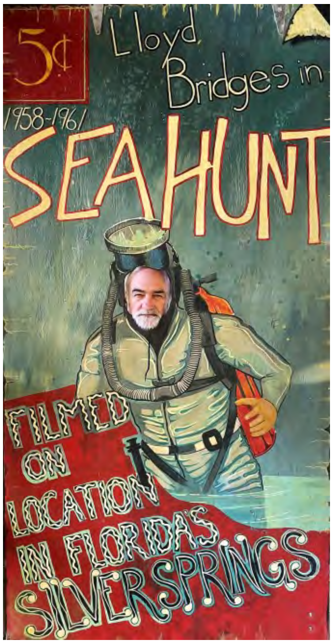
Figure 3.50 The Glass Bottom Boat was invented at Silver Springs in the 1870s and ever since these boats have wowed visitors with breathtaking views of underwater life and the many springs that feed the Silver River. Left photo courtesy of Silver Springs State Park.

In the 1930s, Hollywood discovered Silver Springs and over the years, scenes from at least 20 movies were filmed here, including *Rebel Without a Cause* starring James Dean, *Distant Drums* starring Gary Cooper, the James Bond movie *Moonraker*, *Revenge of the Creature* (sequel to *Creature from the Black Lagoon* which was filmed at Wakulla Spring), and four of the twelve Tarzan movies with Johnny Weissmuller.

Figure 3.51 Hand-colored postcard from 1941. Accompanying note reads "Florida's International Attraction. Largest flowing springs in the world, over 750 million gallons daily. Electric driven glass bottom boats. Greatest depth 80 feet. Temperature of water 72 [degrees] winter and summer. Shown from sunrise to sunset, in all weather, every day in the year." Courtesy of State Archives of Florida, Florida Memory. https://www.floridamemory.com/items/show/259728

Episodes of television shows such as Sea Hunt, were filmed at Silver Springs as well. In fact, legend has it that Sea Hunt star Lloyd Bridges learned to SCUBA dive at Silver Springs (Figure 3.52).

ABC Paramount purchased Silver Springs from Davidson and Ray in 1962, and Silver Springs prospered as an attraction. But beginning in the 1970s, new entrants in the Florida attractions marketplace just south in Orlando, behemoths such as Disney, SeaWorld and later, Universal Studios, led to a steady decline in Silver Springs' attendance. Resources to properly care for the attraction and its precious natural resources dwindled.



In 1971 Silver Springs was designated a National Natural Landmark. In 2013, the Florida Park Service took control of the property, merging it with the adjacent Silver River State Park, forming the present Silver Springs State Park (Figure 3.53) which offers many experiences and amenities in addition to traditional boat tours. The park offers camping, lodging, canoeing and kayaking, birding, historic gardens, geocaching, hiking trails, equestrian trails, mountain bike trails and wilding viewing opportunities. However, swimming is not allowed anywhere in the spring run including the springs. State park fees apply for day-use and camping, and glass-bottom boat tours and other concessions also have related fees (https://www.floridastateparks.org/silversprings).

Figure 3.52 Visitors to the Siver Springs State Park can literary submerge themselves in the Springs' glorious past as they explore its many wonders.

Figure 3.53 Photographs from Silver Springs State Park, December 2023.

Florida Springfest is a family-friendly event held at Silver Springs first weekend in March every year. This is part of the 2024 announcement: *Join us for fun and education, learning all about water/springs awareness, conservation efforts, games and fun for all, vendors including artist/photography, food, and more.*

Events like this and many more similar outreach efforts state-wide are badly needed to prevent a downward spiral not just at Silver Springs but many other beautiful Florida springs. As discussed earlier, Mammoth Spring, the largest spring (headspring) of the Silver Springs group, has experienced a catastrophic decline in discharge rate since the 1960s (Figure 3.14) due to excessive, reckless overpumping of the Floridan Aquifer. Below are excerpts from the 2018 report by The Howard T. Odum Florida Springs Institute entitled *Restoring Silver Springs: An Action Plan* which presents a desperate call for action as the environmental conditions at Silver Springs continue to deteriorate.

> ***Not more than thirty years ago Silver Springs had the distinction of being the largest spring in Florida (with a long-term average daily flow greater than 530 million gallons of pure groundwater), the first spring subjected to scientific investigation (in 1859 by Dr. John Le Conte from the University of South Carolina) and perhaps the oldest natural tourist destination in Florida (as described by author Sidney Lanier in 1875).***
>
> ***In spite of those unparalleled qualifications as a natural wonder to be preserved in perpetuity, Silver Springs today is one of the most endangered large springs in Florida. The spring's voluminous flow has declined on average by more than 30 percent, and the pure groundwater praised by dozens of glass-bottomed boat captains to millions of tourists over the past one hundred years is now contaminated by nitrate-nitrogen at a concentration that is more than 3,100 percent higher than the natural background. An insidious combination of reduced flow, increased nutrient pollution, and a downstream dam that blocks fish migration, has resulted in explosive growth of nuisance algae, substantial reductions in fish and wildlife populations, and very evident deterioration of the aesthetic appeal of this National Natural Landmark.***
>
> **Restoring Silver Springs: An Action Plan**
> **Florida Springs Institute**

As emphasized by Sutherland et al. (2017), the clarity of the Silver Springs system is a key issue of concern. Data for horizontal Secchi distance reported by Munch et al. (2006) indicated a possible decrease in water clarity between the 1950s and 2004. Water clarity is essential to allow the passage of light to aquatic vascular plants and algae for photosynthesis, as well as for aesthetic and recreational purposes. Although more recent data is not readily available, and the water of Silver Springs still appears to be clear to those visiting for the first time or not remembering the springs' heyday, grave concern remains that the majestic Silver Springs will eventually have the same destiny as Wakulla Spring, its greatest rival for decades, as explained in the next section.

The exceptional historic clarity and health of Silver Springs were immortalized by famous photographer Bruce Mozert (Figures 3.54 and 3.55). His underwater photography series was initially created as a commercial project for Silver Springs Park as part of the park's marketing campaign. It has stood out as his signature project and many of the photographs are now in public domain and electronically available on the web page of State Archives of Florida, Florida Memory (https://www.floridamemory.com/). Bruce Mozert is also recognized for his work as a set photographer on iconic film projects such as "Tarzan" and "Creature from the Black Lagoon."

Figure 3.54 *Upper Left*: Deane Martin dancing for a fish while man plays ukulele underwater, circa 1960. *Upper Right*: Ginger Stanley using shears while man mows grass underwater, circa 1955. *Lower Left*: Bruce Mozert photographing a model underwater, circa 1950). *Lower Right*: Greetings from Silver Springs, circa 1950. All photographs except for lower left are by Bruce Mozert. Courtesy of State Archives of Florida, Florida Memory.

Figure 3.55 *Left*: Model in a Jantzen bathing suit posing underwater with an anchor, circa 1950; *Center*: Arrilla Jones underwater looking through a telescope, circa 1962. *Right*: Underwater witch riding a broom, circa 1950; All photographs by Bruce Mozert. Courtesy of State Archives of Florida, Florida Memory.

A very informative guide to the Silver Springs State Park was published in 2023 with all proceeds going toward its preservation and restoration of the natural environment (Figure 3.56). The guide can be ordered by contacting Friends of Silver Springs State Park at www.thefriendsofsilversprings.org.

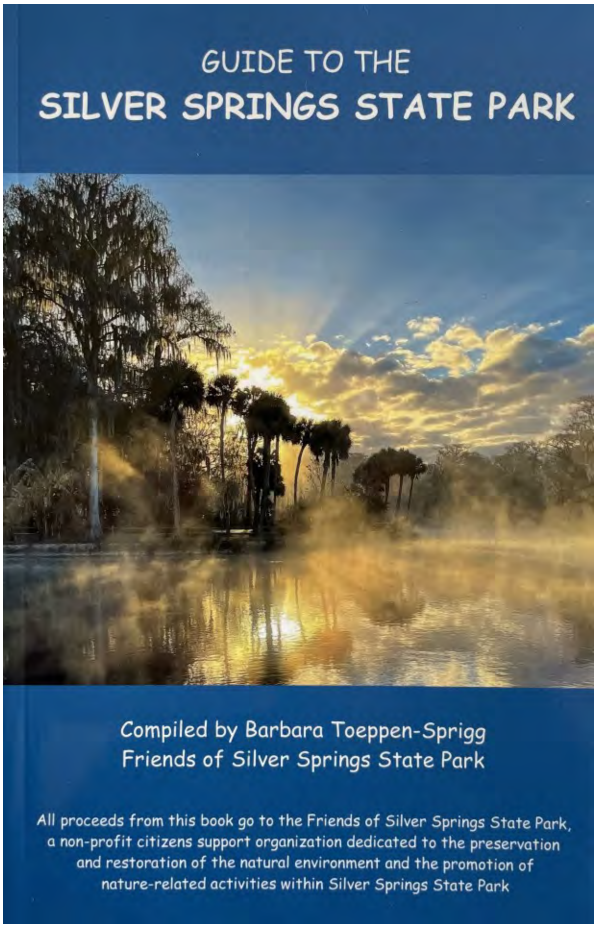


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Figure 3.56 First printed edition of Guide to The Silver Springs State Park was published in 2023 by Friends of Silver Springs State Park (www.thefriendsofsilversprings.org).

3.7 Wakulla Spring

Wakulla Spring is in Edward Ball Wakulla Springs State Park (Figures 3.66 and 3.67), about 15 miles south of Tallahassee via State Route 61 (Wakulla Springs Road), SR 267, and Wakulla Park Drive. After the demise of Mammoth Spring of the Silver Springs Group due to excessive groundwater withdrawal from the Floridan Aquifer, Wakulla Spring is now the largest spring in Florida, with the long-term average flow of 409 cubic feet per second (cfs) based on publicly available USGS data as of December 2023. This is second only to Big Spring, Missouri, the largest spring in the United States (477 cfs for period 2000-2023). However, based on incomplete new data collected since 2007 using different methodology as well as modeling, it appears that Wakulla Spring's average discharge has suddenly increased and then stabilized between 2012 and 2019 at levels above 500 cfs (no newer data is publicly available). If this situation continues and the data and the methodology are confirmed without any doubts, Wakulla Spring may become the largest spring in the country.

Figure 3.66 Map of the Edward Ball Wakulla Springs State Park. https://www.floridastateparks.org/wakullasprings

Wakulla is the most dramatic Florida spring featuring a monumental, deep spring pool and submerged vent opening which leads to a vast network of channels explored by cave divers since 1950s (Figures 3.68 through 3.71). As of January 2023, the newly interconnected cave system of Wakulla Spring-Leon Sinks-Chip's Hole is the longest submerged cave system in the country, extending more than 45 miles below the Woodville Karst Plain (Flanigan, 2023).

The Wakulla Spring pool (Figure 3.58) is roughly circular with a diameter of 315 ft north to south. The maximum pool depth is 185 ft. The vent opening is a horizontal ellipse along the south side of the pool bottom and is estimated to measure 50 ft by 82 ft. Along with a few smaller springs nearby, including Sally Ward Spring (Figure 3.63), Wakulla Spring gives rise to the Wakulla River.

The conduit system that sustains the flow of water to Wakulla Spring is developed in the lower Oligocene Suwannee Limestone. The sediment was deposited in a shallow sea that inundated Florida between 28 and 34 million years ago. The Suwannee Limestone is typically a white to pale orange limestone composed of sand-sized particles and frequently containing larger fossil shells and corals.

Figure 3.67 *Left*: Aerial view overlooking Wakulla Spring pool and spring run, 1967 photo by Richard Parks. Diving tower is in center-right. The spring vent is located below and left (NE) of the diving tower. Courtesy of State Archives of Florida, Florida Memory (available at https://www.floridamemory.com/). *Right*: Tour boat at the spring pool in December 2023.

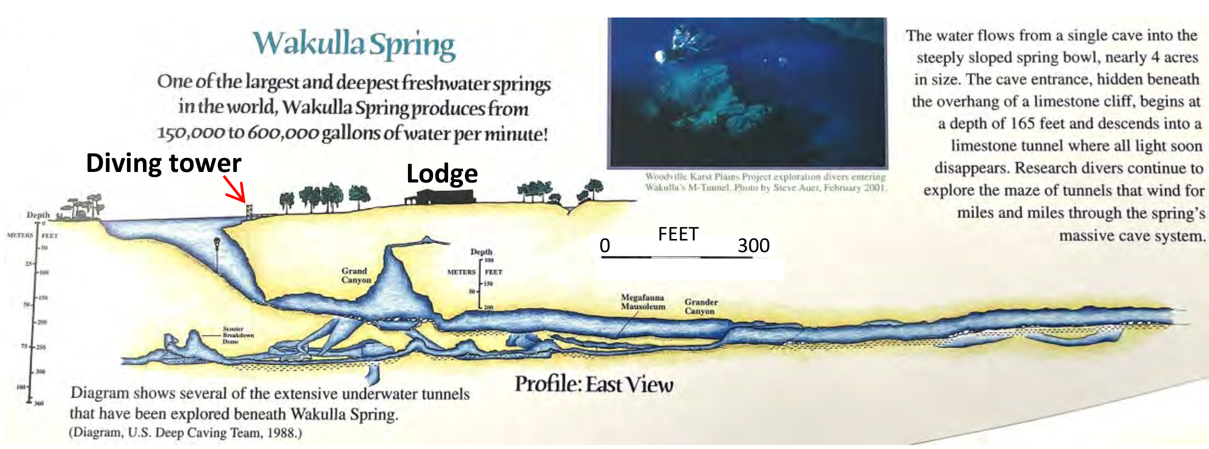


Figure 3.68 Diagram of several underwater tunnels beneath Wakulla Spring on display at the park's ranger station by the tour boats dock. Details of past diving expeditions including diagrams and maps are available at the web site of the U.S. Deep Caving Team https://www.usdct.org/past_expeditions.php

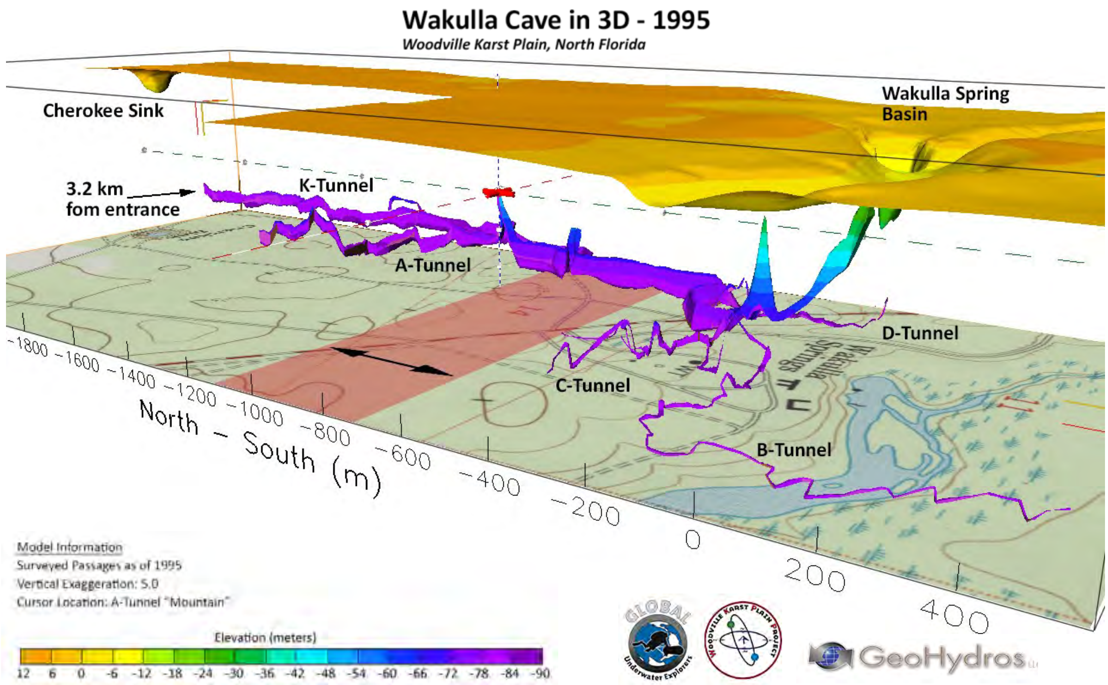


Figure 3.69 Computer-generated 3D view of the submerged Wakulla Cave System passages as of 1995, based on the cave diving surveys. The passages all converge toward the Wakulla Spring. Using such cutting-edge technology as a 3D Digital Wall Mapper (DWM) and the Global Positioning System (GPS), the Wakulla 2 Expedition - with 151 volunteer cave divers, scientists, and engineers from all over the world - created the world's first three-dimensional digital map of an underwater cave. The deepest known channels are more than 295 feet (90 m) below sea level. Courtesy of Dr. Todd Kincaid.

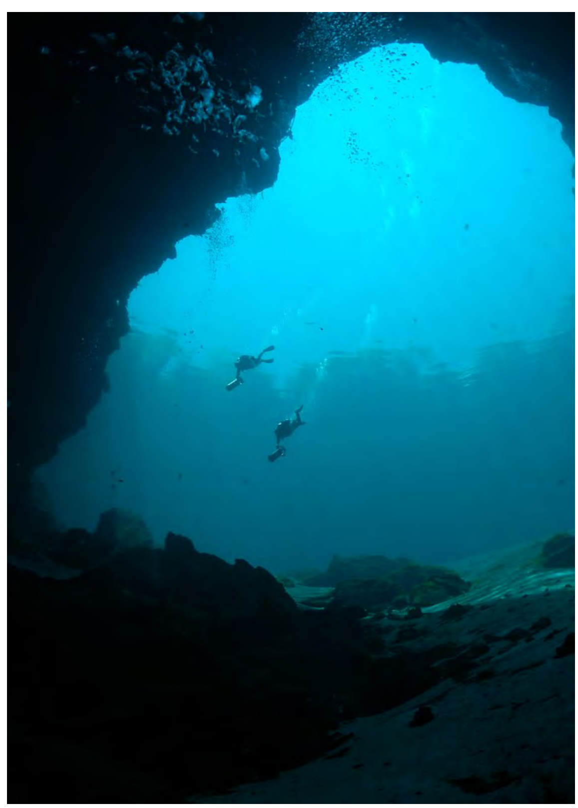


Figure 3.70 *Left*: Map of Wakulla Spring Leon Sinks Cave System which was connected with Chip's Hole Cave in January 2023, creating the longest underwater cave in the country at more than 45 miles. Courtesy of Woodville Karst Plain Project. Copyright 2023 DUI (Diving Unlimited International). *Right*: View of the Wakulla Spring from a cave diver's perspective. Copyright David Rhea & GUE 2006; printed with permission.

Figure 3.71 Wakulla Spring. Note three manatees in the bottom left center. Courtesy of Florida Geological Survey.

The Edward Ball Wakulla Springs State Park was designated a National Natural Landmark in 1967 and listed on the National Register of Historic Places in 1993. On December 20, 2018, it was officially designated the newest State Geological Site. Designated State Geological Sites are areas that DEP's Florida Geological Survey has determined to be significant to the preservation, scientific study and public understanding of geological history and resources in Florida.

The park has many offers described in detail on the park's website https://www.floridastateparks.org/parks-and-trails/edward-ball-wakulla-springs-state-park/experiences-amenities. Here is a summary from the park's landing web page:

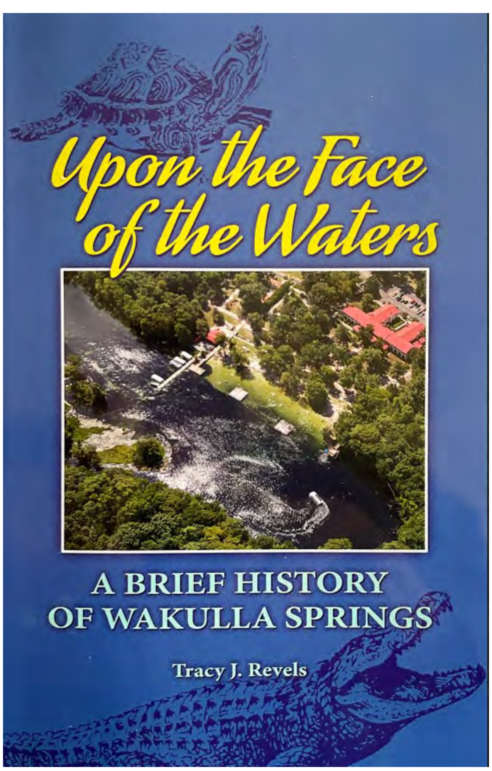
> *The invigorating 70 degree waters are sure to refresh you on even the hottest summer days. The historic lodge is an elegant remnant of old Florida, and the ancient cypress swamps made the perfect backdrop for old Hollywood movies.*
>
> *Wakulla Springs is a place where history stretches back thousands of years, from early Native Americans who lived in shoreline villages to filmmakers who recognized the primeval quality of the park's swamps and wildlife when they decided to film Tarzan's Secret Treasure (1941) and Creature from the Black Lagoon (1954) here.*
>
> *Today, visitors can swim where mastodons once roamed and take guided boat tours where dugout canoes once glided across the cool waters. Alligators, manatees and an abundance of bird life can all be seen.*
>
> *Visitors can also marvel at a 1930s Spanish style lodge with its period furniture, original elevators and colorful painted ceilings that depict wildlife and Old Florida scenes.*

The park also hosts another beautiful spring, Sally Ward Spring (see Figures 3.66 and 3.72) which is upstaged by Wakulla and not frequented by visitors but would be a prime attraction in many countries around the world.

Figure 3.72 *Left*: Sally Ward Spring pool. Spring vent and entrance to the spring cave are in the center, marked by blue color. Courtesy of Northwest Florida Water Management District. *Right*: Sally Ward Spring run, December 2023.

Outside of the swimming area public access on the Wakulla River within the park is restricted to tour boat operations. Fishing, scuba diving, canoeing and private watercraft are prohibited within the park.

A meticulously researched book guide to Wakulla Springs, written by Tracy Revels with lots of care and love, describes history of the spring and the park in great detail (Figure 3.73). The book stands out as one of the most exceptional tributes to this or any other magnificent spring in the world. Importantly, the proceeds of the book help Friends of Wakulla Springs State Park continue with their important mission of protecting this National Natural Landmark. The book, entitled *Upon the Face of the Waters; a Brief History of Wakulla Springs* can be ordered at https://wakullasprings.org/Online-Store.



Wakulla Springs is a sacred place nestled deep in a primeval forest of cypress, live-oak, magnolia and pine. On foggy mornings, one can hear the sounds that were familiar to the First Floridians: the wail of a loon, the bellow of an alligator, the splash of a bass. By day, the great Wakulla spring offers cool comfort against the heat, and at night the fog returns, transforming the spring basin into a haunted cauldron, the grave of prehistoric beasts and the site of spirit revels. "An adequate idea of this mammoth spring could never be given by a pen or pencil," a visitor once wrote, "but when seen, on a bright calm day, it must ever after be a thing to dream or love."

When I wrote Watery Eden: A History of Wakulla Springs (the forerunner of this book), the spring was crystal clear, only occasionally darkened by naturally occurring acids during especially rainy seasons. Today, the spring is clouded and the glass-bottom boats no longer run. Wakulla Springs, a place I love with all my heart, has changed.

Tracy J. Revels

Figure 3.73 This book by Tracy J. Revels stands out as one of the most exceptional tributes to Wakulla Spring or any other magnificent spring in the world. It can be ordered at https://wakullasprings.org/Online-Store

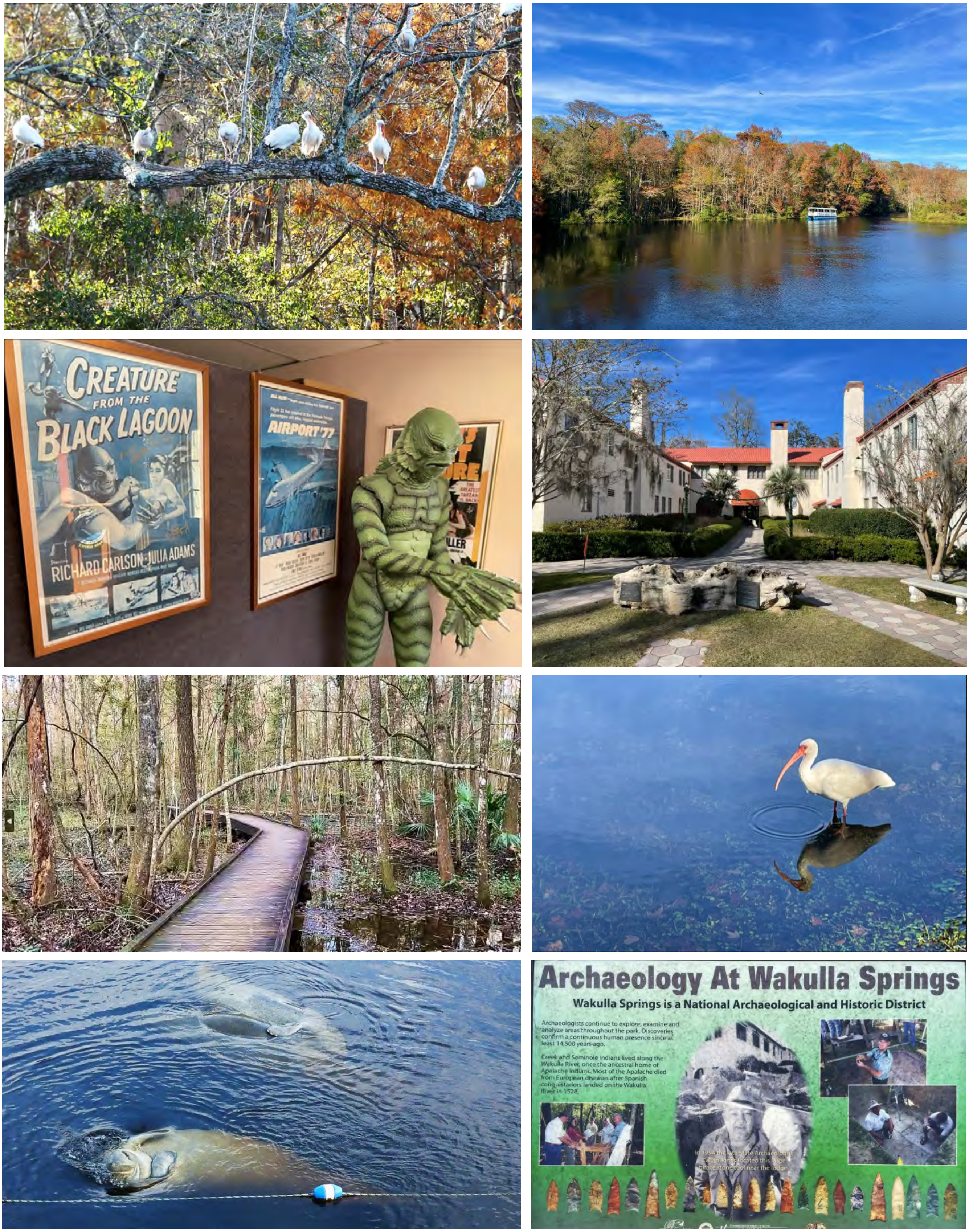


Figure 3.74 Photographs from the Edward Ball Wakulla Springs State Park, December 2023.

3.7.1 Discharge Rate of Wakulla Spring

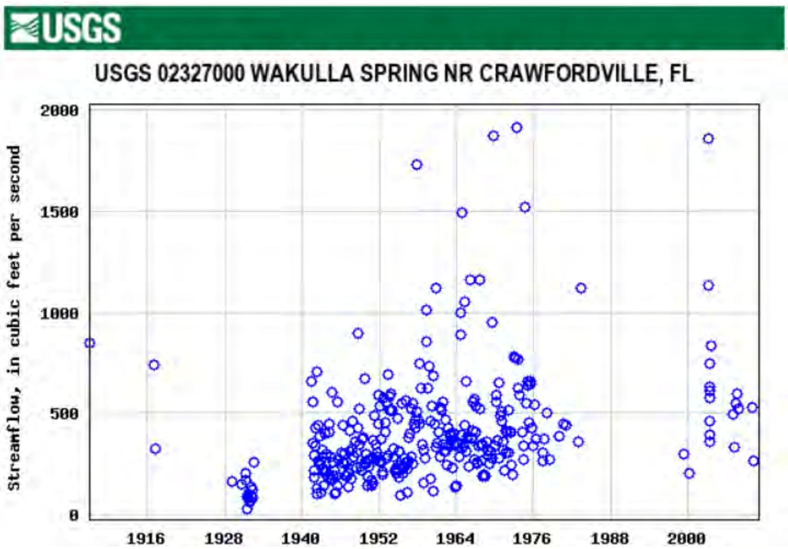


Figure 3.75 Hydrograph of discharge rate of Wakulla Spring measured by USGS.

Based on the available data from USGS (Figure 3.75), Wakulla Spring has the greatest known range in discharge among Florida's springs. The minimum of 25.2 cfs was measured on June 18, 1931, and the maximum of 1,910 cfs on April 11, 1973. The average is 409 cfs for the period of record, between February 1, 1907, and March 17, 2010 when USGS stopped officially reporting the spring's discharge rate.

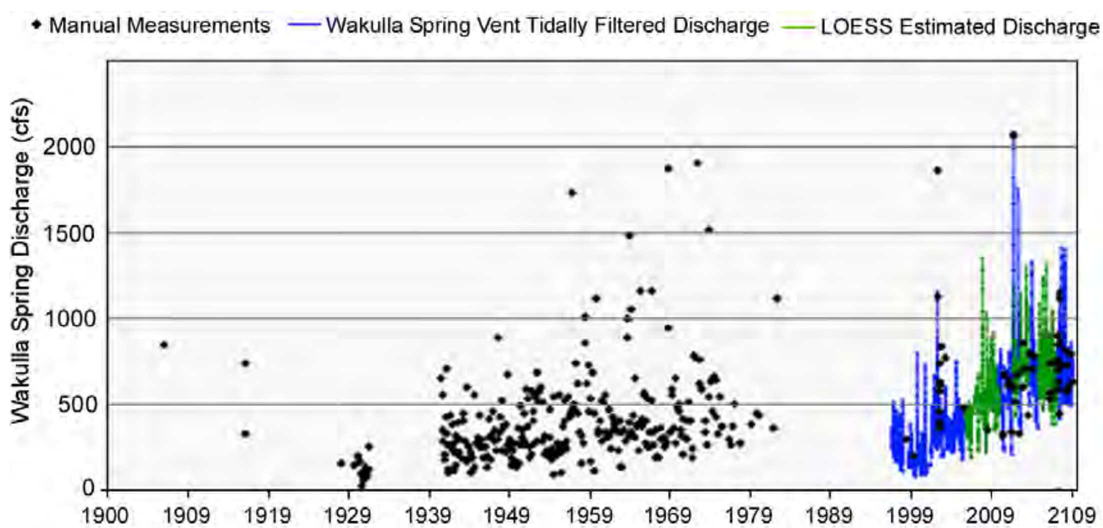


Figure 3.76 Graph of discrete field measurements (black dots) and full composite Wakulla Spring discharge time series from May 10, 1997, through December 31, 2019. The average Wakulla Spring discharge for the full period of the composite discharge time series is 482 cfs, ranging between 72 cfs and 2,086 cfs. Wakulla Spring discharged an average of 575 cfs of water between October 23, 2004, and December 31, 2019. During this period, Wakulla Spring flows ranged between 168 cfs and 2,086 cfs. (From NWFWMD, 2021).

As explained by NWFWMD (2021), discrete discharge measurements have been collected at irregular intervals near the Wakulla Spring vent between February 2, 1907, and December 31, 2019 (Figure 3.76), including measurements not reported by USGS. Discrete discharge measurements are defined here as direct field measurements of discharge, in contrast to discharge estimates from index velocity, stage-discharge, or other types of ratings. The intervals between manual discharge measurements range from less than 1 day to nearly 16 years.

Continuous discharge estimates from Wakulla Spring performed by the District start on May 10, 1997, and extend through 2019 (Figure 3.76). Discharge estimates are made using an index velocity relationship between continuously recorded water velocity measured in the Wakulla Spring vent and the volume of water measured just downstream of the main vent. Several gaps in the continuous discharge time series exist due to equipment malfunction and failure. These gaps were filled using a combination of mathematical models (green line on graph in Figure 3.76).

The rate of increase of Wakulla Spring discharge was larger than the proportional change of rainfall, suggesting other factors have led to the increase in spring flow, including (1) Lower river and spring pool stages resulting from changes in the Wakulla River channel which have resulted in additional spring discharge by increasing the gradient between the upper river and spring pool and the Floridan aquifer; and (2) Increases in coastal sea levels which are likely increasing the equivalent freshwater head at the Spring Creek Spring group resulting in intermittent diversions of water from the Spring Creek Spring group to Wakulla Spring (NWFWMD, 2021).

Davis and Katz (2007) suggested two possible reasons for the long-term increase in Wakulla Spring flow: (1) a small rise in sea level along the Gulf coast of Florida from 1932 to 2007 may have contributed additional sea water head on the Spring Creek Springs causing a reduction in flow and a corresponding increase in Wakulla Springs flow; or (2) the evolution of the submerged cave passages at Wakulla Springs may have allowed for greater groundwater capture in the same way that one river can capture flow from another river through erosional processes. (This process is often called “piracy” and it is common in karst. “Big fish spring eats small fish spring”.)

Davis and Verdi (2014) proposed a mechanism for describing varying flows and the presumed connections between Wakulla Spring, the Spring Creek Spring Group, and nearby swallets such as Lost Creek Sink. Three phases were described based upon a changing balance between precipitation events, baseflow, and equivalent freshwater head pressure at the Spring Creek Spring Group submarine vents (Figure 3.77).

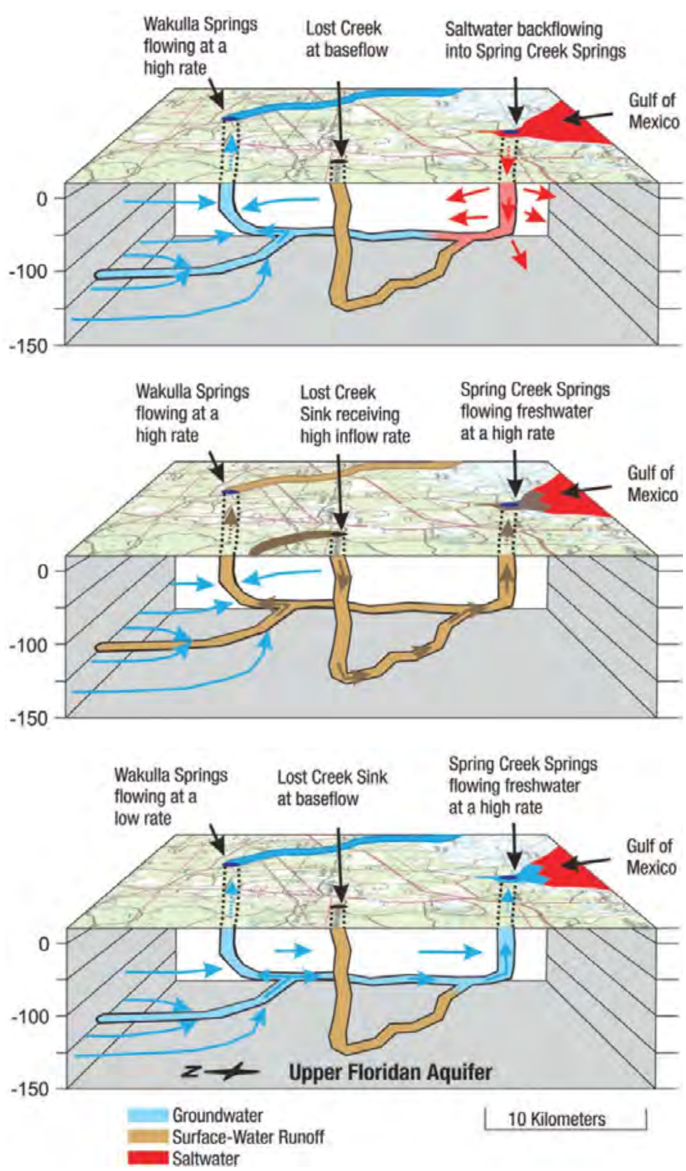
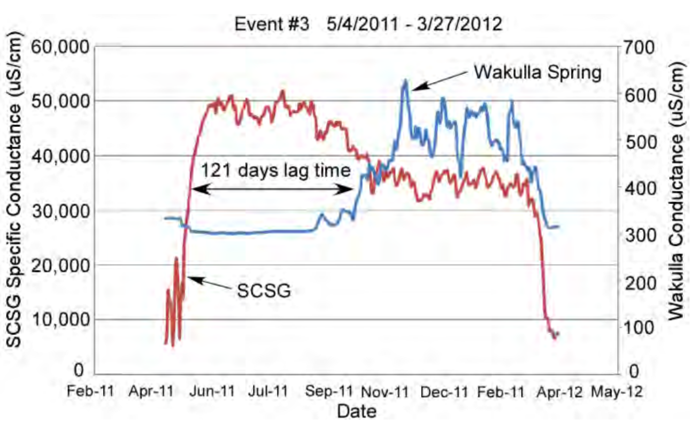


Figure 3.77 Conceptual model of groundwater flow between Wakulla Spring and Spring Creek Springs proposed by Davis and Katz (2007). *Top:* Phase 1: Sea water backflow. *Middle:* Phase 2: Surface water inflow. *Bottom*: Phase 3: Groundwater outflow. Vertical scale is in meters.

Phase 1 occurs when there is an extended period of low precipitation and estuarine/saltwater flows into the Spring Creek Spring Group vents and recharges the Floridan aquifer where freshwater discharge is blocked due to the higher density salt water. Many times during phase 1 saltwater begins flowing into the springs in the Spring Creek Spring Group. During this phase, groundwater which would be discharged at Spring Creek can be diverted towards Wakulla Spring where discharge increases.

Phase 2 is characterized by a heavy precipitation event where large volumes of surface water flow into the subsurface creating enough head pressure to overcome the saltwater plug, resulting in freshwater discharge at Spring Creek in addition to increased flow at Wakulla Spring (due to increased surface water inputs). Phase 3 begins once streams return to baseflow conditions and flow at Wakulla Spring declines with the Spring Creek Spring Group continuing to discharge fresh water.

James Sutton, hydrogeologist with NWFWMD, analyzed the data on specific conductance for Wakulla Spring and Spring Creek Springs waters during periods ("events") of flow reversal when the equivalent hydraulic head of freshwater at Spring Creek Springs was higher than the Wakulla Spring pool elevation. An example of such event is shown in Figure 3.78, together with a table providing information on seven major continuous flow reversal events between 2007 and 2019 (Sutton, 2020).



Event	Date of beginning of reversal event at SCSG	Date of end of reversal at Wakulla Spring	SCSG under reversal conditions (Approximate # of Days)	Wakulla Spring with elevated s. conductance (Approximate # of Days)
1	5/7/2007	2/27/2008	296	203
2	4/15/2008	8/31/2008	138	42
3	5/4/2011	3/27/2012	328	207
4	10/27/2012	3/3/2013	127	87
5	4/22/2014	12/30/2014	252	116
6	9/25/2016	1/17/2017	114	42
7	9/10/2017	3/26/2018	197	105
		Average	207 days	115 days

Figure 3.78 Analysis of flow reversal events between Spring Creek Springs and Wakulla Spring performed by James Sutton, NWFWMD hydrogeologist (available at http://wakullaspringsalliance.org/wp-content/uploads/2016/11/Wakulla-Discharge-Analysis_WSA.Sutton.09-25-20.pdf).

The analysis shows that the average time of the flow reversal was 207 days, and as long as 328 days, during which the specific conductance measured at Spring Creek Springs indicated that the water was highly brackish, approaching sea water for extended periods of time. With a certain delay, the flow reversals caused significant increases in the specific conductance of Wakulla Spring water, sometimes more than doubling it from the baseline levels, and confirming an alarming salt (sea) water intrusion into the Floridan Aquifer.

As the sea level continues to increase, and the Spring Creek Spring's network of submerged cave passages becomes more and more affected by the intrusion of dense (heavier) sea water, the flow reversal will at some point become permanent. In other words, the Spring Creek Springs will cease to flow completely, and the Wakula Spring water will have an increasingly higher specific conductance as heavy sea water invades more karst channels supplying water to Wakulla Spring. This process will only accelerate if there is additional lowering of the regional hydraulic head in the Floridan Aquifer due to groundwater extraction: less fresh groundwater water will flow towards the coast and the dense sea water "plugs" in the karst channels will move inland faster.

The only plausible solution to the ongoing saltwater intrusion described above is a comprehensive regional management of both surface water and groundwater that would result in a very significant increase of the groundwater levels (hydraulic head) of the Floridan Aquifer. If this increase is sufficiently large, it would result in Spring Creek Springs again discharging enough fresh water to flush out the saltwater residing and moving inland through the karst network.

Wakulla Springs success? Not so fast | Opinion

Bob Knight Your Turn, Tallahassee Democrat. Published 5:00 a.m. ET Oct. 14, 2020

https://www.tallahassee.com/story/opinion/2020/10/14/wakulla-springs-success-not-so-fast-opinion/5970795002/

Re: "A watery enigma: Wakulla Springs now producing more water than 20 years ago," Sept. 8, 2020

Florida's governmental leaders wish to proclaim success with springs protection. However, the recent article citing Northwest Florida Water Management District staff needs to be placed in proper context. The article's premise is that, in light of recent increases in spring flow at Wakulla Springs, there is still more groundwater to pump.

The fact is that there is no "new" water coming out of Wakulla Springs. Excessive groundwater pumping by everyone living and working in the region, including South Georgia, is lowering regional spring flows, and increasing saltwater intrusion into the drinking water supply for Wakulla and Leon Counties.

Increasing flows at Wakulla Springs are attributed to tannic water recharging the aquifer through three sinking streams near the Apalachicola National Forest. This "black" water, which historically flowed to the south and discharged at Springs Creek, is now going to Wakulla Springs. The resulting decline in water clarity is the reason glass bottom boat tours at the spring have come to a halt over the last two decades. Currently, a wader in Wakulla Springs swim area cannot see their feet through the dark water.

3.7.2 The Catastrophe

One must give it to Hollywood. Every so often they make movies that, with a frightening accuracy, predict the future. How did Universal Pictures decide to film *Creature from the Black Lagoon* at Wakulla Spring? How did they know that the beautiful spring, with the crystal-clear water (the very reason why it was selected for underwater cinematography in the first place) would one day become the Black Lagoon? Wakulla Spring, the only real rival of Silver Springs for decades, is now just a dark shadow of itself (Figure 3.79). Photographs like the one in Figure 3.80 are things of a distant past.

The reasons for this catastrophe are all too familiar: *Pollution from fertilizers, manure, sewage, pesticides and other toxic chemicals, and aquifer over-pumping which also increases the potential for sinkholes and makes the freshwater layers of our aquifers susceptible to saltwater intrusion*. (The Springs Eternal Project, 2013; https://springseternalproject.org/).

If, however, Hollywood wanted to now film a movie specifically devoted to Wakulla Spring entitled, for example, "*The Black Lagoon*" with many horror twists and turns, an excellent starting point would be a report by Seán McGlynn (2020; Wakulla Springs Dark Water: Causes and Sources, Phase III Final Report). The report reads like a horror story. Some excerpts in italics and key bullet points are provided below for the benefit of a daring Hollywood producer.

- Good-looking lead actress and lead actor, in a laboratory setting, are preparing to analyze some water samples collected and brought in by several graduate students, also good looking and perhaps wearing partially wet T-shirts and shorts, or such (it is summer in Florida).
- The results of the analyses, which start to pop up on several high-tech screens of fancy electronic devices, are discussed amongst the people present in the laboratory and gathered around the screens (they now are all dressed appropriately, perhaps featuring the latest fashion-designer laboratory clothing from Europe). The scene is rather serious, and the dialogue (including occasional monologue) conveys to the movie audience that things are more than alarming (the terms used are also mostly incoherent and therefore appear highly scientific):

  *Fresh water photosynthetic bluegreen algae occur in all the samples, at substantial numbers (as OTUs), in the springs, lakes and conduits. This indicates that these chlorophylls containing aquatic algae are in all four major sinkhole lakes and are also in Wakulla Springs and could only come from these lakes. These are: Cyanobacterium spp.; Cyanothece spp.; Prochlorococcus spp. and Synechococcus spp. Several species of mixed fresh and marine photosynthetic green algae, at substantial numbers of OTUs, occurred in all the samples, springs, lakes and conduits (*red flashing letter on one of the screens indicates a potentially toxic species*). These chlorophyll-containing aquatic algae are in all four major sinkhole lakes and are also in Wakulla Springs and also were traced by their DNA from the sinking lakes to Wakulla Springs. These are: Asterionella; Chrysosphaera; Dinophysis; Guillardia; Heterosigma; Nannochloropsis; Ochromonas; Rhodomonas; Stephanodiscus and Thalassiosira.*

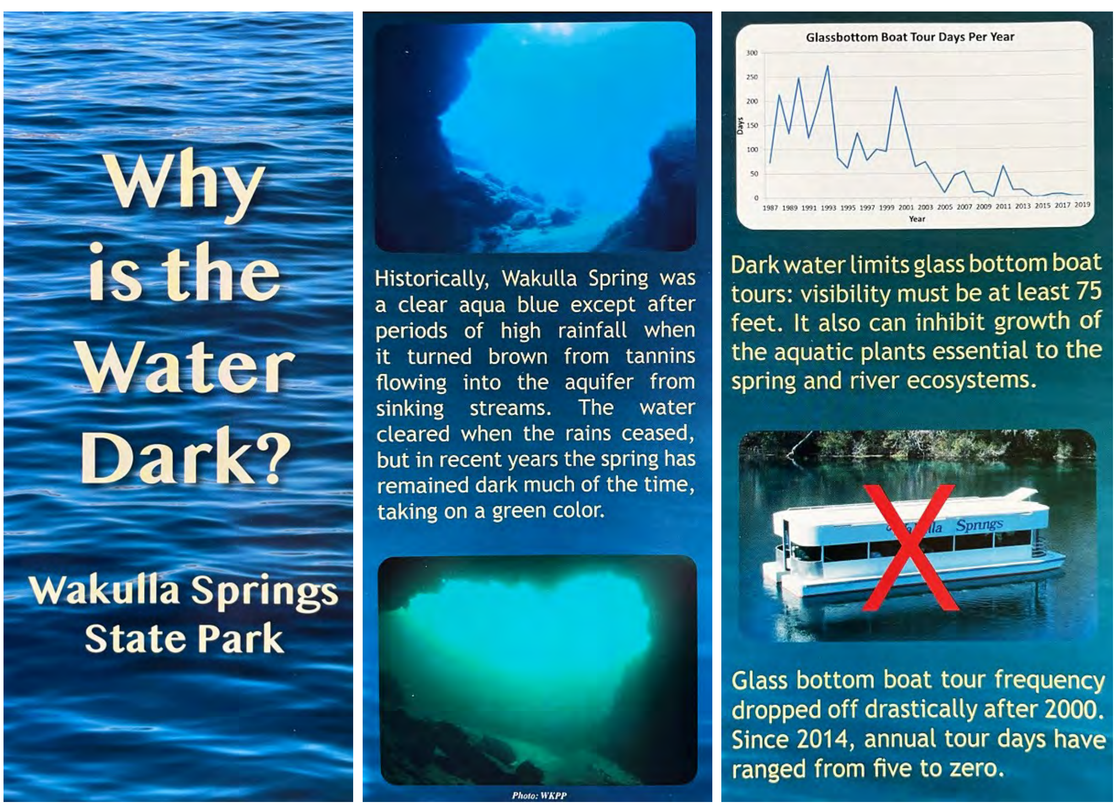


Figure 3.79 Parts of a pamphlet available to visitors of Edward Ball Wakulla Springs State Park.

- Sometime after 30 minutes or so into the movie, Wakulla Spring becomes covered by dense mats of invasive hydrilla plant (*Hydrilla verticillata*) brought in from Asia with the intention to cause harm.

- Efforts of hydrilla removal using many applications of deadly herbicide are mostly successful, but there is serious collateral damage, and many native species are destroyed in the process.
- *The sinking streams are loaded with tea colored brown tannic water draining out of the extensive tracts of national forest. There is also flow into the cave system from the sinking lakes which contribute algae (chlorophylls) to the aquifer*.
- Tracing saltwater from Spring Creek to Wakulla Spring is positive. The prediction made by a hydrogeologist (not-so-good-looking and rather unmemorable) is that *saltwater flow at the spring will increase in the coming years with sea level rising and over pumping*. This causes a gorgeous female graduate student to faint due to an unbearable pain and a shock. Another graduate student (male or female) comes to the rescue and the situation is back to quasi-normal.

- A very important scene is taking place in an amphitheater where a scientist attempts to explain some new, unnerving findings of the ongoing research to an audience some of which are paying attention, and some appear to be distracted from time to time (the reasons for distractions can be various – screenwriters can use imagination here). The presentation includes the following language (it can be edited or made more interesting at will):

Figure 3.80 Glass-bottom boats were once big part of the Wakulla Spring appeal. Courtesy of Edward Ball Wakulla Springs State Park.

Dye studies, both ours and others, have shown that the four largest karst lakes in Leon County, three of which (Lafayette, Munson and Jackson) receive about 33% of storm water from the City of Tallahassee (Tallahassee has minimal surface water discharge of stormwater, personal communication with Harvey Harper) and the fourth receives degraded river water from the Ochlocknee River mostly from Georgia (personal communication with FDEP TMDL staff). All of these lakes are hypereutrophic and three of them (Lafayette, Munson and Jackson), have impaired water quality and are in various stages of enforcement within the Florida TMDL program. Urban storm water and sewage spills (in which the City of Tallahassee is also fined under a consent order and South Georgia has a history of similar problems) cause these lakes to experience frequent and prolonged algae blooms, including potentially harmful bluegreen algae blooms. These lakes have been shown, by these dye traces, to be directly connected to the Wakulla Springs by subterranean cavern system: Lake Iamonia, Lake Jackson, Lake Munson, and Upper Lake Lafayette (ULL).

- One of the key movie scenes covers the results of the laboratory analyses of the water samples from caves collected by brave cave divers. The good-looking, lead actor-scientist apologizes to the audience before he utters the following: *The samples from the caves, while they contain some chlorophyll, are dominated by algae species and by microscopic fecal pellets, occasional amphipods as well as a mucosa like slimy globules.*
- After hearing this, the gorgeous and very sensitive graduate student (who, in one of the previous scenes, was swimming in the spring wearing the latest fashion-designer swimsuit from France), runs out of the

room and disappears behind a restroom door, presumably to vomit (judging by the sounds coming from behind the closed door).

- A top, mean-looking bureaucrat from *FDEP delivers a devastating blow when all the karst features, sinking lakes, sinking streams and sinkholes as well as karst depressions, are dropped from the official state cleanup plan for Wakulla Springs*.
- A good-looking and promising investigative journalist of the local newspaper explains to her editor that there is *a major flaw in FDEP's reasoning and the claim that these lakes and streams are naturally polluted and thus cannot be cleaned up*. "This is not the case!" she passionately exclaims. "*Most of the waterbodies, particularly Lake Munson and Lake Lafayette have received sewage either inadvertently spilled or purposefully released in the past and this has made for a high sediment load of nutrients*."
- Another key scene explains an even more terrifying fact: *The potentially toxic diatom, Nitzschia and unicellular flagellate algae Pelagomonas were both found at highest concentrations at the spring and associated L well. Both are marine species, indicating a connection with the sea*.
- In a filler scene, an old gray couple, still very much in love, remembers the good old days while sitting on a bench overlooking Wakulla. "Remember when the beautiful iconic limpkins were everywhere. They are now gone, just like the once ubiquitous spring's resident, the apple snail, which they cheerfully munched on. It just breaks my heart." The camera closeup shows the old couples' hands, firmly holding and gently squeezing each other. The accompanying music is very sad, to the point of tears.
- The final scene, continuing through the closing titles, could show something like the photograph in Figure 3.81, in motion and with ominous music to accentuate the feeling of despair.

It is of course highly unlikely that the movie would be a commercial hit, given all the gloom and doom. But the brave movie studio and the daring producer may be remembered in history for doing the right thing for the badly wounded Wakulla Spring which cannot speak up for itself.

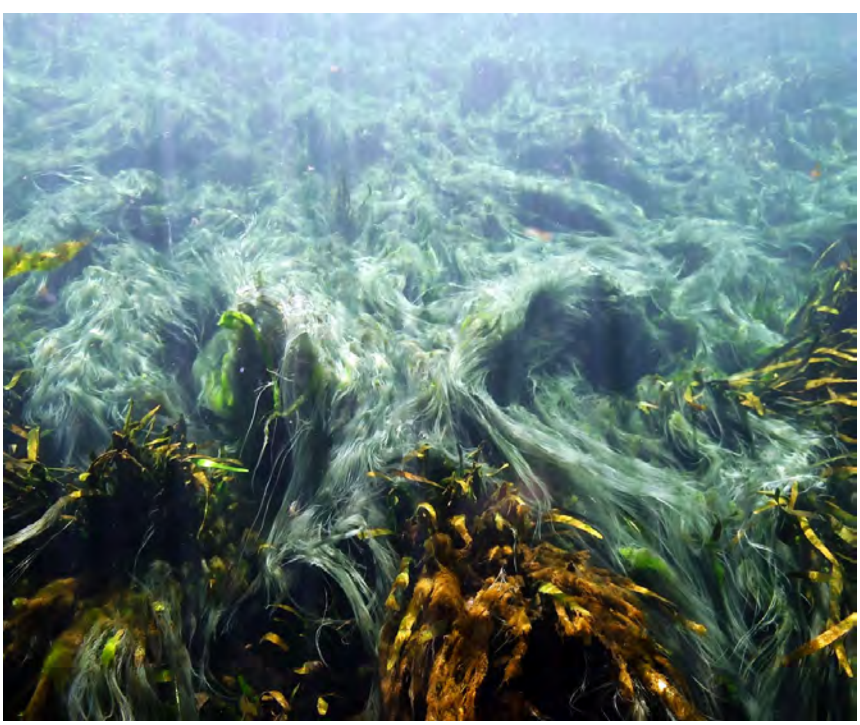


Figure 3.81 An underwater photograph from Wakulla Spring showing algal growth on and damage to native submerged aquatic vegetation (SAV). Courtesy of Wakulla Springs Alliance http://wakullaspringsalliance.org/

A Glimmer of Hope?

Governor Ron DeSantis Awards Over $57 Million to Protect Florida's Springs
On November 16, 2023, in News Releases, by Staff

TALLAHASSEE, Fla. — Today, Governor Ron DeSantis announced the award of over $57 million for 23 statewide springs restoration projects to protect Florida's iconic springs, as well as increase spring flow and improve water quality. Florida's springs attract visitors from across the world and the preservation of these springs plays an important role in the economic resilience of the state.

The Florida Department of Environmental Protection (DEP) and four of Florida's water management districts have identified projects such as wastewater, stormwater, pollution control projects and water-quality projects to protect and restore our springs. Additionally, these projects will help conserve and acquire land in spring recharge zones to prevent nutrients from entering the groundwater that feeds our springs.

"Florida is home to more than 1,000 springs, with more large springs than any other state in the nation, which attract visitors from across the world," said Governor DeSantis. "This $57 million investment will continue to protect water quality and allow Florida's springs to continue to be a world class tourist destination for years to come."

"Thanks to Governor DeSantis for once again continuing to protect one of Florida's greatest assets — our invaluable springs," said DEP Secretary Shawn Hamilton. "In partnership with our water management districts, local governments and community leaders, implementation of these projects will help to continue the protection of this precious resource for generations to come."

Some would comment on press releases like this: "It is a step in the right direction". Some would say "It is just a tiny drop in the bucket." And some would perhaps add: "And what about the huge elephant, or two, or three in the room no one seems to see, or is afraid of, or..." as excerpts from the news media illustrate below.

Wakulla Springs advocates say 'cleanup plan won't clean our spring'
James Call, Tallahassee Democrat. Published 2:22 p.m. ET June 7, 2018. Updated 3:23 p.m. ET June 7, 2018

https://www.tallahassee.com/story/news/2018/06/07/wakullas-friends-say-clean-up-plan-wont-clean-up-our-spring/681781002/

Wakulla Springs advocates say a state roadmap to clean springs is a dead end.

A coalition of groups dedicated to springs protection sent letters Thursday to the Florida Department of Environmental Protection to expose "huge gaps" in the proposed Basin Management Action Plans for springs fouled by pollution. BMAPS are long-range plans to reduce nitrogen in the watersheds of 24 freshwater springs of north and central Florida.

"They are asking farmers to implement best management practices for agriculture," said Bob Knight of the FSC. "But they tried that in 2012 in the Santa Fe basin, after five years there was no improvement – zero nitrogen reduction."

Nitrogen, in the form of fertilizers and human and animal waste, feed algae that then crowds out other life and eventually suffocates water bodies.

'Can't tell agriculture what to do' Retrofitting the septic tanks comes with a cost – as much as $3,000 per unit. And according to the springs advocates, Florida's 2011 Right to Farm Act, written to protect agriculture from nuisance lawsuits, is used to allow pollution from farms to flow unchecked.

Wake up now: Dirty water has grounded Wakulla Springs' iconic glass bottom boats
WUSF | By Sarah Breske. Published August 8, 2022 at 5:00 AM EDT. Updated June 7, 2023 at 6:55 AM EDT

https://www.wusf.org/environment/2022-08-08/wake-up-now-dirty-water-grounded-wakulla-springs-glass-bottom-boats

So far, Leon County has removed 252 septic tanks, according to Michelle Presley, public information specialist in Leon County. The county's strategic plan aims to remove 500 more by 2026.

There are 50,000 septic tanks between Leon and Wakulla County. Yet even as local leaders work to take out old septic tanks, they are allowing new septic systems to be installed every day.

From 2015-2020, over 500 new septic tanks were installed in Leon County and Wakulla County each, according to the Florida DOH.

Fight over protection of Florida spring detonates a furor at county commission meeting
In wild Wakulla County, a citizen-led anti-pollution measure hits a wall of political resistance
By Craig Pitman, Florida Phoenix, July 27, 2023 7:00 AM

https://floridaphoenix.com/2023/07/27/fight-over-protection-of-florida-spring-detonates-a-furor-at-county-commission-meeting/

I checked with the DEP about all this. The agency emailed me a long statement that said the state is not the one blocking a springs protection ordinance.

"The authority to enact a local ordinance — such as the proposed Wakulla Springs Water Quality Protection Regulation — rests solely with the county," the statement said. "DEP never "rejected the county's proposed ordinance. Instead, DEP, and Wakulla County government officials discussed opportunities for the county to undertake and become an approved storage tank program."

The ordinance the citizens came up with found a receptive audience with one of the five commissioners, Chuck Hess, a retired wildlife biologist.

During last week's well-attended commission meeting, Hess made a motion to send the citizen-written springs ordinance to the county's planning and zoning committee for study. This is the usual first step for vetting any ordinance for any legal or scientific concerns before voting on its passage.

But he couldn't get a single one of his colleagues to second the motion. Not one.

Without a second to the motion, no one could even discuss the springs protection ordinance, much less vote on it.

As soon as the crowd attending the meeting comprehended what had happened, people began howling with outrage. I don't mean that figuratively. I mean literal howling, like Wolfman Jack had been resurrected from the dead and was back on the radio spinning platters.

I called up Hess to ask him what happened. Why would his fellow commissioners reject a citizen-led push for springs protection? Why strangle this infant in its crib?

"Our commission didn't have the intestinal fortitude to discuss it," he told me. "They've never seen a developer they didn't like and never seen a citizen they're not willing to offend."

Sweltering standoff with Wakulla Commission over gas station leads to hope for springs
James Call, Tallahassee Democrat. Published 12:05 a.m. ET Aug 8, 2023. Updated 12:34 p.m. ET Aug 8, 2023

https://www.tallahassee.com/story/news/2023/08/08/wakulla-county-hopes-forever-florida-can-end-pauses-gas-station-plans-and-seek-state-money-to-buy-la/70542082007/

The largest turnout for a Wakulla County Commission meeting anyone can remember coupled with excessive heat produced a stunning victory Monday night for a coalition of spring defenders.

They were able to delay and possibly derail plans by the Southwest Georgia Oil Company to construct a mega-gas station four miles from the famed Wakulla Springs.

The parcel of land at issue is currently zoned for agriculture and sits above a serpentine cave through which an underground river flows and connects the aquifer to Wakulla Springs, the world's largest known freshwater spring.

Two weeks ago, residents erupted in anger and began shouting at commissioners when a proposal to discuss stricter springs protection regulations failed. Sheriff's deputies were called to clear a group of protesters from the room, and at least one person received a trespass warning.

The springs defenders had opposed Southwest Georgia's plans since they were first revealed nearly two years ago.

They argue the county's unique karst bedrock and the threat gasoline poses to drinking water – one gallon can poison 750,000 gallons of water – makes the venture too risky.

Southwest Georgia operates 77 inland gas and food stores in Alabama, Georgia and Florida. A list of contaminated sites due to storage tanks failures produced by the Florida Department of Environmental Protection lists the company 11 times for spills in Leon and Gadsden counties.

3.7.3 Glorious Days of the Past

All photographs in this section are courtesy of State Archives of Florida, Florida Memory (available at https://www.floridamemory.com/).

Figure 3.82 *Left*: Tarpon Club of Florida State University. *Right*: Visitors crowd the beach. July 4th, 1946.

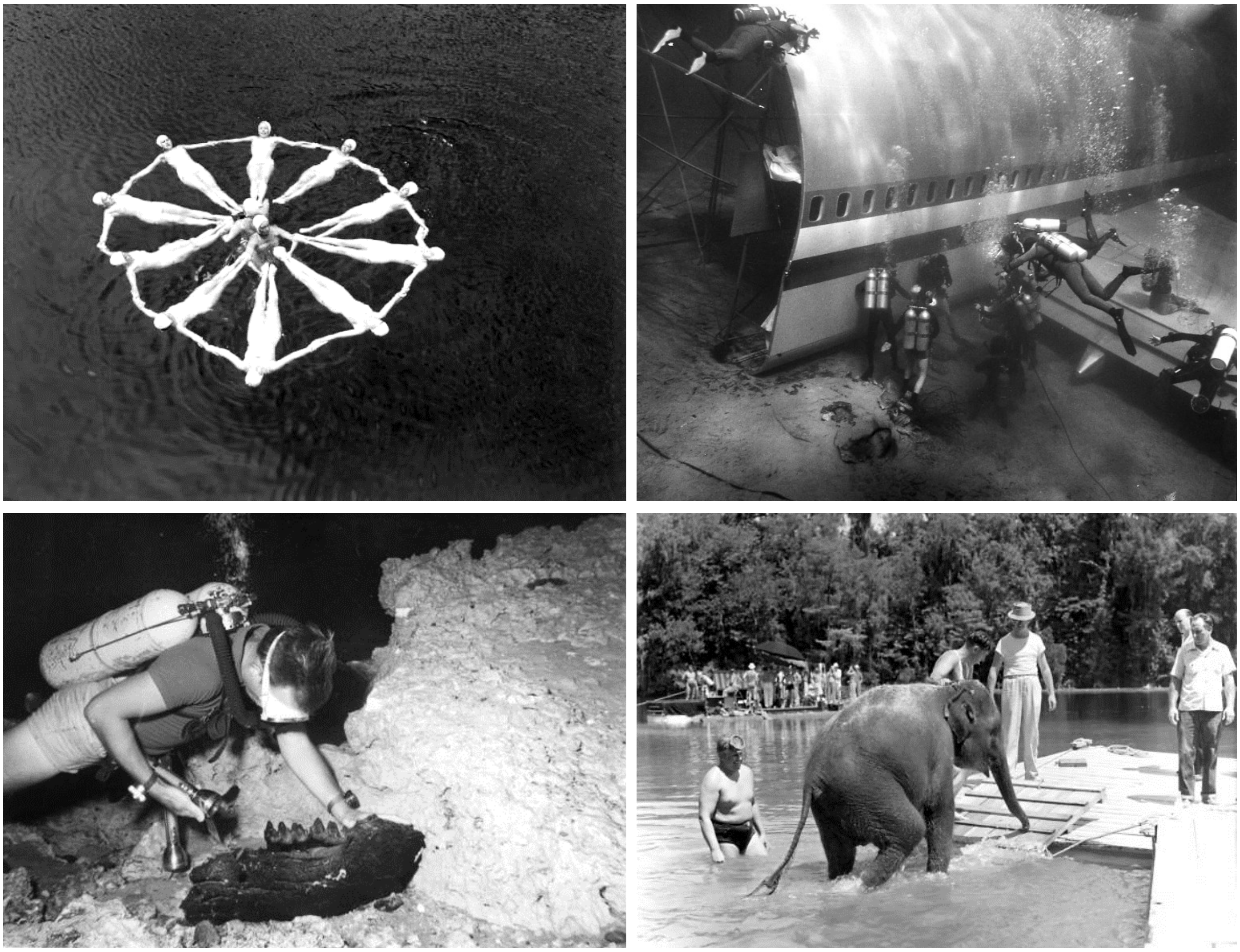


Figure 3.83 *Top Left*: Aerial view of Florida State University Tarpon Club. Photo by Monts de Oca, C. Morris. *Top Right*: Filming of “Airport 77” under water, 1976. *Bottom Left*: “Diver investigates objects in the spring”, photo by Andy Harrold, 1956. *Bottom Right*: Elephant during filming of "Tarzan's Secret Treasure", circa 1940. Photo by Perry Newton.

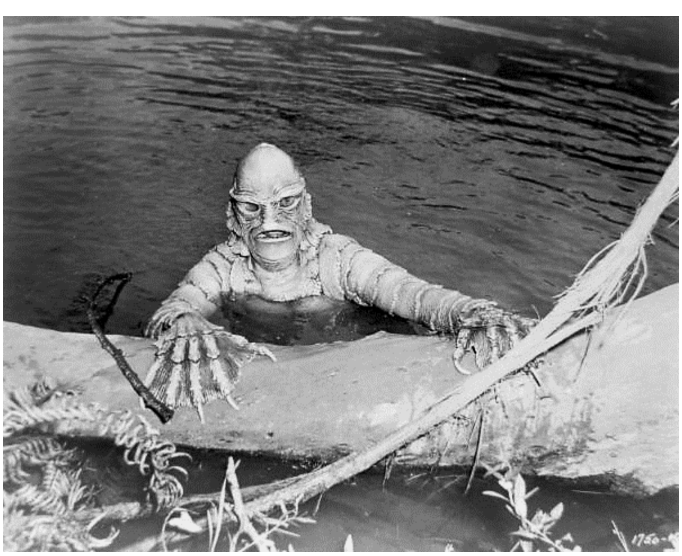


Figure 3.84 *Creature from the Black Lagoon* (1954) was released by Universal Pictures, directed by Jack Arnold, and starring Julia Adams and Richard Carlson. Florida-native Ricou Browning played the creature (Gill Man) in water and Hollywood actor Ben Chapman played him on land. The water scenes were filmed at Wakulla Springs, while the sequel was filmed in Jacksonville, Marineland, and Silver Springs. Both were originally shown in 3-D.

3.8 Rainbow Springs Group

Rainbow Springs Group (Figures 3.45 and 3.85; see Table 3.1 for GPS coordinates) forms the Rainbow River, which flows south for approximately 5.7 miles and merges with the tannic Withlacoochee River at Dunnellon. The surrounding land has high rolling sand hills with a pine forest, agricultural fields and rapidly expanding areas of development. It is in Rainbow Springs State Park which has 3 entrances: (1) the headsprings and day use area entrance is at 81st Place Road, Dunnellon via U.S. 41; (2) the campground entrance is at 18185 SW 94th St., 3.1 miles south of State Rd. 40 or 2.3 miles north of County Rd. 484; (3) and the tubing entrance is at 180th Ave. Road, Dunnellon (tubing is open seasonally and it is currently run by concessionaire. The park's website is at https://www.floridastateparks.org/parks-and-trails/rainbow-springs-state-park.

The Rainbow Springs State Park (Figure 3.86) has many visitors on weekends and holidays. They come from around Florida, the country, and the world to visit the Park, to swim and snorkel in the crystal-clear water, to canoe, kayak, and tube down the peaceful Rainbow River, and to enjoy picnicking with friends and families. When the Park reaches capacity at the headsprings entrance, it closes to all visitors. When the Park is closed, vehicles may not wait in line in the park or on adjacent roads.

The springs (Figures 3.87 through 3.90), in addition to those at and near the head of the Rainbow River, discharge from numerous limestone crevices and sand boils in the bed of the river and along the banks through the upper 2 miles. These locations are easily recognized because of the absence of aquatic vegetation. Rainbow Spring No. 1 is at the head of the Rainbow River. The spring pool measures 330 ft north to south and 360 ft east to west. The large spring pool has multiple vents. The depth over the main vent is about 10 feet. The bottom is sand with occasional limestone boulders. Water is crystal-clear. A boil is visible over the main vent. Aquatic vegetation is patchy, including some exotic plants. Motorized boats are prohibited, but the area is accessible by canoe or kayak. There is a designated swimming area on the west side of pool.

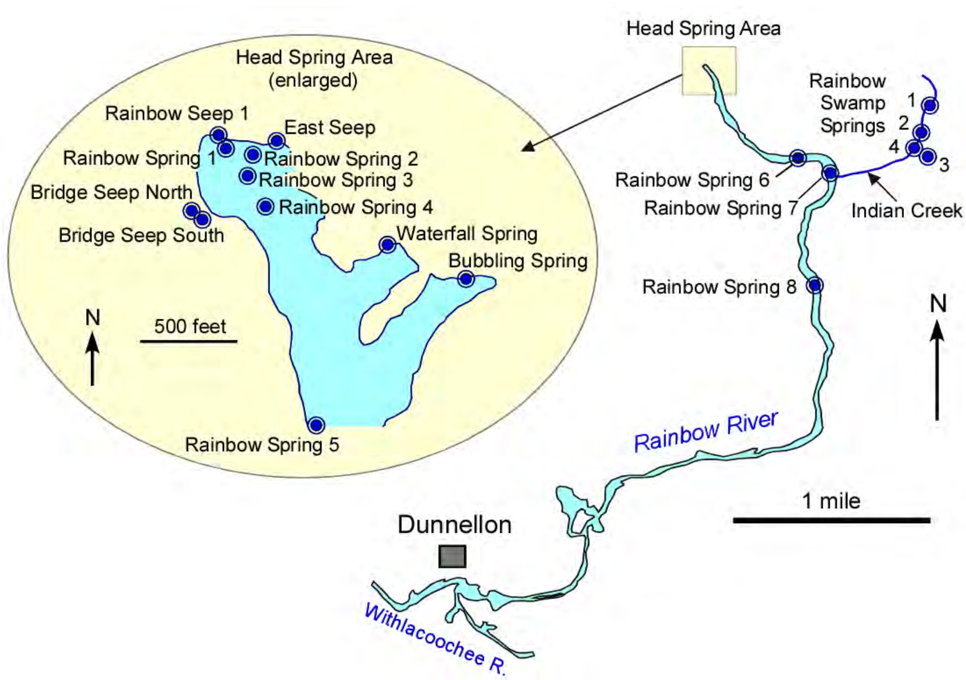


Figure 3.85 Locations of spring vents in the Rainbow Springs spring complex. From Jones et al., 1996. USGS records the flow of the Rainbow River at Dunnellon. Discharge rate of the Headspring area is not reported.

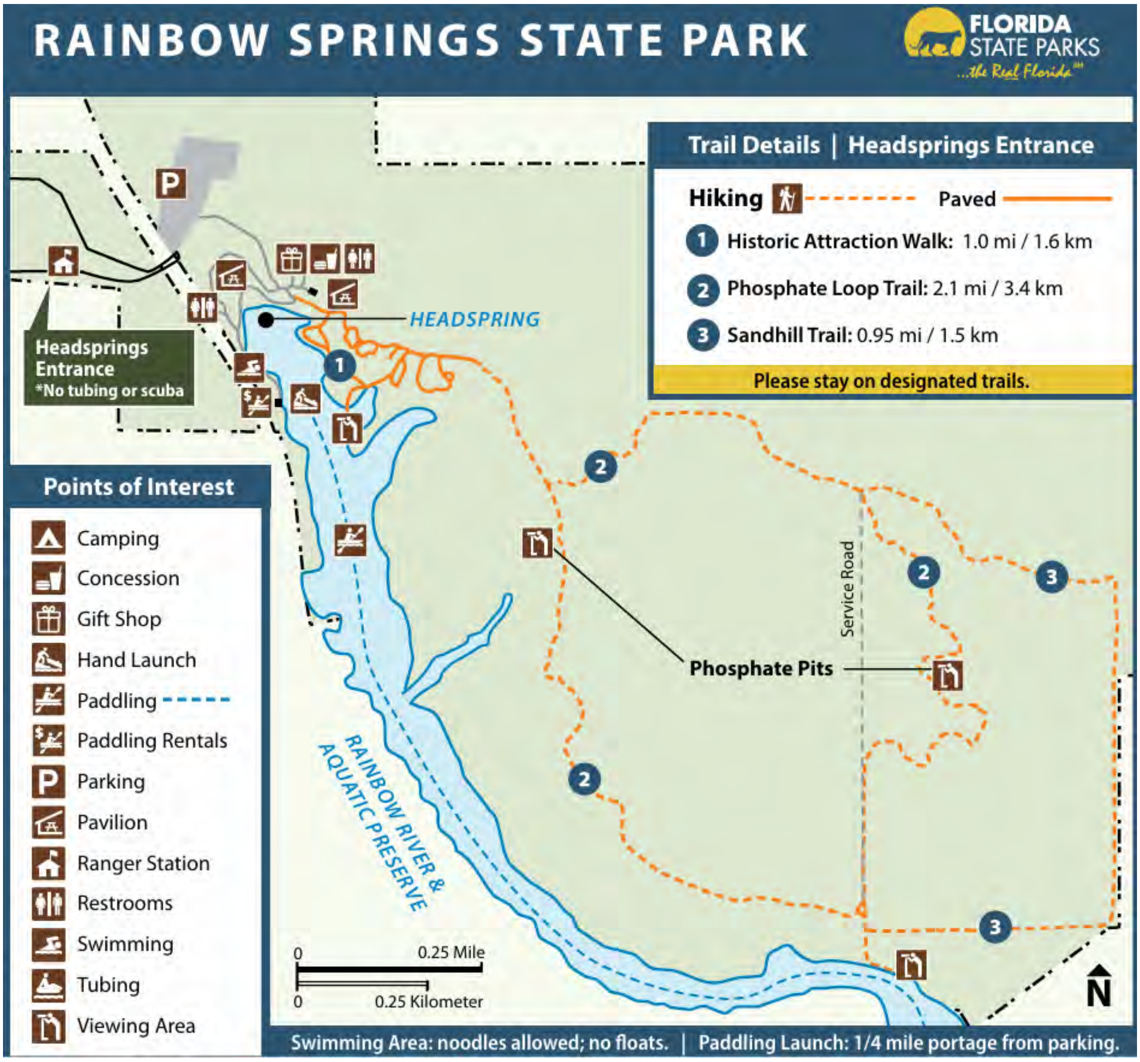


Figure 3.86 Part of Rainbow Springs State Park Map

Figure 3.87 Pool of the headspring of Rainbow Springs, December 2023. Red buoys mark the swimming area with crystal-clear water and a sandy bottom. *Left*: Looking east. *Right*: Looking west.

Figure 3.88 Rainbow River. December 2023.

The area surrounding the park has been inhabited by human cultures for at least 10,000 years. Native Timucua people lived here at the time of European contact. The city of Ocala is named after a nearby Timucuan village and chief called Ocale. Pioneers first settled the headsprings in 1839. By 1883, about 75 people lived in this agricultural community, which had a railroad station, sawmill, hotel, stores, and a post office. In the 1920s, Blue Springs and Blue Run (how the springs were called at the time) were favorite spots for tourists and locals. As the attraction grew (Figure 3.89), the river was dredged for glass bottom boat tours (the distinctive sub-boats had stairs that went below the waterline and visitors could look out at eye level.) A zoo, rodeo, gift shops and a monorail with leaf-shaped gondolas were added.

Figure 3.89 Aerial view of Rainbow Springs, circa 1954. Courtesy of Florida State Parks.

The development of the interstate highway system in Florida eventually led to the demise of Rainbow Springs. The interstate passed by the small towns that hosted such attractions, and newer, modern attractions in Orlando drew many away from the older parks. By 1974, Rainbow Springs was closed. The state purchased the original area that was the Rainbow Springs Attraction in 1990. Volunteers cleared the overgrown park and opened it on weekends to the public and the Florida Park Service officially opened Rainbow Springs State Park on a full-time basis on March 9, 1995.

In 1972, the U.S. Department of the Interior designated Rainbow River as a National Natural Landmark. The unique ecological attributes of Rainbow Springs and the Rainbow River were recognized by the state of Florida when the system was designated an Aquatic Preserve in 1986, and an Outstanding Florida Water in 1987. In 1989, the Southwest Florida Water Management District (SWFWMD) adopted the Rainbow River as a Surface Water Improvement and Management priority water body.

The river supports abundant wildlife, including otters, alligators, many species of turtles and fish, and every variety of water bird—waders, divers, and dabblers. Osprey, hawks, and swallowtail kites soar along the river corridor while smaller birds and animals hide in the lush vegetation. Many animal species, including the endangered gopher tortoise, Florida pine snake, indigo snake, Sherman’s fox squirrel and the Florida mouse inhabit the uplands surrounding the springs and river.

Figure 3.90 Rainbow River, 2017. Photographs by John Moran; all rights reserved. Printed with permission.

Although Rainbow Springs has some of the healthiest submerged aquatic vegetation and fish population (Figure 3.90), it has one of the highest nitrate levels among the west-central Florida spring systems. Excess nitrate levels in water can be harmful to aquatic insects, amphibians, and fish. If algae have an unlimited source of nitrates, excess growth may occur. Large amounts of algae growth can cause reduced water clarity and extreme fluctuations in dissolved oxygen, which is stressful to aquatic life. In addition, unhealthy Hydrilla and Lyngbya dominate at the lower portion of the river.

As in case of many other springs and spring-fed rivers in Florida, the flow of Rainbow River has been generally decreasing due to over-pumping of the Floridan Aquifer (Figure 3.91).

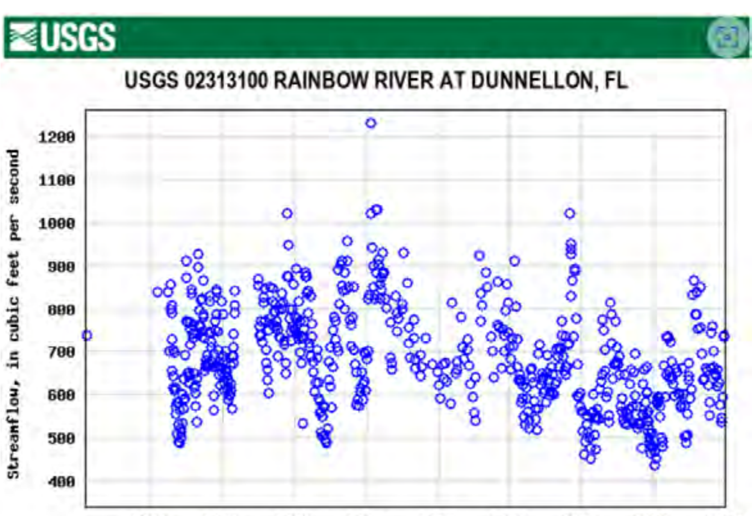


Figure 3.91 No officially reported monitoring data of discharge rates of individual Rainbow Springs is available. Flow rate of the Rainbow River is monitored at Dunnellon, about 3 miles downstream from the last individual Rainbow Spring (No. 8, see Figure 3.85).

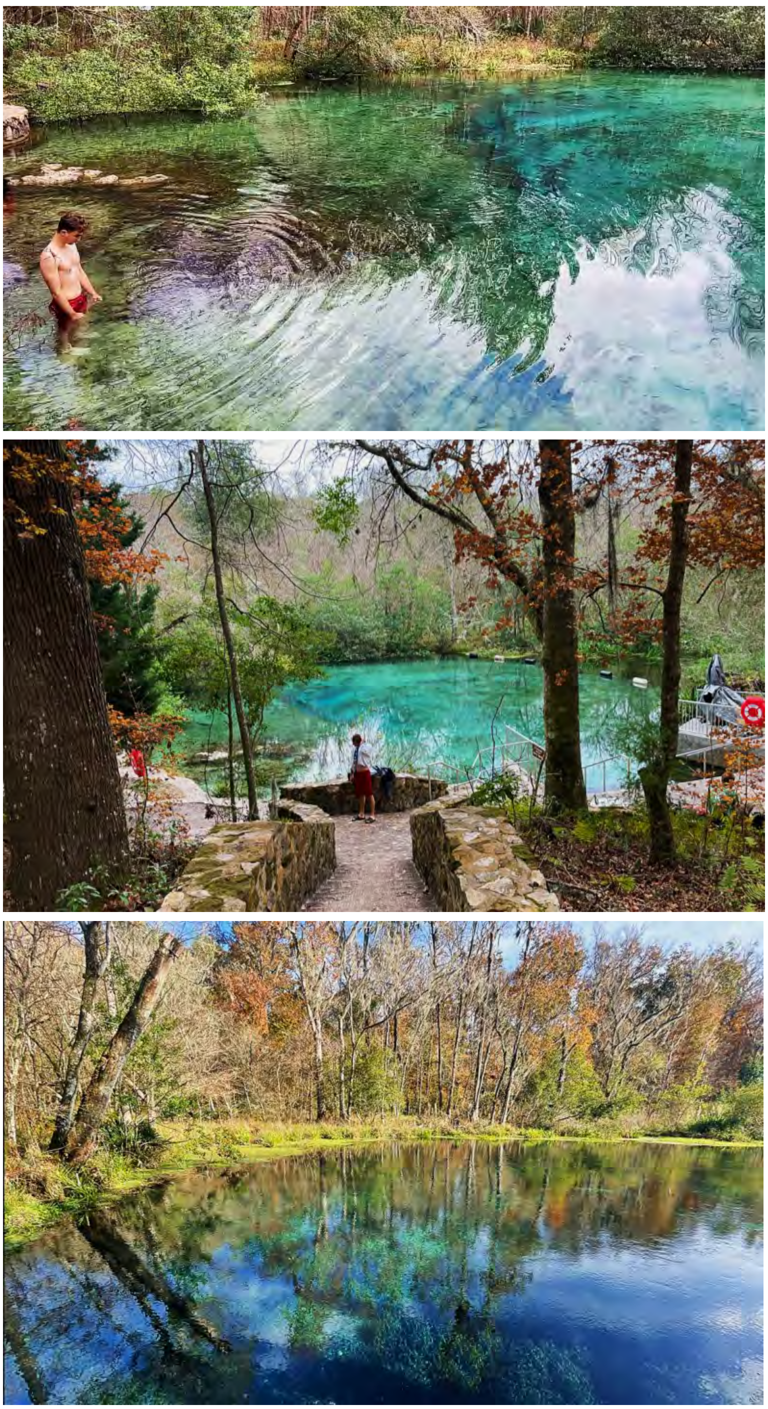
3.9 Ichetucknee Springs Group

The Ichetucknee Springs are in the Ichetucknee Springs State Park which has two entrances (North Entrance is for the swimming areas, and South Entrance is for tubing – Figure 3.92; see also Figure 3.42, and Table 3.1 for GPS coordinates). They comprise a group of eight named and many unnamed springs along the upper 2.5 mile stretch of the Ichetucknee River. The most northerly spring forms the head of the river and is named Ichetucknee Headspring (Figure 3.93). From here, the river flows about 1.5 miles south, then 4 miles southwest to discharge into the normally darker tannic water of the Santa Fe River.

Figure 3.92 Ichetucknee Springs State Park map. Numbers denote park trails (available at https://www.floridastateparks.org/parks-and-trails/ichetucknee-springs-state-park)

Other named springs are Blue Hole (Figures 3.93 and 3.94), Mission Spring, Cedar Headsprings, Devil's Eye Spring (not to be confused with the spring in the Ginnie Springs Group by the Suwannee River), Grassy Hole Spring, Mill Pond Spring, and Coffee Spring.

The Ichetucknee Springs Group is considered by many to be the crown jewel of the Suwannee region. It is popular year-round for its clear, cool waters, and is a tourist destination for its many amenities, including tubing. The two most visited springs are the Headspring and Bue Hole where swimming is allowed at all times, without any concern for brownouts which are common at other springs along the Suwannee and Santa Fe Rivers.



The Headspring pool measures 102 ft east to west and 87 ft north to south. The depth measures 17 ft over the vent. Water is clear and light blue and issues from a fracture in the limestone forming a visible boil. The spring has sand and limestone bottom with little or no aquatic vegetation and is a popular swimming hole.

Blue Hole, also known as Jug Hole among cave divers because of the spring vent's shape, is in the spring run channel of Cedar Head Spring, which is north of Blue Hole. The spring pool and outflow greatly widens the incoming spring run, and the combined run flows south a short distance to the Ichetucknee River.

The spring pool measures 87 ft east to west and 117 ft north to south. The depth measured over the vent is 37 ft. The water is always clear and blue, and a boil is visible on the pool surface. Water issues from a cavern in limestone (Figure 3.94). The pool has a sand and limestone bottom with abundant aquatic grass and some algae.

Figure 3.93 *Top* and *Middle*: Ichetucknee Headspring. *Bottom*: Blue Hole. December 2023.

Figure 3.94 Entrance to cave passage at the bottom of Blue Hole. Photo by John Moran; all rights reserved. Printed with permission.

Although well-known for its warm weather tubing, Ichetucknee Springs State Park is a 2,669-acre wildlife haven where beaver, otter, gar, softshell turtle, wild turkey, wood duck and limpkin all find a home. The upper portion of the Ichetucknee River within the state park was in 1972 declared a National Natural Landmark. It has been argued by many that the river is the most pristine spring run in the state (Figure 3.95), best enjoyed by canoe or kayak or float during the cooler months.

Figure 3.95 Floating down the Ichetucknee River, 1990; Photo by John Moran; all rights reserved. Printed with permission.

During the 1800s, early travelers on the historic Bellamy Road often stopped at Ichetucknee Springs to quench their thirst. Immediately after the Civil War, northern Florida received a great influx of settlers. The area around Fort White was still considered wild frontier when the small community was incorporated in 1870. Soon after, the nearby town of Ichetucknee sprang up along the banks of Mill Pond Spring. By 1884, Ichetucknee had its own post office, grist mill and smithy.

With high quantities of limestone at or just below the ground surface, the area became early headquarters for North Florida's phosphate industry in the late 1890s and early 1900s. Phosphate mining in the park covered two major periods. Exploration mining began prior to the turn of the 20th century, consisting of mule and wheelbarrow-assisted excavation in nearby sinkholes and depressions. Later, the mine used boilers, pumps and steam shovels for ore extraction. A series of narrow-gauge railroads were installed to cart the ore out to local railroad lines. This early phase of mining was never as intrusive as our present-day methods, but many pits were left in the park and are still present today, especially around the Headspring area.

Although tubing the river is a relatively recent innovation, for many decades the springs of the Ichetucknee have been prized by locals as favorite gathering spots. In the days before automobiles, people used to endure hours on dusty, bumpy back roads by horseback or wagon to enjoy the cool waters. The Headspring in particular was popular for family reunions, baptisms, picnics and camping. Old-timers tell stories of chilling watermelons in the small feeder springs around the Headspring. Women used to tie up their skirts to go fishing, trapping their catch bare-handed against logs and throwing them up on shore.

As in case of many other springs and spring-fed rivers in Florida, the flow of Ichetucknee River appears to have a generally decreasing trend since 1980s (Figure 3.96).

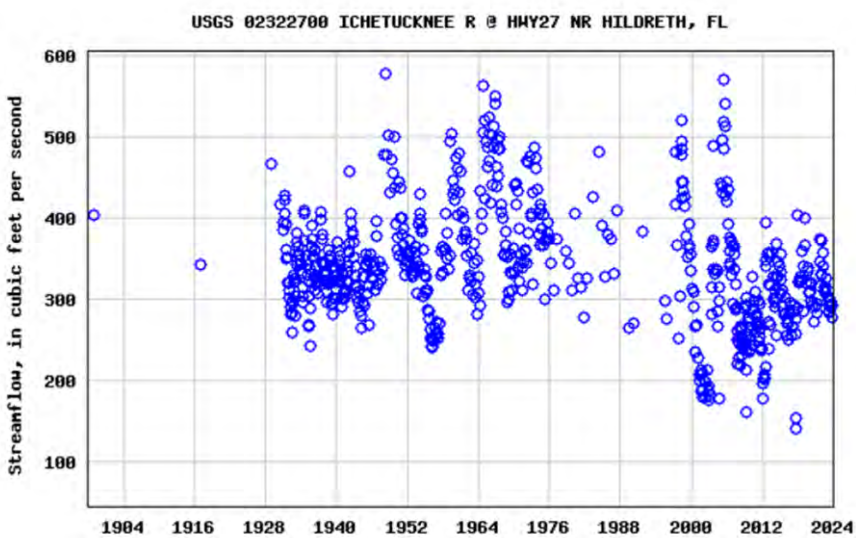


Figure 3.96 Field measurements of the Ichetucknee River flow rate. Average for the entire period of record is 340 cfs.

3.10 Ginnie Springs Group

Ginnie Springs Group is in a privately-owned park about 8.6 miles west of High Springs off County Road 340 (see Figure 3.42, and Table 3.1 for GPS coordinates). The group of seven springs that are known as Ginnie Springs, as well as the surrounding 600 acres, have been privately owned by the Wray family since 1971. Ginnie Springs Outdoors LLC has been in operation since 1976. The park, nestled along the banks of the scenic Santa Fe River, is very popular especially during spring break and summer months and the entrance fee is worth every penny. Strict Park rules are enforced for the safety of all visitors and can be viewed and downloaded prior to visit at (https://ginniespringsoutdoors.com/).

The Park's offer is extensive including (1) Sun decks at all springs which provide easy-to-use stairs leading to the water. (2) Heated, tiled bath houses featuring separate Men's and Women's rooms with warm showers and changing areas. (3) Beach-like volleyball courts, lit for nighttime play. (4) Boat ramp where visitors can launch their own vessels. (5) Picnic tables and grills throughout the park. (6) Covered picnic pavilions. (7) Country store and deli. (8) Free air for tubes and rafts. (9) Tubes, canoes, kayaks, paddle boards and snorkeling/scuba equipment available for rental. (10) Swimming, snorkeling, diving, and walking trails. (11) Over 250 acres of wilderness camping. (12) Camping at electric and water sites where reservations are strongly recommended.

Ginnie Springs achieved an unrivaled fame among scuba divers of all skill levels when Jacques Cousteau dove here in 1974 and praised the crystal-clear water (72°F year-round) as “visibility forever.” It is the international hotspot for scuba diving.

The main Ginnie Spring basin is a large, bowl-shaped depression measuring over 100 feet across and 15 feet deep (Figure 3.97). A 150-foot-long run connects the basin to the nearby Santa Fe River. The chief attraction here is the Ginnie Cavern, whose wide, open entrance can be found at the bottom of the basin. Ginnie Cavern is among the handful of sites that experts consider sufficiently safe to allow exploration by divers who lack formal cavern or cave diver training.

Certified divers of all experience levels may take lights into the water with them at Ginnie Spring and use these lights to explore the underwater cavern. The cavern’s upper room is illuminated by light from the entrance. Looking back toward the entrance from this room provides a breathtaking view. Like most of the cavern, the upper room’s walls are composed of an extremely light and highly reflective limestone, which adds to its natural beauty.

Figure 3.97 Ginnie Spring, December 2023. *Left*: Future scuba diver (in lower right) being introduced to the spring magic for the first time. *Right*: “One for the camera!”

Moving to the back of the upper room, divers pass through a large opening into the amphitheater-sized area called the “Ballroom.” Although surface light is clearly visible from most places within the Ballroom, divers will want to carry dive lights to see everything there is to see.

Figure 3.98 “Ballroom” at Ginnie Spring Cavern. Courtesy of Ginnie Springs Outdoors; available at https://ginniespringsoutdoors.com/dive-sites/ginnie-ballroom/

The Ballroom provides divers with the opportunity to examine many of the unusual geologic formations that are unique to the Floridan Aquifer. The Ballroom’s ceiling contains an excellent example of spongework–a gigantic, limestone Swiss cheese. At the northwest corner of the Ballroom is a beautifully carved phreatic tube–a perfect example of the most common form of underwater cave formation.

The Devil's Spring System is home to three closely spaced but separate springs (Figures 3.99 through 3.102): Devil's Eye, Devil's Ear, and Devil Spring ("Little Devil"), which together are classified as a bona-fide first-magnitude Outstanding Florida Spring producing on average nearly 110 million gallons of water daily (Figure 3.103) and keeping at bay the dark tannic water of the Santa Fe River.

Only certified cave divers may enter the water at the Devil Spring system while carrying dive lights. This helps prevent untrained divers from entering any area where their lack of training, experience, and specialized equipment could get them in trouble.

Figure 3.99 Devil's Spring System at Ginie Springs. Courtesy of Ginnie Springs Outdoors.

Devil Spring (also known as "Little Devil", see Figure 3.100-*Left*) is a four-foot-wide fracture at the head of the Devil's Spring System run. It is 50 feet long and almost as deep. Divers who descend to the bottom of this crack will be rewarded with a breath-taking view as they look skyward. Even from the very bottom, it is not unusual to look up through the clear water and be able to count the leaves on the trees overhead.

Figure 3.100 *Left*: Divers preparing to explore Little Devil Spring at the head of the Devil's Spring System short spring run. *Right*: View down the spring run towards the Santa Fe River visible in the distance. December 2023.

Devil's Eye is a round opening, 20 feet across and equally deep. At the bottom is the entrance to a small, intricately decorated cavern. Certified divers may enter the cavern and explore up to the limit of what they can see, using available sunlight.

Devil's Ear is a canyon-like opening located where the Devil Spring run joins the Santa Fe River. At the bottom of this opening, water gushes from a cave opening with nearly fire-hydrant-like force. Although the water in the Devil's Ear basin is generally crystal clear (Figure 3.101), it is common for it to be covered with a thin layer of tannin-stained river water. This phenomenon enables divers to sit in the basin's clear water and look up at the sun and trees through a unique, stained-glass effect created by the river water.

In his excellent blog on beautiful Florida springs, Frank Moore has the following advice to Ginnie Springs visitors (https://firstmagflorida.com/2020/10/10/devils-spring-system-ginnie-springs/):

Perhaps distracted by the ever-smaller bikini tops and freshly-swollen biceps, many visitors to Ginnie Springs simply float the brownish Santa Fe River without stopping to explore the springs. Thus, this hidden-in-plain-sight Florida jewel is not much talked about beyond the circle of cave divers and spring enthusiasts. During your next visit to Ginnie, pack your mask alongside those beers!

Figure 3.101 Devil's Ear Spring from cave diver's perspective. Photo by John Moran; all right reserved, printed with permission.

A trip to visit Ginnie Springs presents the opportunity to enjoy the journey as much as the destination. Launching from Rum Island Spring County Park, the Devil's Spring System is just a 1.1 mile paddle down stream. You wind along the Santa Fe River, allowing the current to aid in your progress.

Early on in your journey, just 0.2 river miles from Rum Island, you will encounter a clear spring run. The crystal-clear water comes from Gilchrist Blue Springs. Paddle up the secluded, shallow spring run and you will encounter a stunning swimming hole.

Although not a first magnitude spring, Gilchrist Blue's water clarity is astounding and it is easy to see the reasoning behind the spring's name. The park features a comfortable, sandy beach on which to disembark.

Figure 3.102 Drone photo of The Devil's Eye by Frank Moore. Note the contrast between the crystal-clear spring water and dark tannic water of the Santa Fe River. available at https://firstmagflorida.com/2020/10/10/devils-spring-system-ginnie-springs/

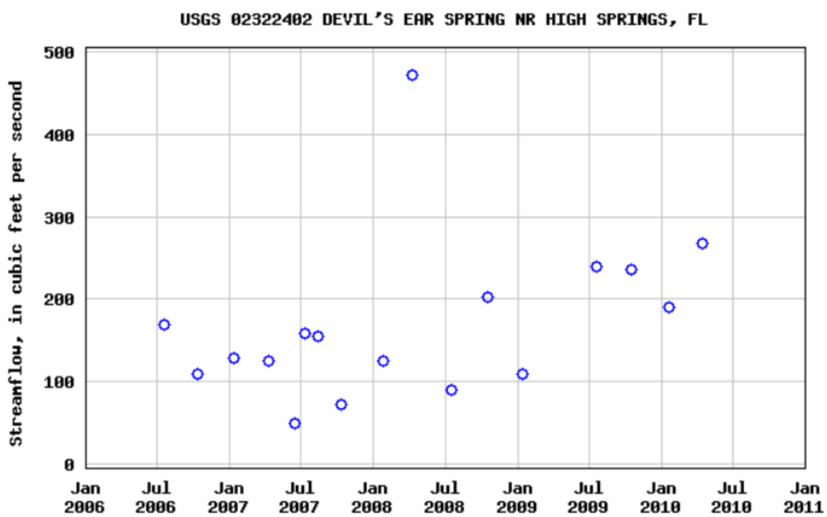


Figure 3.103 Based on 17 available field measurements by USGS, the average discharge rate of Devil's Ear Springs is 170 cfs (no data is available after 2010).

3.11 Gilchrist Blue Springs

Ruth B. Kirby Gilchrist Blue Springs State Park is in Gilchrist County about five miles to the west of High Springs off Northwest 182nd Avenue (County Road 340) in the north-central part of the state along the Santa Fe River (see Figure 3.104, and Table 3.1 for GPS coordinates)

The park is the newest addition to Florida State Parks (https://www.floridastateparks.org/parks-and-trails/ruth-b-kirby-gilchrist-blue-springs-state-park) and contains a collection of springs, including a large second-magnitude spring known as Gilchrist Blue (Figure 3.105). This spring is the headspring of a shallow, about 1/4-mile long run

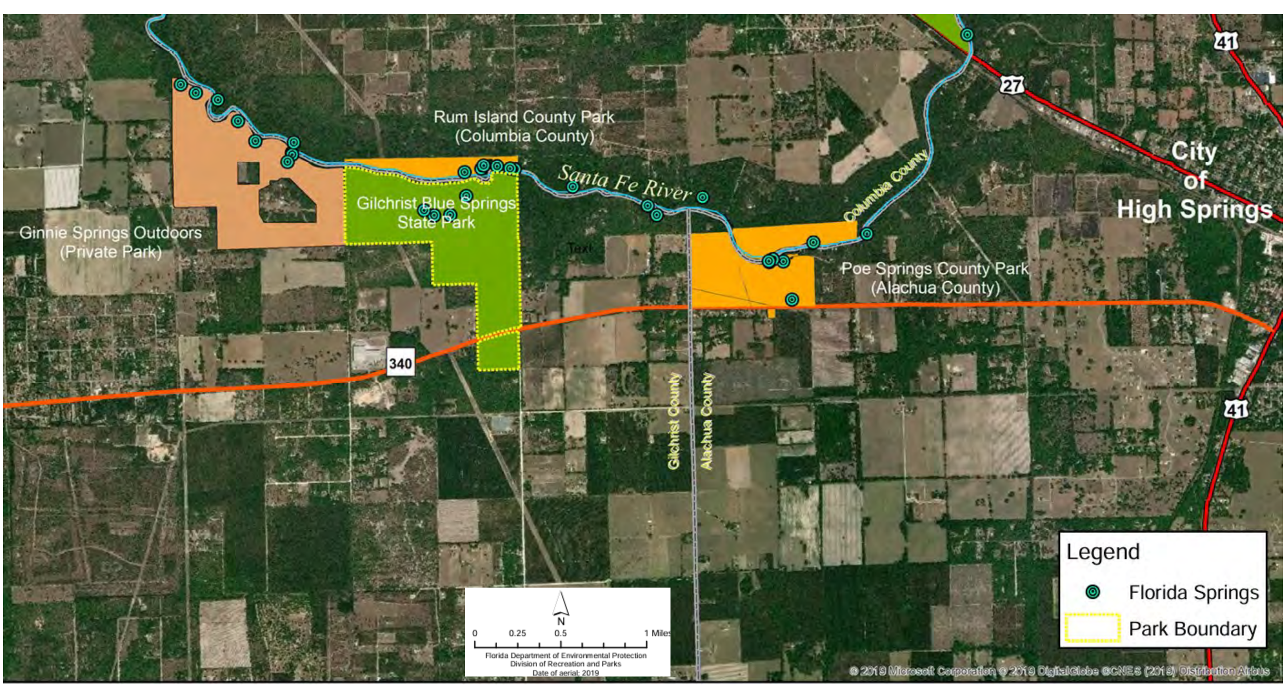


Figure 3.104 Part of Ruth B. Kirby Gilchrist Blue Springs State Park reference map. From FLDEP (Florida Department of Environmental Protection), 2019.

discharging to the Santa Fe River. Its remarkable aesthetic appeal stems from the extraordinary clarity of its waters, owing to the extensive subterranean filtration of aquifers that render it visually transparent. With an average daily discharge of approximately 42 cubic feet per second, the main spring sustains a stable temperature of approximately 72°F (22°C) year-round (Florida Springs Institute, 2020b).

The Park currently offers swimming at the main spring only. The other springs are under restoration (2023-2024) but are available for viewing: Little Blue Spring, Naked Spring (also a second-magnitude spring), Kiefer Spring and Johnson Spring.

Figure 3.105 Gilchrist Blue Spring in Ruth B. Kirby Gilchrist Blue Springs State Park. December 2023.

The most significant ecological habitats include the spring run stream and floodplain communities. The main spring run is renowned for a diversity of wildlife species, including turtles, fish, and invertebrates. Redbreast and spotted sunfish, largemouth bass, bluegill, and channel catfish can be observed in waters with unparalleled visibility.

Paddling, snorkeling, and swimming are all popular at the park. Pavilions are available, and a concession stand provides food and beverage service plus paddling equipment rentals. Other popular activities include camping, hiking, nature study and picnicking.

With mounting anthropogenic impact from increasing visitation and potential introduction of invasive species, the spring and its surrounding environs have encountered environmental challenges, necessitating conservation measures to safeguard the fragile balance between human enjoyment and ecological protection. The headspring sits downhill from a picnic area which has gradually been stripped of vegetation over time. To prevent erosion, plastic barriers were installed (Figure 3.105-*Top*). This erosion control infrastructure may not be sufficient as there are regular erosion issues at Gilchrist Blue (Florida Springs Institute, 2023).

According to FLDEP (2019), the discharge of Gilchrist Blue Spring (combined with Naked Spring and Little Blue Spring at the mouth) was first measured in April 1975 with a flow of 42 cubic feet per second (cfs). The average recorded flow for Gilchrist Blue Spring is 45.16 cfs (based on 106 measurements), with a minimum of 8.43 cfs (April 26, 2012) and maximum of 89.4 cfs (October 21, 2015). Spring flows from Gilchrist Blue Spring have steadily declined since they were first recorded in the 1970s (Johnston et al., 2016).

3.12 Madison Blue Spring, and Lafayette Blue Spring

Madison Blue Spring is in Madison Blue Springs State Park about 10 miles east of Madison via US 90 and Florida State Road 6E (see Figure 3.42, and Table 3.1 for GPS coordinates). The park experiences frequent closures between the hours of 10 a.m. and 3 p.m. on weekends and holidays due to high visitation. It provides a wide variety of recreational activities including swimming, picnicking, hiking, paddling and scuba diving.

The park closes when it reaches capacity but may reopen to additional visitors later that day. For their safety, visitors are not permitted to park and wait in their cars on the side of the road or in the park entrance area for the park to reopen. Local law enforcement will issue citations for violations. More information is available at https://www.floridastateparks.org/parks-and-trails/madison-blue-spring-state-park

Figure 3.106 Madison Blue, photo by Frank Moore.

https://firstmagflorida.com/2023/05/30/madison-blue-spring/

The Spring flows from an 80-foot diameter spring pool, down a 100-foot spring run and into the Withlacoochee River (Figures 3.106 and 3.107). A large opening about 30 feet below the surface of the spring leads to an extensive underwater cave system (Figure 3.108). Over 26,000 feet of passages have been mapped by certified cave divers, making it one of the longest underwater caves systems in the state. The cave system extends well outside of the park boundary and passes under the Withlacoochee River just south of the State Road 6 bridge. The crystal blue waters of Madison Blue Spring are world famous for underwater cave diving and exploration. All divers are required to operate in pairs and complete dives at least one hour before sundown.

Figure 3.107 In 2015, Madison Blue was voted the Best Swimming Hole in the United States by USA Today. It is a family favorite destination and a fantastic place to spend the day. Panoramic photo courtesy of Suwannee River Water Management District (SRWMD).

The spring's clear blue waters originate from the lower Oligocene Suwannee Limestone, part of the Floridan aquifer system. The Suwannee Limestone, which is a white to cream-colored fossiliferous limestone, crops out in the Withlacoochee River and in the spring. The Suwannee Limestone is the upper geologic formation within the Floridan aquifer system throughout the park.

Figure 3.108 Photo by Kiril Egorov Courtesy of Florida State Parks.

The fossil sea biscuit *Ryncholampas gouldii* is an index fossil for the Suwannee Limestone and is commonly found in outcrops of the formation like seen in Madison Blue Spring and along the Withlacoochee River. An index fossil is a special fossil that is found only in a singular formation and helps geologists easily identify the formation and its geologic age. Agatized coral is another unique fossil that can be found at the confluence of the Withlacoochee River and Madison Spring's waters in the gravelly bed of the river.

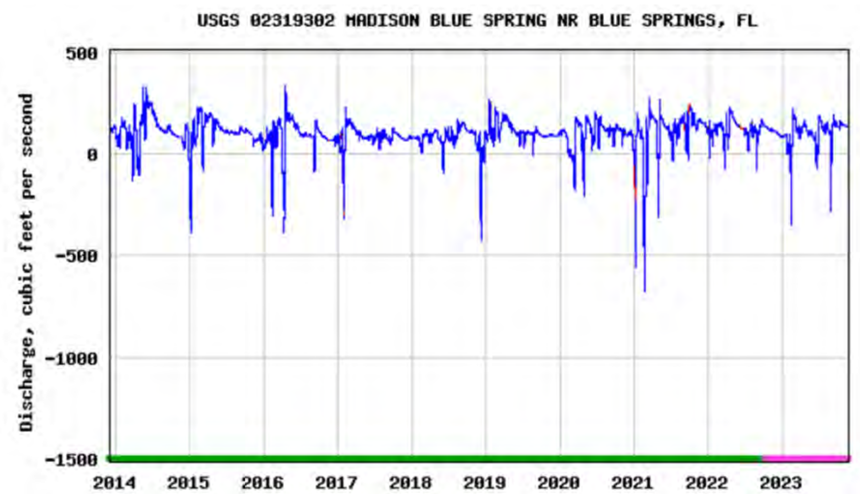


Figure 3.109 Madison Blue Spring's average discharge rate of 103 cfs is uniform over the last 20 years, with occasional flow reversal during very high stages of the Withlacoochee River.

Lafayette Blue Spring is 7.5 miles northwest of Mayo via US Hwy 27N and NW County Road 292 (see Figure 3.42, and Table 3.1 for GPS coordinates). It is in Lafayette Blue Springs State Park which offers many amenities including rental vacation cabins, bicycling, hiking and wildlife viewing, a picnic area with tables, grills and two pavilions, and a tent-only campground for park visitors which doubles as a river camp for paddlers along the Suwannee River Wilderness Trail. A primitive youth camping area is also available. Portable restroom facilities are provided in the campground, and a restroom facility with a cold-water open-air shower is available in the spring area (for more information visit https://www.floridastateparks.org/parks-and-trails/lafayette-blue-springs-state-park).

Hailed by FGS as a first-magnitude spring based on a handful of historic flow measurements, Lafayette Blue has been a second magnitude spring for at least the last 20 years, with frequent flow reversals during which it is closed for swimming due to brownout. USGS hydrographs in Figure 3.110 show that the spring's average discharge rate is 53.5 cfs for the entire period of record of field measurements, and 52.2 cfs for the last eight years with continuous measurements during which it did not flow 14% of time (i.e., it acted as a sink for dark tannic water of the Suwannee River; see also Figure 3.20).

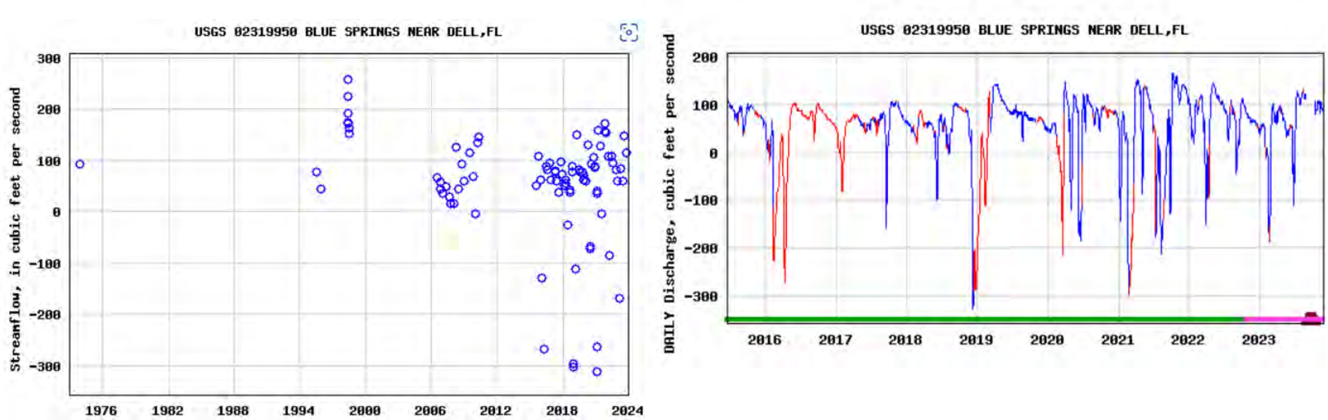


Figure 3.110 Hydrographs of discharge rates of Lafayette Blue Springs measured by USGS. *Left*: Field measurements; the average is 53.5 cfs. *Right*: Continuous measurements; the average is 52.2 cfs. Both graphs show flow reversals (negative values) during which the spring acts as a sink for dark tannic water of the Suwannee River.

Lafayette Blue Spring (Figures 3.111 and 3.112) discharges from a single horizontal vent in the south side of the sink depression. The spring pool measures 57 ft north to south and 102 ft east to west. Spring depth measures 21 ft. Algae are very thick on limestone and sand substrates within the spring pool and run. The spring run flows east approximately 300 ft before reaching the Suwannee River. Limestone is cropped out throughout the spring pool and run. Most of the time (when the spring pool level is not very high), a 20 ft wide natural limestone land bridge can be seen across the spring run approximately 120 ft east of the vent. The spring pool is steep sided with limestone and sand. Adjacent high ground is approximately 20 ft above the average water level, and it is sparsely forested with a few pines and oaks. Several sinks and karst windows are present in the woods west of the main spring (Scott et al., 2004).

Figure 3.111 Lafayette Blue Spring pool east of the limestone bridge part of which is seen in the lower left. Low water level. The Suwannee River is beyond wooden ramp. Photo courtesy of Suwannee River Water Management District.

Figure 3.112 *Left*: Lafayette Blue Spring pool during high water level and backwater conditions. The limestone bridge is under water, by the wooden stairs. The Suwanee River is in far distance, immediately beyond wooden ramp. *Right*: Confluence of the short spring run and the Suwanee River which is on the right. December 2023.

Perhaps the most fascinating part of visiting the spring (at least for hydrogeologists and karstologists) is walking on the trail along a series of sinkholes surrounded by majestic cypress trees. These sinkholes are evidence of the dynamic karst geologic formation, limestone underlying a large portion of Florida that is close to the surface and pockmarked with holes and hollows. Green Sink, Egg Sink and Snake Sink, all of which can be seen from the trail, are often filled with rain and shallow groundwater, forming a recharging area for the Floridan Aquifer and the spring.

3.13 Peacock Springs, and Royal Spring

Peacock Springs is in Wes Skiles Peacock Springs State Park, about 19 miles southwest of downtown Live Oak via FL-51 and 180th St., or about 7 miles north of Mayo via FL-51. It is 47 miles northwest from High Springs via U.S. Hwy 27 and FL-51 (See Figure 3.42, and Table 3.1 for GPS coordinates).

This rural state park is more natural and is much less developed than other state parks in Florida featuring springs. It contains five second-magnitude springs, named Peacock Springs I, II and III, Bonnet Spring and Orange Grove Sink. Activities include scuba diving, snorkeling, swimming, hiking, fishing, and wildlife viewing. Amenities include a picnic area including grills, restrooms, and parking.

Peacock Springs has one of the longest underwater cave systems in the continental United States with over 30,000 feet of surveyed cave passages. It attracts certified cave divers from all over the world (Figures 3.113 and 3.114). They must show proof of their scuba certification before being permitted to explore the underwater caverns.

Figure 3.113 Peacock Spring, mid-December 2023.

Two distinguished individuals lend their names to this park, and both are responsible for preserving and caring for the land and resources. Dr. John Calvin Peacock moved from Troy, North Carolina, with his family to the area near Peacock Springs, settling in 1855 near the Suwannee River. The family grew cotton and raised cattle on about 1,600 acres.

Figure 3.114 Peacock Spring Divers, 2018. Photo by John Moran, all rights reserved. Printed with permission.

Dr. Peacock practiced as a physician, making house calls in town on his horse and buggy. The town of Luraville grew up around the lumber and brickmaking industries and expanding transportation. Railroads crisscrossed the area and goods were transported via steamship on the Suwannee River.

The freshwater springs became a well-loved swimming hole, providing a place to relax and cool off for the town's residents. It wasn't until 1956, however, that the first recorded cave dive into the Peacock system was made. In the subsequent 60-plus years, divers have explored and mapped much of the underwater world here and continue to do so today.

In 1985 the Nature Conservancy purchased 250 acres of land around the springs, hoping to protect the unique stand of hardwood forest Florida maples and cave systems. Peacock Springs State Park was later acquired by the state of Florida and was opened to the public in 1993.

In 2011, the park's name was amended to honor the late Wes Skiles, a cave diver, explorer, photographer, documentary filmmaker and springs advocate who worked tirelessly throughout his life to protect this park and all of Florida's water resources.

Royal Spring (Figure 3.115) is in Royal Springs County Park near O'Brien, about 23 miles northwest of High Springs via U.S. 27 (FL 20), FL 129, and E-N County Road 349 (address is 20051 157th Lane, O'Brien, FL 32071; see also Figure 3.42, and Table 3.1 for GPS coordinates).

The 5-acre park features the beautiful spring, a spring run, and a few short waterfalls in the spring run depending on the height of the river. There are four overlook decks with access to water. One of the most popular aspects of Royal Springs is the jumping platform but there is also a shallow end that is kid friendly. The pool area is 200 feet wide and 42 feet deep and there is exposed limestone around the pool area and a wide limestone ledge in the pool, kids' favorite. Amenities include a public boat ramp, picnic tables with grills, and portable restrooms.

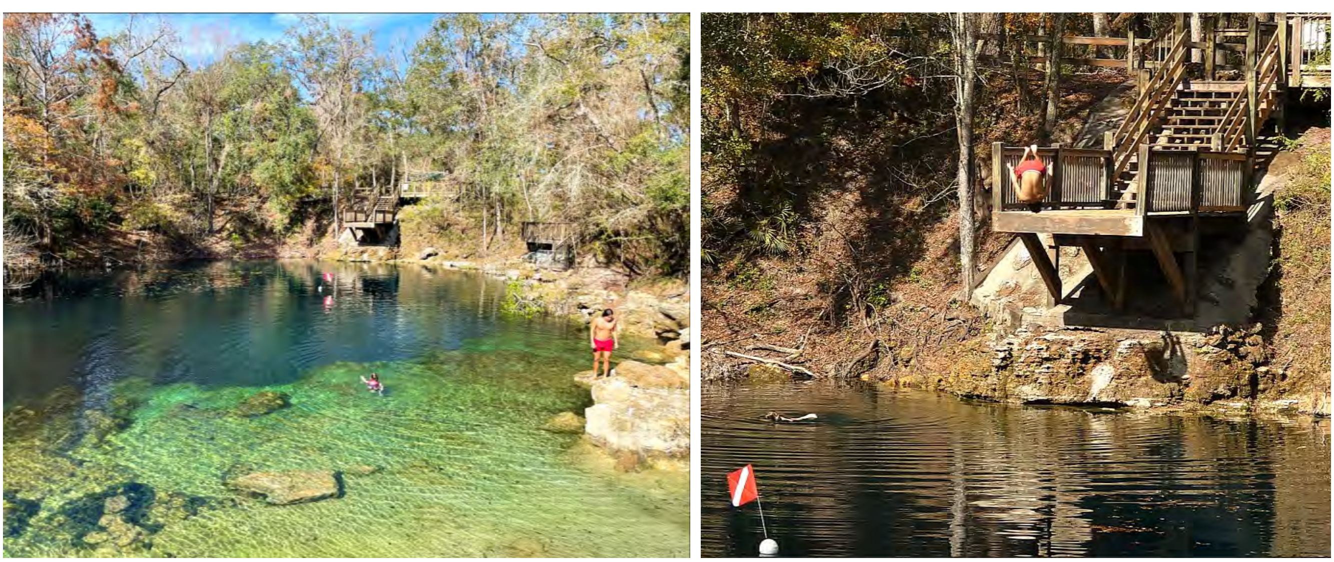


Figure 3.115 Royal Spring, December 2023. *Right*: "One for the camera!"

3.14 Fanning Spring, and Manatee Spring

Fanning Spring is in Fanning Springs State Park and the town of Fanning Springs. The park entrance is located on the east side of the Suwannee River on US 19/27/98. It is approximately 0.2 miles east of the bridge over the Suwannee River (see map in Figure 3.42, and Table 3.1 for GPS coordinates).

The spring is in a conical depression with steep sand and limestone banks (Figure 3.116). The spring pool measures about 200 ft north to south and 140 ft east to west. The depth of the spring pool measured over the vent is 18 ft. The vent area is nearly funnel shaped, with a sand and limestone bottom and limestone sides, and it issues from the southeast side of the depression. The main vent flows horizontally from a small orifice in the limestone; however, multiple small boils can be seen during high aquifer levels (Scott et al., 2004). There are numerous tiny spring seeps flowing into the spring pool from the limestone banks. The water is bluish and clear except for episodes of high river levels and flow reversal. This makes Fanning Spring a favorite swimming hole. There is native aquatic grass in the shallow, mainly sandy, spring pool with some patches of algae.

Figure 3.116 Panoramic view of Fanning Spring with the designated swimming area. 450-ft long spring run to the tannic Suwannee River is beyond red buoys and floating walkway. December 2023.

Visitors to the park can enjoy grilling and picnicking under majestic live oaks or a friendly game of volleyball on the white sand court. A playground provides diversion where young guests can swing and play. A boardwalk allows visitors to step back in time to old Florida with a stroll through a breathtaking cypress swamp with cypress knees standing 6 feet tall. This boardwalk ends with an overlook and view of the Suwannee River. During the summer, visitors can sometimes see massive sturgeons jumping. Visitors can also enter the park by boat from the Suwannee River.

White-tailed deer, gray squirrels, red-shouldered hawks, pileated woodpeckers and barred owls are some of the animals that may be seen around the park. An overlook at the park allows visitors to view the spring in its entirety.

Fanning Spring is classified as a first-magnitude spring by FGS based on 8 field measurements reported in Rosenau et al., 1977, and one measurement by Suwannee River Water Management District in 2001. Only four of these measurements were >100 cfs. Graphs of all publicly available discharge rates measured by USGS in the field, as well as continuously, show that Fanning Spring is a second-magnitude spring with an average discharge rate of 70.6 cfs based on continuous flow measurements in the period 2002-2023 (Figure 3.117).

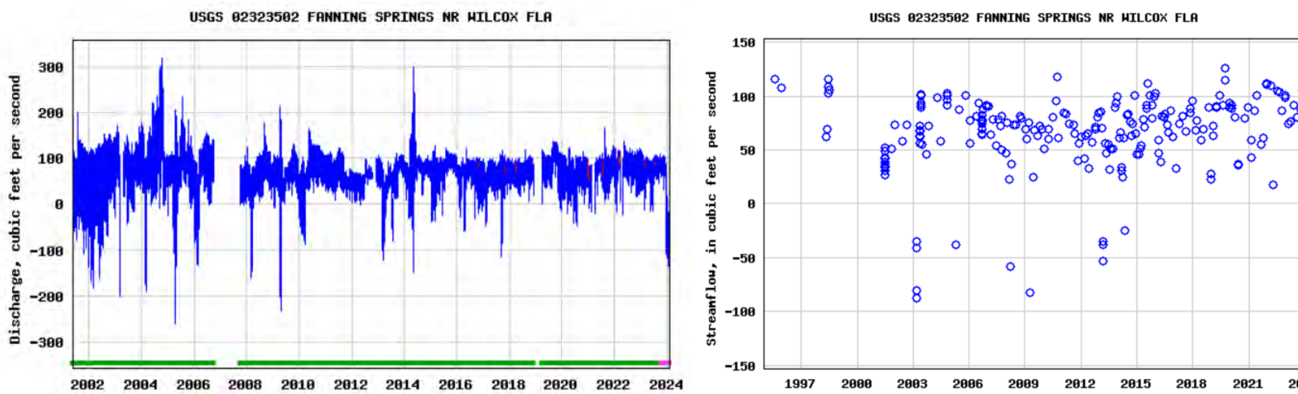


Figure 3.117 Hydrographs of discharge rate of Fanning Springs measured by USGS. *Left*: Continuous measurements; average is 70.6 cfs. *Right*: Field measurements; average is 66.4 cfs.

Manatee Spring is in Manatee Spring State Park approximately 7 miles west of Chiefland via County Road 320 (see map in Figure 3.42, and Table 3.1 for GPS coordinates). The spring and its run are on the east side of the Suwannee River within a densely wooded, lowland floodplain.

Manatee Spring discharges into a conical spring pool which measures 60 ft north to south and 75 ft east to west. The depth of the spring pool reaches a maximum of 30 ft. The bottom is mainly sandy with numerous submerged logs. There is a limestone ledge 3 ft below the water surface. Walkways and a rock wall are built along the south shore of the spring pool where steps lead down into the water for swimming access (Figure 3.118). The north shore is relatively pristine and wooded.

The spring run, approximately 1200 feet long, meanders southward through hardwood wetlands to the Suwannee River (Figure 3.119). It is the longest spring run feeding the Suwannee River. A boardwalk follows the run to a dock at the mouth of the run on the Suwannee River. Uplands on the south side of the spring rise to approximately 15 ft above the water level and are developed into a recreation area underneath a thick canopy of live oak and pine.

Figure 3.118 Manatee Spring, December 2023.

An extensive underwater cave system, once known as the longest in the world, has been mapped at Manatee Spring. There are four unique entrances to the system, however only two are readily accessible to divers, with a third restricted to divers possessing full cave diver certification. Due to the amount of flow produced by the entrance to the cave, most divers choose to avoid entering the cave system from the headspring. However, enjoyable snorkeling and open water scuba diving activities can be had at the headspring (https://extreme-exposure.com/manatee-springs/).

Figure 3.119 Manatee Spring run, December 2023.

Freshwater flounder, crappies (red bellies), catfish, and turtles are found in the spring run generated from the headspring. During the winter months, manatees often migrate up the spring run into the headspring. Diving and swimming are not permitted when the manatees are present.

Manatee Spring is one of the nine first-magnitude springs in Florida. With an average discharge rate of 153 cfs (Figure 3.120), it is tied with Blue Spring in Volusia County for the title of third largest, after Wakulla Spring and Weeki Wachee Spring. Note that there are an additional six spring groups in Florida where multiple individual springs are lumped together and classified by FGS as being of first magnitude, based on an average flow rate of the rivers they form and/or discharge into greater than 100 cfs (see Section 3.3 and Figure 3.37).

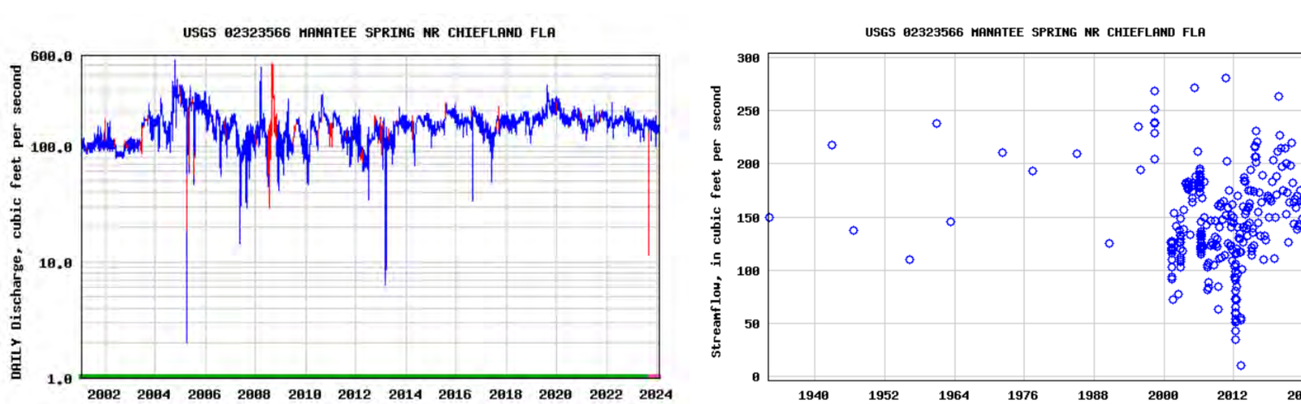


Figure 3.120 Hydrographs of Manatee Spring discharge rates measured by USGS. *Left*: Continuous measurements, average is 153 cfs. *Right*: Field measurements, average is 146 cfs.

Life at Manatee Spring can be traced back 9000 years, and the first recorded residents were Timucuan Indians. The picnic area inside the park was once the site for the Timucuan Indian village. It was chosen for its prime location as it was situated along the Suwannee River and had good access to fresh water and transportation. However, the area underwent a huge transformation after the arrival of the Spaniards in the 1500s.

William Bartram visited the Manatee Spring in 1774 and gave it its current name after witnessing a manatee carcass on the shores of the spring.

Major General Andrew Jackson carried out an attack near the Manatee Spring during the Seminole Wars. It killed many Seminole Indians and forced the rest of the population out of Florida. The area was thus open to the settlers and the farmers who moved to Manatee Spring to harvest timber and grow cotton.

In 1954 Manatee Spring became the first spring to become a Florida State Park. Various excavations at the Manatee Spring Park have revealed that the Indian village was densely populated throughout history. Many articles have been found at the village site, such as arrowheads, bone awls, saltwater shells, and pottery. All these things have led historians to speculate that the natives of Manatee Spring State Park used the Suwannee River to travel to the Gulf of Mexico.

Manatee Spring, once clear and blue, now green from algae
by Cindy Swirko, The Gainesville Sun, October 30, 2021
https://www.gainesville.com/story/news/local/2021/10/30/manatee-spring-once-clear-and-blue-now-green-algae/6195570001/

The park website describes Manatee Springs as "one of Florida's breathtaking first-magnitude springs." It could also be described as one of the most heartbreaking. Severe algal growth has resulted in thick green mats along the surface and algae clinging to anything that will provide a foothold in the pool. Manatee is considered one of the most polluted springs in Florida with typical nitrate levels much higher than the 0.35 milligrams per liter set by the state as a standard for first-magnitude springs that are designated as Outstanding Springs.

3.15 Crystal River (Kings Bay) Springs Group

Crystal River (Kings Bay) Springs Group is in the city of Crystal River, Citrus County on US 19/98 coming from north (see maps in Figures 3.42 and 3.121, and Table 3.1 for GPS coordinates). Crystal River is approximately 40 miles southwest of Ocala via FL-40E, FL-45 and County Roads 488/495, and 80 miles north of Tampa via FL-589.

There are over 70 springs including spring clusters with multiple vents that either issue from exposed limestone at the bottom of the 600-acre Kings Bay embayment or flow into the bay from side creeks (Figure 3.121). Their combined flow forms the headwaters of Crystal River, which flows approximately 7 miles northwest to the Gulf of Mexico. The average depth in Kings Bay is about 8 feet, but the shallow tidal flats in the southwestern part of the bay are sometimes exposed at low tide.

In the early 1960s, a network of 75-foot-wide canals was dredged along the eastern edge of the bay as part of waterfront residential development.

The coastal lowlands with brackish marsh and hardwood-palm hammock lie to the west and the City of Crystal River to the east. The whole system is tidally influenced, and Kings Bay is brackish. Rosenau et al. (1977) referred to the springs discharging to Kings Bay as the Crystal River Springs Group.

As described by the Florida Springs Institute (2016), prior to the 1970s, Kings Bay was a fisherman's and scuba diver's paradise. Eelgrass covered the bottom of the bay like a lawn of unmowed waving grasses. Water clarity was so good that divers and fishermen could see fish, manatees, and other aquatic wildlife hundreds of feet away. The river was originally called *Weewahiiaca* by local Creek Native Americans, which means "clear water".

By the 1980s and 1990s, poorly considered plant management measures had freed the bay from hyacinths and hydrilla dominance but had also largely led to the unintentional eradication of the desirable eelgrass. Spring flows continued to decline as the region's population grew, bringing increased reliance on groundwater use for watering manicured landscapes and for farm irrigation. As a result of declining spring flows, combined with elevated nutrients and the loss of much of the native aquatic vegetation in Kings Bay, undesirable planktonic and benthic algae proliferated and there was a marked increase in salinity in the springs and bay. With these physical changes, water clarity in much of Kings Bay declined to less than 20 feet.

Figure 3.121 Map of individual springs in Kings Bay included in the Florida Department of Environmental Protection Geospatial Open Data. Modified and annotated for clarity. An example of a spring description from the database is shown for Sid's Springs. Springs described in this book are highlighted. Esri Community Maps Contributors, FDEP, Esri, TomTom, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA, USFWS. Basemap with springs available at https://geodata.dep.state.fl.us/.

On the city of Crystal River web page (https://www.crystalriverfl.org/) one can read the following (which this author seconds without any hesitation):

Crystal River is a coastal city in west central Florida on the Gulf of Mexico. This sweet southern town is centered around it's pristine waterway, Kings Bay, and is the self-proclaimed "Home of the Manatee." The small town of approximately 6.8 square miles and 3200 residents welcomes hundreds of manatees each winter to it's many warm springs including the famous Three Sisters Springs. Together with neighboring Homosassa, Crystal River is the site of the largest gathering of manatees in North America.

When the water temperature drops in the Gulf of Mexico, manatees move to the warmer waters of Crystal River and the springs of Kings Bay, followed closely by both national and international tourists. Located along Florida's "Nature Coast," the waters of Crystal River have the only legal "swim-with" Manatee program in the Country, meaning visitors can passively observe the mammals in their natural habitat. The springs flow at a constant 72 degrees, making the water attractive to all sorts of swimmers in the winter as well as the summer months. Kings Bay, is also home to the Crystal River National Wildlife Refuge, the only refuge created specifically for the protection of the threatened Florida manatee.

Crystal River Preserve State Park is located nearby, and Crystal River Archeological State Park is located in the city's northwest side. It is a six mile long winding waterway fed by some 30 springs, connecting Kings Bay with the Gulf of Mexico. The bay and the river combine to provide virtually every aquatic activity conceivable—from swimming and diving, to boating, kayaking, paddle boarding, water skiing, fishing and just drifting along admiring the views.

As explained on a very informative web page of River Ventures, in 1893, Florida passed its first law designed to protect the manatee. In 1907 the law was revised to add a $500 and/or six months of jail penalty for molesting or killing a manatee. In 1966, Congress enacted the Endangered Species Preservation Act, the manatee was one of the first species to be added to this act. On March 11, 1967, the United States Fish and Wildlife Service classified the manatee as endangered and in threat of extinction.

Figure 3.122 Mother manatee and calf pose for the camera in the clear warm water of Three Sisters Springs. Photo by Gregory Sweeney. Courtesy of U.S. Fish & Wildlife Service.

Details about more legislation that followed to further protect manatees can be found at https://riverventures.com/kings-bay-and-three-sisters.

The peak season for observing manatees in Kings Bay is between December and February when the local manatee population swells to its largest size. Manatees are present in Kings Bay all year round, but the population is much smaller during the summer months. The best time to visit the springs and see manatees is in the early morning when they are most active and playful, and during the middle of the week to avoid crowds.

Manatee tours occur year-round. Tour companies on Kings Bay in Crystal River operate under Special Use Permits issued by the U.S. Fish and Wildlife Service's Crystal River National Wildlife Refuge. Between November 15 and March 31, sanctuary markers are in place near spring vents designating critical resting areas for manatees. Swimmers, kayakers, and all watercrafts are prohibited from these areas that are essential to manatee's survival.

Figure 3.123 Manatee sanctuary at the mouth of Three Sisters Springs spring run, 2016. Photo by John Moran; all rights reserved. Printed with permission.

At Kings Bay swimming with manatees is only allowed in a restricted area at Tarpon Hole Spring. This is also the only place in Florida where people are allowed to swim with the gentle mammals. Otherwise, manatees can be seen from water by kayaking, stand up paddle-boarding, and boat tours in non-critical areas where it is allowed. All these tours can be arranged through quite a few local tour companies. More details about arranging a manatee tour can be found at https://www.discovercrystalriverfl.com/. Public kayak launches are Hunter Springs Park and Kings Bay Park.

Except for Three Sisters Springs and Hunter Spring, all other springs in Kings Bay can be accessed only by water as the land along shores is privately owned.

Three Sisters Springs, a unit of the Crystal River National Wildlife Refuge (CRNWR), is the gem of Florida's Nature Coast and one of the most beautiful springs in Florida (Figures 3.124 and 3.125). Its water is always mesmerizingly clear. A restored 50+ acres surrounding the springs attempt to show visitors how Florida's nature may have looked like before the newcomers from the Old World messed it all up.

The Three Sisters Springs Center (https://www.threesistersspringsvisitor.org/sisters) manages land access to Three Sisters Springs by shuttle service, walk-in, or bicycle-in which all require a fee. There is no parking at the refuge except for handicapped vehicles.

To preserve the shoreline vegetation, control erosion, and maintain water clarity, CRNWR and the City of Crystal River do not allow water access to visitors from the refuge, nor do they allow land access from the water. Visitors must arrive by paddle craft or motorized vessel to get to the spring run at Three Sisters Springs; however, motorized vessels are not permitted inside the Springs. Paddle-craft are permitted from April 1 to November 14.

The boardwalk has viewing platforms to observe the springs and native wildlife. There are also nature trails that offer views of Magnolia Springs, Lake Crystal, and the wetlands. Three Sisters Springs is a world-renowned winter sanctuary for the West Indian Manatee. Cold winter days bring 100's of them seeking warm water refuge into the springs. For the safety and protection of the manatees, in-water access to Three Sisters Springs can be closed by US Fish & Wildlife Service when water temperatures in the Gulf of Mexico drop below 62.2 degrees Fahrenheit. Updates on temporary closures can be checked on Crystal River NWR Facebook page.

Figure 3.124 Three Sisters Springs. Photo by Frank Moore. Available at https://firstmagflorida.com/2019/10/05/crystal-river-kings-bay/. In the upper right is Little Sister, in the middle is Deep Sister, and in the lower left (the widest separate pool) is Pretty Sister. The spring run flows to the southwest ("up" in the photo) where it empties into a dredged canal with the stagnant Kings Bay water. At the spring run mouth, another favorite sanctuary for manatees, are three springs with equally clear water (named, for an unknown reason, Idiots Delight #1, #2, and #3,) which add to the unforgettable experience (see Figure 3.123).

Figure 3.125 Three Sisters Springs. Photo courtesy of River Ventures, Crystal River, Florida. https://riverventures.com/kings-bay-and-three-sisters

Tarpon Hole Spring, also known as King's Spring, is the largest spring in the group of springs with the same name (see Figure 3.121). It issues from a deep, conical depression in limestone on the south side of Banana Island. The spring pool measures approximately 450 ft north to south and 550 ft east to west. The depth measured over the vent, which is a large circular hole in limestone, was reported to be 58 ft (Scott et al., 2004). However, more recent information from divers is that the depth is not more than 25-30 feet, and the hole is apparently "gone". In calm weather and during off-manatee season there is visible boil of water above the spring, and water is relatively clear and bluish except for high tide conditions.

Tarpon Hole Spring is a very popular dive site and can get very crowded, which at times significantly reduces visibility. During winter, when hundreds of manatees come to this sanctuary, tour boats bring dozens upon dozens of snorkeling tourists to a designated area to "swim with manatees" (Figure 3.126). During such times, the visibility decreases to just a few feet, especially on weekends and holidays. Since this is the only place in the whole country where people are allowed to swim with the manatees in the wild, most visitors do not mind. All are, however, rewarded with many close and sudden encounters with these beautiful, strange and gentle creatures, appearing sometimes from nowhere. A lucky snorkeler or two in a group may even get a kiss from a manatee and instantly fall in love for life.

Figure 3.126 In peak season, on weekends and holidays sometimes a dozen or so tour boats bring many snorkelers to "swim with manatees" in a small, restricted area at Tarpon Hole Spring. December 2023.

Hunter Spring issues vertically from the bottom of a conical depression in the middle of a side creek channel feeding the eastside of Kings Bay (see map in Figure 3.121). Spring pool is circular and measures 210 ft in diameter. The depth measured over the vent, which is some 100 ft offshore, is 13 ft.

Hunter Spring is in Hunter Spring Park managed by the city of Crystal River (Figure 3.127). The park offers a small beach area leading to a roped-off swimming area, kayak/canoe launch, a boardwalk along the waterway, where one is likely to spot waterbirds, a playground area, and other amenities.

Figure 3.127 Hunter Spring State Park in the city of Crystal River. The beach and swimming area are in the middle, marked by light blue color. Photo courtesy of the city of Cristal River (www.crystalriverfl.org).

The combined flow rate of all springs discharging into Kings Bay and any other groundwater inflow from the Floridan Aquifer along a 3-mile section of the river downstream of the bay is measured at a USGS gaging station on Crystal River (Figures 1.128 and 1.129).

Figure 3.128 USGS streamflow gaging station on Crystal River is shown with red arrow. From https://waterdata.usgs.gov/nwis/nwismap/?site_no=02310750&agency_cd=USGS

There are two periods of daily flow measurements with a very long gap in between: 1964-1977, and 2020 through present (Figure 3.122-*Left*). The average flow of the Crystal River for the first period is 971 cfs, and for the second period it is 672 cfs. Figure 1.122-*Right* is hydrograph for the second period only where measurements are tidally filtered. The filtering results in the same average flow of 672 cfs.

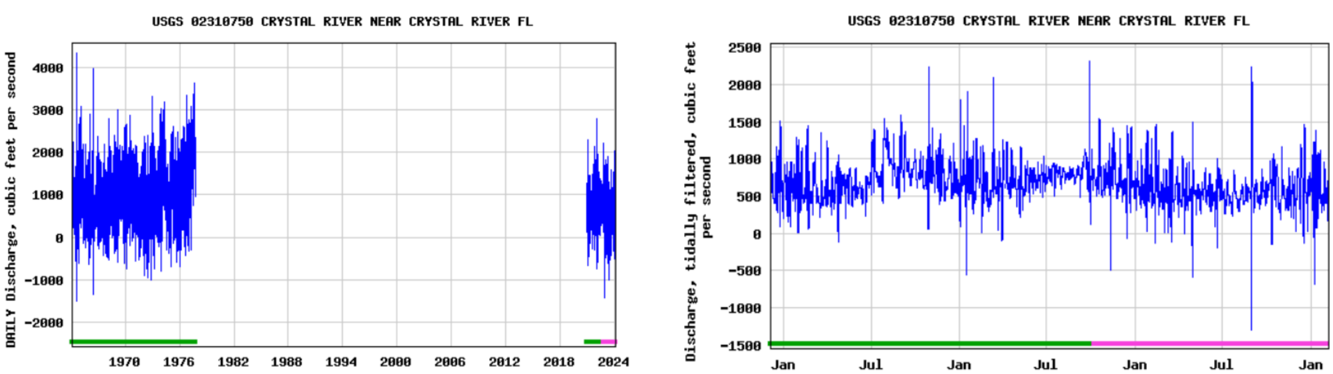


Figure 3.129 Hydrographs of flow rate of the Crystal River measured by USGS. *Left*: Entire period of record. Average for 1964-1977 is 971 cfs. *Right*: Tidally filtered average flow for period January 2020-January 2024 is 672 cfs.

3.16 Homosassa Springs Group

Homosassa Springs is in Ellie Schiller Homosassa Springs Wildlife State Park, in town of Homosassa Springs. There are two ways to enter the park as shown in Figure 1.130. From the Visitor Center on US-19 (4159 S. Suncoast Boulevard), where parking is often crowded, visitors can choose to take tram shuttle service to where "all the action is" or enjoy a leisurely 20-min walk to get there. A smaller parking lot is by the West Entrance.

The park is one of the most visited tourist attractions on Florida's Sun Coast because it serves as a rehabilitation center and refuge for injured wild animals and birds and, most famously, for orphaned or injured manatees. These marine mammals, along with many freshwater and saltwater fish, can be seen year-round at the headspring pool where there is also Underwater Observatory (Figures 3.130 and 3.131).

Figure 3.130 Map of Ellie Schiller Homosassa Springs Wildlife State Park. The main spring pool is where Underwater Observatory is. Most manatees can be seen there and in the short run to the Homosassa River.

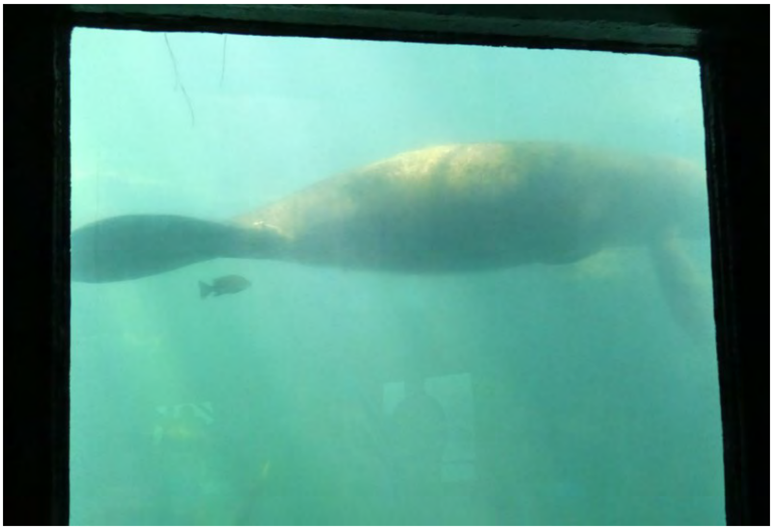
Now a Florida State Park with a new mission

Homosassa Springs Wildlife State Park was purchased by the State of Florida on January 1, 1989, officially becoming a Florida State Park. As a State Park, our focus has shifted from an exotic animal and entertainment theme to the interpretation and preservation of our native Florida species including several endangered and threatened species.

The Park is home to West Indian Manatees, Red Wolves, Whooping Cranes, a Florida Panther, Black Bears, Bobcats, River Otters, alligators, and much more. In addition to working with a variety of agencies to rehabilitate and preserve these native species, the Park strives to protect our natural resources, and this first magnitude spring.

On the park's web page one can read "*When Homosassa Springs was a popular train stop in the early 1900s, passengers could picnic and take a dip in the spring while train cars were being loaded up with cedar, crabs, fish and spring water. On a 1924 visit, Bruce Hoover of Chicago called it "the most beautiful river and springs in the world." In this regard, Homosassa Springs hasn't changed much*."

Sadly, the last sentence has been challenged by quite a few Florida springs' advocates concerned with the continuously deteriorating conditions of Homosassa Springs. Once a beautiful jewel indeed, as described by Mr. Hoover of Chicago, the headspring pool water is now laden with planktonic algae which gives it a cloudy, greenish appearance and low visibility. This is a far cry from when the "Fish Bowl" (now called Underwater Observatory) was built to provide visitors with a breathtaking view of the crystal-clear water swarming with many varieties of



fish and, of course, the manatees. Today, however, the view through the large underwater windows is very different, as seen in Figure 3.131. It is disappointing to both children and adults alike, especially if they just came from visiting Disney World in Orlando where aquariums are meticulously maintained, and the water is always flawlessly transparent.

Figure 3.131 The view through windows of Underwater Observatory at Homosassa Springs, December 2023.Visitors patiently waiting to spot a manatee are rewarded only if the gentle creature swims by within a few feet from the glass.

Homosassa Springs form the headwaters of the Homosassa River. This short, slow-moving tidal river flows eight miles from the headsprings to where it meets the Gulf of Mexico at Homosassa Bay in Citrus County, Florida. The river has numerous canals and seawalls that have had a negative impact on water clarity and habitat. It is designated a Surface Water Improvement and Management priority water body by the Southwest Florida Water Management District.

Homosassa Springs is unique in that the headspring flows from three points underground with varying water quality and different salinities that blend before exiting into the pool (Figure 3.132). In addition, there are two smaller spring-fed tributaries that flow into the Homosassa River, which are the southeast fork and the Halls River.

As a whole, Homosassa Springs is an impaired Outstanding Florida Spring with elevated concentrations of nitrogen, phosphorus, and other substances released to the subsurface by the actions of people living in the springshed. The nutrients and the substances impact the health of the springs and fuel the growth of algae and other organisms harmful to native vegetation and life forms.

Figure 3.132 *Left*: Headspring pool of Homosassa Springs where groundwater from three separate vents blends as it discharges into the pool. Viewing deck with Underwater Observatory is on the left. *Right*: The pool and short spring run are favorite wintering sanctuary for manatees. Photos taken in December 2023.

Incidentally, this author has never seen a statement as ambiguous as the following one from the park's web page (https://www.floridastateparks.org/learn/springs-homosassa):

"The above-ground activities by people in the springshed directly impact, either positively or negatively, the quality and quantity of water exiting the springs."

The hope is that the Park's management and all the staff will spend as much effort on explaining what exactly are "positive" and what exactly are "negative" impacts as they do when it comes to the injured wildlife they are so generously taking care of. Their springs are badly injured as well (see Figures 3.133 and 3.134) and many tens of thousands of visitors, including the young generation of Floridians that come each year to learn about wildlife, should also be educated, in as much detail as possible, about what is happening to the spring in front of them and all other springs in Florida. There is no need for sugar-coating and such – the public, and especially young Floridians, must hear firsthand about all "negative things people in the springshed are doing" and be called to action. They should be given all the credit in the world by the bureaucrats and politicians because they deserve it. And they should be told what any plans for healing this particular spring entail, and if they are working or not. There is no other way if this and many other Florida springs are to be saved.

Figure 3.133 Photo taken at Homosassa Springs State Park in December 2023.

Until and if Homosassa Springs ever heals and approaches its former glory by starting to attract visitors used to nice water scenery at few other Florida springs, the park will continue to draw other visitors simply because it features a variety of animals in need such as alligators, black bears, red wolf, Key deer, flamingos, whooping cranes, pelicans, herons, many other birds, and the oldest hippopotamus in captivity, the famous Lucifer (Figure 3.135-*Top Left*). Understandably, everyone refers to the more-than-60-years old giant as "Lu". Interestingly, Lu became the only official non-human Florida resident by a governor's decree so he can avoid being moved elsewhere due to some new regulation at the time—there was a genuine uproar of thousands of Lu's fans and a threat of state-wide riots!

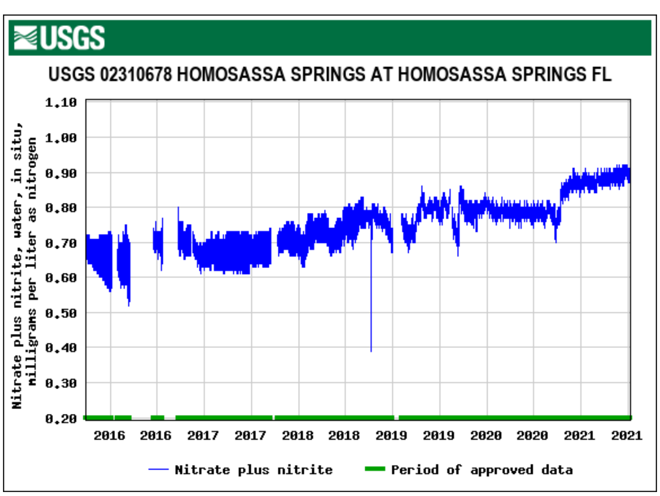


Figure 3.134. USGS monitored nitrate + nitrite concentration at the headspring of Homosassa Springs between 2016 and 2021. The concentrations were rising and greatly exceeding regulatory ("safe") limit of 0.35 mg/L.

The native animals that reside in the park serve as ambassadors for their species, providing visitors with close connections with wildlife and their habitats. Each with a unique life story, all the animal inhabitants are there for the same reason - they are unable to survive in the wild on their own (Figure 3.135). Their shared story, the springs and the animals, is striking.

Figure 3.135 All the animal inhabitants of Ellie Schiller Homosassa Springs Wildlife State Park are there for the same reason - they are unable to survive in the wild on their own. *Top left*: “Lu”, the oldest hippopotamus in captivity and the only official non-human resident of the State of Florida. All photos taken in December 2023.

Figure 3.136 Homosassa Springs – glory days of the past. *Left*: *Visitors in the underwater observatory, "The Fish Bowl"*; photo by Division of Tourism, circa 1964. *Right: Bluegill fish in Homosassa Spring*, photo by Dr. David E. LaHart, circa 1969. Courtesy of State Archives of Florida, Florida Memory.

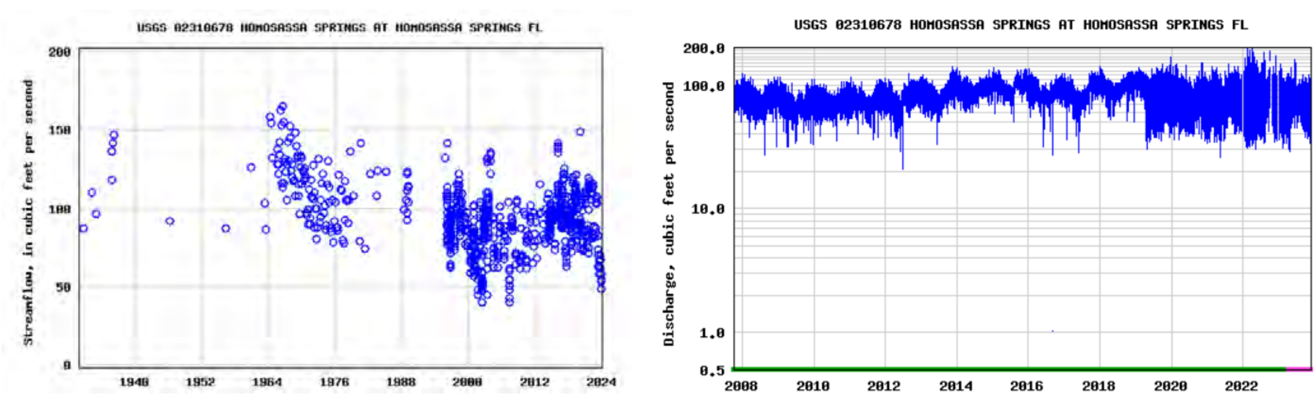


Figure 3.137 Hydrographs of discharge rate of Homosassa Springs headspring measured by USGS. *Left*: Field measurements for the entire period of record; average is 94 cfs. *Right*: Continuous measurements; average is 84.9 cfs.

3.17 Weeki Wachee Spring

Weeki Wachee Springs is in Weeki Wachee Springs State Park located at the intersection of State Road 50 and US-19, 22.6 miles south of Homosassa Springs via US-19, and 50 miles north of Tampa via FL-589N (See map in Figure 3.45, and Table 3.1 for GPS coordinates). Weeki Wachee Springs was designated a National Historic Landmark in 2020.

When it comes to Florida springs, Weeki Wachee is in a league of its own. Its water is still crystal-clear, and the flow of the spring is strong, gifting hundreds of thousands of visitors an amazing array of blue and green colors each year. Weeki Wachee is one of Florida's most legendary and unique family destinations, with exceptionally diverse offerings to entertain audiences of all ages since 1947 (Figure 3.138). The Park is open 365 days a year and during the busy summer months, it often reaches capacity. It is highly recommended to plan a visit early in the day because once the park is full, it does not allow further entry for the remainder of the day. Various Park facts and rules can be found at https://weekiwachee.com/park-rules-faqs/.

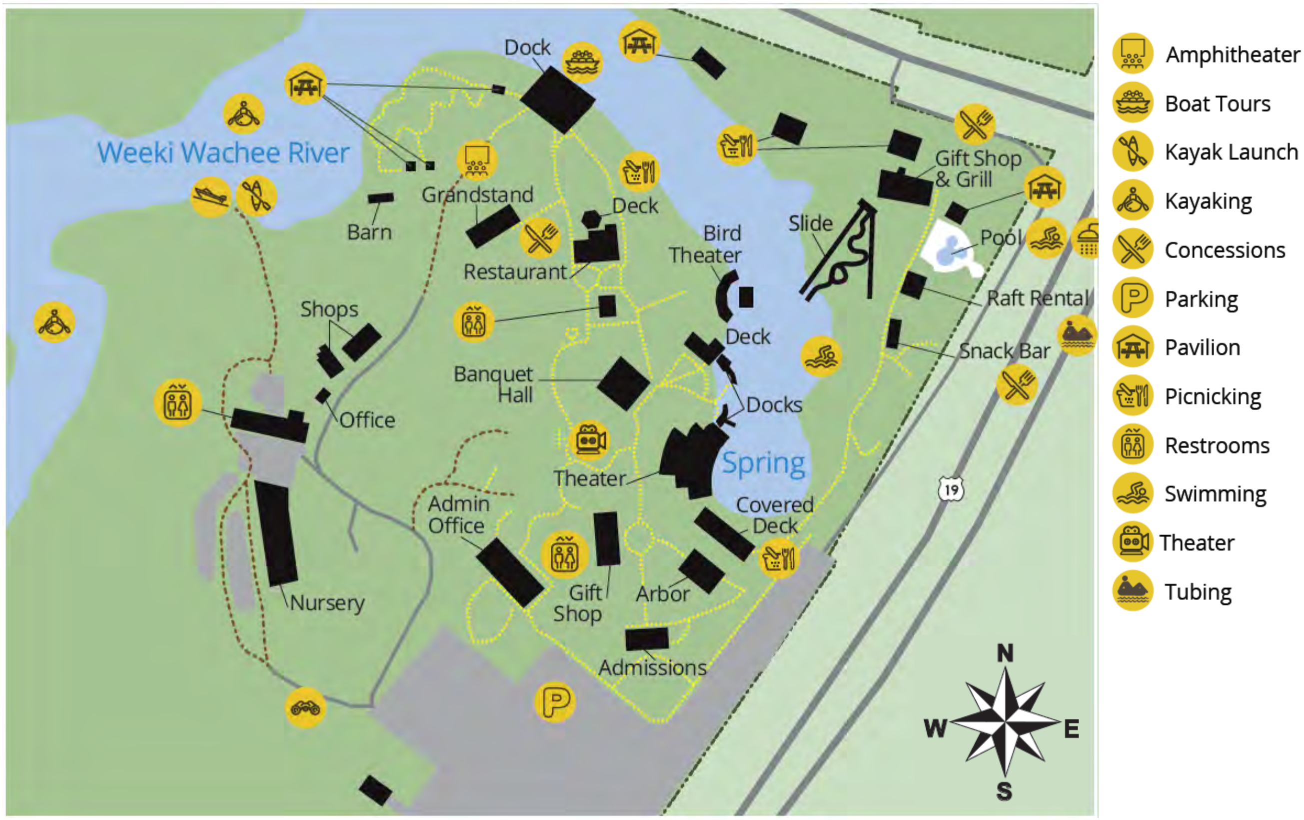


Figure 3.138 Map of Weeki Wachee State Park. The word famous Mermaid shows are held at Theater by the Spring.

"Weeki Wachee" was named by the Seminole Indians. It means "little spring" or "winding river." The main spring is headspring of the Weeki Wachee River which flows 7.4 miles to where it meets the Gulf of Mexico at Bayport in Hernando County, Florida.

Figure 3.139 *Left*: Paddling down Weeki Wachee River. Photo courtesy of Weeki Wachee State Park (https://weekiwachee.com/plan-your-paddling-trip/) *Right*: 2021 Sirens of the Deep Camp; Friends of Weeki Wachee, https://friendsofweekiwachee.com/gallery/

Figure 3.140 Water slides at Weeki Wachee's Buccaneer Bay, the only spring-fed waterpark in Florida. Photo courtesy of Weeki Wachee State Park. https://weekiwachee.com/buccaneer-bay/

The Little Mermaid

We invite you to come see our world-famous Mermaids as they perform their version of Hans Christian Andersen's The Little Mermaid live in our submerged 400-seat auditorium.

You will enjoy this classic told unlike any other as The Little Mermaid celebrates her birthday and comes face to face with her prince!

Yearning to have legs like him, she makes a deal with the sea witch to give her what she wants in exchange for her beautiful voice.

As the prince struggles to save the Little Mermaid's beautiful voice, a fierce battle ensues between him and the evil sea witch. The prince prevails, proving that "love conquers all."

Figure 3.141 The Little Mermaid show advertised at Weeki Wachee Spring for 2023 and 2024 seasons. https://www.floridastateparks.org/parks-and-trails/weeki-wachee-springs-state-park/mermaid-shows

Figure 3.142. Mermaids-in-training with Newt Perry, circa 1948

On the Park's web site one can read a fascinating history of the Weeki Wachee and the Mermaids.

In 1946, Newton Perry, a former U.S. Navy man who trained Navy Frogmen to swim underwater in World War II, scouted out Weeki Wachee as a good site for a new business. At the time, U.S. 19 was a small two-lane road. All the other roads were dirt; there were no gas stations, no groceries, and no movie theaters. More alligators and black bears lived in the area than humans.

Submerged six feet below the water's surface, an 18-seat theater was built into the limestone so viewers could look right into the natural beauty of the ancient spring.

Newt scouted out pretty girls and trained them to swim with air hoses and smile at the same time. He taught them to drink Grapette, a non-carbonated beverage, eat bananas underwater and do aquatic ballets. He then put a sign out on U.S. 19 that read: WEEKI WACHEE.

On October 13, 1947, the first show at the Weeki Wachee Springs underwater theater opened. It was the same day that Kukla, Fran and Ollie first aired on that newfangled invention called television, and one day before Chuck Yeager broke the sound barrier. On that day, the mermaids performed synchronized ballet moves underwater while breathing through the air hoses hidden in the scenery.

In the 1950s, Weeki Wachee was one of the nation's most popular tourist stops. The attraction received worldwide acclaim. Movies were filmed at the spring, like Mr. Peabody and the Mermaid. Sights at the park included the mermaid shows, orchid gardens, jungle cruises, and Indian encampment and a new beach. The mermaids took etiquette and ballet lessons.

Weeki Wachee's heyday began in 1959, when the spring was purchased by the American Broadcasting Co. (ABC) and was heavily promoted. ABC built the current theater (Figure 3.143), which seats 400 and is embedded in the side of the spring 16 feet below the surface. ABC also developed themes for the underwater shows, such as Underwater Circus, The Mermaids and the Pirates and Underwater Follies.

Figure 3.143 Underwater theater at Weeki Wachee Spring. Courtesy of Weeki Wachee State Park. https://weekiwachee.com/history/

Figure 3.144 Underwater theater at Weeki Wachee Spring behind the famous Mermaids. Courtesy of Florida Archives, Florida Memory.

As posted on the Park's website "*The spring is so deep that the bottom has never been found. Each day, more than 117 million gallons of clear, fresh 74-degree water bubbles up out of subterranean caverns. Deep in the spring, the surge of the current is so strong that it can knock a scuba diver's mask off. The basin of the spring is 100 feet wide with limestone sides and there, where the mermaids swim, 16 to 20 feet below the surface, the current runs a strong five miles an hour. It's quite a feat for a mermaid to stay in one place in such a current.*"

With a little update, the average flow of the headspring was 172.5 cfs (111.5 million gallons per day) until 2010 when USGS stopped measuring it (see Figure 3.145).The depth of the vast submerged cave system of Weeki Wachee Spring is 429 feet as of February 2024 (Karst Underwater Research (google.com) making it the deepest underwater cave in Florida and the third deepest in the country, after Roaring River Spring in Missouri (>520 ft; see Section 2.19 in this book) and Phantom Springs Cave in Texas (493 ft; ADM Exploration Foundation - Phantom Cave 2013 (admfoundation.org).

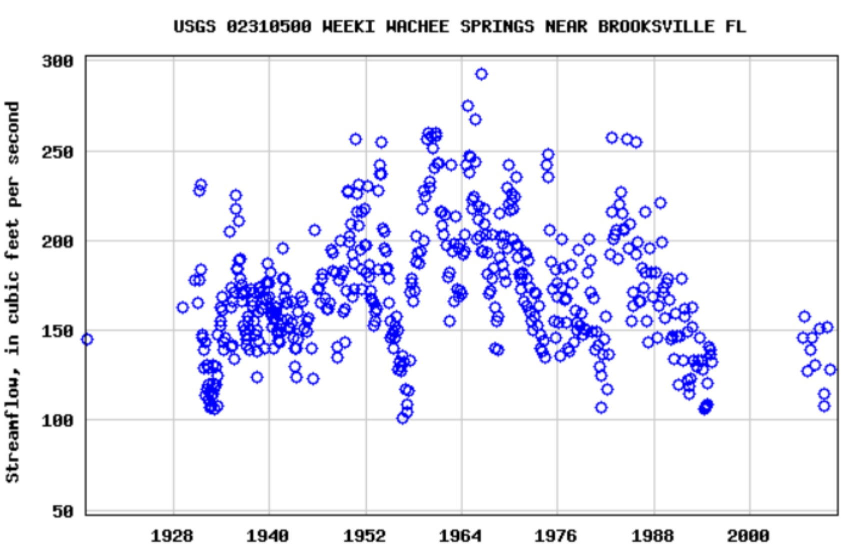


Figure 3.145 Hydrograph of discharge rate of the headspring of Weeki Wachee Springs. Average is 172.5 cfs for the entire period of record. USGS stopped reporting the headspring discharge rate in 2010. The flow of Weeki Wachee River was monitored 4 miles downstream from the headspring between 2004 and 2013. when USGS discontinued reporting it.

All photographs in Figures 3.146 through 3.148 that follow are courtesy of State Archives of Florida, Florida Memory (available at https://www.floridamemory.com/).

Figure 3.146 *Left*: Aerial view overlooking the Weeki Wachee Springs amusement park - Hernando County, Florida, 1965. *Right*: View showing pelicans and tour boat on the Weeki Wachee River, 1980 (circa)

Figure 3.147 *Left*: Nancy Tribble posed with underwater sign at Weeki Wachee Spring in 1947. *Right*: Swimming at Weeki Wachee Spring. Photo by Walton Hall Smith.

Figure 3.148 *Left*: Couples performing underwater at Weeki Wachee Springs, May 1951. *Right*: Olga Rowan and Patsie Boyett performing graceful underwater ballet at Weeki Wachee Springs, May 1951.

3.18 Alexander Spring, and Silver Glenn Spring

Alexander Spring is in Alexander Springs Recreation Area within Ocala National Forest, in the northeast corner of Lake County between Astor and Altoona, Florida. The Area is 44 miles east of Ocala via FL-40E and County Road 445 (See map in Figure 3.45, and Table 3.1 for GPS coordinates).

Alexander Spring (Figures 3.149 and 3.150) is a first-magnitude spring that flows from the large, cavernous opening in the bottom of the central part of the pool. The large pool measures more than 300 feet from north to south and 250 feet from east to west. The pool bottom near the beach is mostly sandy, and the water is a constant 72 degrees and extraordinarily clear. Aquatic vegetation surrounds the area of the main spring vent, where the pool bottom falls away to reveal a large open area of exposed limestone rock and boulders to a depth of about 25 to 28 feet. Flow from the discharging water creates a large and powerful surface boil over the spring opening that is readily visible from the shore. A broad sand beach forms the southwest edge of the pool, with mixed hardwood and palm forests around the spring. The pool discharges to Alexander Springs Creek that flows approximately 10 river miles until it reaches the St. Johns River.

Figure 3.149 Aerial view of Alexander Spring. Photo by Harley Means; from FGS Bulletin No. 66.

The spring area has been developed by the USDA Forest Service into a multiple-use recreational facility open to the public. Visitors can swim, snorkel and dive year-round in the crystalline waters of the spring. The spring is the only place in the Ocala National Forest where scuba diving is permitted, and a broad and naturally gently sloped spring pool feels like a natural water park.

Figure 3.150 Alexander Spring. Photo by John Moran; all right reserved. Printed with permission.

Fishing and canoeing are popular outside the swimming area. Anglers can bring a rod and reel and head down to one of the platforms along the Timucuan Trail to drop a line in Alexander Run. Visitors can rent canoes or bring their own and paddle down Alexander Run into the Alexander Springs Wilderness.

Day hikers will appreciate a short interpretive trail on a boardwalk over the spring and through the palm trees. They can also access two segments of the 1,400-mile Florida National Scenic Trail, which runs through the entire national forest.

U.S. Forest Service provides detailed information including camping arrangements and day-use fees, as well as hours of operation and alerts at the Alexander Springs Recreation Area web page: https://www.recreation.gov/camping/campgrounds/234032?tab=info

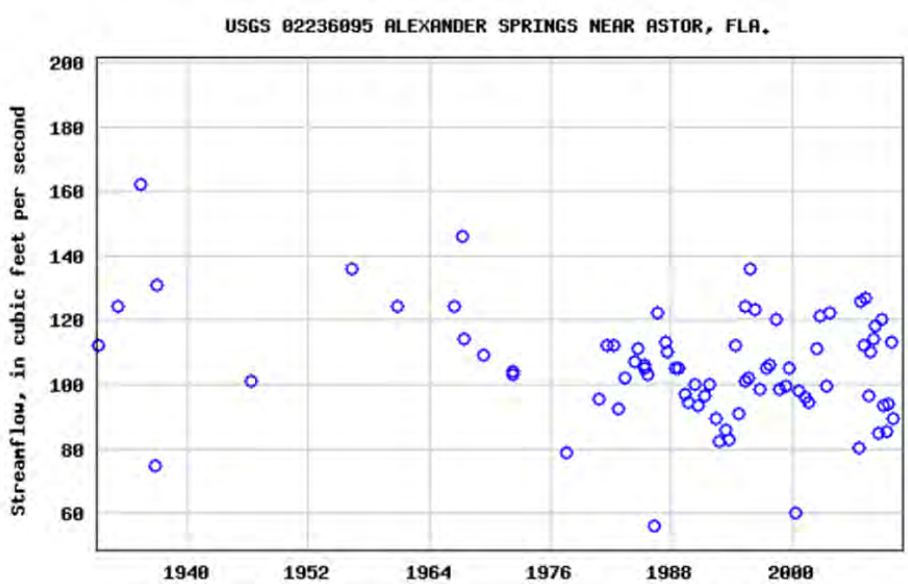


Figure 3.151 Hydrograph of Alexander Springs discharge rate for the period of record. Average is 105.2 cfs.

Silver Glen Spring is part of the USDA Forest Service's Silver Glen Springs Recreation Area within Ocala National Forest. It is located 47 miles east of Ocala via FL-40E and FL-19N 445 (See map in Figure 3.45, and Table 3.1 for GPS coordinates).

Once a first-magnitude spring, this still pristine spring, with an outstanding water quality and clarity, discharges to a large, semicircular pool that measures 200 feet from north to south and 175 feet from east to west (Figure 3.152). Most of the strong flow emerges from two cavern openings in the rock at the bottom of the pool, with large boils at the water's surface over the vents. The vertical cave opening called the Natural Well in the southwestern edge of the pool is about 12 to 15 feet in diameter and 40 feet deep. The vent in the east part of the pool is a conical depression about 18 feet deep. Most of the spring pool has sand and limestone on the pool bottom, with areas of aquatic grasses. Large fresh and saltwater fish are common in the pool and around the vents. Additional flow is from sand boils in the bottom of the spring run downstream from the head of the springs. Water from the springs flows eastward down a run about 200 feet wide for 0.75 mile to Lake George. The water temperature is constat 73 degrees Fahrenheit year-round.

The recreation area is used for swimming, snorkeling, picnicking, fishing, and boating. Boating is not allowed in the spring pool, but the spring run is a popular spot for recreational boaters. Canoe rentals are available onsite. Diving and scuba diving are not allowed, but snorkeling is permitted. The park features two trails, the Spring Boils Trail, and the Lake George Trail, and is an important archeological site.

According to the USDA website (https://www.fs.usda.gov/recmain/florida/recreation) the spring is designated as critical habitat for the manatee, and the spring and run have the potential to serve as a major manatee refuge. However, manatee use has been limited due to a high degree of human activity and damage to aquatic vegetation.

State park fees apply for day-use and camping, and glass-bottom boat tours and other concessions also have related fees. More information can be found at the Silver Glen Springs Recreation Area web page at https://www.fs.usda.gov/recarea/florida/recarea/?recid=83582.

Figure 3.152 Silver Glen Springs Photo by John Moran; all rights reserved. Printed with permission.

Figure 3.153 Silver Glenn Spring. Photo courtesy of SJRWMD.

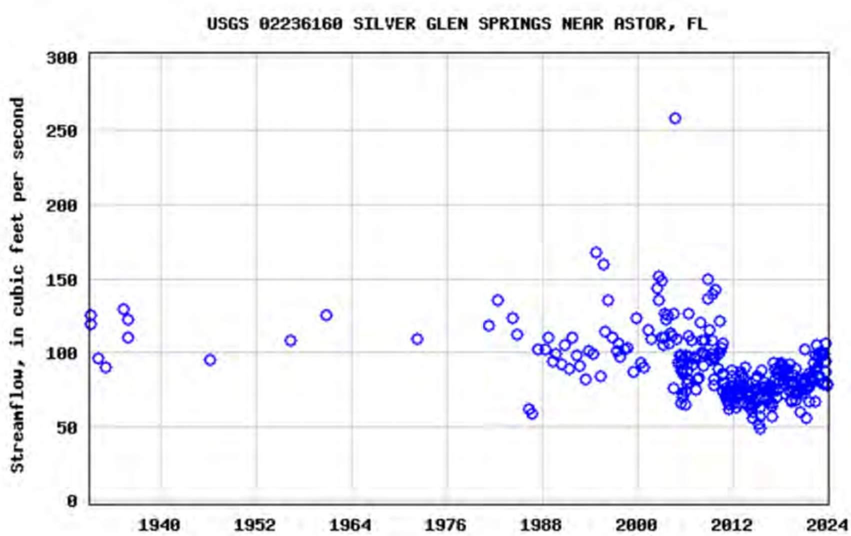


Figure 3.154 Hydrograph of Silver Glen Springs discharge rate for the period of record. Average is 89.1 cfs.

3.19 Blue Spring (Volusia County)

Volusia Blue Spring is 6 miles southwest of Deland in Blue Springs State Park, via US-17/92 (FL-15S) and County Road 4142 (W. French Avenue). See map in Figure 3.45, and Table 3.1 for GPS coordinates.

The spring is at the head of Blue Spring Run about 0.25 miles north of the parking area and is accessed by an elevated wooden boardwalk along the east bank of the spring run. The spring discharges into a circular spring pool in a conical depression with a notable boil in the center. The spring pool measures 135 ft north to south and 105 ft east to west (Figure 3.155). The depth of the spring measured over the vent is 20 ft. The bottom of the spring is limestone and sand. The spring vent is an elongated opening in the limestone about 15 feet from the north edge of the pool. From the limestone ledge, the vent slopes precipitously to about 40 feet in depth.

Figure 3.155 Aerial view of Volusia Blue Spring. Photo by Frank Moore; available at https://firstmagflorida.com/2022/05/08/blue-spring/

The spring run has steep sandy banks and flows south and west approximately 1,050 ft to the St. Johns River through dense hardwood and palm forest. The run varies from 70 feet to 100 feet in width and is bounded by steep wooded slopes except for the lower southeast bank, where the terrain flattens considerably. Flow of the spring is retarded by backwater during high stages of the St. Johns River.

Blue Spring State Park is owned and operated by the state of Florida and provides a wide range of recreational activities, including swimming, diving, canoeing, fishing, hiking, and camping. Full facilities are available (see https://www.floridastateparks.org/parks-and-trails/blue-spring-state-park).

Blue Spring is a designated manatee refuge and the winter home to a growing population of West Indian Manatees. During manatee season, which runs approximately from mid-November through March, hundreds of manatees can be viewed atop the spring's overlooks on cold days. The spring and spring run are closed to all water activity from mid-November to at least mid-March. Swimming or diving with manatees is not permitted; this rule is strictly enforced.

Figure 3.156. Manatees in Blue Spring, January 2024. Courtesy of Blue Springs State Park.

On January 21, 2024, Blue Spring State Park posted on Facebook, "*Record-breaking morning at Blue Spring State Park*," announcing that park authorities had counted 932 manatees in the region, about 200 more than their previous record of 736, which they had set on New Year's Day (Figure 3.156).

Figure 3.157 Blue Spring in Volusia County. Courtesy of SJRWMD.

The Blue Spring State Park area is known to have been inhabited by Timucuan Indians centuries ago. In 1766, it was visited by Colonial American botanist John Bartram, but it wasn't until 1856 that it was settled by Louis Thursby and his family. Gold Rush prospector turned orange grower Louis Thursby purchased Blue Spring in 1856 and built his house atop a large Indian midden. Before the railroad rolled through in the 1880s, Thursby's Blue Spring Landing was a hotbed of steamboat activity, transporting tourists and goods to Jacksonville and beyond. Mrs. Thursby was Orange City's first postmistress.

Years later in 1971, "The Forgotten Mermaids" episode of the Underwater World of Jacques Cousteau was filmed here. The documentary brought attention to the importance of Blue Spring as a winter refuge for manatees, greatly influencing the state's decision to purchase the land.

The state acquired this land from private ownership and the park was established in 1972 to preserve the largest spring on St. Johns River and to protect its natural features including manatees that winter there due to warm water temperature.

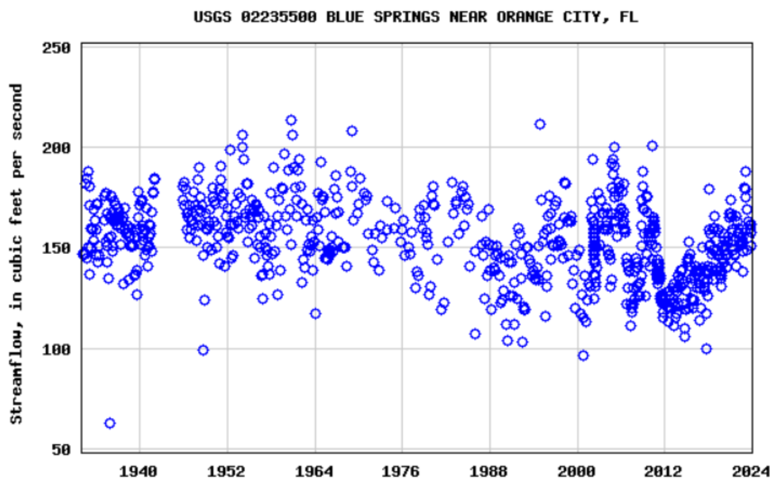


Figure 3.158 Hydrograph of Blue Springs discharge rate for the period of record. Average is 153 cfs.

3.20 Wekiwa Spring, and Rock Spring

Wekiwa Springs is part of Wekiwa Springs State Park, approximately 9.7 miles northeast of the town of Apopka via East Welch Road and Wekiwa Road (see map in Figure 3.45, and Table 3.1 for GPS coordinates).

Wekiwa Spring (Figure 3.159) is a second-magnitude spring in a semitropical forest setting at the base of a northeast-sloping, grassy, open-wooded hillside. Two areas of discharge can be observed as surface boils near the edge in the southeast half of the spring. The strongest boil is over a large, irregularly shaped vent, about 35 feet long by 5 feet wide, located in the limestone bottom about 15 feet below the surface. The other boil is above a rock ledge in the extreme southeast edge of the pool. Except for the limestone rock bottom in the southeast part of the pool, the pool bottom is mostly sand. The spring pool is kidney-shaped, about 200 feet long and 100 feet wide, elongated southeast. A sidewalk surrounds the pool, and a wooden footbridge crosses the run just below the pool. A 2- to 3-foot-high retaining wall encloses the pool and extends a short distance down the run. The clear, bluish-green water forms the headwater of the Wekiva River, which flows northeast through state land approximately 17 miles into the St. Johns River.

Thirteen miles of trails in Wekiwa Springs State Park provide opportunities for hiking, bicycling and horseback riding. Canoeists and kayakers can paddle along the Wekiva River and Rock Springs Run. Canoe and kayak rentals are available from the park's concessionaire. The area also offers camping, picnicking, swimming, fishing, boating, nature trails and abundant wildlife. Fees apply for day-use, camping and other concessions at the park. More information can be found on the park's web page at https://www.floridastateparks.org/parks-and-trails/wekiwa-springs-state-park.

Figure 3.159 Wekiwa Spring. Photographs courtesy of Wekiwa Springs State Park.

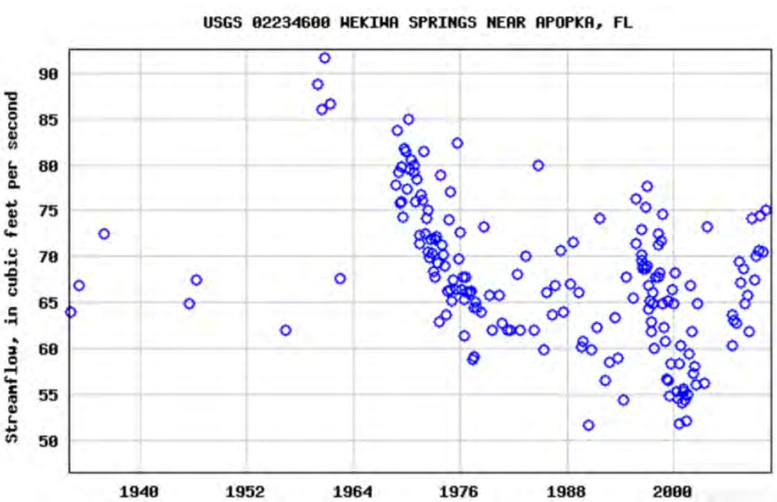


Figure 3.160 Hydrograph of Wekiwa Springs discharge rate for the period of record. Average is 67.7 cfs.

Rock Springs is in Dr. Howard A. Kelly County Park next to Rock Springs Run State Preserve, approximately 6 miles northeast of Apopka, via FL-435 and E. Kelly Park Road (see map in Figure 3.45, and Table 3.1 for GPS coordinates).In contrast to most large springs in peninsular Florida, Rock Springs has no well-defined large pool at the spring head—it emerges from a horizontal cave at the base of a 20 ft high vertical limestone and sand bluff (Figure 3.161). The cavern opening is about 5 feet in diameter at its mouth and tapers horizontally inward to a throat about 3 feet in diameter. Clear, blue water discharges with considerable turbulence that cuts into the limestone, eroding sand and fossil shells into the bottom of the 15- to 20-foot-wide spring run. Rock ledges jut out from the banks of the run for about 100 feet below the cavern opening. About 10 feet downstream from the cavern opening, additional water is discharged through a submerged opening in the channel bottom.

For a few hundred feet, the stream bottom has sand and marine fossil shells that eroded out of the limestone. There is no vegetation and only minor algal growth. Lush ferns and moss blanket the bluff and upper stream banks. The upper part of the run averages 15 – 20 ft wide and 5 ft deep. The cave and immediate vicinity are closed to use, but the rest of the run serves as a swimming, snorkeling, and tubing hotspot. A dense cabbage palm and oak hammock occupies lands adjacent to the cave and upper part of the run.

A boardwalk crosses over the run about 120 feet downstream. Several hundred feet below the spring, some of the flow is diverted left from the spring run to a large swimming area mostly bounded by concrete retaining walls (Figure 3.162).

Figure 3.161 Rock Springs. Photo courtesy of SJRWMD.

The spring is bordered on all sides by high, rolling sand hills that are owned and maintained as a county park. Information about park fees for day-use, camping and rentals can be found on Orange County Parks website at [Parks (orangecountyfl.net)](orangecountyfl.net).

Rock Springs Run is an 8.6-mile river which forms the boundary between Wekiwa Springs State Park and Rock Springs Run State Reserve. After 8 miles, Rock Springs Run eventually flows into the Wekiva River, which then runs 15 miles and empties into the St. Johns River.

Figure 3.162 Swimming area at Rock Springs. Photo courtesy of SJRWMD.

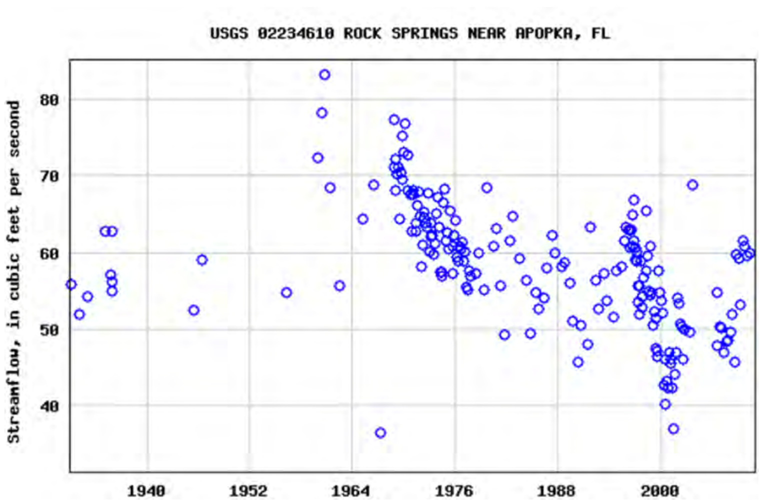


Figure 3.163 Hydrograph of Rock Springs discharge rate for the period of record. Average is 58.3 cfs.

3.21 Jackson Blue Spring

Jackson Blue Spring in Jackson County is in Florida Panhandle, approximately five miles east of Marianna via US-90, FL-71, and Blue Springs Road (see map in Figure 3.37). The headspring and six smaller springs supply water to a 202-acre artificial reservoir known as Merritt's Millpond, a nationally known fishing site. More than forty years ago, the Federal Government owned the Blue Springs site and operated an officer's club for members of Graham Air Force Base.

Figure 3.164 Jackson Blue Spring, 2015. Photo by John Moran; all rights reserved. Printed with permission.

Jackson Blue Spring is the main spring at the head of the pond (Figure 3.164). Its vent is situated about 10 ft west of the diving platform. The spring pool diameter is approximately 240 ft southwest to northeast and 233 ft northwest to southeast. Maximum depth over the vent is 16.5 ft. The vent is elliptical and approximately 5 ft high and 25 feet wide (Figure 3.165). Limestone is exposed near the vent, and it bears backhoe scars. Clear bluish water issues from the vent. A boil is slightly visible at the surface. An extensive underwater cave system has been mapped at Jackson Blue Spring.

The spring pool is a designated swimming area separated from the rest of Merritts Mill Pond by a chain link fence across the channel approximately 300 ft downstream. Surrounding the spring, are a concrete retaining wall near shore, slides, a diving board, and picnic tables.

Figure 3.165 Jackson Blue Spring; spring vent below diving platform. Photo by Harley Means, FGS, 2001.

For approximately forty years, the primary spring and head water of the Millpond has been leased to Jackson County and managed as Blue Springs Recreation Area with swimming, picnicking, and limited SCUBA training and exploration. Merritt's Millpond serves as one of Jackson County's most popular fishing and boating areas including equipment rentals: https://jacksoncountyfl.gov/services/parks-recreation/blue-springs-recreation-area/.

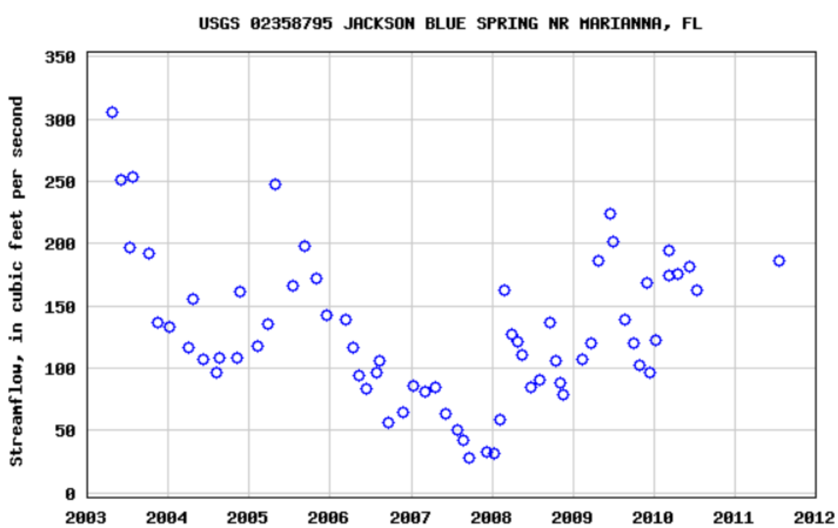


Figure 3.166 Hydrograph of Rock Springs discharge rate for the period of record. Average is 130 cfs.

3.22 Radium Springs, Georgia

Radium Springs (Figures 3.167 through 3.172) are in Radium Springs Gardens located on the outskirts of Albany in Dougherty County, Georgia (address is 2501 Radium Springs Rd. Albany, 31705 GA; GPS coordinates are: 31^{o}31'35.29''N 84º08'12.28''W; https://visitalbanyga.com/attraction/radium-springs-gardens). The park is located on the site of a casino that had its heyday in the 1930s. The casino was demolished in 2003 after sustaining serious damage when the Flint River flooded in 1994 and 1998. The spring is now preserved as an ecological and environmental park which features a restored terrace, new sidewalks, garden, and gazebos of the former casino, as well as nature trails and an observation desk along Skywater Creek (the spring run) outside the gardens. Although swimming is no longer allowed, the spring served that purpose for many years and once was one of Georgia's most popular resort areas.

Radium Springs, which discharge from a large main and several nearby, smaller vents into the spring pool (Figure 3.167) are close to the up-dip limit of productive part of the Upper Floridan Aquifer in South Georgia (see Figures 3.1 and 3.7). An extensive submerged cave system (Figure 3.168), developed in highly porous and karstified young Ocala limestone, is drained by the springs and has been explored by cave divers entering through the main vent. A 3300-feet long spring run flows into the Flint River through a nice southern marshland teaming with wildlife (Figure 3.169).

Radium Springs is the largest spring in Georgia and was reported as a historic first-magnitude spring by USGS (see Figure 3.7). On an information panel by the spring, and on various web sites one can read that the spring is flowing at "70,000 gallons per minute" (equivalent to 187 cfs). However, it is unknown where this number came from since the only available official record of any flow measurements at the spring is by USGS, painting a very different picture (Figure 3.171).

Figure 3.167 Radium Springs in Albany is the largest spring in the state of Georgia. The main vent discharges from a submerged cave in Ocala Limestone. Entrance to the cave ("blue hole") is in the center right.

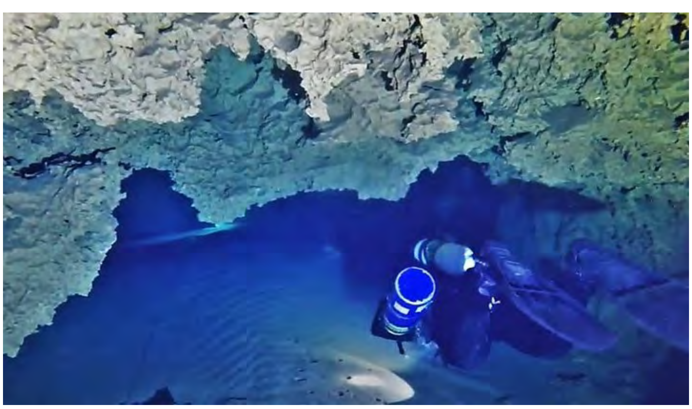


Figure 3.168 Screenshot of a diving video at Radium Springs, October 31, 2015, taken by Guy Bryant with divers Kelly Jessop and Peter Buzzacott. Note high matrix ("sponge") porosity of the upper Eocene Ocala limestone enhanced by dissolution. Video available on YouTube (CDroHO56F-Y)

The fascinating history of Radium Springs is described in detail on the excellent *Explore Southern History* website (https://exploresouthernhistory.com/naturalwonders.html). The Spring was well known to both prehistoric and later Creek Indians, who lived and hunted in the surrounding area while fishing in the crystal-clear water. By the time English settlers arrived in South Carolina and Georgia, the area around Albany was controlled by the Lower Creeks and early accounts mention the magnificent spring. English settlers and explorers began to use the springs for swimming and fishing, marveling its depth, constant 68-degree temperature, and clarity of the water.

In 1925, traces of radium were discovered in the water, and Blue Springs was renamed Radium Springs as the first step in its development as a major resort. Bathing in mineral waters was believed to be beneficial for improving health of people suffering from a variety of illnesses.

Figure 3.169 Google Earth map of Radium Springs, Albany, Georgia. The Spring run called Skywater Creek flows south into the muddy Flint River shown on the left. Image acquired on January 26, 2023. Copyright 2024 CNES/Airbus.

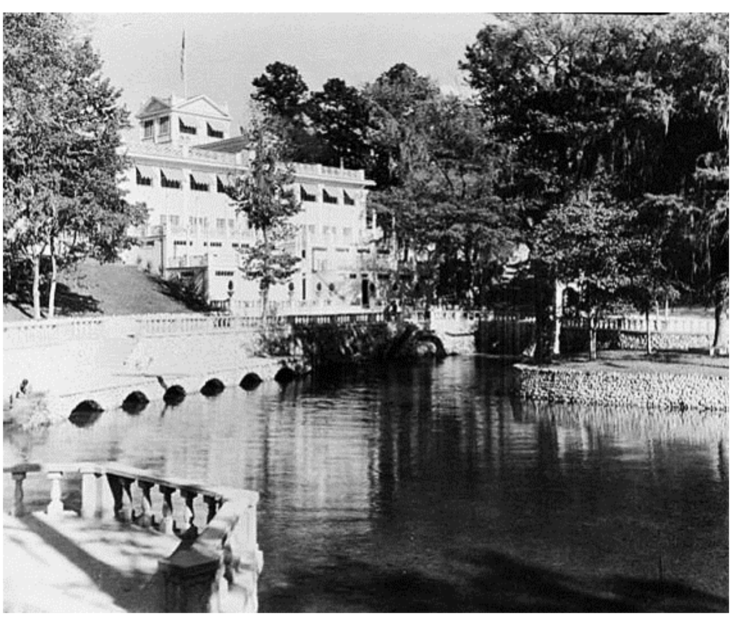


Figure 3.170 Radium Springs, one of Georgia's Seven Natural Wonders, was the site of a casino that had its heyday during the 1930s. The casino was demolished in 2003. Courtesy of Georgia Archives, Vanishing Georgia, #DGH-4 https://dlg.usg.edu/record/dlg_vang

Barron G. Collier (Collier County in Florida is named in his honor), a noted developer and national figure of the early 20th century, purchased the springs and began work on a major development there. His plans for Radium Springs were magnificent and it was reported at the time that he spent nearly $1,000,000 on the project. The development included a casino and bathhouses overlooking the spring, a hotel named *Skywater* (after the Creek Indian name for the spring), cottages, riding and walking trails and one of the finest golf courses in the South. The resort opened to the public in 1927 and was an instant success. Guests came by train to Albany from across the country to soak in the waters and enjoy the other amenities.

The Spring was still a popular swimming place for Albany area residents until 1994 when the casino and other historic structures suffered heavy damage in the Tropical Storm Alberto flooding. A second flood inflicted even more damage beyond repair in 1998, and the casino was demolished in 2003. The property and remains of the spring area of the resort, however, were acquired by state and local governments. Radium Springs Gardens, a beautiful historic site and botanical garden, opened in 2010.

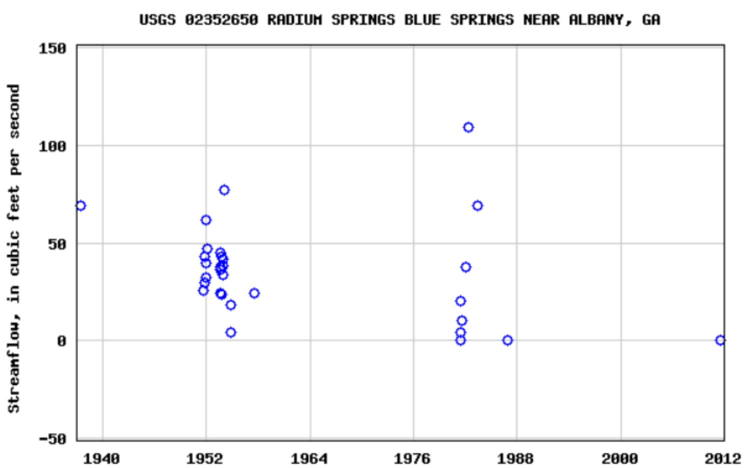


Figure 3.171 Discharge rate of Radium Springs (aka Blue Springs) was measured in the field 31 times between 1937 and 2011. The spring nearly or completely dried up 3 times during this period (in July 2011, September 1986, and July 1981). The maximum of 109 cfs was recorded in April 1982.

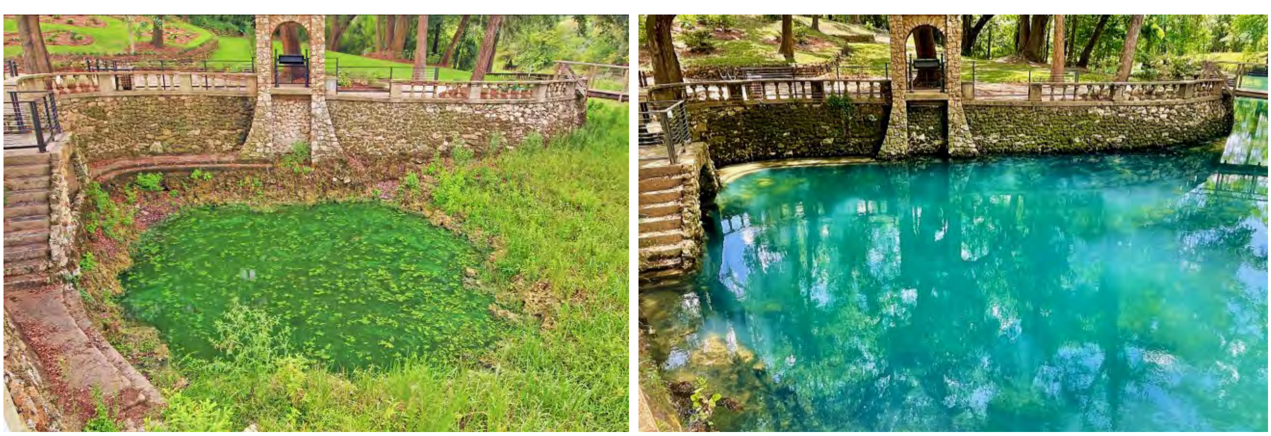


Figure 3.172 *Left*: In the summer of 2012, when South Georgia was experiencing drought conditions and excessive groundwater withdrawals for irrigation purposes, the flow in Radium Springs stopped due to falling water table levels in the Floridan aquifer supplying water to the spring. Photo by Allan Cressler, USGS. *Right*: Spring in April 2024.

3.23 And Now Something Completely Different: Wakulla Spring, Again

In the late fall of 2023, Prof. Dr. Zoran Stevanović, who was leading the IAH Karst Commission (KC) project "Most Important Karst Aquifer Springs" in the world (MIKAS), called me up with a nice news: KC received an invitation to nominate several exceptional springs for inclusion in the list of world's Geological Heritage Sites maintained by International Union of Geological Sciences (IUGS). The invitation was special because there were never before any hydrogeological sites on that list. This fact was not surprising to us hydrogeologists because hydrogeology was always considered somehow different than other "real, pure" geological sciences (for one, it is very quantitative and includes many elements of engineering).

Zoran asked me which spring from the United States, out of all that were now on the MIKAS list, would I propose. He and the European colleagues already settled on three very famous springs: Fontaine de Vaucluse in France, the *locus typicus* ascending spring with globally the longest history of recorded discharge; Kläffer Spring in Austria used for the water supply of Vienna (it is the core of the largest European spring-based water supply system); and the spectacular Buna Spring in Herzegovina, one of the largest in the world. Zoran trusted my judgment, not only because I was coordinating the MIKAS effort for North America. We both received our hydrogeology degrees from University of Belgrade, worked together on many groundwater projects in the Dinaric Karst where there are the most first-magnitude springs in the world, participated in the activities of KC, and even managed to jointly edit the first professional book on springs published by Elsevier.

Without hesitation, I told Zoran it was an easy choice: it had to be Big Spring in Missouri. I visited the spring more than once and was each time totally blown away. And that was it. However, later that day I started having second thoughts. I then called Zoran well after midnight his time (he did not mind) and told him to wait a few days. I wanted to see Wakulla Spring in Florida myself before I finally made up my mind. I never personally visited the spring but learned "everything" about it from very competent people, long time ago.

I arrived at The Lodge at Wakulla Spring State Park late at night and went straight to bed. In the morning, after a nice breakfast and a chat with a friendly waitress very knowledgeable of the spring including its many troubles, I went to the diving platform above the spring, dispersing tens of vultures along the way, made friends with a family of manatees that came to say hello, and then explored around, asked a few people including a young park ranger why was the water so dark, walked the park trails, sat at benches looking at the spring, several times, and even read a book on the spring by Tracy Revels that I bought in the souvenir store.

Then I wandered around a bit more and went to the diving platform again. While looking at the mysterious, dark, and yet majestic spring in front of me, I thought to myself how Big Spring in Missouri everything had going for it—it was as pristine, crystal-clear, mesmerizing, and strong as ever. It was protected as the national treasure ever since people of Missouri donated it to the Nation. And everyone in the state, including politicians and various bureaucrats were proud of Big Spring, just as they were proud of many other springs of Missouri, taking good loving care of them all and keeping them beautiful for generations to come. And this spring in front of me had everything going against it.

Later that afternoon I called Zoran (waking him up, again) and told him I had changed my mind. It will be Wakulla Spring. I asked Zoran if he had everything needed for the nomination and he said we were OK. I left the spring with a heavy feeling in my heart.

On February 29, 2024, I got a call from Zoran: three springs made it to the list, Wakulla was one of them. I silently thanked Dr. Todd Kincaid, David Rhea, Tracy Revels, all the people I met back in December 2023 at the spring, a young park ranger that gave me many materials about the spring, the friendly waitress, the family of manatees, and all the wild creatures I saw while walking around the majestic spring.

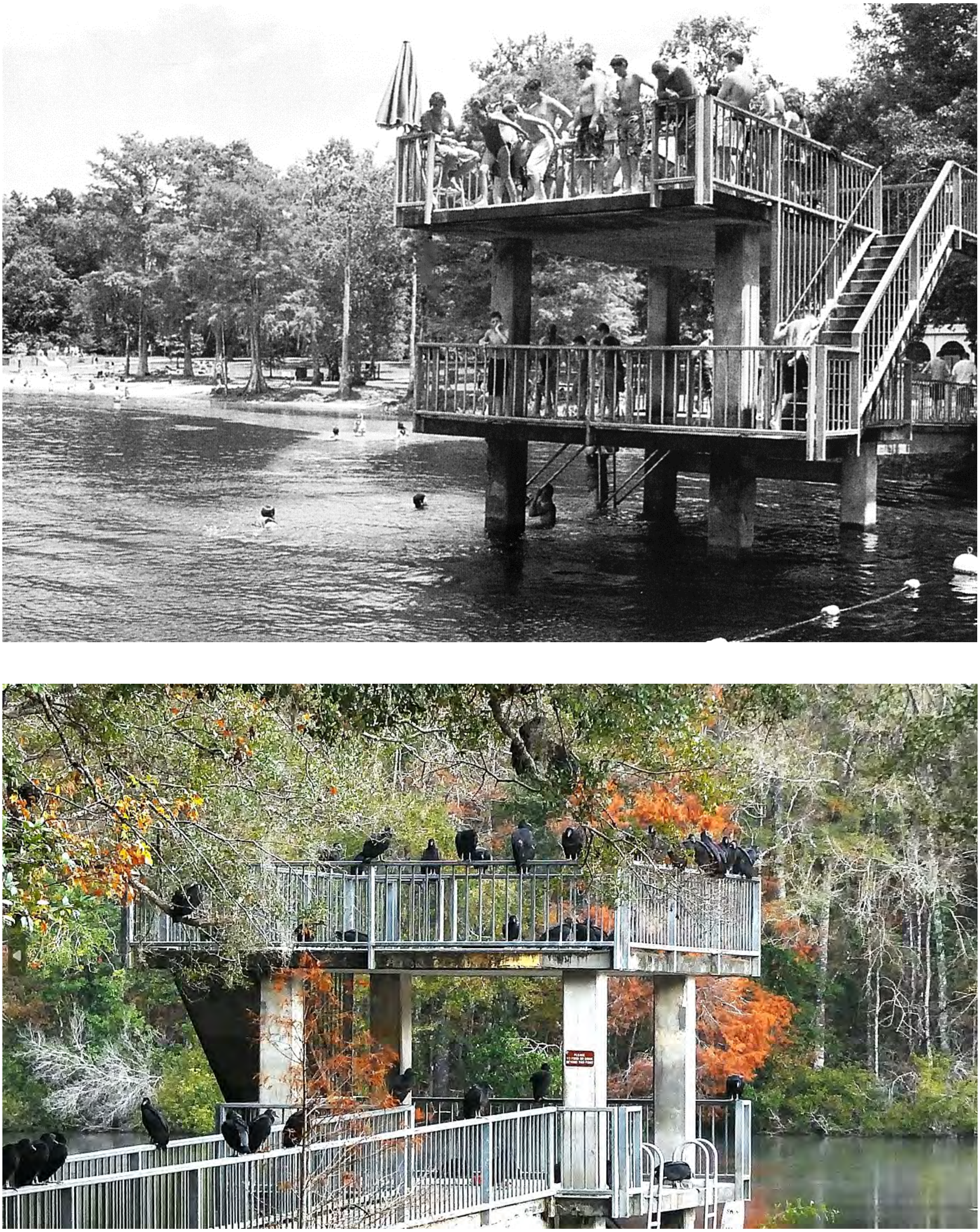


Figure 3.173 Will the vultures have the last laugh? Top photo courtesy of Florida Archives, Florida Memory. Bottom photo taken in December 2023.

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Chapter 4 Idaho

4.1 Introduction

The Snake River has its source on the Continental Divide, in the southern part of Yellowstone National Park. It flows southward through Wyoming for about 75 miles, enters Idaho, and at Heise emerges from its mountainous headwater area, into the great Snake River Plain which hosts some of the largest springs in the country (Figure 4.1). A short distance farther downstream it is joined by its major tributary, Henrys Fork, which drains the upper part of the Snake River Plain. This plain extends for more than 300 miles entirely across southern Idaho, roughly along the arc of a circle. The Snake River flows near the southern boundary of the plain, a position that has been forced upon it by lava flows, which cover the region between the present river and the northern edge of the plain and which have displaced the stream from its ancient channel in the axis of its valley (Stearns et al, 1938).

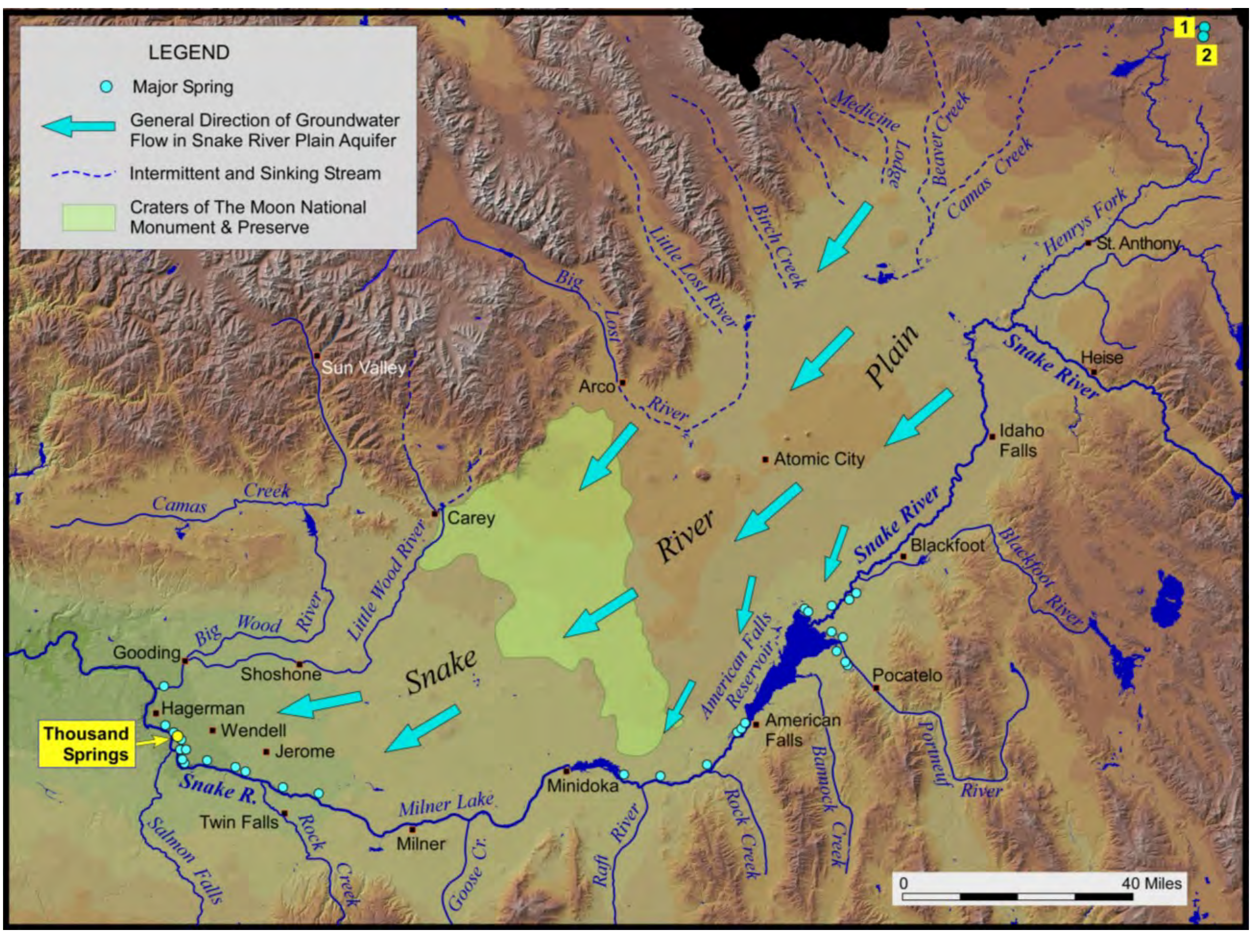
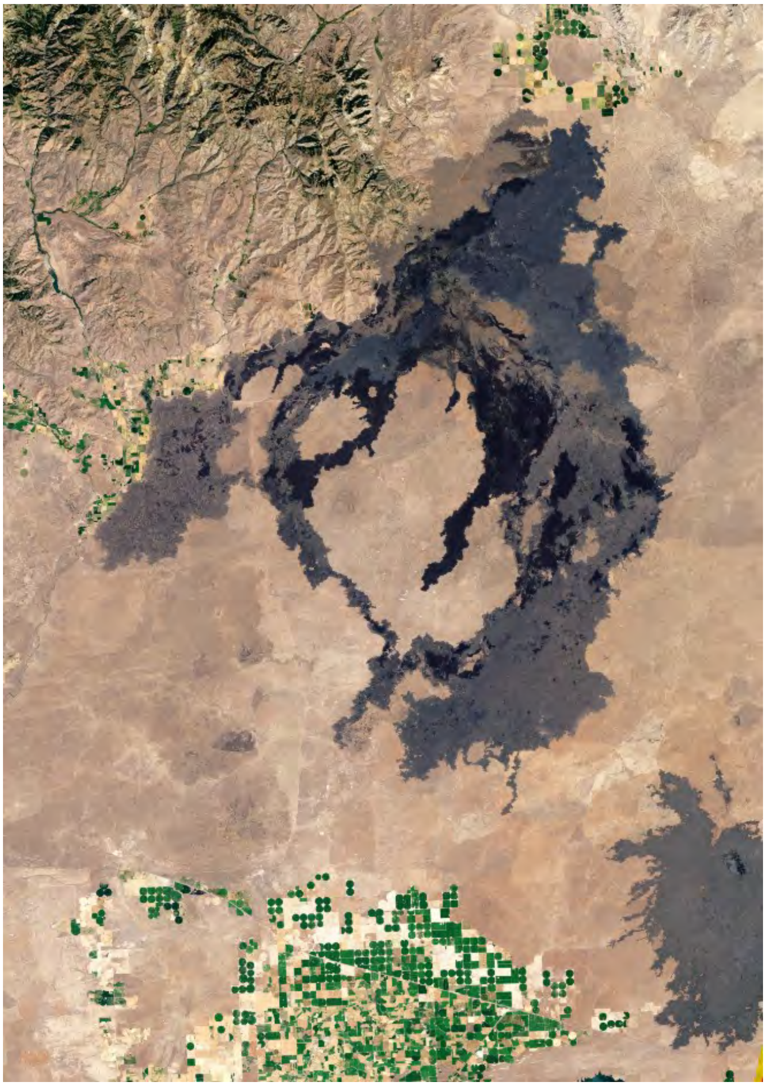


Figure 4.1 Eastern Snake River Plain with general directions of groundwater flow in the underlying basalt aquifer and locations of major springs. No.1 is Big Springs, No.2 is Warm River Springs. Shaded relief basemap courtesy of USGS.

Although this region presents the appearance of a great level valley floor, it has been built up by successive lava flows from numerous vents within the valley itself rather than by fluvial depositional processes. Its topography is determined by the source and extent of these lava sheets and not by erosion, except that the Snake River and several tributary streams have cut deeply into it.



Though vegetation in one form or another covers much of the area, the desolate black lava flows (Figure 4.2), the drifting white sand dunes, and the bleak, bare lake beds serve to impress upon the traveler the desert character of the country. Throughout many square miles in the central part of the plain, water can be found only in the ice caves in the lava flows or at some stock well at which the water is pumped hundreds of feet. With the increase in the area irrigated on the plain well before WW2, the people inhabiting the area started to refer to the irrigated part of the plain as the "Snake River Valley" (Sterns et al, 1938).

Figure 4.2 This natural-color image of Craters of the Moon lava field was acquired by the Enhanced Thematic Mapper Plus (ETM+) aboard the Landsat 7 satellite on August 1, 2001. The lava flows appear black, dark brown, and even dark blue. They range from approximately 15,000 to 2,100 years old and together cover 620 square miles with a total volume of 7.2 cubic miles. Thick vegetation (forest in the Pioneer Mountains and irrigated fields on the Snake River Plain) is green, while the scrubby vegetation surrounding the lava field appears brown. Scrub-covered areas surrounded by lava flows are called kipukas. Image width is approximately 50 miles. NASA Earth Observatory image and caption by Robert Simmon. U.S. National Parks Collection.

The generally flat plain is relieved by several buttes, chief among which are Big Southern Butte, West Twin Butte, and East Twin Butte, which stand prominently above the general land surface about 30 miles northwest of Blackfoot. Big Southern Butte rises 2,350 feet above the surrounding plain (Figure 4.3). It is called by the Native Americans "Be-ah Car-did" (great stay), referring to its permanence. It may be seen from points over 100 miles distant. East Twin Butte rises about 1,100 feet and West Twin Butte about 800 feet above the adjacent plain.

There are many lower buttes scattered over the lava plain, all of which, unlike the three highest, are extinct basaltic volcanoes. Besides the cones that are prominent enough to be individually named, there are innumerable minor elevations that can be discerned if the surface of the plain is viewed against the skyline. These features rise to heights of 100 to 300 feet, but their bases, commonly 4 to 6 miles or more in diameter, are so broad that their slopes merge gradually into each other or into the surrounding plain. These minor elevations are also volcanic vents, and from those now visible as well as from many others buried by later eruptions, vast quantities of highly fluid lava formerly flowed in all directions.

Figure 4.3 Big Southern Butte in Eastern Snake River Plain, Idaho. The butte is among the largest rhyolite domes in the world. Photo by James Neeley, BLM (https://flic.kr/p/CsA4TV).

The largest and most productive aquifers in the Eastern Snake River Plain are composed of multiple Quaternary basalt flows of the Snake River Group, which underly most of the 10,8000-square-mile plain and are estimated to be more than 5,000 feet thick. Basalt thickness is known from only a few drill holes and is estimated elsewhere by geophysical methods. As a result, variations in thickness are approximate and speculative in some areas. These younger basalts are the most permeable units of the Snake River Group.

Miocene Banbury Basalt of the Idaho Group and the Miocene (Tertiary) Columbia River Basalt Group or equivalent Miocene basalt underlie or flank much of the western plain and part of the eastern plain. In several areas, Banbury Basalt or basalt of equivalent age is separated from the basalts of the Snake River Group by the sedimentary rocks of Glenns Ferry Formation and Lake Idaho origin which are several tens to several hundreds of feet thick. According to prevalent interpretations (e.g., see materials provided in Digital Atlas of Idaho at https://digitalatlas.cose.isu.edu/geo/snkrvpln/basalt/srpbslt.htm) these older basalts are, in general, much less permeable than the younger basalts.

However, as discussed by Farmer and Blew (2014), the brown Tertiary Basalts can have high permeability based on previous tracing results by Dallas, 2005; and Farmer and Larsen, 2001. These studies document high groundwater velocities within a Tertiary Age brown basalt that is interbedded within the Glenns Ferry Formation west of Hagerman. It is sometimes assumed there are no grey colored basalts below the brown Tertiary Age basalt. However, grey basalts are described below the brown basalts in the Chen-Northern engineers report which recorded cores inspected by licensed Geoengineers. Empirical field evidence supports, at least in part, that grey colored basalts are described below the brown basalts; it therefore is concluded that the presence of Tertiary age basalts does not necessarily mean this is the base of the ESPA aquifer (Farmer and Blew, 2014).

The general groundwater flow direction in the aquifer is from the northeast to the southwest where the main discharge zone is represented by a series of large springs (Figure 4.1) along the Snake River canyon. In 2021, the estimated total discharge of the springs was 5,047 ft^3/s (Treinen et al., 2024). Along much of its length, the Snake River gains large quantities of groundwater, mostly as spring flows from the north side. However, upstream from Blackfoot, the river loses flow to groundwater during the year.

The aquifer is recharged primarily from infiltration of irrigation water (both surface water from numerous irrigation canals and ditches, and groundwater from center-pivot systems), water from sinking streams, infiltration of precipitation, and groundwater inflow from adjoining mountain drainage basins.

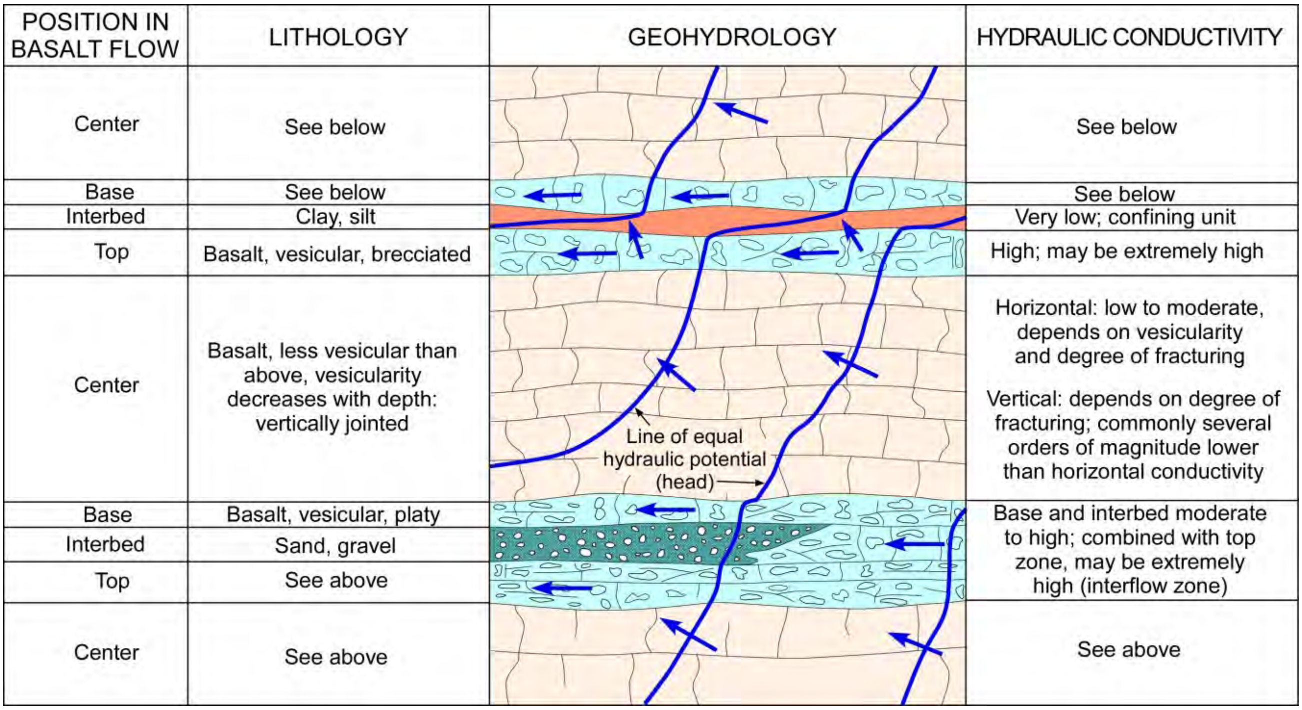


Figure 4.4 Effect of basalt aquifer lithology and sedimentary interbeds on hydrogeologic characteristics and groundwater movement. Blue arrows show general direction of groundwater flow in cross section. Modified from Lindholm, 1996.

Aquifer tests and simulation indicate that transmissivity of the upper 200 feet of the basalt aquifer in the eastern plain commonly ranges from about 100,000 to 1,000,000 feet squared per day. However, transmissivity of the total aquifer thickness may be as much as 10 million feet squared per day. Specific yield of the upper 200 feet of the aquifer ranges from about 0.01 to 0.20. Average horizontal hydraulic conductivity of the upper 200 feet of the basalt aquifer ranges from less than 100 to 9,000 feet per day. Values may be one to several orders of magnitude higher in parts of individual flows, such as flow tops (Lindholm, 1996; Figure 4.4).

Voids in basalt differ greatly in shape, size, and degree of interconnection. Large-scale features include lava tubes (Figure 4.5) of 15 ft or more in diameter and a few yards to some miles in length (Nace et al., 1975). Vesicles (voids formed during rock solidification by the escape of entrapped gas) may be minute to about 1 in. in diameter and, if elongated, several inches to 1 ft in length. The volume of voids attributed to vesicles may exceed 25 percent of total rock volume; 10 to 20 percent is common in the upper parts of flows. Laboratory tests on cores of basalt of the Snake River Group at the INEL site indicate that total porosity ranges from about 6 to 37 percent, and effective porosity, the percentage of rock volume that is interconnected voids, ranges from 4 to 22 percent (Johnson, 1965). Effective porosity is greatly enhanced by fracturing.

Figure 4.5 Indian Cave lava tube in Craters of The Moon National Monument & Preserve, Idaho.

Zones of blocky, rubbly basalt near tops of flows and pillow lava typically have the highest porosity and permeability. Pillow lava was deposited in water that ponded behind basalt dams in ancestral valleys of the Snake River. Pillow lava in the north wall of the Snake River canyon between the mouth of Salmon Falls Creek and King Hill was first described by Russell (1902). The north canyon wall between Milner and King Hill was mapped as part of the Regional Aquifer Study Analysis (RASA) by Covington and Weaver (1991) to determine geologic controls on springs. They concluded that the largest springs in the Milner-to-King Hill reach issue from pillow lava.

One of the principal results of the 1938 study by Stearns et al. is the conclusion that the exceptionally large springs along the canyon of the Snake River owe their existence to the fact that the modern canyon intercepts a series of roughly parallel former canyons of the river that are now filled with especially permeable lava and hence serve as channels for preferential groundwater flow. The coves present where many of the springs emerge are thought to have been formed to some degree by solution.

The area north of the plain consists of mountain ranges as high as 12,500 feet which are drained by many smaller and several larger streams that sink at the norther edge of the lava plain. The Big Lost River (Figure 4.6), the Little Lost River, Birch Creek, Medicine Lodge Creek, and Beaver-Camas Creeks collectively make up the so-called “Sinks Drainages” which provide most of the natural recharge to the aquifer as the average annual precipitation over the plain is less than 10-12 inches. Most precipitation in the Sinks Drainages falls as snow at high altitudes during the winter months and snowmelt drives streamflow.

Figure 4.6 *Top*: Looking northwest from Leslie Butte up the Big Lost River Valley towards Mackay, Idaho. Big Lost River is in the middle, Lost River Range is on the right, and White Knob Mountains are on the left. During average precipitation years the Big Lost River disappears north of Arco because all its water is consumed for irrigated agriculture, domestic, stock, municipal, and other uses, or naturally lost (infiltrated) to the subsurface. During high precipitation years it flows past Arco onto the Idaho National Engineering and Environmental Laboratory (INEEL) where it sinks into what are locally known as The Playas. Photograph by Lauren M. Zinsser, U.S. Geological Survey, March 30, 2021. *Bottom*: Sinks area (The Playas) of the Big Lost River, southeastern edge of the Lost River Range, and Naval Reactors Facility. Photograph by U.S. Geological Survey INL Project Office, December 6, 2017.

Figure 4.7 Rare summer storms over Snake River Plain do not contribute much to the aquifer recharge due to high evapotranspiration rates. *Left*: Storm backdrop for the center-pivot irrigation system.

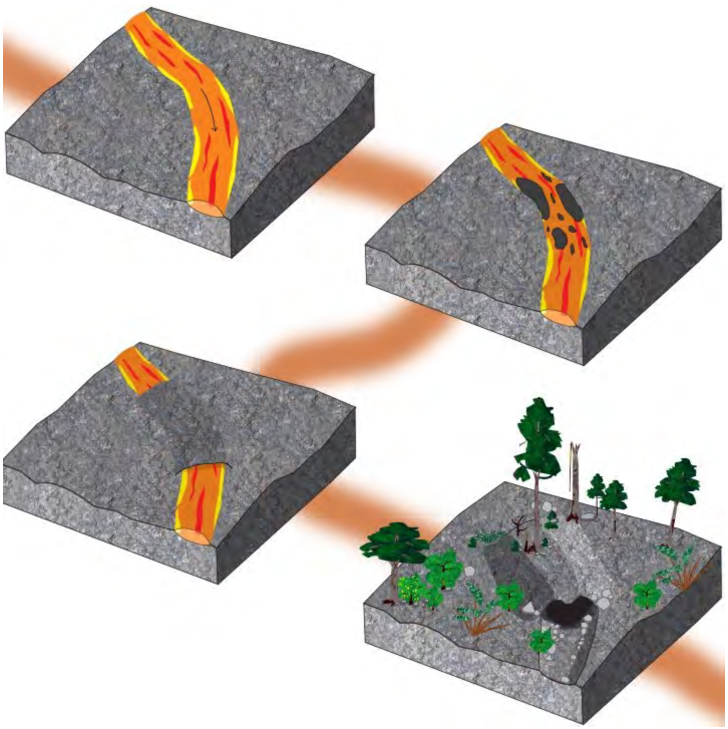
4.1.1 Pseudokarst

Snake River Plain is one of the largest regions with pseudokarst terrain in the country, together with parts of the Columbia Basalt Plateau in Washington and Oregon, and the lava fields of northeastern California. This is where many of the largest springs in the country are, precisely because of their pseudokarstic nature. Pseudokarst can occur in non-soluble rocks including metamorphic and volcanic and has features similar to those developed in classic karst – hummocky topography, sinking streams, sinkhole-like closed depressions, preferential flow paths, open fissures, and even caves. These landforms are created through mechanical processes rather than the chemical dissolution typical for carbonate bedrock such as limestone, dolomite, and gypsum deposits. Ninety-nine (99) percent of Craters of the Moon National Monument and Preserve was identified as containing pseudokarst (KellerLynn, 2018).

While limestone caves with stalactites and stalagmites might be what most people think of when they think of caves and karst, there are several other types of caves. The second most common are lava tubes which abound at Craters of The Moon National Monument & Preserve (CMNMP) and contribute significantly to the groundwater flow characteristics in the underlying basaltic aquifer. It is virtually certain that paleo lava tubes, i.e., lava tubes formed during major previous phases of volcanic activity in the Snake River Plain, are present throughout the >5,000 thick Quaternary basalt flows of the Snake River Group and not only within the limits of the CMNMP. Although paleo lava tubes must have been altered multiple times due to the pressure of overlying rocks and magmatic/tectonic activity, they still play a role in groundwater movement at greater aquifer depths.

The following description of lava tubes formation and presence in CMNMP, other geologic features related to pseudokarst, and photographs in Figures 4.8 through 4.10 are courtesy of National Park Service (NPS). This and other information, illustrative diagrams, and color photographs are available in the excellent NPS publication entitled "*Craters of the Moon National Monument and Preserve. Geologic Resources Inventory Report*" by Katie Keller Lynn (2018).

Lava is thousands of degrees hot and can flow like a river. The top of this white-hot river will cool with exposure to the much colder temperatures in the air above. As it cools the lava solidifies into black stone while down below the molten river keeps flowing. The rock above keeps cooling. It thickens and widens and will finally form a roof across the molten rock below creating the ceiling of the cave. Eventually as the eruption ends or the lava flow moves to someplace else, the lava tube drains of molten rock leaving a cave tunnel behind (Figure 4.8).



Most often lava tubes are close to surface. This makes collapses and entrances more common than in other types of caves. With more entrances there can be a closer connection between these caves and the surface. While most lava caves are shallow, some are buried by newer lava flows. Occasionally new lava may fill an older existing tube destroying it.

Figure 4.8 When fluid, molten lava flows out of the ground, it works its way downhill. Soon the surface of this lava stream cools and hardens into a crust. Although the outer crust is hard, the lava inside is still molten, and continues to flow downhill. Once the molten lava has passed through, it leaves an empty tunnel called a lava cave, or more commonly, a lava tube. NPS image by Joel Despain.

Figure 4.9 Top two photographs: Examples of lava tubes in Craters of The Moon National Monument & Preserve, Idaho. *Bottom Left*: Photograph of Buffalo Cave, housed in the Broken Top flow, which has multiple levels and six entrances. The height of the opening in the upper level shown in the photograph is about 4 ft. NPS photograph from Niles et al. (2011). *Bottom Right*: Photograph of Indian Tunnel entrance. The 800-ft-long Indian Tunnel lava tube is accessible by a metal staircase and rock steps. NPS photographs available at https://www.nps.gov/crmo/learn/photosmultimedia/photogallery.htm

Many lava caves are single tubes that can extend for miles. But occasionally lava tubes can be quite complex with passage splits and junctions, multiple levels, and even sudden drop offs, all of which reflect how the lava flowed and formed. The number of documented caves within the park currently exceeds 700 and more are found each year. Figures 4.8 and 4.9 illustrate only some of their shapes and dimensions.

Lava caves are born of fire, but at high elevations or in cold regions they can contain ice (Figure 4.10). Caves are very well insulated with constant temperatures reflecting the average temperature of the region where they form. Summer high temperatures and winter lows have almost no effect underground. Lava tubes in cold places eventually become cold once the volcanic eruption ends. Often this means cold enough for ice.

In some instances, the shape of cave passages may make a trap for cold air that sinks into the tube in the winter and remains cold through the summer. These caves lack stalactites and stalagmites, but they can have large, spectacular ice formations. Their wet surfaces and transparent nature make for a delightful light show in the ice caves. Ice caves are well represented in Craters of the Moon National Monument in Idaho.

Like limestone caves, lava caves have lots of interesting features inside. Some have stalactite-like “lavacicles” hanging from the ceiling where molten rock had dripped (Figure 4.11). The drips can

Figure 4.10 Ice Formations in King's Bowl. Some caves in Craters of the Moon hold ice year-round like this fissure cave at King's Bowl. This cave is located inside the Great Rift and has been measured to be more than 600 feet deep. Courtesy of NPS.

also hit the floor making stalagmite-like features that rise like stacks of tiny pancakes. Lava curbs and gutters form when molten lava sticks to cave walls. Sometimes blocks of rock get stuck in the lava flow and may end up in any location in the cave: stuck to the ceiling or wall or protruding from the floor. Lava can also be colorful. Usually when lava cools it becomes black rock basalt. But impurities in the rock can color it orange or red, and sometimes purple.

Figure 4.11 Lava stalactites form when lava is still flowing through the tube. As molten portions of the ceiling drip downward some portions cool and harden, forming stalactites. Craters of The Moon National Monument & Preserve, Idaho. Courtesy of NPS.

Most caves in the park are lava tubes but other types of caves are also present including caves developed along fissures (fissure caves), and caves formed by differential weathering of lava flows.

Fissure caves are found within the deep cracks that make up the Great Rift. Some of these caves are remarkably deep, including one particular fissure that may be passable to a depth of 600 feet from the surface (Figure 4.10). King's Bowl is an excellent example of one of these caves, but entry is restricted due to extreme safety hazards in and around the caves. All caves at Craters of the Moon, except for Indian Tunnel, the most famous lava tube, are closed for safety reasons and to protect sensitive bat habitat.

Figure 4.12 *Left*: Aerial view of King's Bowl. Photo courtesy of NPS. *Right*: Photograph of Kings Bowl. The Kings Bowls lava field received its name from the Kings Bowl explosion pit, which resulted from a steam-driven explosion referred to as a "phreatic eruption." For a sense of scale, note the two people in the gap at the top of the explosion pit. The pit is 100 ft deep. NPS photograph from Owen (2011).

On the regional scale, one of the most striking characteristics of Snake River Plain is the absence of surface water streams between the mountain ranges in the north and the Snake River (Figure 4.1). Streams that drain the mountains quickly sink once they reach the lava plain and the highly dissected land surface (Figure 4.13). High surficial permeability of the basalt lava flows does not allow formation of any surface runoff – all precipitation over the plain not lost to evapotranspiration during hot summer months quickly infiltrates into the subsurface.

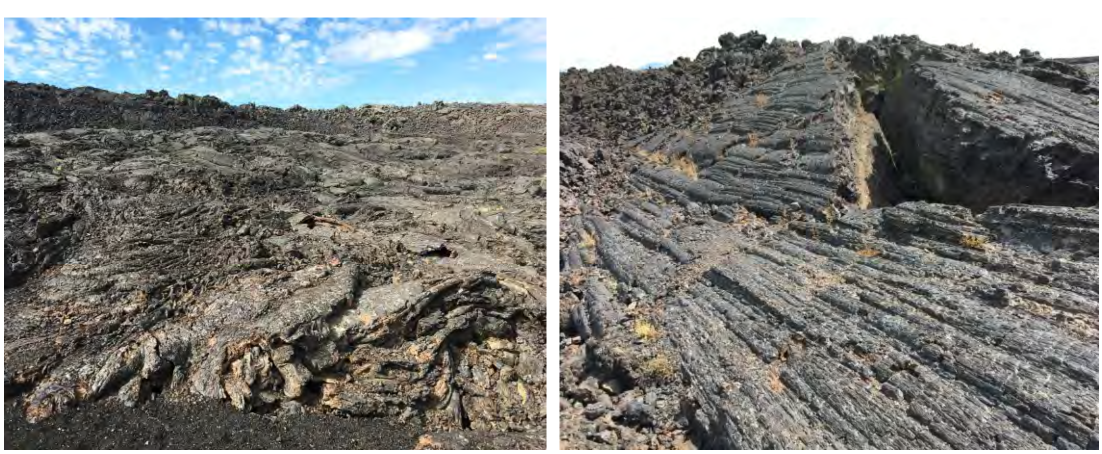


Figure 4.13 Surface of lava flows looks like complete "chaos" with stone rubble and innumerable cracks and crevices.

"Sinkholes" in lava generally lack the symmetry of those developed in solution terrain but there are nice examples of perfect “karst-like” sinkholes (Figure 4.14). The lava sinks are commonly less than 100 ft (30 m) wide, but a few large sinks are as much as 1 mile or wider. Most of the lava sinks are irregular in shape and generally are shallow features (less than 30 ft deep), although some are 150 ft or deeper. Many of the sinks have near-vertical sides or overhangs. The basalts of Snake River Plain host one of the largest concentrations of closed depressions in the country (Figure 4.15).

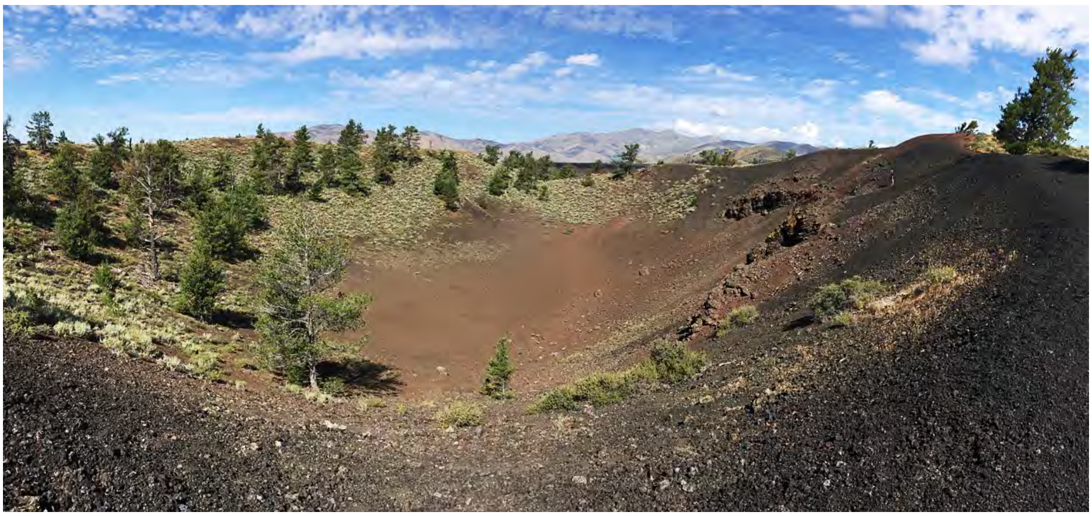


Figure 4.14 One of many large, closed depressions (“sinkholes”) in the basalts of Craters of The Moon National Monument & Preserve, Snake River Plain.

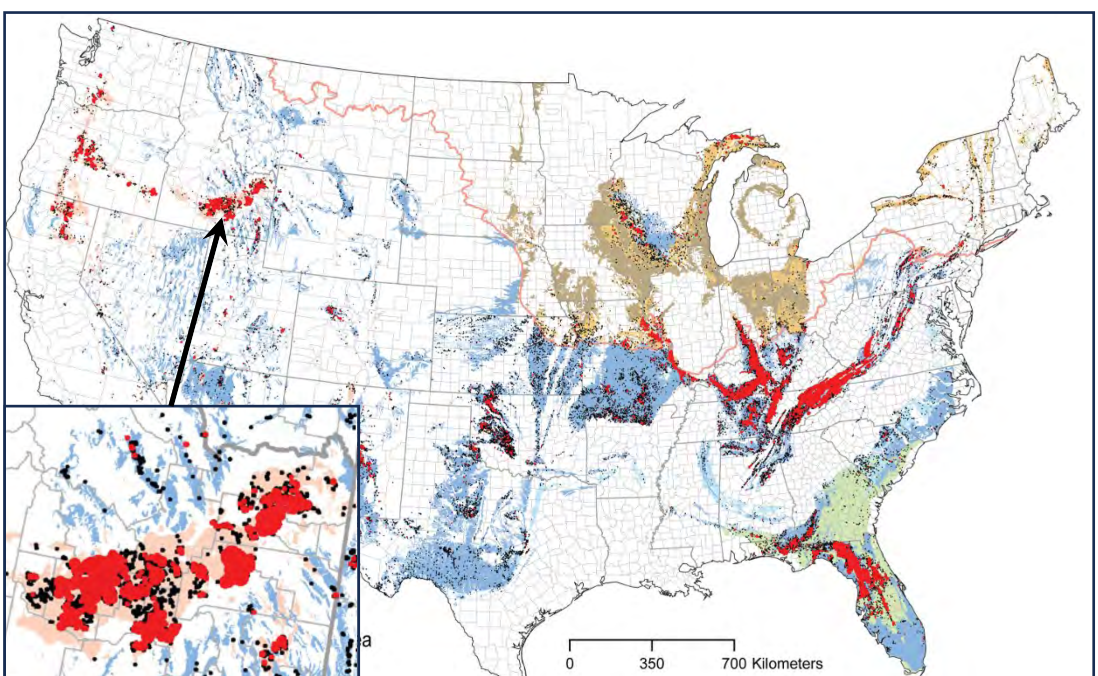


Figure 4.15 Closed depression “hot spots”(large red dots) resulting from the automated delineation methods located in areas having bedrock potential for karst within the conterminous United States. Blue areas are carbonate or evaporite rocks; black dots are depressions greater than 600 square meters in area and greater than 2 meters in maximum depth. Inset: blowup of Snake River Plain Aquifer. From Doctor et al., 2020.

The most important for groundwater flow characteristics in the aquifer and the emergence of large springs are preferential flowpaths in the basalt where transmissivity and groundwater velocity can be extraordinarily high, like in real karst, as illustrated in Figure 4.4 and dye tracing results shown in Figures 4.16 through 4.18.

Figure 4.16 Monitoring locations and estimated dye flow paths for the Strickland well trace (the Strickland well is in the center right). The tracing results show a significant dispersion of the dye and its divergence along two and possibly three preferential flow paths in the basalt aquifer. There are sharp turns from the generally westerly direction (to Banbury Springs) to the south (Briggs Springs), and probably to the northwest towards the Box Canyon Springs. The maximum velocity to Briggs Springs was calculated at 700 ft/day and Banbury Springs south side at 706 ft/day. The dominant velocity was calculated at 404 ft/day to Briggs and 427 ft./day to Banbury south side. From Farmer and Blew, 2022 (three green arrows are added to the original figure to indicate the possible third preferential flowpath).

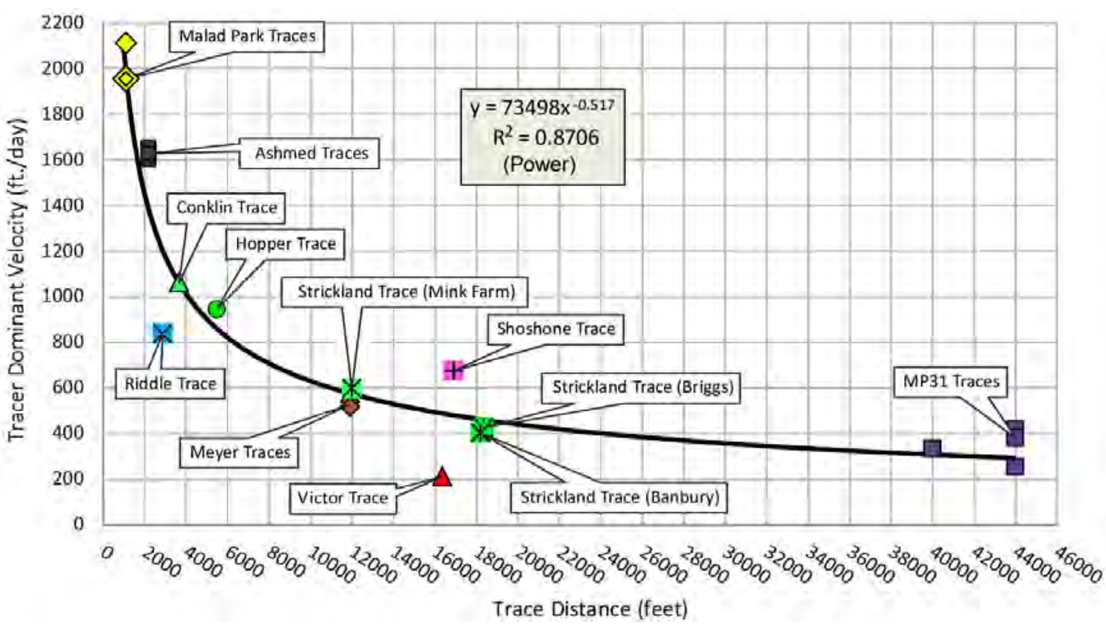


Figure 4.17 Relation between dominant tracer velocity and distance for various tracers completed on the ESPA (Eastern Snake Plain Aquifer). From Farmer and Blew, 2022.

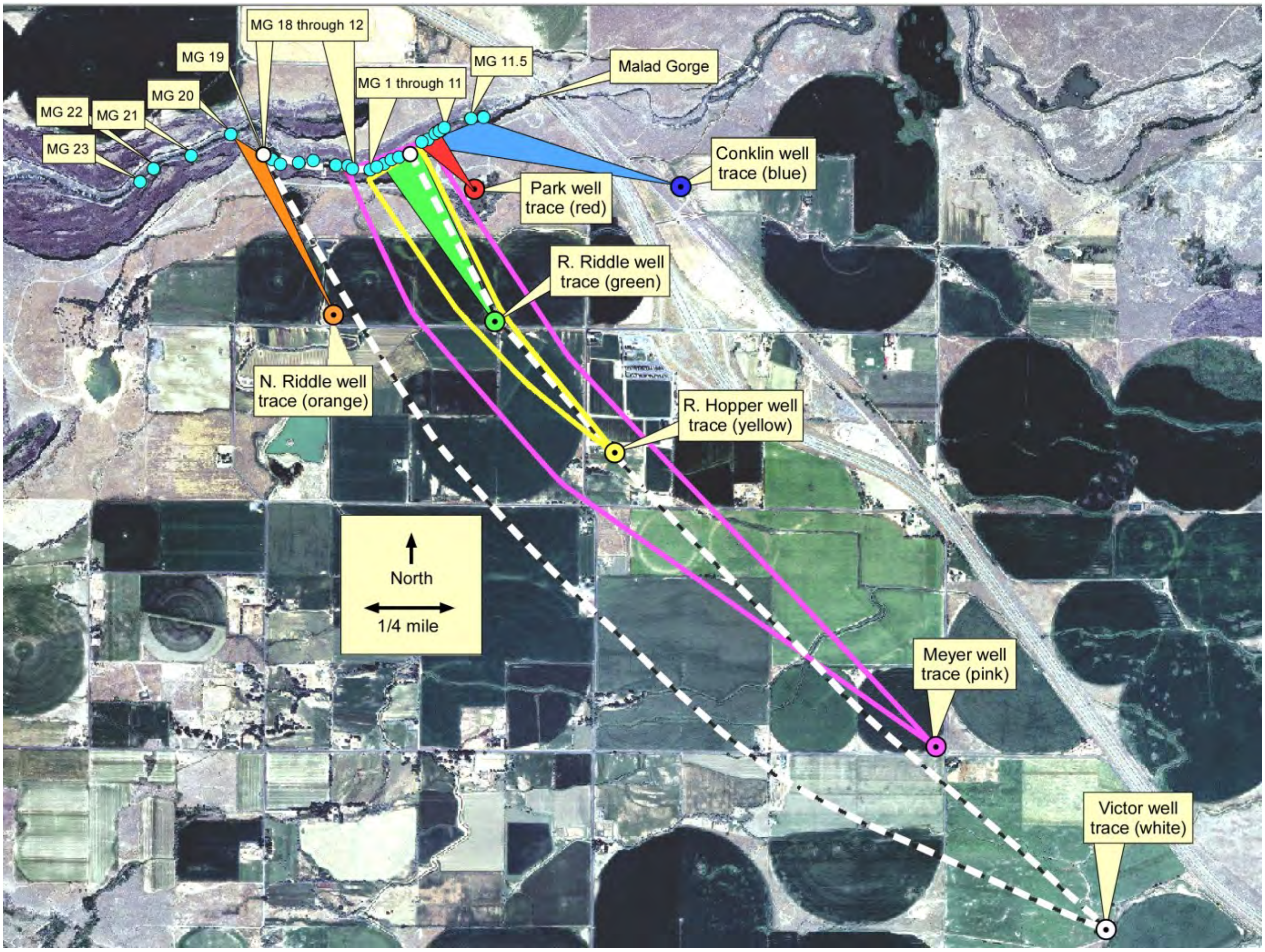


Figure 4.18 Map showing inferred, but field data supported paths of dye from all of the dye traces south of Malad Gorge as of year 2014. Note how the flow path of the Victor trace shown with white dashed lined polygon overlays with previous traces. Malad Gorge springs are shown with blue circles. From Farmer et al., 2014.

As discussed by Farmer and Blew (2022), velocities are not likely constant throughout the flowpath, and gradients generally steepen in the near rim areas which are largely driven by hydraulic conductivity and the elevation of spring discharge. Based on previous tracer studies on the lower basin ESPA (Farmer and Blew, 2009, 2010, 2011, 2012, 2014; Farmer et al., 2014) groundwater velocities appear to increase in the near spring areas and are 3 to 10 times faster than the 100 to 150 ft/day as calculated by Baldwin using Darcy's Law (2006, p.15).

The lower basin ESPA tracer tests also show a strong correlation between dominate velocity and trace distance (Figure 4.17). These traces all followed similar flow paths with varying distances from the dye emergent springs. Not only did the distance change, but the hydraulic gradient decreased as distance increased. The Meyers and Victor traces near the Malad Gorge were the two longest traces completed in that area with dominant velocities of 541 ft/day and 212 ft/day respectively. The Hopper trace was 5,490 feet which is approximately half the distance of the Meyers trace of 11,900 feet and a third of the distance of the Victor trace or 16,350 feet. The Hopper trace had a dominant velocity of 948 feet, nearly twice the velocity of the Meyers trace. In comparison, four wells monitored for the Mile Post 31 trace (Farmer and Blew unpublished data) were over 40,000 feet from the dye injection point and dominant velocities range from 256 - 419 ft/day. Despite a longer flow path, the velocities recorded for the Mile Post 31 trace are not substantially different from the Meyers and Victor trace. The Strickland trace, at over 18,000 feet, had dominant velocities of just over 400 ft/day which are comparable to the Mile Post 31 trace. Based on dominant trace velocities, the groundwater velocities on the western portion of the ESPA are generally between 250 ft/day and 400 ft/day except close to (within about 2 miles) spring areas where they can increase to 1,000 to 2,000 ft/day range (Farmer and Blew, 2022).

Most large springs in the Eastern Snake Plain Aquifer (ESPA) issue from vesicular and brecciated tops of lava flows and pillow lavas which represent the most obvious preferential flow paths in the aquifer (see Figure 4.2 and Figures 4.19 through 4.21). However, because of multiple episodes of Quaternary lava flows of various magnitudes and sizes, and in many different directions, these preferential flow zones are quite convoluted and unpredictable, similar to conduit networks in karst aquifers (e.g., see Figure 4.16). In addition, as described earlier, the brown Tertiary brown basalts can have high permeability and empirical field evidence supports, at least in part, that grey colored basalts are also present below the brown basalts. All this further complicates the question of three-dimensional distribution of preferential flowpaths feeding the springs.

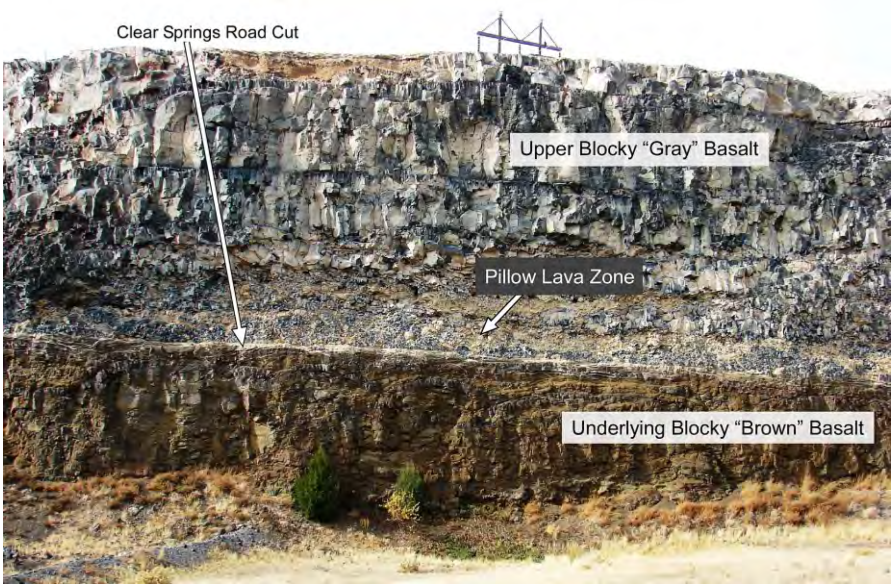
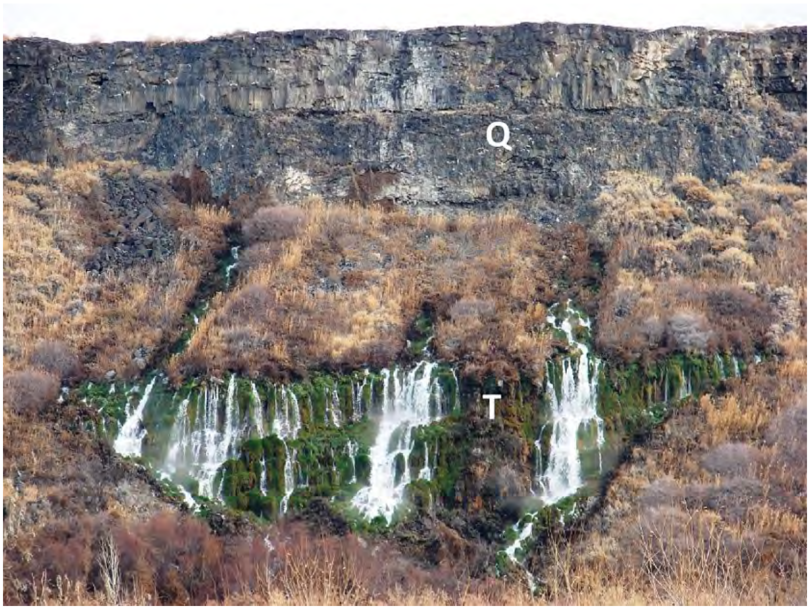


Figure 4.19 Clear Springs road cut showing Quaternary age “grey” basalt overlying less permeable Tertiary age “brown” basalt with a highly transmissive pillow lava and sediment zone in between. Modified for clarity. From Farmer and Blew, 2014.

Figure 4.20 Blind Canyon Spring waterfall over late Pliocene Glenns Ferry Formation (GFF) clay rich sediments which here form the effective base of the East Snake Plain Aquifer. The spring emerges from a highly transmissive pillow lava zone directly above GFF. Overlying the pillow lava is Quaternary blocky gray basalt starting with a notable overhang. Photographs by David Blew, from Farmer 2021.



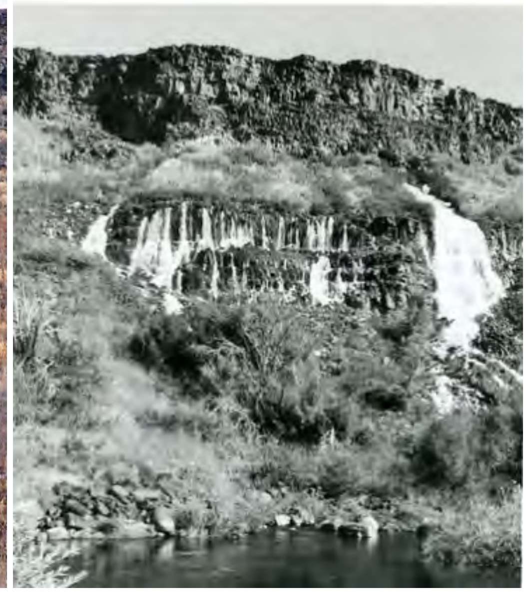


Figure 4.21 Minnie Miller Falls Springs, in Thousand Springs State Park south of Hagerman, issue from a rubble/pillow lava zone at the base of Quaternary basalt (Q) sitting over Tertiary basalt (T). A higher level of spring discharge is also visible above this contact, within the gray blocky Quaternary basalt. This level can be quite active depending on the pattern of aquifer recharge and groundwater withdrawal for irrigation as seen in the historic photograph on the right (note the far-right waterfall). Some of the primary groundwater discharge locations may be covered by talus. Left photograph and annotations from Farmer, 2021. Right photograph courtesy of WaterArchives.org (ID-Q-0006), circa 1940. Photographer: Wesley Andrews. https://www.flickr.com/photos/waterarchives/albums/72157626404379179/

4.2 Discharge Rates of Large Springs in Eastern Snake River Plain Aquifer

The section of Snake River between American Falls Reservoir and King Hill, Idaho hosts the largest concentration of first magnitude and other large springs in the country (see Figure 4.1). Although the lower river section between Milner Dam and King Hill is what most researchers and professionals think of when referring to "Snake River Springs", a significant number of large springs that are usually ignored in various discussions and publications are between Ferry Bute, located about 12 miles upstream of American Falls Reservoir, and Milner Dam. This includes at least one first magnitude and several second magnitude springs. In general, however, great confusion exists when naming and grouping springs along the Snake River, especially when it comes to famous "Thousand Springs". Even more recent publications or internet web pages still refer to all the springs downstream of Milner Dam as "Thousand Springs", sometimes citing and misquoting seemingly reliable sources.

One example of such past practices is publication by Hackett et al. (1986) which includes a graph shown here in Figure 4.22. A note on the graph states "USGS data" and the graph undoubtedly shows the discharge rate of Thousand Springs between 1902 and 1980. However, USGS never published this or similar graphs stating it is for Thousand Springs. All USGS publications about the large Snake River springs make it clear what exactly was and has been recorded for more than 100 years. Various figures in this section illustrate this, starting with Figure 4.23 published in 1992 by USGS (Kjelstrom, 1992). This USGS graph is an estimate of "*The annual average ground-water discharge (mainly spring flow) along the north side of the Snake River between Milner Dam and King Hill for the period 1902 through 1991*." Thousand Springs is only a part of this entire discharge, although a significant one as explained further.

In the late 1890s and early 1900s, the USGS, Idaho power companies and major irrigation entities started showing keen interest in the Snake River water potential. This included evaluations of the springs which were its main contributors. USGS started discharge measurements at Thousand Springs and some adjacent springs in early 1900s (see Nace et al., 1958). Discharge of Thousand Springs and many other springs was determined by subtracting upstream from downstream discharge of the Snake River reach that contains the springs. Discharge measurements of some individual springs came next, followed by establishment of official gages at major large springs including Box Canyon Springs, Niagara Spring, Crystal Springs, and others as illustrated further. Several key reports describing the geology and hydrogeology of the area, including descriptions of major springs and their discharge characteristics, were published by USGS in 1902 (Russel); 1927 (Meinzer); 1936 (Stearns et al.); 1958 (Nace et al.); 1967 (Mundorf); 1986 (Kjelstrom); 1991 (Covington and Weaver); 1992 (Whitehead et al.; Kjelstrom); 1995 (Kjelstrom); and 1996 (Lindholm). The locations of these springs are shown on various maps in the figures that follow.

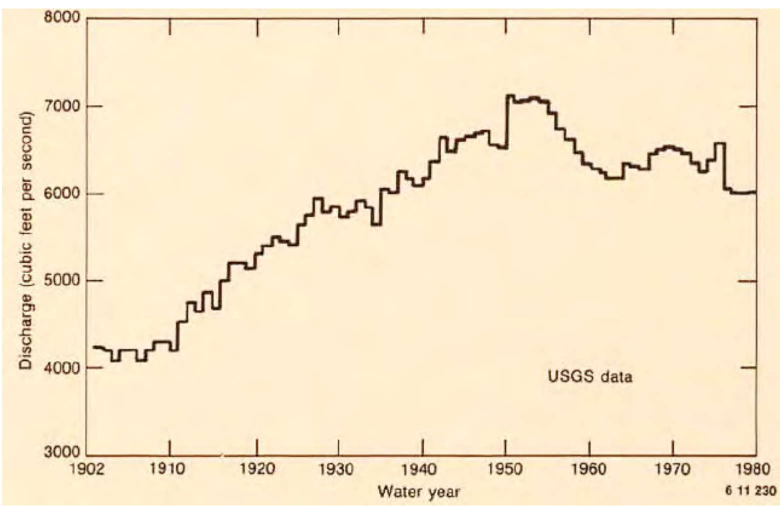


Figure 4.22 This graph is Figure 4 from Hackett et al. (1986). The caption reads: *Discharge of springs from the Snake River Plain Aquifer at Thousand Springs, showing response of the springs to irrigation diversions during the past 80 years*.

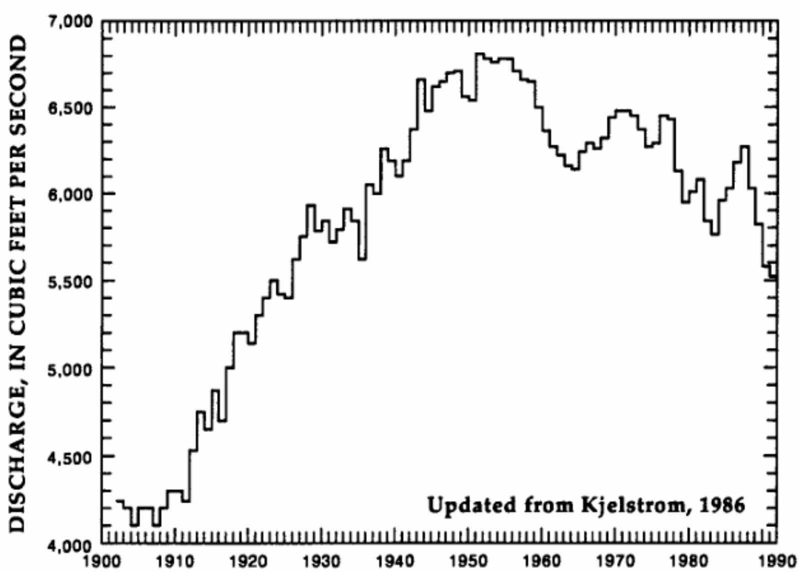


Figure 4.23 This is Figure 2 from Kjelstrom (1992; USGS) The explanation reads: *The annual average ground-water discharge (mainly spring flow) along the north side of the Snake River between Milner Dam and King Hill has been estimated for the period 1902 through 1991. Estimates of discharge for 1902-50 were based on water-budget analysis of flow in the Snake River; estimates for 1951-80 were based on discharge measurements of 10 springs that were indexed to water-budget estimates. After 1980, development of some of these springs precluded measurements of discharge. Therefore, estimates for 1981-91 were made on the basis of discharge from springs that could be measured, correlation of unmeasured with measured spring flow, and discharge records of Blue Lakes Spring and Box Canyon Springs.*

The first scientific description of the Snake River springs was by Russel of USGS in 1902. His report is a pure delight to read, and not just for geologists and hydrogeologists. It is written with engaging language, covering many aspects of the fascinating environment surrounding the Snake River. Figure 4.24 includes two photographs of and a few excerpts about the famous Thousand Springs.

Figure 4.24 "*One of the remarkable features of Snake River Canyon is the abundance of large springs which pour out from its northern wall, especially in the portion of its course between Shoshone Falls and Bliss. Perhaps the finest known exhibition of cataracts formed by springs of large volume issuing from rocks far up the faces of nearly vertical precipices is furnished at what is known as The Thousand Springs, situated on the northern side of Snake River Canyon, near the town of Hagerman, between Salmon Falls and the point where Salmon River enters from the south.*

Views of a portion of the springs, which leap from the canyon wall at this locality and descend as white sheets of foam and spray over the verdure-covered precipices below, are shown on PI. III. The more general of the two views (PL III, B; bottom photograph here on the left*) was taken before attempts had been made to utilize the springs, and indicates the natural conditions; PI. III, A (*top photograph on the left*), is from a photograph taken in August, 1901, and shows a portion of the springs where their waters had been concentrated by a flume. Most of the water descends over the face of a vertical wall of clay and lapilli from the cut edge of a layer of cellular scoriaceous basalt, which has an elevation of about 185 feet above the base of the precipice. The water does not make the descent in a single leap, but makes cascades of remarkable beauty and novelty and is churned into foam by its contact with the rocks. The volume of water has never been accurately measured, but within a space about half a mile in length at The Thousand Springs proper is estimated by Mr. A. Ferguson, a hydraulic engineer familiar with the locality, at 20,000 miner's inches or approximately 500 cubic feet per second."* (Russel, 1902).

Over the years, discharge measurements of different groups of springs within the Thousand Springs complex were performed to better understand their contributions to the overall discharge. The average discharge of the entire Thousand Springs Group is second only to Malad Springs Group in the Malad River Canyon eight miles to the north, the largest in the Nation.

Thousand Springs emerge from the pillow lava facies of the Thousand Springs Basalt contact with the Banbury Basalt as a string of springs stretching for about 3,700 feet at elevations ranging from about 3090 feet to about 2,994 feet. These springs are grouped in several main clusters but also include disconnected strings of smaller springs. This line of springs and their waterfalls continues downstream of Ritter Island and Thousand Spring proper which has caused quite a bit of confusion in the past. For example, these springs were considered part of Thousand Springs by some or were given different name(s) such as Magic Spring(s) or Bickel Springs by others. This includes the USGS which apparently changed its mind a few times as to how to name them (see Figures 4.26 through 4.29).

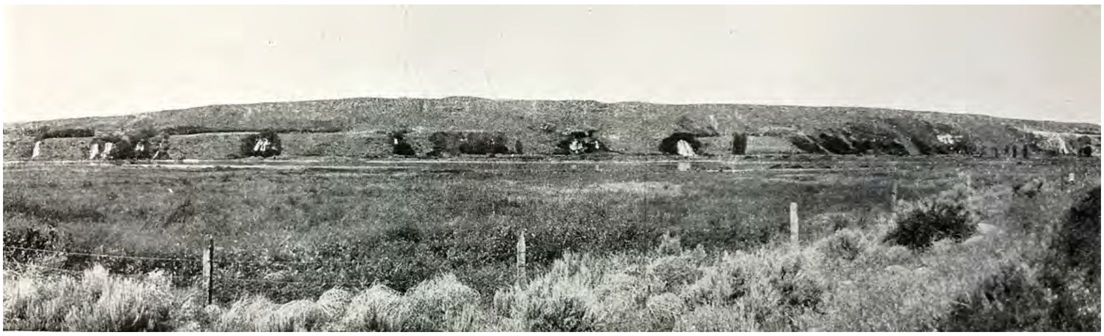


Figure 4.26 Plate 10 from Meinzer, 1927. The caption reads: *Distant view of Bickel Springs and a part of Thousand Springs, Idaho. Photograph by W.G. Hoyt. Compare map of Bickel Springs (fig 14)*. In the far right is the Thousand Springs portion used for Power Plant (the flume is marked by straight horizontal line; outlet waterfall is also visible). Second from right is Minnie Miller Spring/Waterfall. Third from right is a line of smaller springs marked by vegetation. This would be the northern end of what is today referred to as Thousand Springs, all being across Ritter Island and in Thousand Springs State Park. All other springs to the left, referred to as Bickel Springs by Meinzer, have been captured for various trout hatcheries and the entire landscape has changed to the point of non-recognition. In the far left is a group of springs referred to as “Quartette Waterfalls” in the past which now does not exist as seen on this photograph (see also Figure 4.30 in this book).

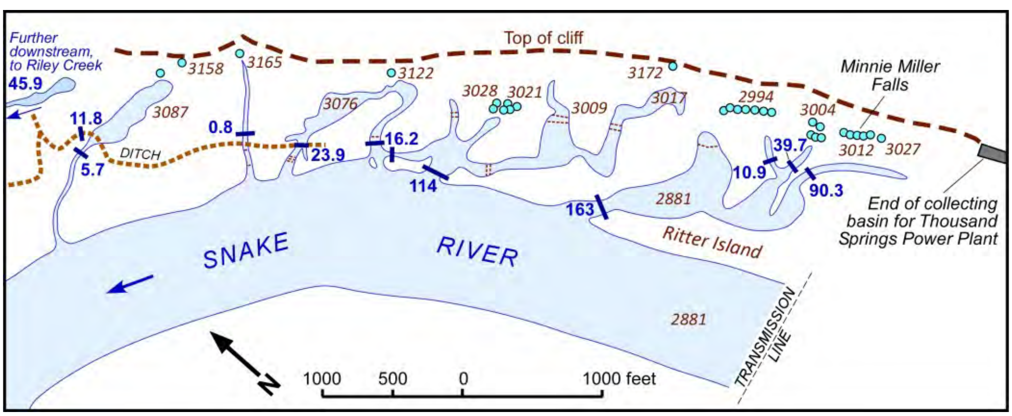


Figure 4.27 Map of springs downstream of Ritter Island referred to as *Bickel Springs* by Meinzer (fig. 14 in his 1927 publication). Modified for clarity. Brown numbers are elevations in feet above datum. Blue numbers are added from USGS Publication by Stearns et al. (1938, column 1 in table on page 163) and represent measured discharge in cubic feet per second. Group of Thousand Springs north of the Power Plant flume, including Minnie Miller Springs, collectively discharged 163 cfs when the measurements were made in July 1921. All Bickel Springs north of this group of Thousand Springs and Ritter Island discharged about 218.3 cfs including 45.9 cfs shown in the upper left which may correspond to discharge of headspring of Riley Creek located off this map. See also Plate 2 in Nace et al., 1958.

Today, USGS operates a gaging station named Bickel Spring which records the discharge rate of the headspring of Riley Creek located northwest of all the springs shown on the photograph in Figure 4.26 and in Figure 4.27. Other springs visible in the photograph in Figure 4.26 have been captured by hatcheries, are not accessible, and are not referred to as Bickel Springs today. Their remnants and outfalls from hatcheries can be best viewed from air or on satellite images as shown with Google Maps in Figures 4.28 and 4.29. On some of its maps USGS now uses name “Bridal Wreath Springs” for several springs immediately north of Ritter Island. Covington and Weaver (1991) refer to these springs as “Magic Spring”.

Figure 4.28 Google Earth Map of area shown in Figure 4.27. In the far center-right is the end of collecting basin (flume) of Thousand Springs Power Plant. Minnie Miller Spring/Waterfall is to the left of it (white inside green vegetation). Satellite image by Landsat/Copernicus acquired on June 8, 2016.

Figure 4.29 Closeup of Google Earth Map in Figure 4.28 showing remnants and outfalls of springs historically called Bickel Springs, including springs of The Quartette Waterfalls on the left, which are all utilized by fish hatcheries. Northern tip of Ritter Island is in the bottom right. Satellite image by Landsat/Copernicus acquired on June 8, 2016.

Figure 4.30 Left: Historic photograph of The Quartette Falls, circa 1930. Photographer Wesley Andrews. Courtesy of WaterArchives.org (ID-Q-0007). *Right*: Historic photograph of the Hagerman Valley and wider area of Thousand Springs, circa 1920. Photographer Wesley Andrews. Courtesy of WaterArchives.org (IDAHO-J-0014).

Discharge from the main, long continuous line of Thousand Springs is diverted into a collection flume above the Thousand Springs Power Plant (Figure 4.31). The entire flow of all the springs in the Thousand Springs group shown in Figure 4.32 has been measured in the field by USGS since 1952 (Figure 4.33). Discharge measurement is the difference between discharge measured at the Snake River upstream and downstream of the springs. Diversion from the Sand Springs Creek (Figures 4.33 and 4.34) to the power plant is included in this measurement.

Figure 4.31 *Left*: Thousand Springs flume. Springs emerge from pillow lavas of Thousand Springs Basalt at left. Flume is constructed on the Banbury Basalt. Spring water is transported by the flume to an electrical generating plant that has been in operation at this site since 1911. The photograph shows part of spring location number 1 in Figure 4.32. From Covington and Weaver, 1991. *Right*: Thousand Springs Power Plant. Q: Quaternary Thousand Springs Basalt (pillow lavas); T: Tertiary Banbury Basalt (low permeable). From Farmer, 2021.

Sand Springs rise about 250 feet above the river level, about 1.5 miles east of the Snake River. Part of the flow was used for irrigation and the rest formerly spilled over the rim rock as arguably the most striking and powerful spring waterfall on the Snake River (Figure 4.34). The entire Sand Springs Creek has since been diverted and utilized by the Thousand Springs Power Plant. Sand Spring issues from the Sand Springs basalt at the foot of a bluff of Thousand Springs basalt about 50 feet high (Stearns et al., 1938).

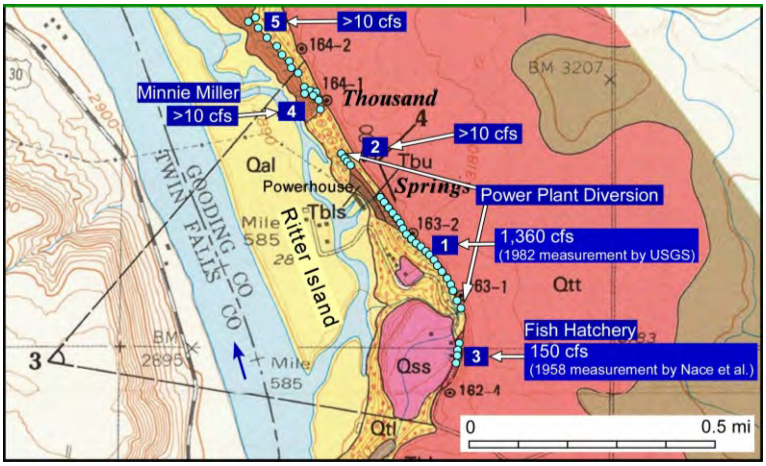


Figure 4.32 Geologic map of Thousand Springs with five distinct groups of springs and their discharge rates. Qal—Stream alluvium; Qtl—Talus; Qss—Sand Springs Basalt; Qtt—Thousand Springs Basalt; Tbu & Tbls—Banbury Basalt. From Covington and Weaver, 1991; modified and annotated for clarity.

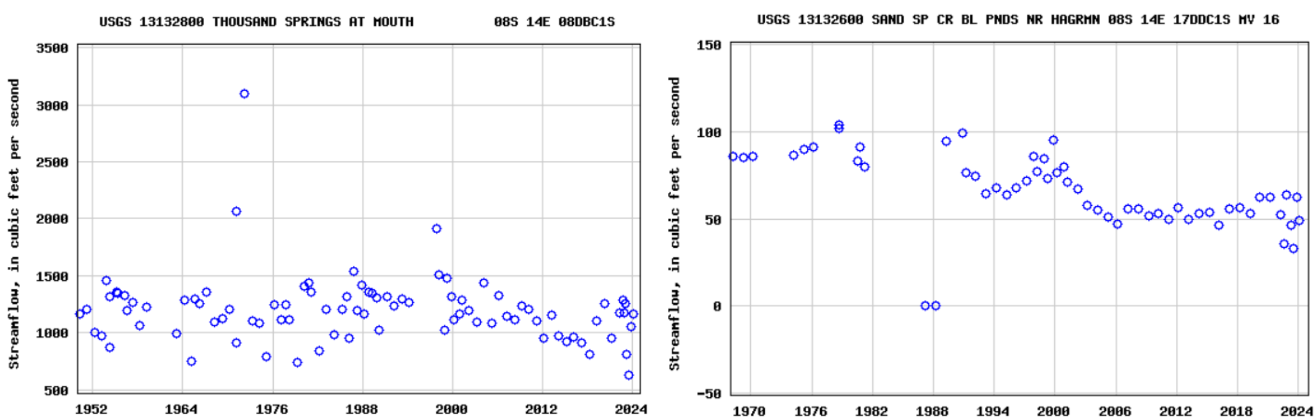


Figure 4.33 *Left*: Hydrograph of field measured discharge rate of Thousand Springs for the period of record. Average rate is 1198 cfs, including diversion from Sand Springs Creek. *Right*: Hydrograph of field measured Sand Springs Creek flow rate for the period of record. Average is 65 cfs.

Figure 4.34 Waterfall of Sand Springs Creek entering Snake River south of Hagerman, circa 1940. Photographer Wesley Andrews. Courtesy of WaterArchives.org (ID-Q-0008). Sand Springs Falls used to be the tallest and potentially most powerful of the spring waterfalls on Snake River. As the waters from Sand Springs Creek have been diverted entirely into the Thousand Springs hydroelectric system, the falls are now dry and will likely remain so until and unless major maintenance needs to be performed on the dam and / or pipe which diverts the creek.

As explained by Kjelstrom (1995), discharge from nearly all major springs along Snake River was measured or estimated in 1902 and discharge from most springs was measured in 1917 and 1924. Since 1950, discharge from many of the springs has been measured each March at the same site. For several key springs field measurements at different intervals and in different seasons are also available. Records of continuous daily mean discharge through 2024 are available for less than a handful of springs: Box Canyon Springs, Briggs Spring, and Spring

Creek Spring north of American Falls Reservoir and east of Snake River. The map in Figure 4.35 shows major springs along Snake River between Milner Dam and King Hill with reported or estimated discharge rates at various times (Table 4.1). There are also dozens of mid-size and smaller springs without any available measurements along this section of the Snake River.

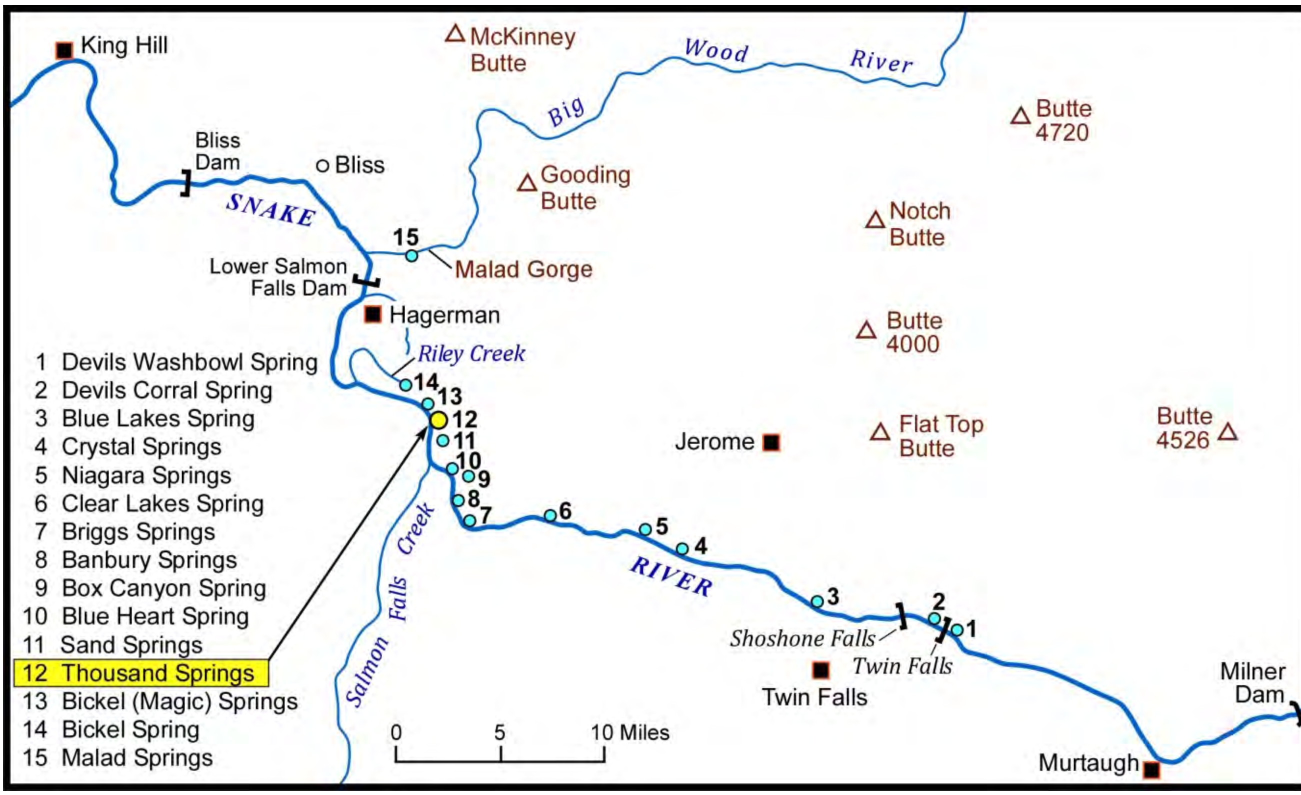


Figure 4.35 Major springs on the Snake River between Milner Dam and King Hill with reported or estimated discharge rate at various times (see Table 4.1). Modified from Covington and Weaver (1991) for clarity and to include additional springs.

Malad Springs (with Thousand Springs a close second) is the largest spring group in the country based on available data. More than twenty springs issue directly from the Malad Basalt in and near the floor of deep Malad Gorge (Figure 4.36; see also Figure 4.18). Malad Gorge is one of the units in Thousand Springs State Park (see Chapter 4.4). Discharge from spring openings above the river is visible, whereas the discharge that occurs along the floor of the river channel is apparent only as a gain in flow in the reach extending about 2.5 miles above the mouth. As explained by Kjelstrom, the discharge from Malad Springs (Figure 4.37) was computed by subtracting discharge of the Malad River near Gooding (USGS station 13152500) from the sum of discharge of the Malad River near its mouth (13153500) and discharge of the Malad River power flume near Bliss (13152940).

Irrigation-return flow estimates based on the record of W-drain near Tuttle (13152895) also were subtracted from the discharge of the Malad River near its mouth. The remainder was assumed to be discharge from Malad Springs and is subject to the accumulated error of measurement at the gaging stations. Discharge of Malad Springs was computed similarly in April-September 1899 (Nice et al. (1958), and the average discharge rate for that period was 1,148 cfs, slightly less than for the 1951-1992 period (Table 4.1 and Figure 4.37). More recent measurements of Malad Springs discharge are not readily available.

Table 4.1 Discharge rates (in cubic feet per second) of major springs along Snake River between Milner Dam and King Hill, Spring Creek Springs north of American Falls Reservoir, and Big Springs near Island Park, Fremont County.

No.	Spring Name	GPS Coordinates	Kjelstrom (1995) Average for Years 1951-1992	USGS Gaging Station Average (or limited/single measurements)	
				Period	Discharge
1	Devils Washbowl Spring	42° 35′ 23.33″ N, 114° 20′ 48.92″ W	16.3	Mar 1950-Jan 2024	14.4
2	Devils Corral Spring	42° 35′ 57.09″ N, 114° 21′ 58.46″ W	46.4	Mar 1950-Nov 2023	37.6
3	Blue Lakes Springs	42° 36′ 53.79″ N, 114° 27′ 58.87″ W	196	May 1917-Dec 1920	204
				Sep 1913-Jan 2024	186
4	Crystal Springs	42° 39′ 35.70″ N, 114° 38′ 35.18″ W	470	Mar 1950-Jan 2024	442
5	Niagara Springs	42° 39′ 55.40″ N, 114° 40′ 28.48″ W	279	Oct 1958-Sep 1972	258
				Mar 1973-Jan 2024	252
6	Clear Lakes Spring	42° 40′ 28.63″ N, 114° 46′ 24.09″ W	503	Mar 1950-Jan 2024	484
7	Briggs Spring	42° 40′ 25.88″ N, 114° 48′ 23.63″ W	109	Mar 1950-Jan 2023	105
8	Banbury Springs	42° 41′ 22.76″ N, 114° 49′ 15.71″ W	118	Mar 1950-Jan 2024	127
9	Box Canyon Headspring	42° 42′ 29.97″ N, 114° 48′ 12.00″ W	372	Apr 1950-Feb 2024	364
9	Box Canyon Springs (All)	42° 42′ 26.67″ N, 114° 49′ 09.54″ W	794	-	-
10	Blue Heart Spring	42° 42′ 39.03″ N, 114° 49′ 48.25″ W	-	Oct 1931-Jan 2024	55
11	Sand Springs	42° 43′ 33.66″ N, 114° 49′ 19.27″ W	87.2	Mar 1968-Jan 2024	65.3
12	Thousand Springs	42° 44′ 38.99″ N, 114° 50′ 24.54″ W	1,097	Mar 1950-Jan 2024	1,198
13	Bickel (Magic) Springs	42° 45′ 15.93″ N, 114° 50′ 59.84″ W	-	7/13/1921	192[a]
14	Bickel Spring	42° 45′ 39.84″ N, 114° 51′ 23.57″ W	65.2[b]	Nov 1967-Jan 2024	17.4
15	Malad Gorge Springs	42°51′ 55.42″ N, 114° 51′ 40.27″ W	1,229	Apr 1899-Oct 1899	1148[c]
Spring Creek Springs (N. of American Falls Reservoir)		43° 06′ 12.17″ N, 112° 30′ 28.45″ W	-	July 1980-Feb 2024	316
Big Springs near Island Park, Fremont County		44° 29′ 59.38″ N, 111° 15′ 18.82″ W	-	Sep 1968-Jan 2024	182

[a] Nace et al., 1958; Table 24, p. 49; Plate 2; Sections E,F&G, H, K, L. [b] Not clear which spring(s) in the group were analyzed. [c] Nace et al., 1958; Table 3, p. 15.

Figure 4.36 Discharge of always clear groundwater from springs in Malad Gorge is most obvious when the Malad River coming from upstream is muddy. Photograph from PowerPoint presentation *Hydrogeology and Dye Tracer Tests in the Lower ESPA (Malad Gorge State Park)* by Neal Farmer and David Blew, Idaho Department of Water Resources and Idaho Power, February 7, 2011.

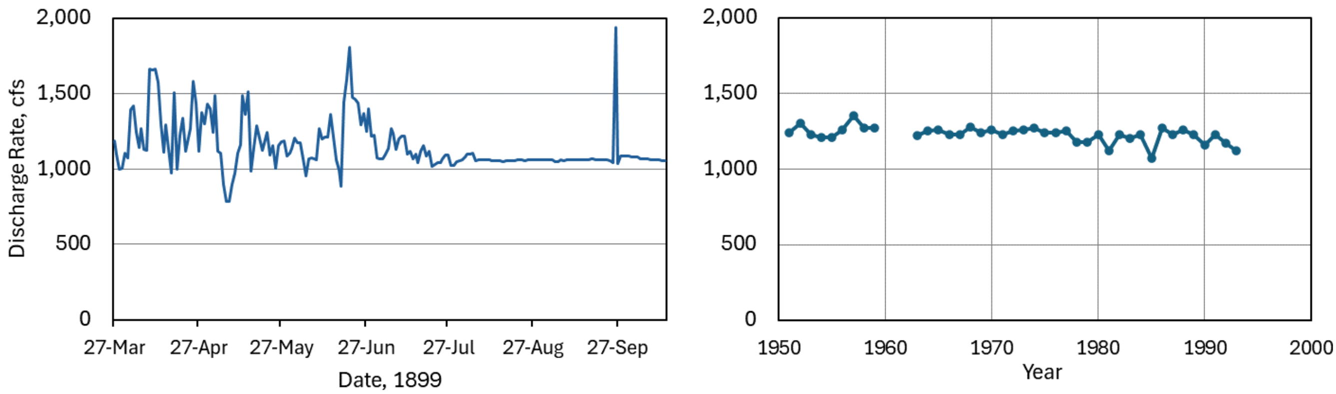
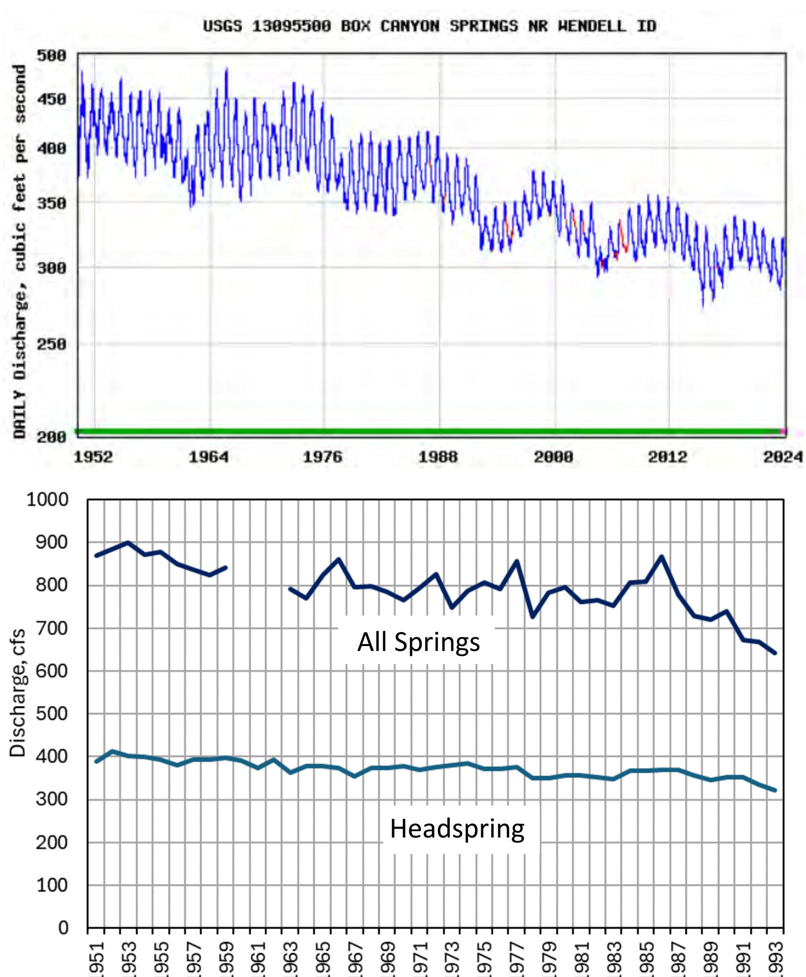


Figure 4.37 Hydrographs of discharge rate for Malad Springs in Malad Gorge north of Hagerman (see Map in Figure 4.35). Left graph data from Nace et al., 1958; Table 3, p. 15. Right graph data from Kjelstrom, 1995; Table 5, page 6.



Discharge of the headspring of Box Canyon Springs, one of the strongest and most striking individual springs in the country, has been recorded daily at the USGS gaging station 13095500 since April 1950 (Figure 4.38). As explained by Kjelstrom (1995), for many years diversion structures for trout hatcheries have prevented measuring combined total discharge of all springs in Box Canyon.

Figure 4.38 *Top*: Daily discharge rate of streamflow in upper Box Canyon corresponding to discharge rate of headspring. The average is 364 cfs. *Bottom*: Observed and calculated average annual discharge rate of handspring and all springs in Box Canyon respectively (data from Kjelstrom. 1995).

The total annual average discharge from Box Canyon springs for 1951-1993 was calculated based on the recorded discharge of headsprings and correlation between a limited number of discharge measurements from springs in lower Box Canyon and measured discharge from Clear Lakes Spring Outlet which correlated well with each other for the period before diversion.

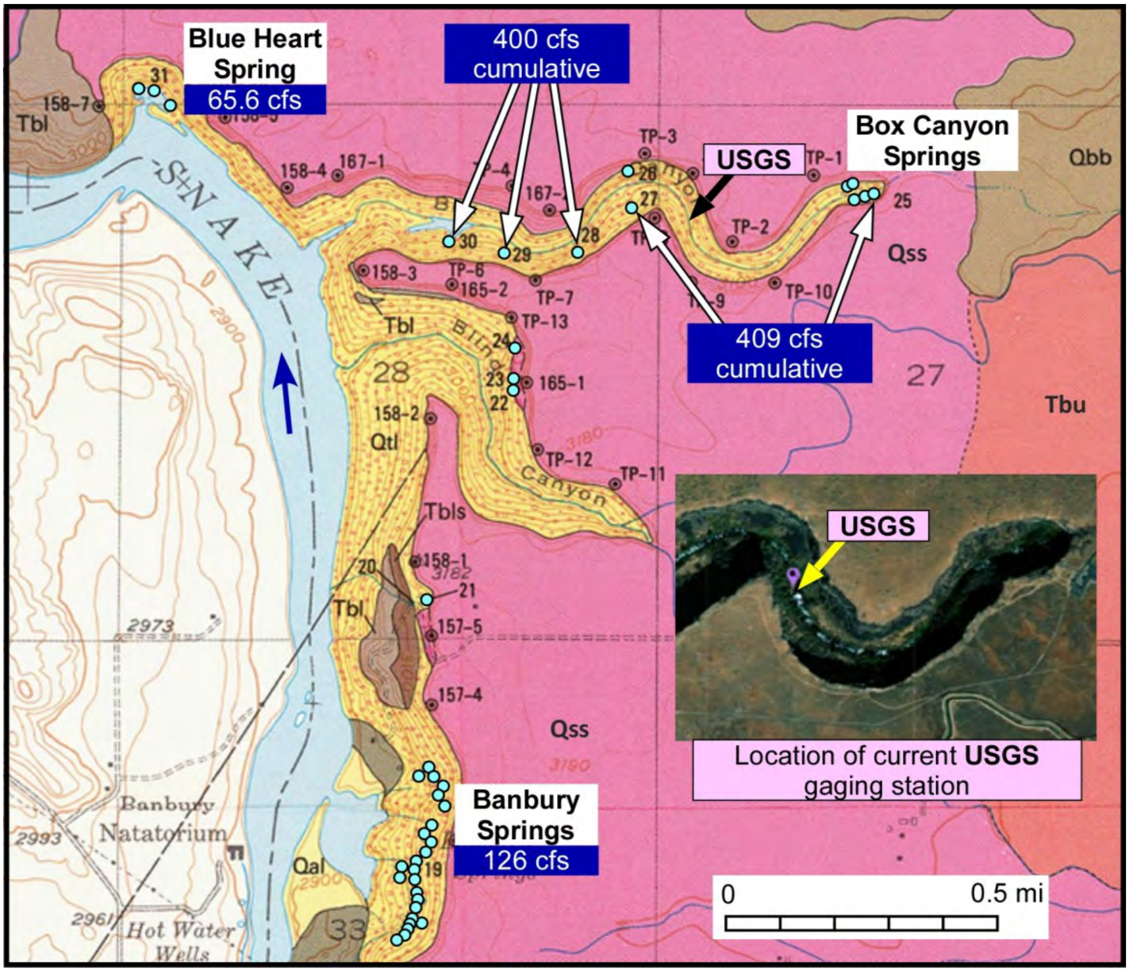


Figure 4.39 Geologic map of Box Canyon and surrounding area with discharge rates of springs reported by Covington and Weaver (1991). Qal—Stream alluvium; Qtl—Talus; Qss—Sand Springs Basalt; Qtt—Thousand Springs Basalt; Qbb—Basalt of Bacon Butte; Tbu, Tbl & Tbls—Banbury Basalt. From Covington and Weaver, 1991; modified and annotated for clarity.

Figure 4.39 shows geologic map of Box Canyon and areas of two other notable springs along Snake River, Blue Heart Spring, and Banbury Springs, together with discharge measurements reported by Covington and Weaver (1991). USGS graphs of infrequent field measurements of Banbury Springs and Blue Heart Spring discharge rates for the period of record are shown in Figure 4.40. Although these two springs have a limited number of measurements with long, multiyear gaps, it appears that Banbury Springs may not have experienced a more recent decrease in discharge rates like Blue Canyon headspring (compare Figures 4.38 and 4.40; the available data is limited for Blue Spring to make a conclusion). In contrast, most other springs along Snake River do show a similar decrease in discharge rates as illustrated with figures that follow.

The main reason for the decline of discharge rates of springs draining Eastern Snake Plain Aquifer (ESPA) is excessive groundwater withdrawal for irrigation. This is illustrated in Figure 4.41 which shows the seasonal effect of groundwater withdrawal by irrigation wells and the overall decreasing trend in both minimum and maximum recorded daily flows of Box Canyon headspring. The spring discharge is not fully recovered after the annual irrigation cycles indicating a significant removal of groundwater from aquifer storage. Another, longer, multiyear cycle is also visible on the graph in Figure 4.38-*Top*. Average duration of the full cycle of wet and dry years is approximately 8 years.

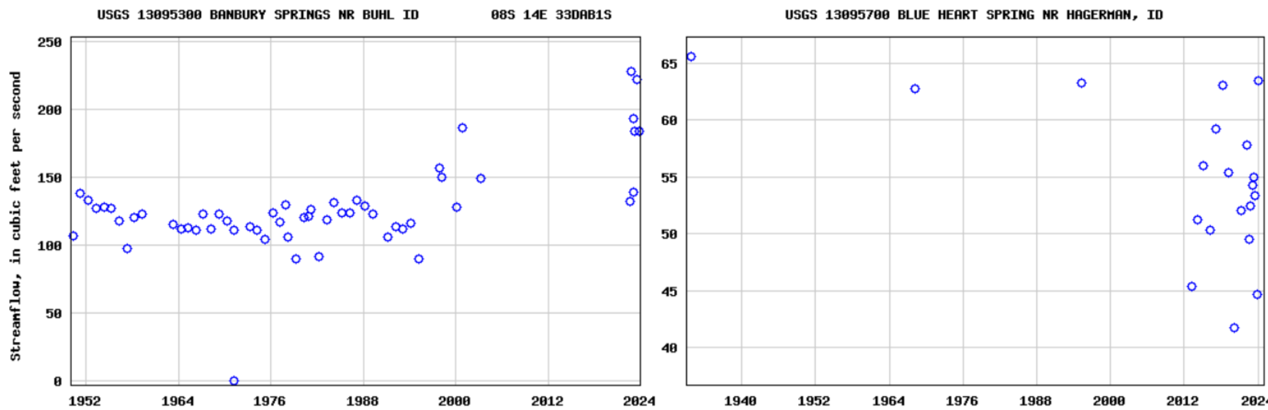


Figure 4.40 Available field measurements of discharge rate for Banbury Springs (left) and Blue Heart Spring (right). The average of all measurements is 127 cfs and 55 cfs respectively.

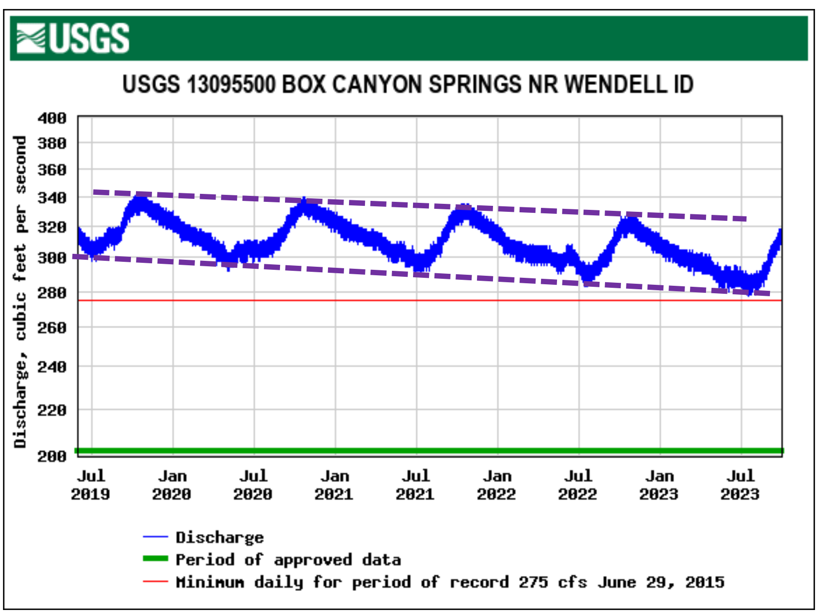


Figure 4.41 Daily discharge rate of Box Canyon headspring showing seasonal influence of groundwater withdrawal by irrigation wells. The related decrease in aquifer storage is illustrated with two dashed purple lines added to the original USGS graph for emphasis. In 4 years, the portion of the aquifer feeding the headspring lost about 2.5 billion cubic feet of water from storage, equivalent to 57,400 acre-feet.

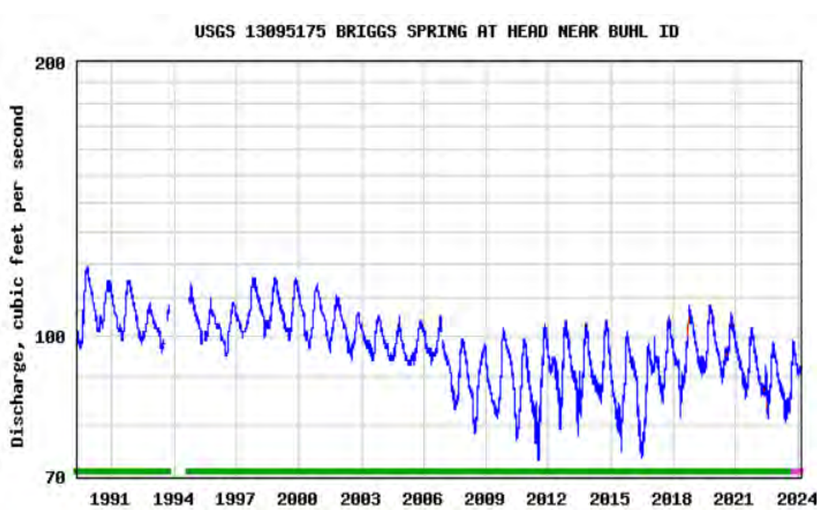
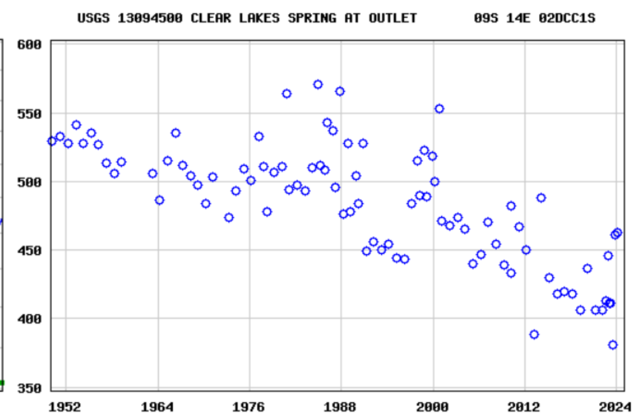


Figure 4.42 Daily discharge rate of Briggs Spring showing seasonal influence of groundwater withdrawal from the aquifer by irrigation wells, similar to Box Canyon Spring (see Figure 4.39).



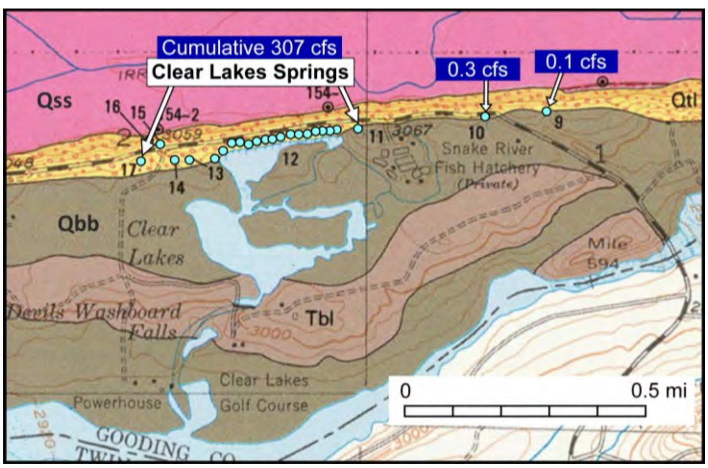
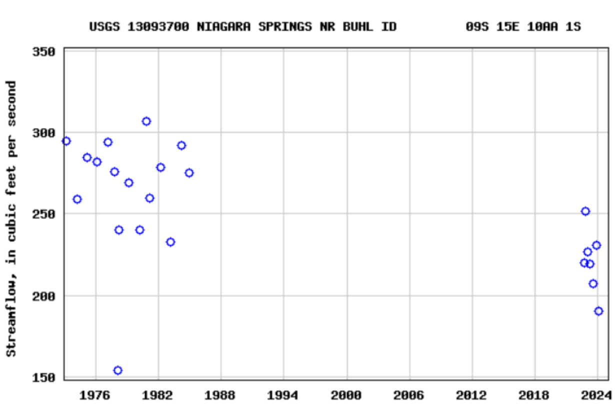
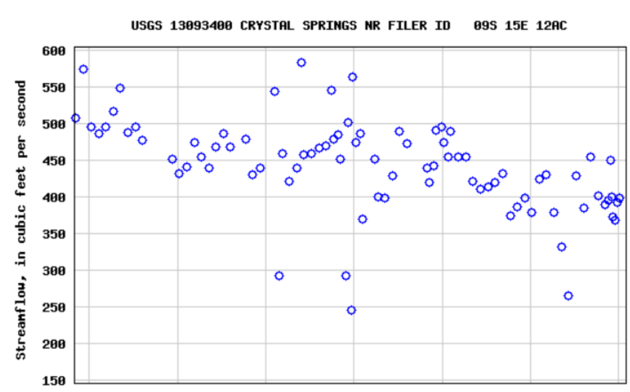


Figure 4.43 Hydrographs of discharge rates of Clear Lake Springs. *Top Left*: Daily measurements for 1917-1920; average is 489 cfs. *Top Right*: Field measurements for the period of record, March 1950-January 2024; average is 484 cfs.
Left: Geologic map of Clear Lakes Springs with discharge rates reported by Covington and Weaver (1991). Qtl—Talus; Qss—Sand Springs Basalt; Qbb—Basalt of Bacon Butte; Tbl—Banbury Basalt. From Covington and Weaver, 1991; modified and annotated for clarity.





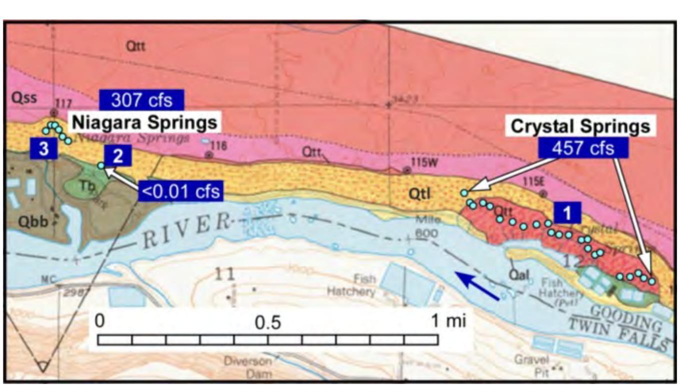


Figure 4.44 Top Left: Field measurements of Niagara Springs discharge rate for March 1973-January 2024; average is 252 cfs. *Top Right*: Field measurements of Crystal Springs discharge rate for the period of record, March 1950-January 2024; average is 442 cfs. *Left*: Geologic map of Niagara Springs and Crystal Springs with discharge rates reported by Covington and Weaver (1991). Qtl—Talus; Qtt—Thousand Springs Basalt; Qss—Sand Springs Basalt; Qbb—Basalt of Bacon Butte; Tb—Banbury Basalt. From Covington and Weaver, 1991; modified and annotated for clarity.

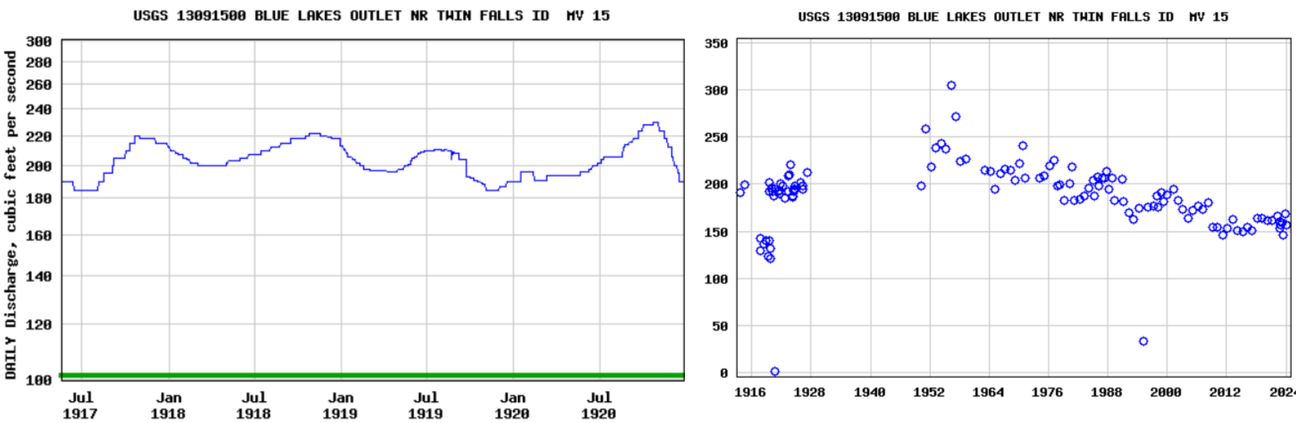


Figure 4.45 Hydrographs of discharge rates of Blue Lakes Springs. *Left*: Daily measurements for 1917-1920; average is 204 cfs. *Right*: Field measurements for the period of record, Sep 1913-January 2024; average is 186 cfs.

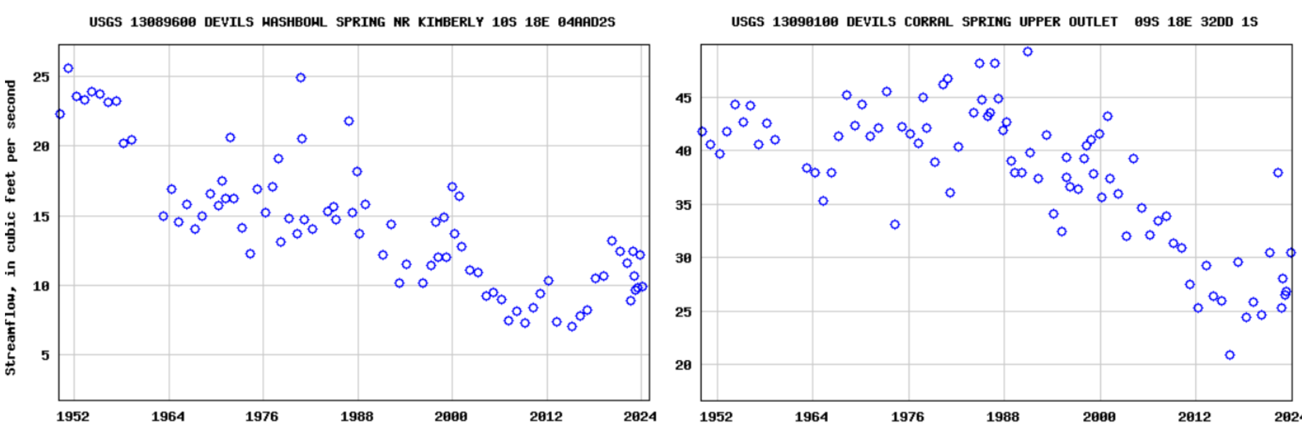


Figure 4.46 Discharge rate field measurements for the period of record, Mar 1952-January 2024.
Left: Devils Washbowl Spring, average is 14.4 cfs. *Right*: Devils Corral Spring, average is 37.6 cfs.

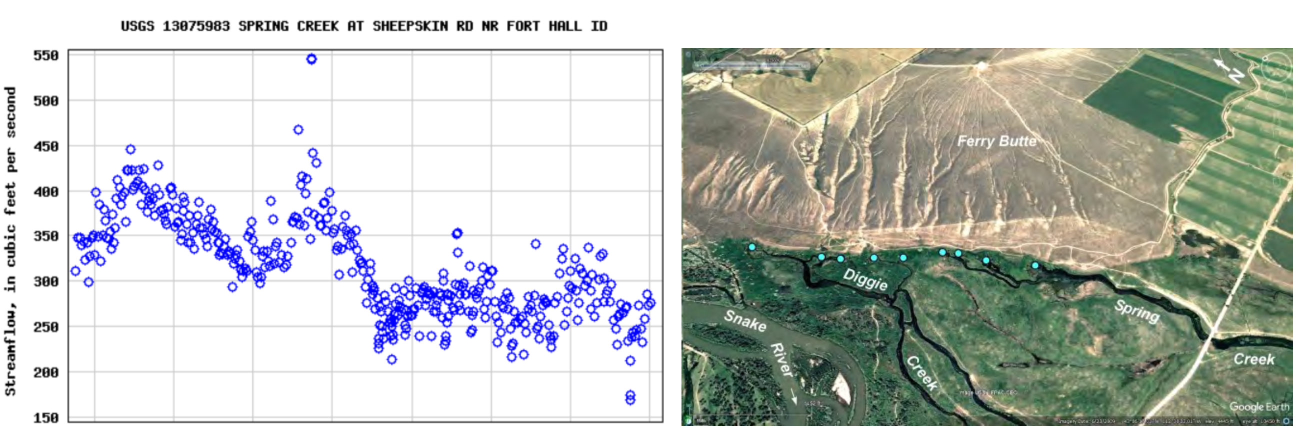


Figure 4.47 *Left*: Hydrograph of field measured streamflow of Spring Creek which originates from a group of large springs shown in the image on the right. Average is 326 cfs. *Right*: Google Earth, Oblique NE view of springs at the base of Ferry Butte north of American Falls Reservoir. Approximate distance between two springs farthest apart is 4,500 feet. Discharge of large springs that form Diggie Creek has not been measured. Aerial photograph acquired on 06/23/2009; Image USDA/FPAC/GEO. Annotation added.

4.3 Aquifer and Springs Under Threat

The highly productive Snake River Plain Aquifer is classified as a sole source aquifer by the U.S. Environmental Protection Agency, due to the nearly complete reliance on the aquifer for drinking water supplies for over 350,000 people in the area. It is also a prime example of close interactions between surface water and groundwater and their effects on discharge of the most powerful groups of springs in the world. There is a growing awareness by all stakeholders in the area and the state of Idaho that only an integrated management of both surface water and groundwater resources can solve the many tensions that exist between various users of a common, limited water resource. This includes agriculture, irrigation, aquaculture, hydroelectric power production, and public and domestic drinking water supply.

As explained in publications by the Idaho National Laboratory (INL), Radiation Control Division (2006), and Idaho Water Resources Research Institute, University of Idaho (2007), the history of the Eastern Snake Plain Aquifer (ESPA) aquifer is inexorably tied to the history of irrigation in this vast semiarid desert area (less than 10 inches of annual precipitation), now one of the agriculturally most productive in the world. Development of the arid Snake River Plain was encouraged by the Carey Act of 1894 (also known as the Federal Desert Land Act) which allowed private companies to develop irrigation systems in the western semi-arid states, and profit from the sales of water. The act was not as successful as intended, because few western states had the financial resources to make it effective. However, it was successful in Idaho which in 1908 received an additional two million acres of land to develop under the Carey Act. Today, approximately 60% of the Carey Act lands irrigated in the United States are in Idaho.

One example of successful Carey Act irrigation is Minidoka Project which, through a combination of private and federal investments, resulted in the construction of seven large dams by 1938 including Minidoka Dam, Milner Dam, and American Falls Dam, as well as an elaborate network of thousands of miles of canals, laterals and drain canals that diverted water from the Snake River and its tributaries for irrigation of more than one million acres (see Figures 4.48 and 4.49).

The Minidoka Dam was the first U.S. Bureau of Reclamation project in Idaho. Construction began in 1904 and by 1906 most of the dam's canals and laterals were finished. By 1909, Minidoka Dam's power plant, the first federal power plant in the northwest, was completed. The Minidoka Dam was initially designed and constructed without power generation facilities, but the Minidoka power plant was soon added. It was designed to generate electricity for pumping operations to support irrigation on the south bank of the Snake River. While irrigation water could flow by gravity to the north bank, water for the south bank had to be raised to a higher elevation. Excess power from the original powerplant was sold to local farmers, making the Minidoka area one of the first rural areas to have an electric power distribution system.

Figure 4.48. Minidoka Dam, historic (circa 1912) photo courtesy of U.S. National Archives and Records Administration.

Flooding fields with water is a relatively inefficient means of providing water to crops. The amount of water applied to the fields and furrows prior to more modern irrigation methods was sometimes as much as seven times what the crop could use. However, all that excess water (sometimes as much as 12 ft) applied during an irrigation season recharged the aquifer. This water became stored for later use and water levels rose substantially in some areas.

Figure 4.49 *Top*: Minidoka Project, North Side Canal near Rupert, Idaho, circa 1920. Published by Pacific Photo Co., Salem, Oregon, photographer Wesley Andrews. Courtesy of WaterArcives.org (IDAHO-E-0009 version 1). *Bottom*: North Side Canal Headgates, Minidoka Dam, circa 1915. Published by Pacific Photo Co., Salem, Oregon, Photographer Wesley Andrews. Courtesy of WaterArchives.org (ID-F-0002).

Figure 4.50 The Snake River Plain basalt-rock aquifer supplies large volumes of groundwater from great depths for irrigation. Here, a single well produces over 1,000 gallons of groundwater each minute to irrigate the surrounding fields. There are over 100 of these irrigation wells in the A&B area of the Snake River Plain where groundwater is pumped and applied to crops, and then excess irrigation water is recharged back to the groundwater. This cycle causes dissolved constituents, such as salts and nitrate, to become more concentrated. Photograph by Charles D. Hunt, USGS. From Rupert et al., 2014.

For example, groundwater levels rose from 60 to 70 ft during 1907 to 1959 in areas near Kimberly and Bliss, and as much as 200 ft in areas near Twin Falls. Across the entire aquifer, the average rise was about 50 ft. This rise in aquifer levels became most evident by the increase in discharges from the major springs along the Snake River

Although groundwater had been used for irrigation since early 1900s in some areas on the Eastern Snake River Plain, the development of powerful and efficient electric pumps allowed significant and ever-increasing groundwater use, causing many farmers to switch from surface water to groundwater (Figure 4.50). With the transition to irrigation with groundwater along with more efficient means of applying surface water to fields, less water was added to groundwater storage, and more was taken from it, resulting in a decrease of spring flows and water levels in the aquifer (see spring hydrographs in the previous section 4.2 and Figure 4.51).

As discussed by Lindholm in 1996 (similar, updated information is not readily available): *About 8.9 million acre-feet of Snake River water was diverted for irrigation during 1980 and 2.3 million acre-feet of ground water was pumped from 5,300 wells. Most irrigation wells on the eastern plain are open to basalt. About two-thirds of them yield more than 1,500 gallons per minute with a reported maximum of 7,240 gallons per minute; drawdown is less than 20 feet in two-thirds of the wells*."

Depending upon the seasonal hydrologic conditions in the river and diversions for irrigation, some reaches of the river can lose water during times of the year when the aquifer level is lower, and gain water when the aquifer level is above the bed of the river. During the growing season, and especially during dry years, the Snake River may nearly dry up before it reaches the famous Shoshone Falls, about 30 mi downstream of Milner Dam, due to irrigation diversions (Figures 4.52 through 4.54).

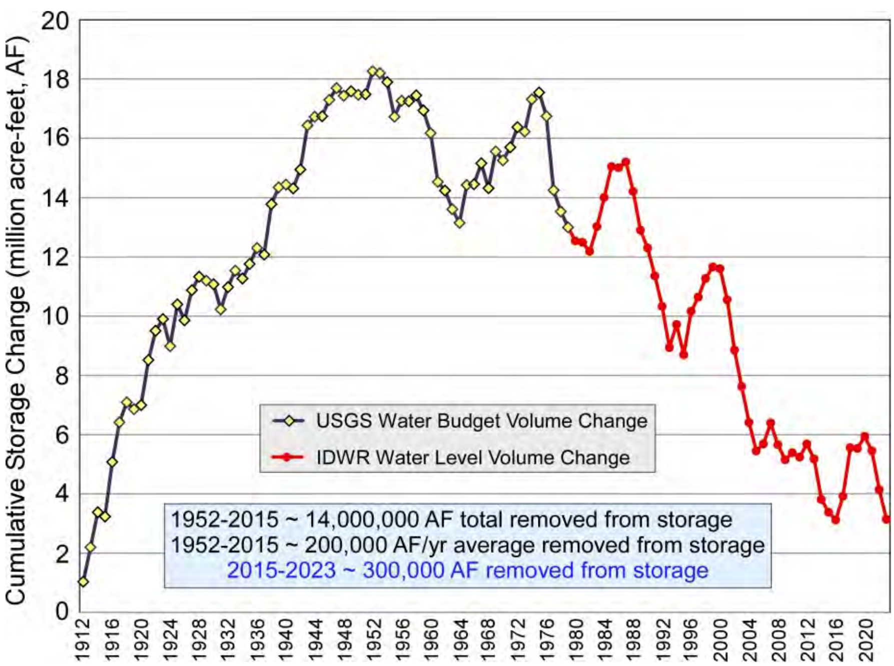


Figure 4.51 Change in volume of water stored in Eastern Snake Plain Aquifer (ESPA) estimated based on USGS water budget calculations, and changes in groundwater levels monitored by Idaho Division of Water Resources (IDWR). From McVay, 2024; modified for clarity.

Figure 4.52 Extensive irrigation canal systems divert water from the Snake River and distribute it across the Snake River Plain to irrigate fields. The Northside Canal, shown here, is located near Milner Dam where, depending on season, the entire flow from the Snake River may be diverted for irrigation. Photograph by Michael G. Rupert, USGS. From Rupert et al., 2014.

Figure 4.53 Photograph of Shoshone Falls taken in 1871, before the beginning of surface water irrigation in the 1880s. Photograph possibly by Timothy O'Sullivan, USGS, Wheeler Survey 1871 Expedition; U.S. Geological Survey Photographic Library.

Figure 4.54 Photograph of Shoshone Falls on the Snake River near Twin Falls taken in 2006 during irrigation season. Visible are powerhouse and diversion dam of the Shoshone Falls Power Plant. Courtesy of Denise Tegtmeyer.

Built in 1907, Shoshone Falls Power Plant was the first power plant in Idaho's Magic Valley. It was acquired by Idaho Power in 1916 and rebuilt in 1921. A new generation unit was installed in 2020 to replace two smaller aging generators, increasing the plant's capacity to 14,729 kilowatts.

The following excerpts from a news article by Barker (2007) illustrate the major consequence of the dwindling groundwater resources of ESPA and the question of senior and junior water rights in Idaho:

Water experts, state officials and the businesspeople and farmers at the heart of Idaho's most heated water dispute are entering their third week of testimony in a case that could dictate how the state uses one of its most precious resources in the future.

At stake is whether the state shuts off the pumps that bring water to thousands of acres of farmland, factories and towns across central and eastern Idaho. Or will fish farmers, Clear Springs Foods and Blue Lakes Trout Farm, which have lost millions of dollars due to dropping flows from the springs on which they depend, face permanent losses?

The debate turns on legal principles that have been teased out in disputes among surface water users for nearly a century. But Schroeder and the Supreme Court may plow new ground on how the law treats disputes between people who pump their water from the ground and those who get their water from springs and rivers.

The justices will have to weigh two competing sections of constitutional water law: prior appropriation—first come, first served; and the imperative to use water for its full economic development.

The primary case in surface water law upheld the constitution's prior appropriation doctrine, but the U.S. Supreme Court also ruled in favor of full economic development in 1912. In that case, Henry Schoedde was watering his crops and running a mining operation by using water wheels with buckets to take the water out of the Snake River and lift it into his canals. He sued the Twin Falls Canal Co. because its Milner Dam threatened to lower the river to a point where his water wheels wouldn't turn. The U.S. Supreme Court ruled Schoedde did not own the current in the river and could not stop others from diverting water to protect it.

Schroeder, Tuthill and the Idaho Supreme Court will have to decide whether fish farmers, who use artesian springs that flow from an aquifer that was later tapped by thousands of groundwater pumpers, are like Schoedde and his water wheels.

The dispute was eventually resolved after the two parties agreed to a mitigation plan developed by the groundwater irrigators ("Groundwater Districts"), as illustrated by the following "dry" legal language from the final order signed on March 18, 2012, by the Interim Director of IDWR Gary Spackman:

On July 8, 2005, the Director entered a final order finding that pumping by junior ground water users causes material injury to certain water rights held by Clear Springs. The order was subject to an administrative hearing, judicial review, and an appeal to the Idaho Supreme Court, which upheld the Director's decision.

Figure 4.55 The largest trout fisheries in the world are along the Snake River section between Milner Dam and King Hill. They all utilize crystal-clear, cold waters of numerous large springs. Photo courtesy of Clear Springs Foods Inc.

On March 5, 2012, the Director of the Department of Water Resources ("Director" or "Department") received a Stipulated Mitigation Plan and Request for Order ("Mitigation Plan") filed jointly by counsel for Clear Springs Foods, Inc. ("Clear Springs") and the Ground Water Districts ("GWD").

Having reviewed the Mitigation Plan, the CM Rules, and the proceedings herein, the Director approves the Mitigation Plan. CM Rule 43.03. ORDER Based upon and consistent with the foregoing, IT IS HEREBY ORDERED as follows: The Mitigation Plan entered into between Clear Springs and the GWDs is APPROVED.

As the above lawsuit was progressing, and highly likely because of it, Idaho Water Resources Board (IWRB) developed Eastern Snake River Plain Aquifer Comprehensive Aquifer Management Plan (CAMP; **https://idwr.idaho.gov/IWRB/water-planning/CAMPs/ESPA/**). Below are excerpts from the Plan illustrating a quantum leap the State of Idaho made regarding water rights and management of water resources as compared to all other Western states where "First Come First Serve" principle is still the law of the land.

The ESPA is a key element of southern Idaho's economy and covers approximately 10,800 square miles of Idaho. The ESPA region produces approximately 21% of all goods and services within the State of Idaho—resulting in an estimated annual value of $10 billion. Water is the critical element for this productivity.

For a variety of reasons, groundwater levels in parts of the ESPA declined, leading to a cumulative decrease in aquifer storage, decreased spring flows, and changing Snake River flows that resulted in insufficient water supplies to satisfy existing beneficial uses. IWRB, at the request of the Idaho State Legislature, prepared and submitted a Comprehensive Aquifer Management Plan to address the water supply-and-demand imbalance.

The goal of the Plan is to: "Sustain the economic viability and social and environmental health of the Eastern Snake Plain by adaptively managing a balance between water use and supplies."

The Plan establishes a long-term program for managing water supply and demand in the ESPA through a phased approach to implementation, together with an adaptive management process to allow for adjustments or changes in management techniques as implementation proceeds.

The Plan sets forth actions which stabilize and improve spring flows, aquifer levels, and river flows across the Eastern Snake Plain.

The objectives of the Plan are to:

1. Increase predictability for water users by managing for a reliable supply.
2. Create alternatives to administrative curtailment.
3. Manage overall demand for water within the Eastern Snake Plain.
4. Increase recharge to the aquifer.
5. Reduce withdrawals from the aquifer

Phase I includes site-specific implementation actions based on the anticipated hydrologic effect of those actions, as outlined in Section 3.2.1. The water budget adjustment mechanisms include:

A. Ground water to surface water conversions.

B. Managed aquifer recharge.

C. Demand reduction, including:

- *1. Surface water conservation.*
- *2. Crop mix modification in the Aberdeen/ Bingham groundwater district.*
- *3. Buyouts, buy-downs, and/or subordination agreements.*
- *4. Rotating fallowing, dry-year lease agreements, and Conservation Reserve Enhancement Program (CREP) enhancements.*

D. Pilot weather modification program.

E. Minimizing loss of incidental recharge.

2.3 Consequences of Inaction

The continued viability of irrigated agriculture, aquaculture, industry, hydropower, municipalities, future development, domestic uses and environmental resources will be adversely impacted if the current water supply trends continue on the ESPA. Implementation of the Plan is expected to change these trends and help protect the economic viability of Idaho as a whole. Without increased precipitation and an adaptive plan to manage a balance between water use and supply in the ESPA, the following scenarios are expected:

- *An escalation of conflict between water users.*
- *Increased litigation.*
- *Increased likelihood of ground water curtailment.*
- *Limited opportunities for community growth.*
- *More expensive water for industries and increased power costs, resulting in limited opportunities for economic and community growth.*
- *Adverse impact to the health of the state economy.*

The State of Idaho and the Board, by implementing a collaborative approach to water management, have demonstrated that different interests that depend on the aquifer, springs, and the river can work together to develop *a comprehensive water management plan. Therefore, it is essential that the State and the Board continue to provide direction and financial support to implement the Plan.*

In an article by Rachel Cohen, Environment and Outdoors Reporter for *Boise State Public Radio News*, published July 13, 2020, one can read the following excerpts about the first visible results of CAMP (https://www.boisestatepublicradio.org/news/2020-07-13/five-years-after-water-rights-agreement-idahos-largest-aquifer-is-improving)

Five Years After Water Rights Agreement, Idaho's Largest Aquifer Is Improving

Another important component of the plan to rebuild the aquifer was the state agreed to recharge an average of 250,000 acre feet a year into the aquifer — more in wet years and less in dry years — at sites like the one Olmstead visited in March (see Figures 4.56 and 4.57 in this book).

Five seasons later, water levels in the Eastern Snake Plain Aquifer have started to come back up. Partly because they've been good precipitation years, Patton of the water resource board said, and partly because the state and other partners have rallied around aquifer recharge, bringing the money to the table to make it happen.

"This is pretty unique and pretty historic and is really kind of at the forefront of integrated groundwater and surface water management movement in the West," Patton said.

It's something other states could learn from, too, said Michael Kiparsky, who runs the Wheeler Water Institute at the Center for Law, Energy & the Environment at the UC Berkeley School of Law. Kiparsky is looking at the Eastern Snake Plain Aquifer as an example of how Western states can manage groundwater.

"They have managed to reconcile an incentive for recharge at very large scale," he said.

Part of what sets Idaho apart, Kiparsky said, is the state has recognized in law for more than 20 years the hydraulic connection between groundwater and surface water, or the Eastern Snake Plain Aquifer and the Snake River.

"That is the lynchpin for why [the Eastern Snake Plain Aquifer] is an interesting case, and why it's a more holistic water management solution than you see in other places in the West," Kiparsky said.

Figure 4.56 Photo of a Managed Aquifer Recharge (MAR) basin on the ESPA, Mile Post 31 behind the Milner-Gooding Canal from April 2019. Mile Post 31 (MP31) is one of the major first milestones of the IWRB's MAR program. The IWRB partnered with AFRD#2 to construct the MP31 site completed in 2013. The original turnout structure was designed for 200 to 250 cfs. Using this structure only inundated approximately half of the available basin. In 2016 a second turnout structure was constructed consisting of an obermeyer weir and headgate structure. This allows for water to be raised in canal and diverted into the basin. The site can infiltrate upwards of 650 cfs of water. Due to canal improvements at the MP28

hydroelectric plant, recharge can occur during the coldest parts of the winter, a major hurdle for winter recharge in Idaho. IWRB maintains an informative webpage dedicated to MAR including real-time updates and monitoring data: **https://iwrbrecharge-idwr.hub.arcgis.com/**.

Rachel Cohen's article **Water levels in the Eastern Snake Plain Aquifer are back down** published July 27, 2023 by *Boise State Public Radio News* (https://www.boisestatepublicradio.org/news/2023-07-27/water-levels-in-the-eastern-snake-plain-aquifer-are-back-down) is reflecting a harsh reality of limited groundwater resources availability and their management in the desert environment as illustrated with the following excerpts:

In the first few years after the 2015 ESPA agreement, aquifer levels began to climb. A few snowy winters helped, plus the state set a goal of sending an average of 250,000 acre-feet of Snake River water back into the aquifer each year to revive it, with funding from the legislature. Farmers who rely on groundwater also agreed to reduce their pumping.

Now, after a few years of severe drought, the aquifer has dropped once again, and is currently about 300,000 acre-feet below 2015 levels, according to well measurements taken by the Idaho Department of Water Resources this spring.

Last year alone, the aquifer lost one million acre-feet of water, Mike McVay, a hydrologist for IDWR, told board members this week.

"It's painful," he said. "But that's where we're at."

Water managers emphasize that the 2015 agreement's recharge and pumping reduction efforts have prevented a worse scenario.

"It's significantly better than what it would have been if we hadn't done all the work that's been done," Wesley Hipke, who manages ESPA recharge for IDWR, said in an interview.

Still, the dry years have meant benchmarks intended to reverse the aquifer's decline are not being met.

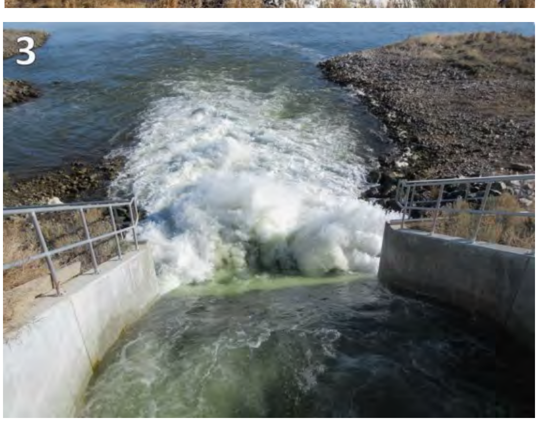


Figure 4.57 MP31 MAR site. (1) View from the headgate of a full basin. (2) Obermeyer weir fully deployed and some water flow past towards Shoshone MAR Site 3. (3) The headgate drop into the basin. Courtesy of IDWR.

4.3.1 Another Kind of Threat

As discussed by USGS (Rupert et al., 2014) and the Idaho Conservation League (2019 and 2021), the Eastern Snake Plain Aquifer (ESPA) and its magnificent springs are facing an equally serious threat with the depletion of groundwater for various uses—worsening water quality.

Of the various land uses in the Snake River Plain, urban and agricultural land use have the greatest potential to adversely affect groundwater quality. The quality of groundwater underlying urban land can be affected by chemical leaks and spills, leachate from landfills, pesticide and fertilizer use, and wastewater disposal. The quality of groundwater underlying agricultural land can be affected by the leaching of fertilizer, manure, and pesticides applied at the land surface (Figures 4.58 through 4.62). Crop rotation, tillage practices, and irrigation practices can affect groundwater quality by either promoting or reducing the leaching of contaminants to the groundwater (Rupert et al., 2014).

The high crop productivity in the Snake River Plain is possible only through irrigation. Crop irrigation is the dominant use of surface and groundwater in the area. Some of this irrigation water is applied to fields more than what is needed by plants, so the excess water infiltrates down to the water table, potentially carrying nitrate, phosphorus, and pesticides with it.

Rapid growth of Idaho's dairy industry is one of the key drivers affecting groundwater quality. Over the past several decades, Idaho has become the third largest milk-producing state in the country (Lauer et al., 2018). Since 1980, the number of dairy cows in Idaho has increased substantially, from 148,000 head in 1980 to 646,000 in 2021. Roughly 470,000 of these dairy cows are in the Magic Valley region (USDA, 2021).

Various state and federal regulations pertaining to fertilizer and waste management apply to dairies, feedlots, and other agricultural operations. But these efforts have not prevented growing contamination of groundwater in Magic Valley. Despite regular environmental inspections of Idaho dairies and feedlots, a glaring loophole still exists where dairies can "export" their waste to third-party fields that avoid waste management requirements. (Idaho Conservation League, 2021).

Figure 4.58 Irrigation by groundwater (center-pivot systems) and dairy farms in the Snake River Plain. Photographs courtesy of Ecoflight.

Regardless of existing industry regulations, the sheer volume of manure produced every day in the Magic Valley ultimately hinders efforts to disperse and properly dispose of that massive amount of waste. In many areas of the Magic Valley, the combined nitrogen and phosphorus input from fertilizer and animal waste far exceeds what typical crops can uptake, with the remaining nitrogen and phosphorus available to leach into surface and groundwater (Hirsh and Weil, 2019).

Figure 4.59 *Left*: Typical Jerome County dairy farm with large piles of animal waste. From Gillerman and Schiappa, 2001. *Right*: Spreading (land application) of manure-based fertilizers can be an agricultural source of pathogens and nutrients to groundwater. Photograph by Laboratory for Infectious Disease and the Environment, USGS.

Figure 4.60 *Left*: This makeshift chemigation system supplies fertilizers and pesticides to irrigation water pumped by this large-capacity irrigation well. The water is then applied to the fields. Groundwater contamination can occur if a backflow preventer is not properly installed in the chemigation system or if the chemicals are applied at rates in excess of what the plants can use. *Right*: Ammonia nitrogen fertilizer is injected into irrigation water in the A&B area of the Snake River Plain, as indicated by the gray discoloration of the water. The concrete ditch conveys water to the fields where it irrigates and fertilizes the crops. Excess irrigation water can infiltrate to groundwater, carrying dissolved nitrogen with it. Photographs by Michael G. Rupert, USGS. From Rupert et al., 2014.

Concentrated animal feeding operations (CAFOs), where animals are kept and raised in confined areas, abound in the Snake River Plain area. CAFOs congregate animals, feed, manure and urine, dead animals, and production operations. They can pose various risks to groundwater quality and public health, mainly because of the amount of animal manure and wastewater they generate. Animal feedlots often have impoundments from which wastes may infiltrate into groundwater (Figures 4.58, 4.59, and 4.61). Livestock waste is a source of nitrate, phosphorus, and ammonia, pathogens including bacteria (e.g., *E.coli*), antibiotic-resistant bacteria, viruses, protozoa (e.g., *Cryptosporidium* and *Giardia*), hormones, antibiotics, total dissolved solids (TDS), heavy metals such as zinc and copper, and sulfates (CDC, 2024; Kresic, 2009).

The ESPA is especially susceptible to contamination compared to most other aquifers due to both geologic and human factors (Rupert et al., 2014):

1. Geologic Characteristics. The same characteristics that make the ESPA such a voluminous aquifer – well-drained soils and permeable volcanic rock – also make it susceptible to contamination. The high permeability of the aquifer, which stems from the fractured and porous nature of the basaltic rock, gives contaminants fast pathways into the groundwater system.
2. Irrigation techniques. Excess irrigation water applied to fields seeps into the groundwater, carrying nutrients and chemicals with it. That shallow groundwater is often withdrawn again and reapplied to the fields, which further concentrates nitrates and other dissolved constituents.
3. Young Groundwater Age. The average age of groundwater in the ESPA is only 15 years (Plummer et al., 2000). Young groundwater is more susceptible to contamination because most contaminants are associated with human activities that came into practice within the last 60 years.
4. Oxic Conditions. Groundwater in the ESPA typically displays oxic conditions, meaning it contains at least 0.5 mg/L dissolved oxygen (Rupert et al., 2014). In oxic conditions, nitrate is unlikely to break down into inert nitrogen gas and can therefore persist for decades in the groundwater system (Dubrovsky et al., 2012).

Figure 4.61 Aerial view of a large dairy in Magic Valley. Photo courtesy of EcoFlight.

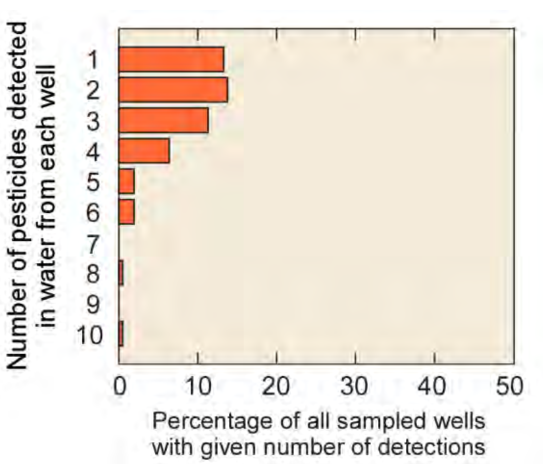


Figure 4.62 Number of individual pesticides in water from wells sampled in Snake River Plain Aquifer. Pesticides most commonly occur in groundwater as mixtures—detections of two or more pesticides in a sample were more common than detection of just one pesticide. It is unknown what the health effects might be from drinking water with mixtures of pesticides because health-based standards are based on individual compounds. From Rupert et al., 2014.

Pesticides simazine, metribuzin, metolachlor, and prometon were detected in groundwater from the Snake River Plain Aquifer. These pesticides are used on row crops including alfalfa, cereal grains (barley, oats, and wheat), potatoes, and corn. Broad-spectrum herbicides, such as atrazine, that are used on many crops in many different areas of the United States were detected frequently in groundwater from the Snake River Plain Aquifer. Samples from 37 percent of all wells contained two or more pesticides (Rupert et al., 2014; see Figure 4.62).

Toxicologists have evaluated the health risks and established drinking-water regulations for many individual chemicals, but risks associated with mixtures of chemicals are far less known and, in some cases, may be greater than those of individual chemicals (Bartsch et al., 1998; Carpenter et al., 1998).

As discussed by Idaho Conservation League (ICL, 2021), the available groundwater data for the ESPA clearly indicates that nitrate contamination continues to be a significant, widespread issue affecting the drinking water resource. In the ICL analysis of all publicly available nitrate monitoring well data for the Magic Valley (Gooding, Twin Falls, Lincoln, Minidoka, Jerome, and Cassia counties) going back to 2001, 73% of all well samples had nitrate concentrations greater than background levels (>2 mg/L), including 38% of samples above 5 mg/L.

Particularly worrisome are the ICL's highlights of several USGS reports: *Based on numerical modeling simulations, a 2012 USGS report concluded that current hotspots of high nitrate concentrations (8-12 mg/L), such as southwest Minidoka County and northern Twin Falls and Cassia counties, will continue to increase in severity (Skinner and Rupert, 2012). Paradoxically, areas of high nitrogen input, such as western Jerome County and southern Gooding County, will continue to have relatively low nitrate concentrations (<2 mg/L) because of consistent upwelling of low-nitrate groundwater in these areas (Skinner and Rupert, 2012;* see Figure 4.63*). USGS numerical model simulations of nitrate in the ESPA indicate that it will take 40 to 50 years for concentrations to fully respond to the effects of drastically increased nitrogen inputs in recent decades (Skinner and Rupert, 2012). Thus, even if nitrogen inputs were held constant for the next several decades, concentrations would continue to increase for a significant amount of time before eventually leveling off (Skinner and Rupert, 2012). This same study also showed that if all agricultural nitrogen input was stopped immediately, nitrate concentrations would begin to decline in five to 10 years. This phenomenon highlights the notable lag time between land use activities and changes in groundwater quality (Rupert et al., 2014).*

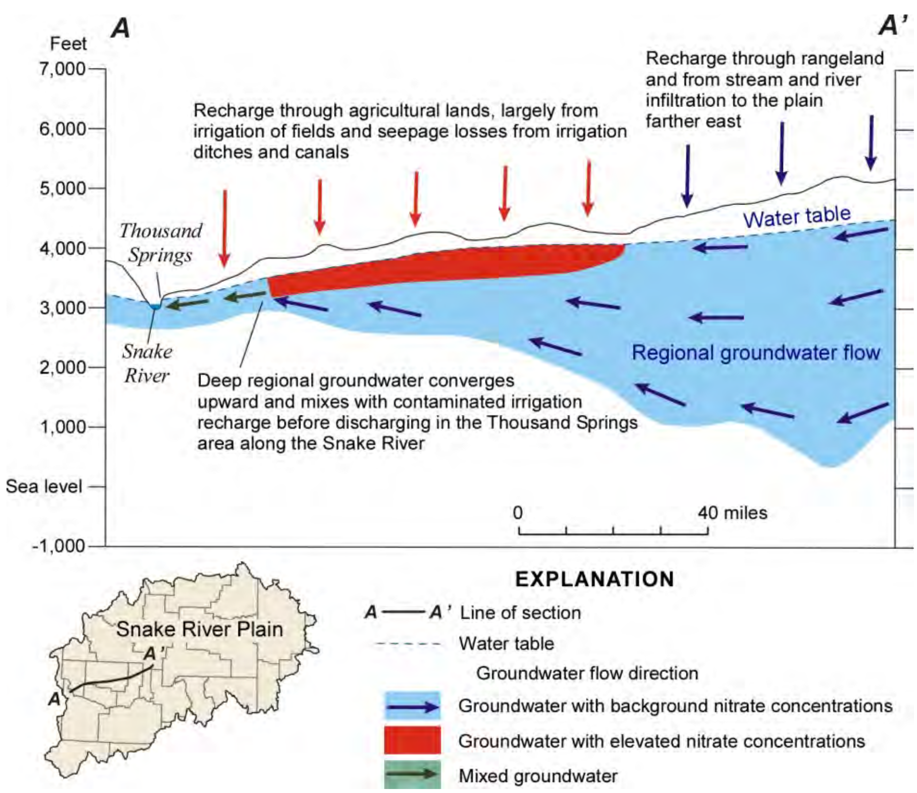


Figure 4.63 The Eastern Snake River Plain basalt aquifer thins to the west toward the Thousand Springs discharge area. As groundwater flows to the southwest in Jerome and Gooding Counties, Idaho, deep groundwater with low nitrate concentrations moves upward, mixing with and diluting nitrate-rich recharge from overlying agricultural lands. From Rupert et al., 2014.

The schematic of groundwater flow and nitrate migration shown in Figure 4.63 is applicable to Box Canyon headspring, which discharges from the regional groundwater flow system. The spring has the lowest nitrate concentration and the smallest annual fluctuation in nitrate concentration of the five springs analyzed by Baldwin et al. (2006): Box Canyon Spring, Niagara Spring, Crystal Spring No.1 and No.2, and Snake River Farm Springs. Box Canyon Spring, which is downgradient of the highest density of dairies in the study area, is the only spring with long-term nitrate data from the regional ground water flow system. The small annual fluctuations and low nitrate concentrations are most likely due to greater dilution (larger volume of water flowing through the aquifer) compared to smaller flow volumes moving through the local flow system.

Generally high-quality, snowmelt-derived water naturally recharges the aquifer, eventually mixing with lower quality groundwater closer to the Snake River. This reduced-quality groundwater (indicated in red on Figure 4.63) derives mainly from human-recharged, agriculturally-impacted water with elevated concentrations of nitrogen. North of the Snake River, mixing of the shallow, high-nitrate groundwater with the deeper, low nitrate groundwater occurs as the aquifer thins with increasing proximity to the river (Rupert et al., 2014). Without this mixing which forces the higher quality groundwater to the surface, nitrate concentrations would be even higher than are currently observed in the ESPA (Skinner and Rupert, 2012).

In 2017, the USGS published a report on groundwater quality in Jerome and Gooding counties. USGS researchers took groundwater samples from 36 wells and analyzed several constituents, including nitrate. The data showed generally increasing concentrations with increasing proximity to the Snake River (Figure 4 in Skinner, 2017), consistent with expected concentration patterns based on groundwater flow dynamics. Nitrate concentrations above 2 mg/L were widespread in southern Jerome County and southeastern Gooding County, with an isolated maximum of 9.93 mg/L (Skinner, 2017).

As discussed by ICL (2021), *The growing body of epidemiological evidence linking nitrate in drinking water with a myriad of human health problems, other than blue-baby syndrome, raises troubling questions about whether the current drinking water standard protects the general population (Temkin et al., 2019). A comprehensive 2018 review of drinking water nitrate and human health found that a large body of epidemiological research supports a connection between the presence of nitrate in drinking water and an elevated risk of colorectal cancer, adverse birth outcomes, and other health impacts, such as thyroid disease (Ward et al., 2018). Many cancer risks do not have an absolute threshold value, but the risk rises as the carcinogen level (in this case, nitrate concentrations) rises.*

Crucially, many of these studies observed increased risk of health conditions with nitrate levels below the regulatory level of 10 mg/L (Ward et al., 2018). Given that the nitrate drinking water standard of 10 mg/L was developed in 1962 specifically for blue-baby syndrome, this standard should not be viewed as any sort of "magic number" by the general public or by the regulatory agencies. Quite often, we find that health officials downplay elevated nitrate levels in the Magic Valley because they do not exceed the 10 mg/L standard.

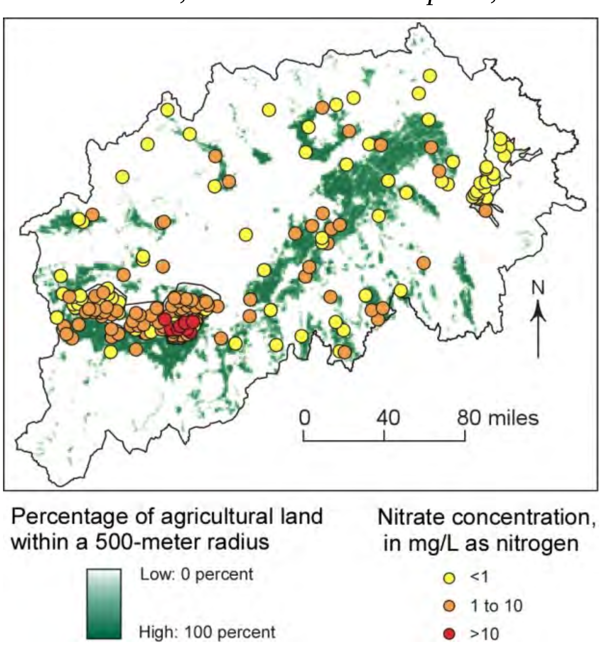


Figure 4.64 Elevated nitrate concentrations in groundwater coincide with agricultural areas in the Snake River Plain. From Rupert et al., 2014; modified for clarity.

Phosphorus concentrations have shown a notable upward trend during recent years in various springs fed by ESPA (e.g., see Figures 4.65 and 4.66). Although it is too early to tell if this is a long-term trend, it is reasonable to expect these increases to continue given ongoing land-use practices. In addition, more evidence suggests that continued phosphorus loading from animal waste and other sources could be saturating soils in different areas of the Magic Valley (ICL, 2021). Soil saturation prevents phosphorus adsorption and leads to increased leaching of dissolved phosphorus into the groundwater (Lentz et al., 2018). Previous studies have shown that once phosphorus leaching zones develop, they can have long-term, negative effects on groundwater quality. And that it can take several decades to return to compliant water quality standard levels (Schoumans and Groenendijk, 2000; Sharpley et al., 2013).

The presence of phosphorus in drinking water is not known to have direct human health effects. However, phosphorus in the ESPA contributes to the overall rise of phosphorus concentrations in the Snake River. The overabundance of phosphorus in the Snake has contributed to the formation of harmful algal outbreaks, particularly in the numerous slow-moving reservoirs along the length of the river. (Higgins et al., 2017). In some circumstances, harmful algal outbreaks can produce toxins that cause a variety of illnesses in humans (Fleming et al., 2002). Outbreaks of harmful algae on the Snake River and its reservoirs regularly result in closures of swimming areas and present dangers to humans, animals, livestock, and pets (ICL, 2021).

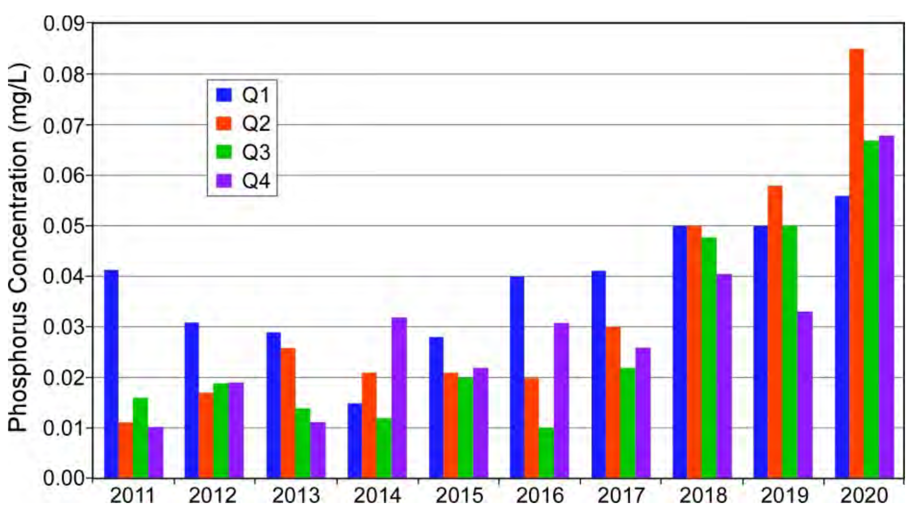


Figure 4.65 Hagerman State Fish Hatchery, influent phosphorus concentrations per quarter (Q). Data obtained from IDFG via public records request. From Idaho Conservation League, 2021

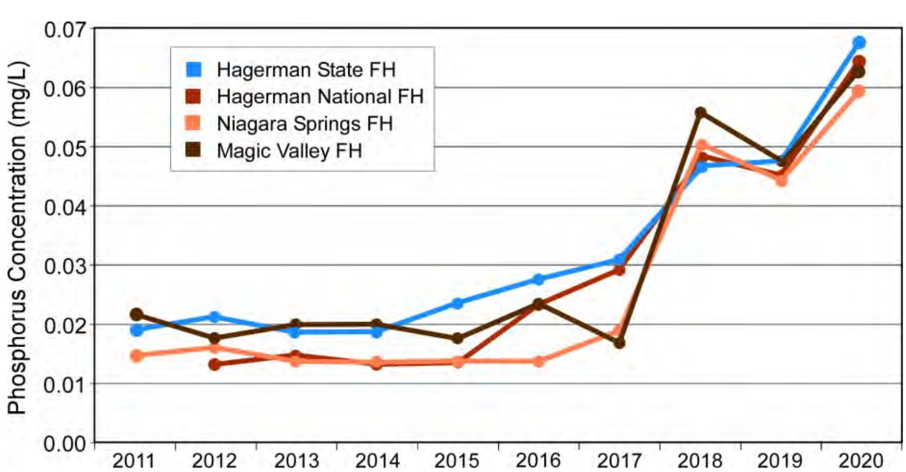


Figure 4.66 Graph showing increasing phosphorus concentrations in springs fed by the ESPA that flow into Idaho Department of Fish and Game hatcheries along the Snake River. Data obtained from IDFG via public records request. From Idaho Conservation League, 2021.

4.4 Thousand Springs

Thousand Springs are in the Ritter Island unit of the Thousand Springs State Park which has five additional units that are all within short driving distance of each other as shown in Figure 4.67: Malad Gorge, Kelton Trail, Billingsley Creek, Earl M. Hardy Box Canyon Springs, and Niagara Springs.

Across from Ritter Island are Minnie Miller Springs (commonly referred to as Minnie Miller Waterfalls), the largest remaining undisturbed, natural spring group of the Thousand Springs complex, as well as two additional spring groups: Thousand Springs proper (the main, largest group) captured for power generation, and the southernmost group captured for a trout hatchery (see Figure 4.32, and Figures 4.68 through 4.74).

Recognizing the importance of Ritter Island to the Middle Snake River's clean water and wildlife, The Nature Conservancy purchased the property in 1986 and established the Thousand Springs Preserve. In 2006, the land was passed on to the Idaho Department of Parks and Recreation and is now part of the Thousand Springs State Park.

The preserve has remained a real haven for wildlife. Waterfowl use the wetland habitat, herons nest on the island, and raptors like golden eagles and prairie falcons nest along the canyon walls. During annual Christmas bird counts, Ritter Island often has one of the highest counts of bird species in the state.

The Thousand Springs site had many developers and owners, but it wasn't until 1912 that power was first generated at the site by the Thousand Springs Power Company. Idaho Power acquired the site in 1916 and updated the plant in 1921. The current plant includes diversion structures and a powerhouse with three generators with a total nameplate generating capacity of 6,800 kilowatts.

Figure 4.67 Map of Thousand Springs State Park units.

Figure 4.68 Google Earth map of two largest spring groups of Thousand Springs. Lemon Falls in the center bottom is outfall of trout hatchery. Other waterfalls to the north are outfalls from the power plant flume (long dark structure), active only when there is surplus of water not needed for electric power production. The longest waterfall is from the location of historic Snowbank Spring, the strongest among now captured Thousand Springs. June 8, 2016 image by Landsat/Copernicus.

Figure 4.69 Historic postcard of the Thousand Springs near Hagerman, Idaho, before development for power plant. *Northwest Historical Postcards Collection*, PG 9, Postcard Collection, University of Idaho Library Special Collections and Archives http://www.lib.uidaho.edu/special-collections/.

Figure 4.70 Thousand Springs Power Plant (right) and Minnie Miller Springs/Falls (left), circa 1920. Photographer Wesley Andrews, Baker, Oregon. Courtesy of WaterArchives.org (ID-G-0026).

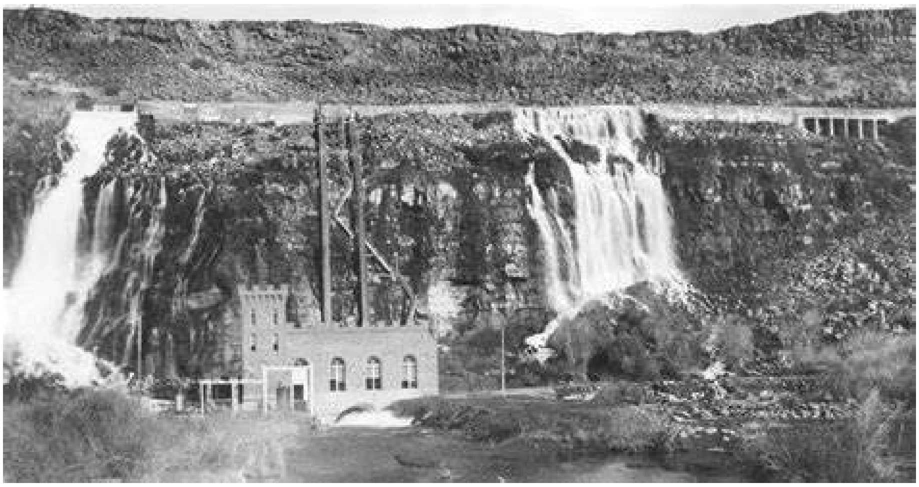


Figure 4.71 Thousand Springs with the original powerhouse built in 1912 from black volcanic rock with a light mortar and arched windows. Photo courtesy of Idaho Power.

Figure 4.72 Thousand Springs Power Plant in 2021. Photo courtesy of Geary Schindel.

Ritter Island is centrally located to enjoy this area. Its special location has long been recognized, giving the island an interesting history as a dairy farm, private retreat, nature preserve and now a state park for future generations to enjoy.

The recorded history of the area began with the arrival of French trappers in the 1800s. Pioneers started traveling the Oregon Trail in the 1840s, and entrepreneurs settled in the area to provide services, including a ferry that crossed the Snake River at the south end of the island.

The property was purchased in 1918 by Minnie Miller, a Salt Lake City businesswoman who wanted to make the property a demonstration farm. Miller was a big game hunter, traveler and entrepreneur who appreciated the unique setting of the island and its proximity to the springs.

Minnie Miller set up what was then a state-of-the-art dairy with the intent to breed the world's finest herd of Guernsey cattle. The house on Ritter Island—known to this day as the Rock House—was built in 1920, as was the barn. The primary purpose of the farm was to produce breeding cattle rather than commercial milk production. Farm workers were able to take the cream produced on the farm home with them in the evenings.

Figure 4.73 Minnie Miller Springs across Ritter Island. Photograph courtesy of Idaho Conservation League. Available at https://www.idahoconservation.org/blog/a-refreshing-exploration-of-ritter-island/

Miller welcomed visitors to the island, and many people remember her practicing judging on the Guernseys, coming to her July ice cream socials and enjoying the beauty of the farm.

The Minnie Miller Farm became known for the finest Guernseys in the world, just as Miller wished. These cattle were featured in agricultural and popular magazines around the country during that time.

The farm featured a milking parlor in the barn, which can still be visited on the island.

In 1954, the farm was sold to Federal Judge Willis W. Ritter, who used the island as a private hunting and fishing retreat. The Ritter family owned the island for 32 years.

In 1986, The Nature Conservancy purchased the property. Ritter did not allow public usage, but many local people thought the future of the property should allow access to the island and canyon.

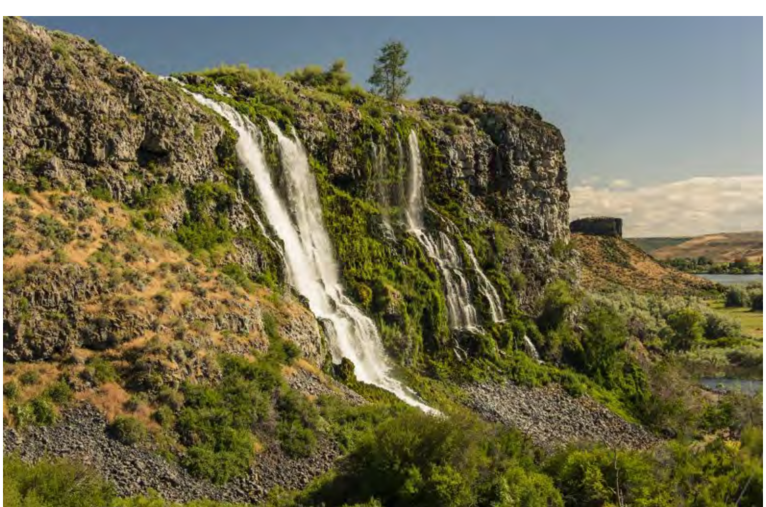


Figure 4.74 Lemon Falls, an outlet from a fish hatchery located at the southernmost end of Thousand Springs complex. Photograph courtesy of Visit Idaho; available at https://visitidaho.org/things-to-do/state-parks/thousand-springs-state-park/#gallery-3

The Nature Conservancy, a non-profit conservation organization that protects special places around the world for people and nature, recognized the importance of the property for its unique ecology and the importance to the local community. The Conservancy believed that protecting the springs of the area was important for the Middle Snake River's clean water and wildlife habitat. It purchased 385 acres, including Ritter Island, two miles of riverfront, and many springs and spring creeks along the canyon. The springs support a number of invertebrate and fish species, including the Shoshone sculpin, a fish found nowhere else on Earth.

The preserve remains a real haven for wildlife. Waterfowl use the wetland habitat, especially in the spring and fall. Herons nest on the island, and raptors like golden eagles and prairie falcons nest along the canyon walls. During annual Christmas bird counts, Ritter Island often has one of the highest counts of bird species in the state.

Each September, Ritter Island has been the location of the popular Thousand Springs Festival. The festival includes artists from around the region, regional food specialties, music, children's activities, natural history displays, and wagon rides. Originally started as a fundraiser for the Nature Conservancy, for the past several years, the festival has also benefited the Magic Valley Arts Council.

The Nature Conservancy was also instrumental in the purchase of Box Canyon and Billingsley Creek, two other important units of Thousand Springs State Park.

4.5 Box Canyon Springs, and Blue Heart Springs

Box Canyon Springs are in Earl M. Hardy Box Canyon Springs Nature Preserve, one of six units of Thousand Springs State Park (see Figures 4.67 and 4.75). The headspring (Figures 4.76 and 4.77), with the long-term average discharge rate of 365 cfs (see Figure 4.38), is the third largest individual spring in the country after Big Spring in Missouri (454 cfs for the period of record) and Wakulla Spring in Florida (409 cfs for the period of record) based on publicly available, long-term USGS discharge measurements through year 2023. Majority of the spring inflow enters at the head of Box Canyon, but more is received via additional springs as the stream flows toward the Snake River (see Figure 4.39). The combined flow of all springs in Box Canyon (Figure 4.38), if considered as a spring group using Florida standards, would make it one of the top five such groups in the country together with Malad Springs and Thousand Springs in Idaho, Fall River Springs in California, and Silver Springs in Florida.

Figure 4.75 Google Earth oblique view of Box Canyon (middle) and Blue Heart Spring (left). Blind Canyon is on the right. Clear Springs Foods fish hatchery is on the west bank of Snake River. Note the north sign in upper right of the image; see also Figure 4.39. Landsat / Copernicus image acquired on June 8, 2016.

Figure 4.76 Left: Headspring of Box Canyon Springs. Right: View down the canyon from the spring overlook.

Unfortunately, as painfully obvious from Figure 4.38, the discharge rate of this undisturbed, crystal-clear spring of the Snake River Plain Aquifer has been steadily declining since the mid-1970s. This is the main reason for the lawsuit against groundwater irrigators brought in 2000s by Crystal Clear Foods, the largest producer of trout in the world, as explained earlier.

Figure 4.73 The extraordinarily large discharge rate of the majestic Box Canyon headspring can be best appreciated at this waterfall some 2,300 feet downstream of the spring. The USGS gaging station is about 20 yards downstream of the waterfall. Photograph taken in July 2019.

Box Canyon and Blind Canyon spring coves (Figure 4.71) are near the mouth of Salmon Falls Creek. The springs in both coves issue nearly 200 feet above the Snake River. They form narrow blind canyons extending east from the Snake River and are supplied with water from the Sand Springs basalt. They have an origin similar to that of Blue Lakes Cove (see Section 4.7). The rock exposed in their vertical walls is the typical Sand Springs basalt. Its great thickness locally is due to the filling of a valley-shaped depression cut in Banbury basalt. From its proximity to the mouth of Salmon Falls Creek this depression may be the place where this creek emptied into the ancient Snake River Canyon now filled with Sand Springs basalt (Stearns, 1938).

On the web page of Thousand Springs State Park Thousand Springs State Park Box Canyon Springs Nature Preserve | Department of Parks and Recreation (idaho.gov), one can read the following

Keep your eyes peeled for the turnout to the front parking lot to Box Canyon, as it's a bit tucked away. You can park in the front parking lot, or you can drive to the new parking lot in the back, saving you a mile walk.

Make sure to read the interpretive signs which contain loads of interesting information about this unique canyon, including what Box Canyon has in common with Mars.

As if this site in front of you wasn't impressive enough, follow the trail and hike down into the canyon to reach a 20-foot waterfall that is simply beautiful.

Because the water must flow through the cracks and crevices of the basalt rock that contains the aquifer the water is very pure. You may notice that there is a bright light green plant in the water. That plant is Water Veronica which is an indicator of stream health.

Figure 4.74 Confluence of the Box Canyon spring run and Snake River. Water from a diversion pond, located about 2,550 feet upstream from the confluence, is piped along the canyon and then under the Snake River to the Clear Springs Foods fish hatchery shown here. Part of the water from the diversion pond is allowed to flow directly into the Snake River. Photograph courtesy of Clear Springs Foods.

Blue Heart Spring is one of the most beautiful and striking springs in the country (Figures 4.75 through 4.76; see also Figure 4.39). Decades ago, the spring was known as Sand Spring, but a more romantic name emerged when droves of kayakers started visiting it after hearing fairytales about a real paradise, and climbing steep slopes of the canyon to see it from higher up.

> ***Half a mile below the mouth of Little Canyon, near the level of the river at its lowest stage, an immense spring of wonderfully clear water of a delicate bluish color rises through a bed of clear white sand, and for this reason is named Sand Spring. This great spring is situated in a slight reentrant of the canyon wall, which indicates the nature of the beginning of a spring-formed alcove.***
>
> **Russel, 1902**

Nice descriptions of Blue Heart Spring and how to get to it are available at websites of Visit Southern Idaho (https://visitsouthidaho.com/blue-heart-springs-the-hidden-oasis/) and Idaho Conservation League https://www.idahoconservation.org/blog/exploring-the-snake-river-canyon-blue-heart-springs/. Here are a few excerpts:

Tucked into a bend of Idaho's Snake River is Blue Heart Springs, an oasis that truly earns its enchanting name. This sapphire spring is hidden about halfway between Hagerman and Buhl and is only accessible by water transportation, but it's worth the extra work to get there. As you float on your paddleboard and peer into the piercing blue waters below – you'll see crystal clear spring water bubbling up from the bottom. The rugged cliffs rising from the turquoise waters are reflected in the clear water, and if you turn your eyes to the skies – you may spot a bird of prey soaring among the thermals overhead.

To get to Blue Heart Springs, put in at the boat launch at Banbury Hot Springs and paddle downstream along the Snake River for about a mile. On the north side of the river about 3/4 of a mile from the boat launch, you'll see the outflow from Box Canyon Springs. It is worth paddling up to the outflow to see the clear water coming out of the side canyon. About 1/4 mile further down the river, at a bend in the river and a caved-in area of the canyon, a narrow opening to a passage on the right (north) side of the river will lead you to Blue Heart Springs. Once you've paddled through the passage, a large opening emerges, filled with the purest, bluest, clearest water you have ever seen! This is Blue Heart Springs.

The water is so clear it will appear as if you are floating in the air! The water stays at about 58 degrees even on the hottest days! Look to the bottom of the water and watch sand bubble up as the spring water emerges from the ground below.

Figure 4.75 Google Earth oblique view of three springs marked by dark blue color as opposed to greenish color of the Snake River. Blue Heart Spring is the largest one on the left. Note kayaks and scale bar (200 ft) in the lower left for scale. NASA/Landsat/Copernicus image acquired on August 7, 2020.

Figure 4.76 Blue Heart Spring. Photographs courtesy of Idaho Conservation League. See also an article by Hannah Smay at https://www.idahoconservation.org/blog/exploring-the-snake-river-canyon-blue-heart-springs/

4.6 Niagara Springs, and Crystal Springs

Niagara Springs (Figures 4.77 and 4.78) are a National Natural Landmark and part of the Thousand Springs State Park (see map in Figure 4.67). They appear in a well-defined outlet under the canyon rim rock, about 130 feet above the river level. A small amphitheater is forming at their head. A tunnel driven into the canyon wall nearby shows that the water escapes along the contact of Banbury and Sand Springs basalts (Stearns, 1938; see also map in Figure 4.44).

Figure 4.77 Google Earth oblique view of Niagara Springs which are captured for Niagara Springs Hatchery, owned and financed by Idaho Power Company, and operated and staffed by the Idaho Department of Fish and Game. Landsat/Copernicus image acquired on September 21, 2011.

Niagara Springs Hatchery was built in 1966 as a rearing facility for steelhead. In 2013, Idaho Power completed a two-year renovation of the hatchery. The new hatchery building includes an observation room that allows visitors to get a good look at the indoor rearing operation. With a capacity to rear nearly two million steelhead smolts annually, it is one of America's largest privately-owned steelhead rearing facilities.

Figure 4.78 Niagara Springs, with an average discharge rate of 252 cfs (see Figure 4.44) is one of the strongest groups of tightly spaced (200 feet across) spring orifices in the Unites States.

Steelhead (Figure 4.79) are large rainbow trout native to Idaho and the northwest region which migrate to the ocean as juvenile fish and return to fresh water as adults to spawn. When adult steelhead leave the ocean and swim back to Idaho, they create one of the state's most amazing fishing opportunities. They are popular for sport fishing because they are strong and agile.

The Niagara Springs water is clean, always clear and, most importantly, warmer than the water in which naturally spawned steelhead grow up. The spring water creates the ideal environment for the fish to achieve the equivalent of two years' growth in just one year.

Each April and May, eggs from adult steelhead spawned by crews at Idaho Power hatcheries in the Snake and Salmon river basins are delivered to Niagara Springs Hatchery to begin the rearing cycle. Fish are initially reared indoors and then finish their rearing cycle outdoors in concrete raceways. In March, crews begin hauling the year-old fish back to Hells Canyon and the Pahsimeroi River, where they will begin a journey of more than 500 miles to the ocean. The spring fish haul takes about six weeks to complete.

Niagara Springs Hatchery has proven to be a tremendous asset in the rearing of steelhead. In the wild, less than 5 percent of the eggs hatch and survive to migrate to the ocean. At Niagara Springs Hatchery, more than 80 percent of the eggs received from Pahsimeroi and Oxbow hatcheries survive to make their ocean journey (https://idfg.idaho.gov/visit/hatchery/niagara-springs).

Figure 4.79 Male and female steelhead trout. Photograph courtesy of NOAA Fisheries. Steelhead trout are a unique species. Individuals develop differently depending on their environment. All wild steelhead trout hatch in gravel-bottomed, fast-flowing, well-oxygenated rivers and streams. Some stay in fresh water all their lives and are called rainbow trout. Steelhead trout that migrate to the ocean typically grow larger than the ones that stay in freshwater. They then return to freshwater to spawn.

Immediately west of Niagara Springs is Niagara Springs Wildlife Management Area (WMA; https://idfg.idaho.gov/visit/wma/niagara-springs) which provides pond fishing and access to fishing the Snake River (Figure 4.80). A wild trout fishery is sustained by natural reproduction in the Thompson-Mays Canal fed by Niagara Springs. As a result, the WMA ponds and the canal are popular draws for rainbow trout fishing.

There are few access points to the Snake River in the Magic Valley because of the steep slopes of the canyon walls. WMA provides public access to 3.5 miles of the Snake River where anglers often fish for trout, catfish, and sturgeon. There are two designated sturgeon fishing holes on Niagara Springs. These fishing holes are located along the Snake River in the middle of the WMA and access routes are marked by signs.

Niagara Springs WMA is 976 acres nestled between the rim of the Snake River canyon and the banks of the river. The water, wetlands and natural areas make it a destination for waterfowl and for the people interested in hunting, fishing, and wildlife viewing. The WMA attracts horse riders from the area and holds the Backcountry Horseman Trail Ride. Dog trials are held on the WMA in the spring. Bowhunter groups hold a regular 3-D Shoot. No overnight camping is allowed on the WMA.

Over 5,000 ducks and several hundred Canada geese winter along this portion of the Snake River annually. Golden eagles, prairie falcons, red-tailed hawks, and other raptors patrol the canyon's talus slopes and river year-round. The riparian zones along the canal and shoreline of the Snake River provide habitat for a variety of songbirds.

Figure 4.80 View of Niagara Springs Wildlife Management Area. Courtesy of https://idfg.idaho.gov/visit/wma/niagara-springs

Crystal Springs discharge into Crystal Springs Lake (Figures 4.81 and 4.82; see also map in Figure 4.44) and consist of numerous large springs, which extend for over a quarter of a mile along the canyon side and are collected artificially by a dam in form of a long flute and utilized by a commercial fish hatchery. They issue from the bottom of the Sand Springs basalt near the contact with the underlying impermeable Banbury basalt. It is believed that these spring outlets are spillways for groundwater moving through the ancient lava-filled canyon of the Snake River not far to the north (Stearns, 1938).

Figure 4.81 Google Earth oblique view of Crystal Springs and Crystal Springs Lake. The springs are captured for a commercial hatchery shown in the bottom right. The Snake River water is in the lower left. NASA/Landsat/Copernicus image acquired on September 21, 2011.

Crystal Springs Lake can be accessed from Niagara Springs and Crystal Springs can be viewed from across the lake (Figure 4.82; there is no direct access to the springs). The park features modern restrooms, picnic tables, a group picnic shelter, and a handicap-accessible site. Wildlife—especially waterfowl—is abundant.

Figure 4.82 View of part of Crystal Springs across Crystal Springs Lake. https://parksandrecreation.idaho.gov/

4.7 Malad River Gorge and Springs

As explained by Stearns (1938), the Malad Springs constitute the largest of the Snake River springs and indeed one of the largest known groups of springs in the world (Figure 4.37 and Table 4.1). The deep Malad River Gorge which crosscuts an extensive ancient canyon filled with Malad basalt, acts as an efficient intercepting drain, and only a few minor springs appear along the banks of the Snake River below the mouth of Malad River. The flow is used for power generation at two Malad plants of the Idaho Power Company.

The Malad River Gorge is a spring cove partly enlarged by landslides and river action. The Malad River is about 12 miles long and is formed when the Big and Little Wood Rivers combine near Gooding, Idaho, northeast of the park. It crashes down stairstep falls and into the Devils Washbowl, the amphitheater at the head of 250-foot high and 2.5 miles long beautiful Malad Gorge. The upper section of the gorge contains most of the springs (see Figure 4.18). It is estimated that the volume of the Malad River above the springs prior to irrigation was not more than a fifth of the combined flow of the springs (Stearns, 1938).

Figure 4.83 Western, downstream view of the Malad River Gorge from the foot bridge crossing the gorge right next to I84 (see Figure 4.84). Multiple springs discharge below the white rapids, and more springs are further downstream, off the photograph. Photo courtesy of https://parksandrecreation.idaho.gov/parks/thousand-springs/malad-gorge/

The lower (downstream) part of the gorge has been enlarged by landslides caused by thin deposits of the Hagerman Lake beds, which underlie the Malad basalt and overlie the Banbury volcanics at the mouth of the gorge. These impermeable beds form the western rim of the ancient canyon filled with the Malad basalt and serve as a divide causing the water to issue far above the Snake River. The Malad cove is the largest, and apparently the oldest, of all the coves in the Snake River valley (Stearns, 1938).

Springs in the Malad River Gorge are not accessible and are best viewed from the trails along the northern and southern gorge rims. The northern rim trail also provides a nice view of a smaller, parallel spring cove to the north, named Farmers' Cove (Figure 4.84).

Figure 4.84 Oblique Google Earth view of upper portion of the Malad River Gorge where most of the springs are (see also Figure 4.18). The Devil's Washbowl where the Malad Gorge begins is in center right, next to interstate I84 (two yellow lines). The Idaho Power Company diversion structure (Figure 4.85) is just upstream of the mouth of short Farmer's Cove in the center which has springs as well. Landsat/Copernicus image acquired on June 8, 2016.

The interesting history of Malad River is described with a historic marker erected in 2008 by Idaho Power Company (https://www.hmdb.org/m.asp?m=71603):

The River Has Seen Many Uses

In 1899, a gauge was established to determine the yield of springs flowing into the Malad and the feasibility of using its water for placer mining and irrigation.

Several claims to the water were filed between 1902 and 1908 when the Kin Hill Irrigation and Power Company constructed a diversion dam, flume and siphon to pipe water from the Malad across the Snake River to irrigate land in the King Hill area.

In 1909 land and rights to 700 cubic feet per second (cfs) of water were acquired by the Malad Power Company for power development. The agreement also allocated 300 cfs to the King Hill Irrigation and Power Company for irrigation and ongoing maintenance of the diversion dam and flume across the Snake River.

Electricity has been generated here continually since 1911 when the Beaver River Power Company purchased the Malad Power Company's rights. The company constructed the 5,000 kilowatt (kW) upper power plant and wooden gravity flume, making it the largest power generator on the Snake River at that time.

Beaver River Power Company was purchased in 1913 by Idaho Power and Light which in 1916, became one of the five companies originally incorporated into the Idaho Power Company.

The 8,270 kW upper power plant was rebuilt in 1948 from plans drafted decades earlier by the Beaver River Power Company. The post WWII building boom also replaced the wooden flume with one made of concrete and moved the lower plant site to the bank of the Snake River and increased the output from 5,000 kW to 13,500 kW.

The annual average combined generation for the Malad Project is 168,733 megawatt hours, enough to power more than 13,750 Idaho homes.

Figure 4.85 One of the Malad Gorge Springs. Photograph from Farmer and Blew, 2011b.

In an article entitled *Idaho Power Creates A New Passage For Trout In The Malad River* published in Outdoor Hub on November 8, 2021 (https://www.outdoorhub.com/news/2021/11/08/idaho-power-creates-new-passage-trout-malad-river/) Nicolas Lenze writes:

It's not news that humans impact wildlife in a significant way. Expansion and industrialization of areas that were once rural have threatened local populations of deer, fish, and other animals. In fact, the devastation of nature that's caused by humans is almost all we ever hear. The truth is that there are people all across the globe working constantly to preserve our natural resources. A power company might not be the first entity you'd think of when talking about conservation, but that's exactly what has happened in Idaho. Doing their part, Idaho Power has just created a new passage for local trout to pass through to their spawning grounds in the Malad River (see Figure 4.86).

Figure 4.86 Idaho Power innovative fish passage project that allows native rainbow trout to move between the Snake River and their spawning grounds in the Malad River. Before, much of the Malad was off-limits to these fish, which spawn and rear in this tributary before moving into the Snake River. Text and photo Courtesy of Nicolas Lenze.

4.8 Blue Lakes Springs

Russel (1902) gives this description of Blue Lakes Springs, yet another fascinating first magnitude spring draining the East Snake River Plain Aquifer with an average discharge rate of 186 cfs: *At Blue Lakes, about 5 miles below Shoshone Falls, where the walls of Snake River Canyon are about 700 feet high, and nearly vertical, except for the talus lodged against their bases, there is a tributary canyon-like alcove in the north wall which is about 2 miles long, and about 2,000 feet across at the top and which heads in a semicircular amphitheater with vertical walls about 300 feet high. There is no stream entering the alcove from the surface of the neighboring plain, but springs discharging probably several hundred cubic feet of water per second boil up in the amphitheater at its head. One of the striking features in this alcove is the small quantity of talus at the bases of the bordering cliffs. This is most noticeable in the semicircular expansion of the alcove at its head. In the view of the Blue Lakes alcove presented on PI. XXIV* (Figure 4.87-*Right* in this book) *some of the features referred to may be recognized.*

The great springs undermine the basalt by removing the soft material on which it rests. Thus blocks of the usually more or less vertically jointed rock break away and fall into the spring, and sooner or later sink into the soft bed beneath, as the emerging waters remove the silt and sand from beneath them. By this process vertical walls without talus slopes are produced. This process continuing, the cliff recedes, leaving a side cut or alcove in the wall of the main canyon, which becomes lengthened into a lateral canyon. The process would seem to be cumulative, as the farther the head of a side canyon receded the greater would be the tendency of the escaping waters to converge toward it. The marked tendency to an enlargement into an amphitheater, observable especially at the head of the Blue Lakes alcove, is apparently due to this cause.

As noted by Stearns (1938), one reason for the paucity of springs between Blue Lakes and Shoshone Falls is that the impermeable Shoshone Falls andesite retarded their development and permitted those which once existed to be drained through the more advantageously situated Blue Lakes.

Figure 4.87 *Left*: View of Blue Lakes looking N-NE, circa 1920. Photographer Wesley Andrews, Baker, Oregon. Courtesy of WaterArchives.org (ID-C-0001). *Right*: Blue Lake alcove, looking south into Snake River Canyon, Idaho. (Plate XXIV from U.S. Geological Survey Bulletin No. 199; Russel, 1902).

Blue Lakes are owned by Blue Lakes Country Club (https://www.bluelakescc.com/): *From humble beginnings forged by Mother Nature, Blue Lakes continues to evolve. Orchards were cultivated by original settlers in the late 1880's to produce prize winning fruit in the early 1900's. Tradition, family, and legacy continue to be cornerstones of this property. In fact, the family cemetery of I.B. Perrine, founder of Blue Lakes Ranch is located between Hole #8 and Hole #9. After the passing of Mr. Perrine club formation was established in 1944 with many of the same* *names found on today's membership rolls. Golf began to take shape in the late 1940's with the design of the first nine holes of golf. Staying true to these humble roots, the club, slowly, and organically has evolved into a hidden gem of the west.*

Figure 4.88 Blue Lakes Springs, lower lake. Photograph courtesy of Blue Lakes Country Club.

Figure 4.89 Blue Lakes Springs, upper lake. Photograph by Kenneth Skinner, U.S. Geological Survey, Idaho, 2005.

4.9 Big Springs, and Warm River Springs

Big Springs (Figures 4.90 and 4.91) is outside Island Park, Fremont County, in the far northeastern corner of Idaho (see map in Figure 4.1), about 22 miles south of West Yellowstone, Montana, and 64 miles northeast of Rexburg, Idaho. It is the headwaters of Henry's Fork, the main tributary of the Snake River, which is considered one of the best fly-fishing streams in the nation.

The springs drain an aquifer developed in one of the largest rhyolite lava fields in the United States—the Madison Plateau in the Targhee National Forest. With an average discharge rate of 182 cfs (Figure 4.92), Big Springs group is also one of the top 20 first-magnitude springs in the United States. The springs are at the foot of a cliff which consists of rhyolite and spherulitic obsidian. This cliff marks the edge of an extensive forested plateau with little surface runoff. Most of the spring water issues from several large vents within less than a quarter of a mile, flowing from both obsidian and rhyolite into a large pool.

Figure 4.90 Google Map oblique view of Big Springs near Island Park, Fremont County, Idaho. Landsat/Copernicus image acquired on June 8, 2013.

The crystal-clear spring water maintains a year-round temperature of 52 degrees Fahrenheit, perfect for the large Brook and Rainbow trout which thrive in the area. However, they are protected, and fishing is not allowed until below the outlet to Henry's Lake, several miles away. One can feed and watch the trout from the bridge over the pool's outlet (Figure 4.91). The clean gravel bottom and the constant cool water temperature make for an ideal trout habitat—the Big Springs' trout gets BIG.

The Big Springs Campground, owned by USDA Forest Service and operated by a concessionaire (https://www.recreation.gov/camping/campgrounds/234576), is located next to the spring area, at an approximate elevation of 6,300 feet. It is situated in a clearing surrounded by a forest of lodgepole pines.

Visitors come to Island Park and Big Springs for outstanding scenery, wildlife viewing opportunities, and first-class fishing on Henry's Fork. The area is known for its dense forests of lodgepole pine, broad grassy meadows bursting with summer wildflowers and a wide variety of wildlife, including black and grizzly bears, moose, elk, deer, bald eagles, Sandhill cranes and much more.

The Big Springs National Recreation Water Trail can be accessed from the Big Springs Boat Launch and ends 4.5 miles away at Macks Inn. It offers a lazy three-hour float or canoe trip through beautiful scenery. The charming and historic John Sack Cabin is nearby, noted for its unique location, construction, and furnishings. Hiking, biking, horseback riding and ATVing are popular activities. Many miles of trails crisscross Island Park, including the Continental Divide National Scenic Trail and the Nez Perce Trail.

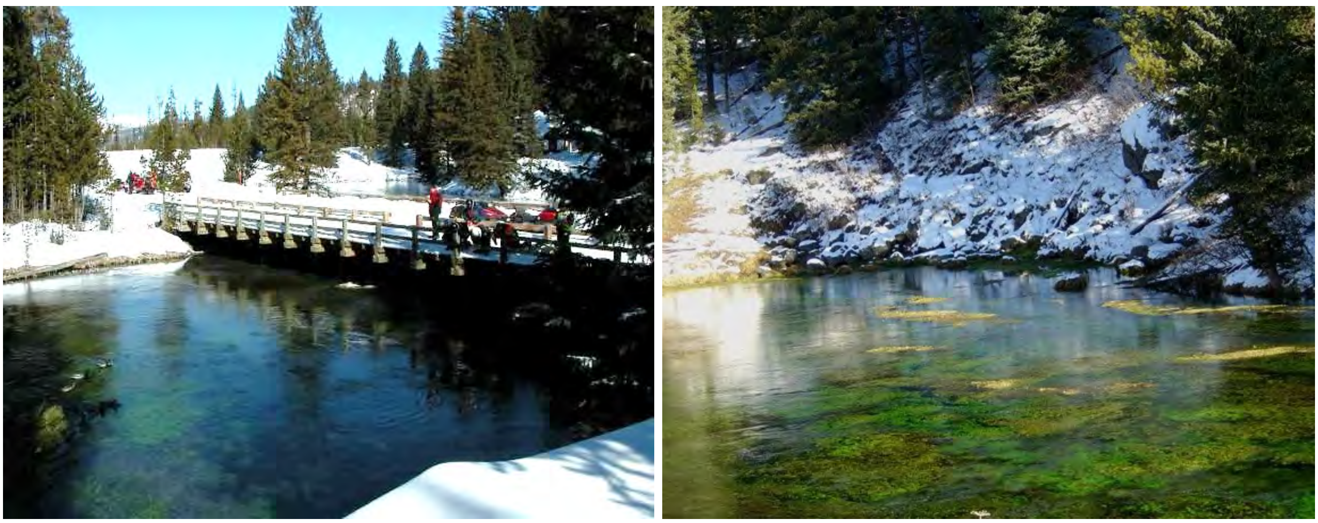


Figure 4.91. Left: Bridge over the outlet from the headspring pool of Big Springs. Photo courtesy of Island Park, Idaho; available at https://islandparkidaho.com/island_park_idaho/bigsprings.html. *Right*: Photo of Big Springs, courtesy of U.S. Forest Service.

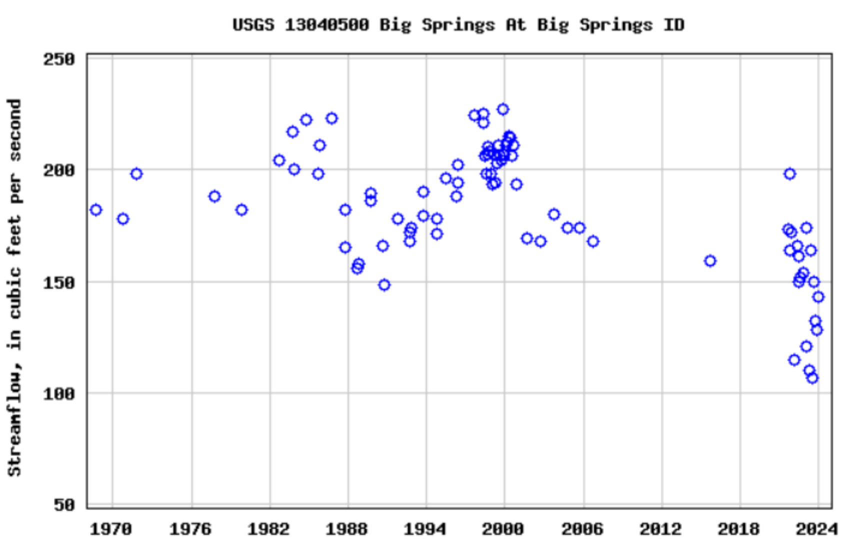


Figure 4.92 Hydrograph of Big Springs discharge rate for the period of record. Average is 182 cfs.

Warm River Springs (Figure 4.93; see also map in Figure 4.1) in Caribou-Targhee National Forest issue from very permeable silicic volcanic rocks and have a reported discharge rate of 200 cfs, although more specific information is lacking. As described by Whitehead (1994), specific-capacity values of wells completed in these rocks range from 1 to 2,000 gallons per minute per foot of drawdown but commonly are less than 400 gallons per minute per foot of drawdown. The known thickness of the rocks is about 3,000 feet.

Figure 4.92 Warm River Spring in far northeastern Idaho (see map in Figure 4.1 for location). *Left*: photograph of the springs from Whitehead (1994). *Right:* Warm River is short walk from the springs and the cabin (photo courtesy of the U.S. Forest Service).

Warm River Cabin at Warm River Springs is located less than 20 miles from Ashton, Idaho. An Idaho fish and game hatchery operated here from the 1930s to the 1950s. The cabin was formerly the hatchery manager's house. It was constructed by the Civilian Conservation Corps (CCC) in 1938. The cabin is open year-round and can be accessed by car in the warmer months. Snowmobiles and cross-country skis are required to access the cabin on a groomed trail from early December through mid-May. The trek from the nearest available parking at Bear Gulch Trailhead to the cabin is 6 miles. Guests should be prepared to bring much of their own gear and supplies to make their stay comfortable (visit Warm River Cabin, Caribou-Targhee National Forest - Recreation.gov).

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Chapter 5 Edwards Aquifer, Texas

5.1 Introduction

All notable springs in Texas, including the only two remaining first magnitude springs, San Marcos Springs, and Comal Springs, are draining parts of the greater Edwards-Trinity Aquifer System. As explained by Mace and Angle (2004), The Edwards Plateau (Figure 5.1) occupies the west-central part of Texas, extending from the Hill Country near Austin and San Antonio up to the mountains of West Texas and into the High Plains. Because of low rainfalls, the frequency of drought, and few major rivers, groundwater is an important source of water to the people and environmental resources of the Edwards Plateau area. The hydrogeologic centerpiece of the Edwards Plateau is the Edwards–Trinity (Plateau) aquifer, one of the major aquifers of the state. Around and in hydraulic connection with it are several major and minor Texas aquifers including the Capitan Reef, Cenozoic Pecos Alluvium, Dockum, Edwards (Balcones Escarpment/Fault Zone), Ellenburger-San Saba, Hickory, Lipan, Marble Falls, Ogallala, Rustler, and Trinity aquifers (George et al., 2011).

Figure 5.1 Physiographic map of west-central Texas showing various components of the greater Edwards-Trinity Aquifer System including notable springs. Modified from Land and Veni, 2018, Figure 5; and Barker and Ardis, 1996, Figure 3.

This part of Texas is in the southern portion of Great Plains Province (Fenneman, 1931), which is characterized by asymmetric ridges or mountains and broad intervening basins (Bates and Jackson, 1984). Elevations range from 5,000 feet above sea level in the western portion of the region to 500 feet above sea level on the eastern side.

The Rio Grande and the Colorado and Pecos rivers are the major rivers that cut through the Edwards Plateau area. Flow in the Rio Grande in this part of Texas is primarily controlled by inflows from the Rio Conchos near

Presidio. The Pecos River is a major tributary to the Rio Grande that originates in New Mexico. The river is impounded in Red Bluff Lake in Loving County and is used for irrigation in Pecos, Reeves, and Ward counties.

The climate of most of Edwards-Trinity Aquifer System area ranges from subhumid in the eastern portion to semiarid in the western portion (Walker 1979). Average annual precipitation ranges from less than 10 inches in the west to more than 30 inches in east. Late spring and early summer bring the greatest rainfalls to the eastern portion of the plateau while late summer results in the heaviest rainfall in the western areas (Mace and Angle, 2004).

The Edwards Aquifer of the Balcones Fault Zone which is geographically also referred to as the Balcones Escarpment, is the most productive major aquifer within the Edwards-Trinity Aquifer System, with most major springs in Texas. It is typically divided into two segments mainly because of the groundwater management aspects (Figures 5.2 and 5.3): the San Antonio segment managed by the Edwards Aquifer Authority and the Barton Springs segment managed by the Barton Springs Edwards Aquifer Conservation District (BSEACD).

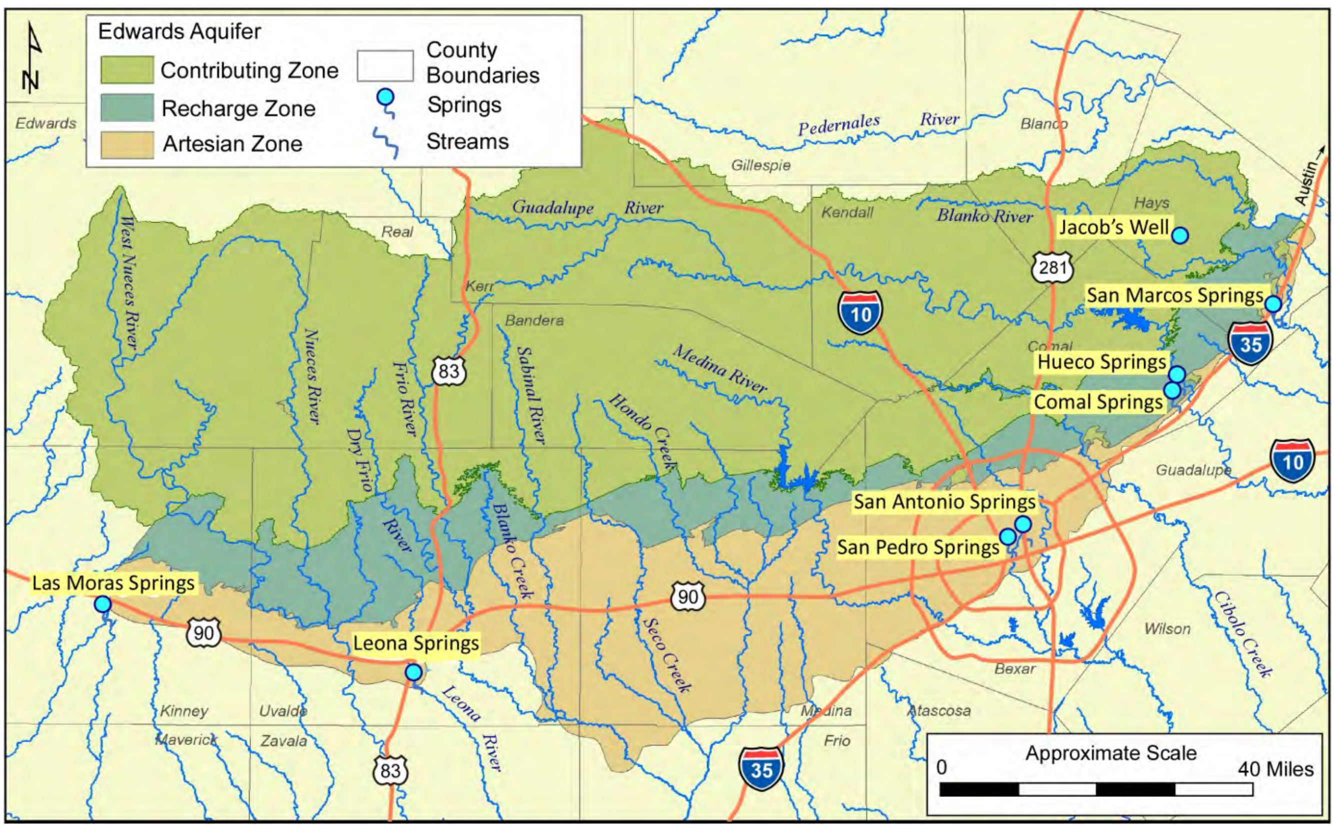


Figure 5.2 Major Springs in the San Antonio segment of the Edwards-Trinity (Balcones Fault Zone) Aquifer. Modified from Edwards Aquifer Authority, 2021.

The Edwards Aquifer is one of the most productive aquifers in the United States. The competition for groundwater from it has created many controversial water issues in central Texas. It is designated a sole-source aquifer in the San Antonio and Austin areas by the U.S. Environmental Protection Agency. The Aquifer is critical for farming and ranching economies west of San Antonio and recreational economies northeast of the city. Comal and San Marcos Springs and their effluent streams (rivers) support seven Federally listed endangered and one threatened species.

Edwards Aquifer is a typical karst aquifer characterized by the presence of sinkholes, sinking streams, caves, large springs, and high yielding water wells including the largest capacity artesian well ever drilled in the world—the Ron Pucek's Catfish Farm well near San Antonio—capable of producing 45 million gallons per day, enough water to support 250,000 people, about one-fourth of San Antonio's population at the time.

The story of this extraordinary well and many facts about the history, hydrogeology, springs, management, and numerous other topics related to Edwards Aquifer are available at The Edwards Aquifer website (https://www.edwardsaquifer.net/) which is created and maintained by Gregg Eckhardt, an environmental scientist from San Antonio. This site, started by Gregg in 1995, is universally recognized as the most comprehensive web-based resource on an aquifer in the country. More recently, Gregg has included a large batch of historic photographs and postcards, many of which feature the Texas springs described in this book.

Another sources of information on Edwards Aquifer are dozens of technical reports available on the EAA web page at https://www.edwardsaquifer.org/all-documents/, on the web page of Texas Water Development Board (https://www.twdb.texas.gov/, and on the USGS webpage at https://www.usgs.gov/centers/oklahoma-texas-water-science-center/science/edwards-aquifer-studies-texas.

Edwards Aquifer is the primary water source for much of the Balcones Escarpment area, including the City of San Antonio and its surrounding communities. Historically, the cities of Uvalde, San Antonio, New Braunfels, and San Marcos were founded around large springs that discharged from the Aquifer. As the region grew, wells were drilled into the Aquifer to supplement the water supplied by those springs. The Aquifer also serves as the principal source of water for the region's agricultural and industrial activities and provides necessary spring flow for endangered species habitat.

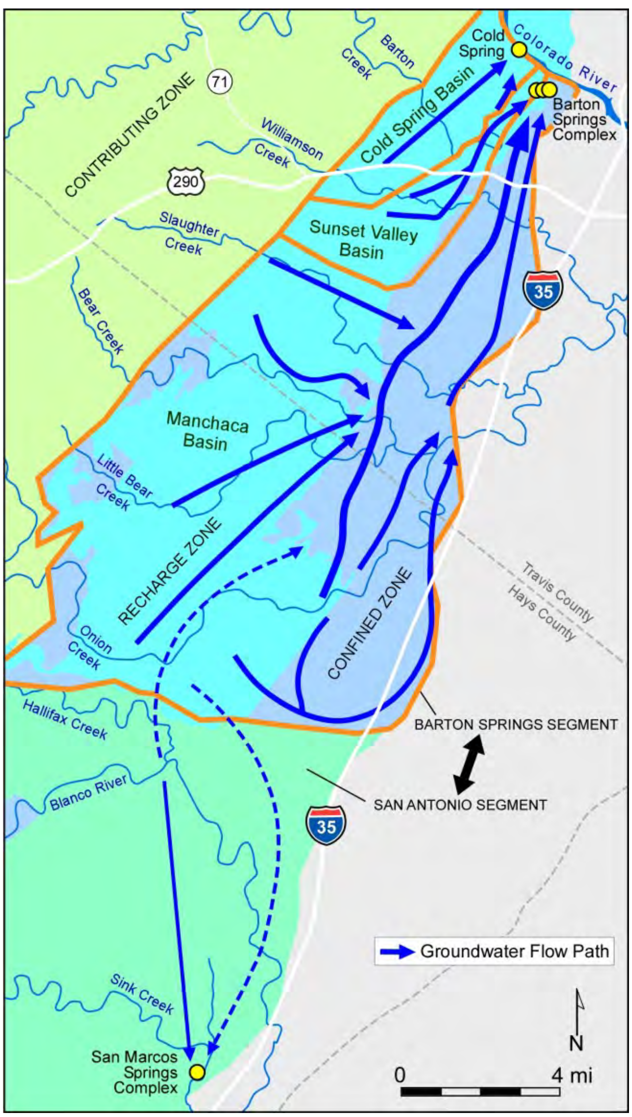


Figure 5.3 Barton Springs segment of the Edwards Aquifer. Groundwater basins and flowpaths adapted from Hauwert et al 2004, Hunt et al 2005, Smith et al 2006, Hauwert 2009, Smith et al 2012, Hauwert 2012, Hunt et al 2013, Zappitello and Johns 2018b. The boundary between the Barton Springs segment and the San Antonio segment of the Edwards Aquifer varies under different aquifer conditions. The dashed flow paths represent groundwater tracing results that have crossed the groundwater divide. Modified from Zappitello et al., 2019.

Edwards Aquifer consists primarily of karstified limestones and ranges in thickness from 200 to 600 feet, with freshwater saturated thickness of about 560 feet in the southern part of the aquifer (George et al., 2011). The groundwater, although hard, is generally fresh and contains less than 500 milligrams per liter of total dissolved solids. The water is primarily used for municipal, irrigation, and recreational purposes. San Antonio obtains almost all of its water supply from the Aquifer which also feeds several well-known springs, including Comal Springs in Comal County, the largest spring in the state, and San Marcos Springs in Hays County, which is the second largest. Hueco, San Pedro, San Antonio, Las Moras, Leona, and Barton springs also discharge from the aquifer (Figures 5.2 and 5.3).

Approximately 1,560 square miles of Edwards Limestone is exposed at the ground surface and composes the recharge zone where water enters the Aquifer (Figures 5.2 through 5.12). Surface water from springs and streams originating in the catchment area (i.e., contributing zone) reaches the recharge zone where much of the flow sinks into the Edwards Group Limestone. The confined zone (i.e., artesian zone) or that part of the aquifer contained between Del Rio Clay and other less permeable sediments (above) and the Upper Glen Rose Limestone and other less permeable sediments of the Trinity Group (below) has an area of 2,314 square miles (George et al., 2011). Some water also enters the Edwards Aquifer from formations adjacent to the Edwards Group Limestone and from direct precipitation on the recharge zone.

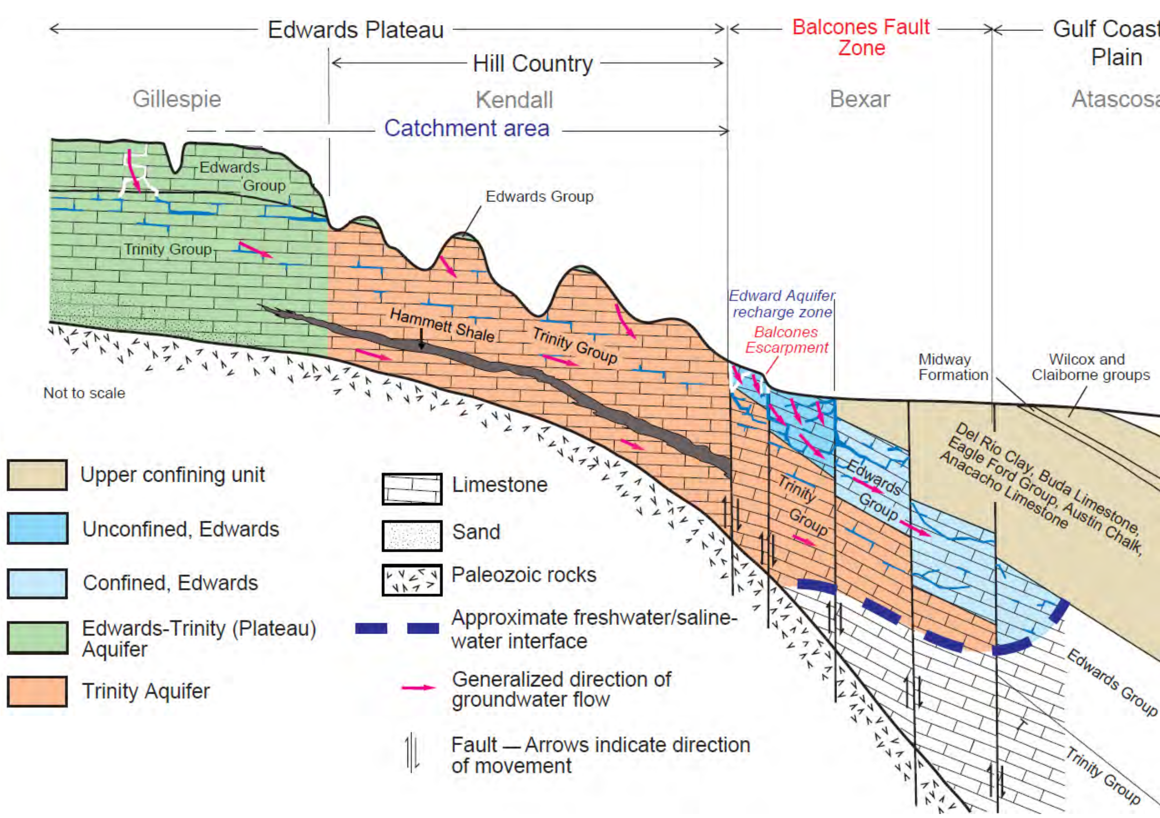


Figure 5.4 Diagrammatic cross section showing hydrogeologic framework and generalized groundwater flow through the Edwards (Balcones Fault Zone) Aquifer, San Antonio region, Texas. From George et al, 2011; modified from Barker and Ardis, 1996; Lindgren et al., 2004).

Portions of the artesian (confined) zone are as much as 3,400 feet below the surface where it still contains fresh water. The southern boundary of the artesian zone marks the Aquifer's transition from freshwater to saline water (water with a total dissolved solids concentration greater than 1,000 mg/L).

The residence time of water in the Aquifer ranges from a few hours or days to much longer, depending on depth of circulation, location, presence of karst conduits, and other aquifer parameters. For example, the results of groundwater tracing in the Barton Springs segment demonstrate that a significant component of groundwater flow is rapid, discrete, and occurs in an integrated network of conduits, caves, and smaller dissolution features. Groundwater generally flows from northwest/west to southeast/east within the recharge zone in secondary conduit systems that converge with northeast trending primary conduits defined by troughs in the potentiometric surface parallel to faulting and fracturing (Zappittelo et al., 2019). Groundwater flow is very rapid from recharge features to wells and springs, with velocities ranging from 1 to 7 miles/day depending on hydrologic conditions. Multiple tracing studies since 1996 have further revealed the complexity of groundwater subbasins and helped define the divide between the San Antonio and the Barton Springs segments of the Edwards Aquifer (Figure 5.3).

Because of the Aquifer's highly permeable karstic nature (see Figures 5.5 through 5.14 for examples) water levels and spring flows respond quickly to rainfall, drought, and pumping.

Figure 5.5 Edwards Aquifer recharge dam on Seco Creek. Part of the flood water is diverted towards the Valdina Sinkhole, shown on the right photo, via artificial channel incised into Edwards Limestone. Courtesy of Edwards Aquifer Authority.

Although water levels periodically and seasonally decline rapidly in wells throughout the aquifer, they also rebound quickly with adequate rainfall. The regional water planning groups, in their 2006 Regional Water Plans, recommended several water management strategies for the Aquifer including drilling new wells, constructing small dams along streambeds to enhance recharge to the aquifer (Figure 5.5), and reallocating supplies from irrigation to municipal users. They also recommended expanding an existing aquifer storage and recovery facility that stores water from the Edwards (Balcones Fault Zone) Aquifer in the Carrizo-Wilcox Aquifer in southern Bexar County (George et al., 2011; Eckhardt, 2010).

Figure 5.6 *Left*: Valdina Sinkhole during recharge when Seco Creek water is clear. Photo courtesy of USGS. *Middle*: The drop in Valdina Sinkhole when dry. Photo courtesy of Dave Bunnell; all rights reserved; printed with permission. *Right*: Cave passage at the bottom of Valdina Sinkhole when dry. Photo courtesy of Geary Schindel.

Figure 5.7 Devil's Sinkhole, a National Natural Landmark, is a 50-foot-wide karst shaft near the city of Rocksprings in Edwards County, the Edwards Plateau. The shaft drops 140 feet into the cavern which itself has a diameter of over 320 feet and reaches 350 feet deep. The Devil's Sinkhole, managed by Texas Parks and Wildlife (https://tpwd.texas.gov/state-parks/devils-sinkhole) is home to one of Texas' largest colonies of Mexican free-tailed bats, some 3 million strong. The bats roost in the cavern from late spring through early fall. They migrate to Mexico for the colder months of the year. Each evening the bats begin a nocturnal quest for food, creating a spectacular sight as they emerge from the cavern. The park offers bat tours while the bats are in residence. Photo courtesy of Geary Schindel.

Figure 5.8 0-9 Well, a natural 120-foot-deep pit near Ozona, on the Edwards Plateau. Wagon trains used to stop here for water as they could lower a bucket on a rope and get water from the pit. The panel by the well reads: *The 0-9 well is a Texas historical landmark. The date of discovery of this natural cavern is unknown. It has played a major role in the development of the northern part of Crockett County by providing an endless supply of fresh water for the cattle and sheep industry. As early as mid-1800's, cattle were watered at the well on their long journey north from Mexico to Kansas. The "natural well", also served as a regular stop for the stage route between Ozona and San Angelo until the early twentieth century. The well and surrounding property was granted to the University of Texas by the State of Texas in 1876 and remains a part of the U.L.S system today. 0-9 well is protected under the Texas Cave Protection Act and under the management of the Texas Cave Management Association. – No unauthorized entry –.* Photo courtesy of Geary Schindel.

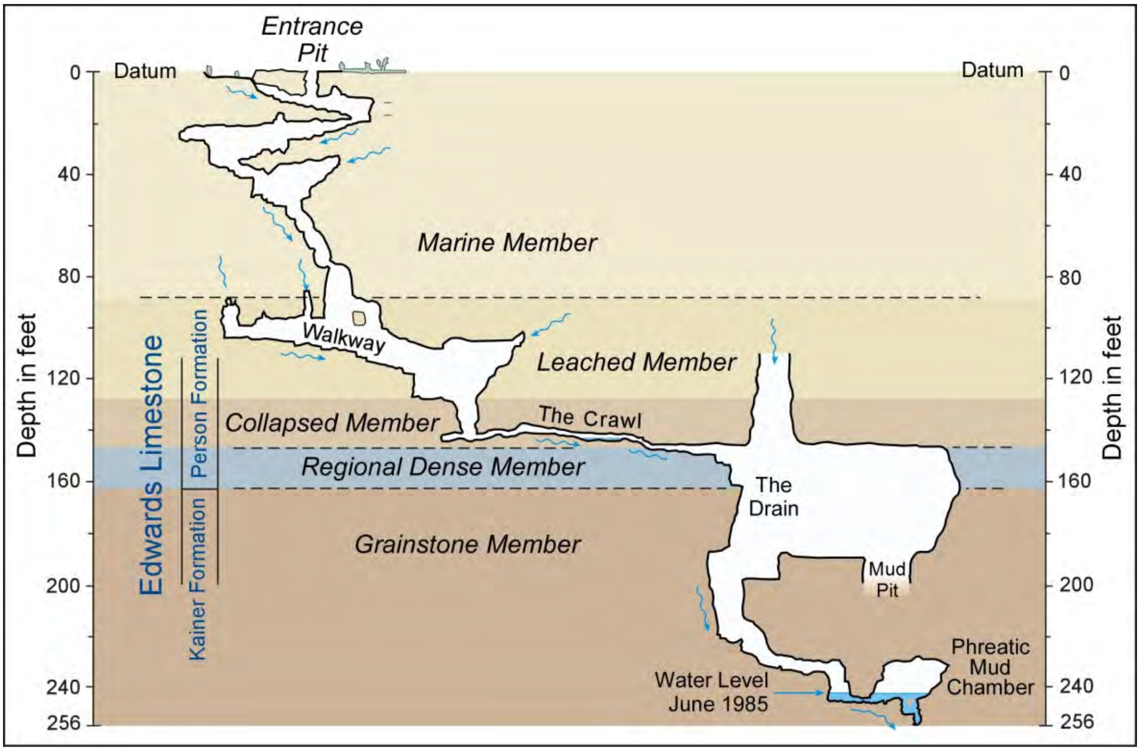


Figure 5.9 Profile of Genesis Cave (R.M. Waters, Texas Speleological Survey, 1986; adapted from Veni 1988; modified from Johnson et al., 2010)

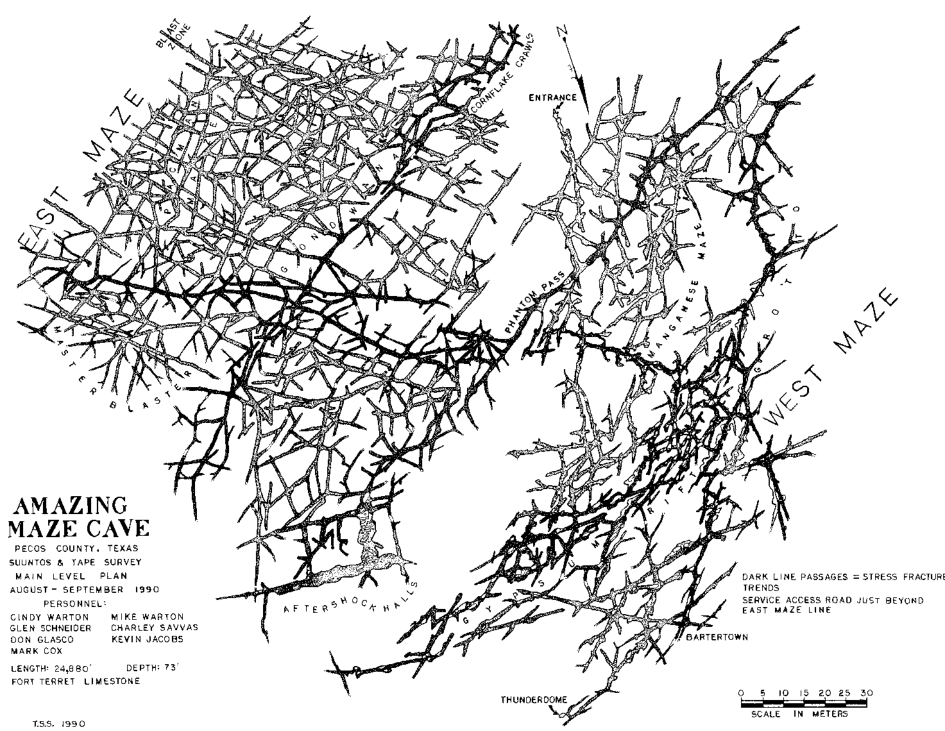


Figure 5.10 Amazing Maze Cave near Bakersfield in Pecos County, 30 miles east of Fort Stockton is the fifth longest in Texas with 4.3 miles of surveyed passages. The cave is developed in Fort Terret limestone (Courtesy of Texas Speleological Survey; https://www.texasspeleologicalsurvey.org/deeplong/longcaves.php)

Figure 5.11 *Left*: Karstified limestone of Edwards Group exposed in a road cut in Austin, Texas. Note subvertical fractures/faults. *Right*: Cavity in a natural outcrop of Edwards Limestone.

Figure 5.12 Examples of karstification in Edwards Limestone. All photos are from the Aquifer recharge zone, taken during a 1995 field trip of TCU hydrogeology students.

Figure 5.13 Jeff Hoese examines trash around a flowstone waterfall at the bottom of the entrance to Midnight Cave on November 20, 1993. This cave is in southern Travis County. The trash includes household garbage, used oil filters, corroded 55-gallon drums, glass pesticide bottles, partially filled turpentine cans, and automobile parts. Note the trash on the higher ledges of the cave. During high aquifer conditions the cave fills with water causing some of the trash to float onto the higher ledges. Cleanup efforts were coordinated by the Austin Nature Preserves, with assistance from the Barton Springs/Edwards Aquifer Conservation District, the Austin Parks and Recreation Department's Public Safety Office, and the Texas Cave Management Association. Volunteers, including members from the University Speleological Association, the Texas Speleological Society, and other individuals, removed an estimated 3,000 cubic feet of trash from November 1993 through July 1994. Photograph by Nico M. Hauwert. From Hauwert and Vickers, 1994.

Figure 5.14 On January 24, 2012, a 4.5-inch rainfall filled a Storm Water Retention Pond (SWRP) located in the recharge zone of the Barton Springs segment of the Edwards Aquifer with about 10 feet of stormwater. Subsequently, a cover-collapse sinkhole developed within the floor of the SWRP, measuring about 30 ft in diameter and 12 ft deep. About 7 million gallons of stormwater drained into the aquifer through this opening. To determine the path, velocity, and destination of stormwater entering the sinkhole, a dye trace was conducted. Phloxine B was injected into the sinkhole on February 3, 2012. A mass of 16.27 lbs (7,382g) was mixed with water and then gravity injected via a hose using storm water from an adjacent pond.

The dye was detected at one well and arrived at Barton Springs in less than 4 days, corresponding to a minimum velocity of 1.3 mi/day. The successful dye trace confirmed conclusions of previously published reports by demonstrating that the sinkhole is well integrated into the aquifer system, and that groundwater in the study area is within the Sunset Valley Groundwater Basin. Phloxine B proved to be a very good, conservative tracer through the collapsed terra rosa material of the sinkhole. Text and photograph from Hunt et al., 2013a.

5.1.1. Challenge of Modeling and Managing Karstic Edwards Aquifer

As emphasized by the Southwest Research Institute (SWRI; Fratesi et al., 2015, page iv), "*The Edwards Aquifer Authority (EAA) relies heavily on groundwater flow models to characterize groundwater flow conditions in the San Antonio segment of the Edwards Aquifer (hereafter referred to as the Edwards Aquifer) and to serve as the basis for predicting impacts of water-resource management scenarios.*"

Edwards Aquifer is one of the most researched, investigated, and modeled aquifers in the United States. Starting in the early 1990s, there have been so far at least a dozen computer models of the Aquifer as a whole or some of its parts, developed by various agencies, consultants, and others. For example, an overview of some of the more complex models is provided by Lindgren et al. of USGS (2009). In the introduction to this report, the authors state that "*A substantial number of public water system wells in south-central Texas withdraw groundwater from the karstic, highly productive Edwards aquifer. However, the use of numerical groundwater flow models to aid in the delineation of contributing areas for public water system wells in the Edwards aquifer is problematic because of the complex hydrogeologic framework and the presence of conduit-dominated flow paths in the aquifer. The U.S. Geological Survey, in cooperation with the Texas Commission on Environmental Quality, evaluated six published numerical groundwater flow models (all deterministic) that have been developed for the Edwards aquifer San Antonio segment or Barton Springs segment, or both. This report describes the models developed and evaluates each with respect to accessibility and ease of use, range of conditions simulated, accuracy of simulations, agreement with dye-tracer tests, and limitations of the models*."

In addition to common pressures such as population growth and water demands by agriculture, this unprecedent proliferation of groundwater models of the Edwards Aquifer is, to a large extent, consequence of a lawsuit against U.S. Fish and Wildlife Service (USFWS) and the state of Texas brought up by the Sierra Club in 1991. The Sierra Club sued under the Endangered Species Act, arguing that state water policy was driving five endangered Texas species native only to the San Marcos and Comal Springs toward extinction. The Sierra Club won the lawsuit and the groundwater use in the San Antonio segment of Edwards Aquifer changed forever.

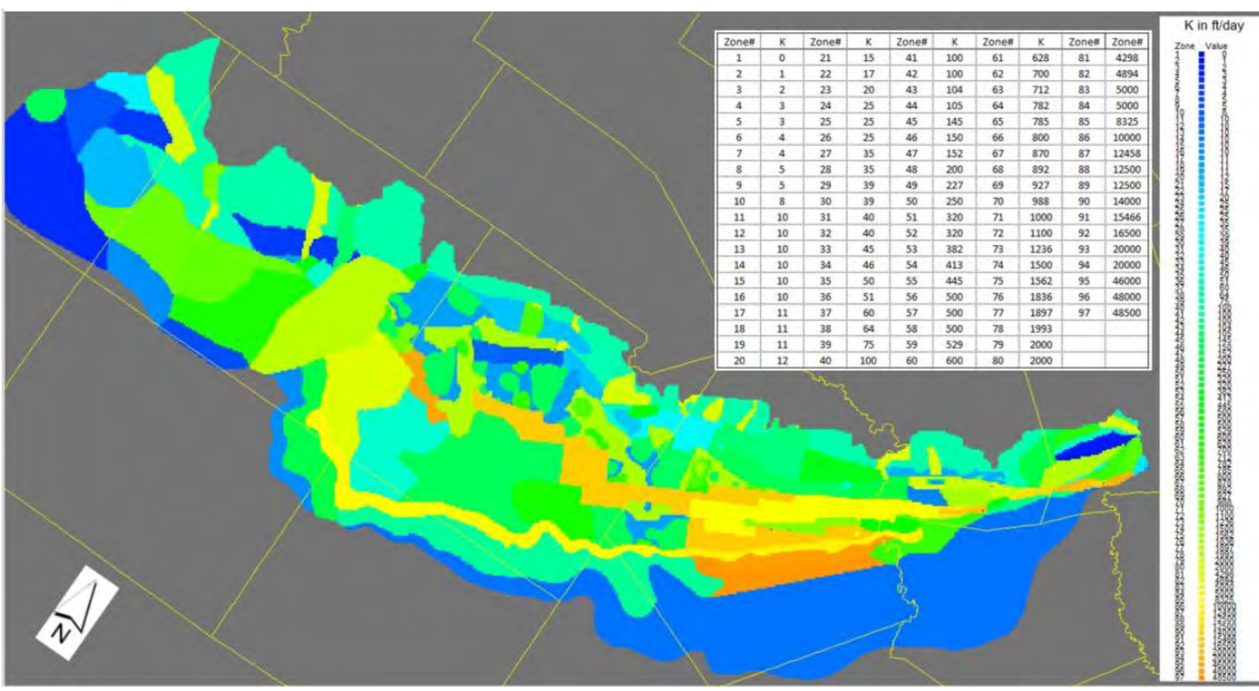
As explained by LBG-Guyton Associates (2004), in the summer of 1956, Comal Springs and Landa Lake stopped flowing. Between June and August 1956, lake levels in Landa Lake declined 6 feet. The flow rate at San Marcos Springs decreased to 46 cfs. In 1966, 1971, 1984, 1989, and 1990 additional dry periods occurred such that some of the springs at Comal Springs went dry or had the potential to go dry. In 1993, the USFWS defined the take and jeopardy discharge values for both springs as a result of a February 1, 1993 Judgment (amended on May 26, 1993) in the case of Sierra Club vs. Secretary of the Interior (No. MO-91-CA-069, U.S. Dist. Ct., W.D. Texas). The court ordered the USFWS to make certain determinations relative to minimum spring flows and aquifer levels necessary for the endangered and threatened species associated with the Edwards Aquifer. The purpose of these determinations was to provide guidance to Federal agencies and pumpers from the aquifer to assist them in taking appropriate actions to ensure their activities do not take or jeopardize listed species or result in adverse modification or destruction of critical habitat.

In response, various agencies and entities started developing groundwater (aquifer) management plans and not just in the Edwards Aquifer area. This included groundwater models as one of the main tools for quantitatively assessing groundwater availability, and sustainable pumping rates by various users. As expected, the models and the plans were, and continue to be challenged by those not happy with any restrictions on groundwater pumping and the groundwater withdrawal permitting role of agencies. For example, the newly formed Edwards Aquifer Authority (EAA) became fully operational on June 28, 1996, only after the Texas Supreme Court unanimously overturned the district court ruling which stated that EAA Act is not constitutional. During that very summer, Texas experienced a severe drought which showed that many municipal water purveyors did not have adequate supplies for their customers (https://www.edwardsaquifer.org/eaa/history/eaa-timeline/).

Unfortunately, at the time of this writing (spring of 2024), virtually none of the numeric groundwater flow models of Edwards Aquifer has been developed in a scientifically and hydrogeologically justifiable manner which would ensure its reasonable, defensible utilization for the Aquifer management. Namely, all such models, including the currently utilized EAA model (Liu et al., 2017), are based on equations and laws of groundwater movement that are not at all applicable, in any shape or form, to the physical reality of "conduit-dominated flow paths in the aquifer." Instead, all authors of the models use various surrogate approaches in a hope that, somehow, it would work, and their model may be useful.

> ***"However, the use of numerical groundwater flow models to aid in the delineation of contributing areas for public water system wells in the Edwards aquifer is problematic because of the complex hydrogeologic framework and the presence of conduit-dominated flow paths in the aquifer."***
>
> **United States Geological Survey (Lindgren et al., 2009).**

Most such approaches assume that a karst aquifer can be approximated as an "equivalent porous medium" (EPM) which means that the groundwater flow equations developed for unconsolidated sediments such as sand and gravel, including the most famous equation in hydrogeology, Darcy's Law, are applicable to "conduit-dominated flow paths" in the aquifer. The EPM modelers then freely assign very high, improbable values of the hydraulic conductivity to those model cell known, or suspected, to contain highly transmissive conduits (see Figure 5.15) or assign a very low (<< 0.01) effective porosity to simulate the high groundwater velocities. Needless to say, a porosity of any kind of an empty but water-filled conduit (submerged cave) is 100% and any equation that features porosity or specific yield parameters for "conduit-dominated flow paths" is not applicable.



Zone#	K	Zone#	K	Zone#	K	Zone#	K	Zone#	Zone#
1	0	21	15	41	100	61	628	81	4298
2	1	22	17	42	100	62	700	82	4894
3	2	23	20	43	104	63	712	83	5000
4	3	24	25	44	105	64	782	84	5000
5	3	25	25	45	145	65	785	85	8325
6	4	26	25	46	150	66	800	86	10000
7	4	27	35	47	152	67	870	87	12458
8	5	28	35	48	200	68	892	88	12500
9	5	29	39	49	227	69	927	89	12500
10	8	30	39	50	250	70	988	90	14000
11	10	31	40	51	320	71	1000	91	15466
12	10	32	40	52	320	72	1100	92	16500
13	10	33	45	53	382	73	1236	93	20000
14	10	34	46	54	413	74	1500	94	20000
15	10	35	50	55	445	75	1562	95	46000
16	10	36	51	56	500	76	1836	96	48000
17	11	37	60	57	500	77	1897	97	48500
18	11	38	64	58	500	78	1993		
19	11	39	75	59	529	79	2000		
20	12	40	100	60	600	80	2000		

Figure 5.15 Map of hydraulic conductivity (*K*) zones assigned to active model area of the updated EEA MODFLOW Groundwater Model of the San Antonio Segment of the Edwards Aquifer. Zone 1 is the inactive model area and assigned a zero value for *K*. Calibrated *K* values zones range from a low of 1 ft/d (dark blue) to a high of 48,500 ft/d (orange). Inset table lists the calibrated *K* values for each zone as numbers on color scale are impossible to read. Caption and figure from Liu et al., 2017 (page 13). Incidentally, the author of this book has never heard of nor was presented with evidence of hydraulic conductivity as high as 48,500 ft/day, in any type of aquifer, anywhere in the world. A note for non-hydrogeologists: the hydraulic conductivity is not the same as the groundwater flow velocity.

The EPM solutions are simply inadequate and cannot mimic the dynamics of groundwater flow and flow velocity in karst environments. Again, and most importantly, the concept of hydraulic conductivity does not apply at all to "empty" spaces such as karst conduits where groundwater flow is governed by laws of hydraulics of pipes. In addition, none of the EPM models can simulate an important hydraulic interaction between the conduits and the surrounding rock matrix following some rapid recharge episodes – namely, as the hydraulic head quickly rises in the conduits because of a recharge event, there may be a significant transfer of water from the conduits into the surrounding matrix. An EPM model will virtually always keep the heads in the high hydraulic conductivity cells representing surrogate conduits lower than in the surrounding model cells (Kresic and Panday, 2018, 2021). Such models are also incapable of simulating rapid hydraulic pressure propagation through conduits that can cause an equally rapid increase in a spring discharge after major rainfall events.

Regardless of the methodology used for model development (i.e., based on laws of physics or using some surrogate), the true test for any model is how accurately it simulates real changes in the groundwater system, such as groundwater pumping by a well or group of wells and the impact of such pumping on other groundwater users or a spring discharge. It is not clear if and how EAA uses its current model to, for example, change the existing permits, or deny permit applications for groundwater pumping. It is also not clear if the effects of these changes are evaluated using real-life data from the field. In other words, the validity of any model can be quickly tested – an existing well or a new test well can be pumped, its zone of influence and drawdown can be measured in the field, and this reality can be compared with what the model predicted. This is the standard procedure for any aquifer management based on models to be successful. Judging grom Figure 5.15, it is virtually certain that large capacity wells exist in and close to the simulated preferential flow paths and away from them. Any number of such wells could be used for model verification.

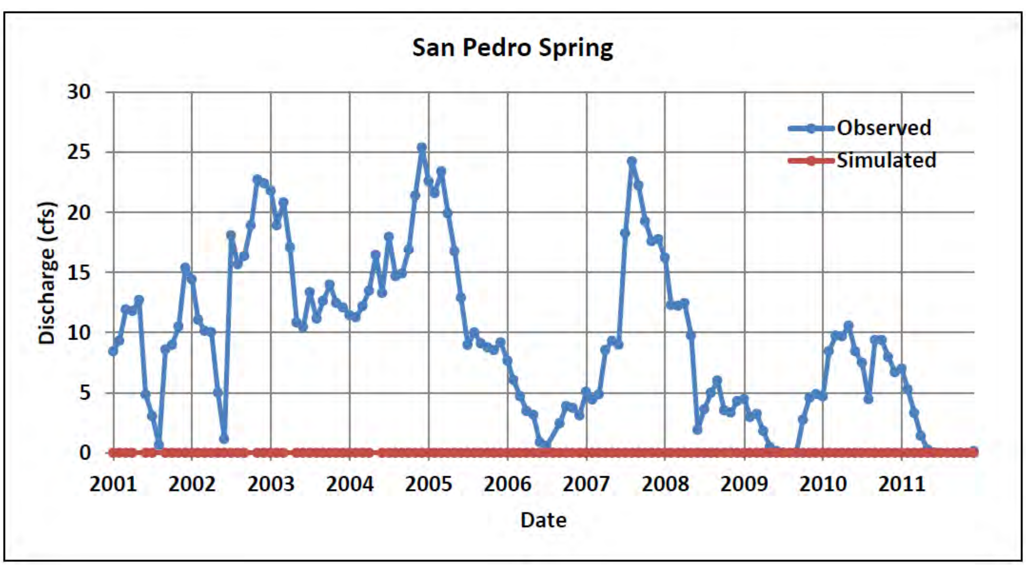


Figure 5.16 Observed (blue) and simulated (red) discharge at San Pedro Spring for the years 2001-2011. Figure 4.3.1-4 from the Southwest Research Institute (SWRI) groundwater flow model of Edwards Aquifer (Fratesi et al., 2015). A note to readers: the symbols/explanation on the graph are indeed correct. The SWRI model says there was no discharge at San Pedro Spring, when in fact the spring was flowing almost all the time at a significant average rate of approximately 5-10 cfs.

It is of course not unexpected that some institutions and their modelers, when a model is not "cooperating", blame everything else other than their own concept, which may be flawed, and cannot be reproduced numerically (quantitatively) regardless of the computer program or the underlying mathematical equations. Without trying to fully understand the modeling problem at hand, including perhaps learning how to better use the computer program and what the physics of groundwater flow in karst really is, they fall back to using something they are familiar with, such as an EPM model. If there is a notable discrepancy between the model simulation and the reality, they may qualify that as not significant in a grand scheme of things. When they choose to justify use of a surrogate model instead of one based on physical reality, they sometimes may do it in astonishingly creative ways. This includes referring to equations of the model based on laws of physics as "stiff". The following quote from a SWRI report (Fratesi et al., 2015, page 103) illustrates these points:

Groundwater flow aligned with rivers in the Contributing Zone was initially represented as conduits using the discrete feature option in FEFLOW (Diersch, 2014). This approach resulted in numerical instability in the downgradient portion of the Contributing Zone which exhibits the largest hydraulic gradients. The large hydraulic gradients coupled with the abrupt change in the hydraulic properties of the matrix versus the discrete features (i.e., conduits) resulted in a numerically stiff system of equations. The numerical instability is attributed to the stiffness in the governing flow equations.

The SWRI finite-element groundwater flow model of Edwards Aquifer, commissioned by EAA, was apparently developed as an alternative to the existing USGS MODFLOW model by Lindgren et al. (2004) with an idea to utilize features available in the FEFLOW computer program for simulating groundwater flow through discrete conduit networks. After three years of development and presumably a significant six-figure cost, the SWRI model ended up being yet another EPM model in karst. However, groundwater scientists and modelers at SWRI elevated this approach to a never-before-seen new level as discussed further.

After three years in Texas, where I taught hydrogeology and groundwater modeling courses at Texas Christian University, I had a chance to visit some notable Texas springs described in this book, some of them multiple times. After moving back East, my family and I kept visiting Texas springs whenever we had a chance. This includes our favorite spring in Texas, and one of my favorite springs in the country, San Solomon Springs in west Texas. After leaving TCU I worked on several groundwater projects in Texas as a professional consultant and was an invited speaker at a 1997 NGWA conference in Austin organized by Robert Masters and dedicated to Texas Senate Bill 1 which greatly influenced groundwater management in Texas. My desire to carefully read published groundwater modeling reports on Edwards Aquifer as they appeared is therefore not surprising.

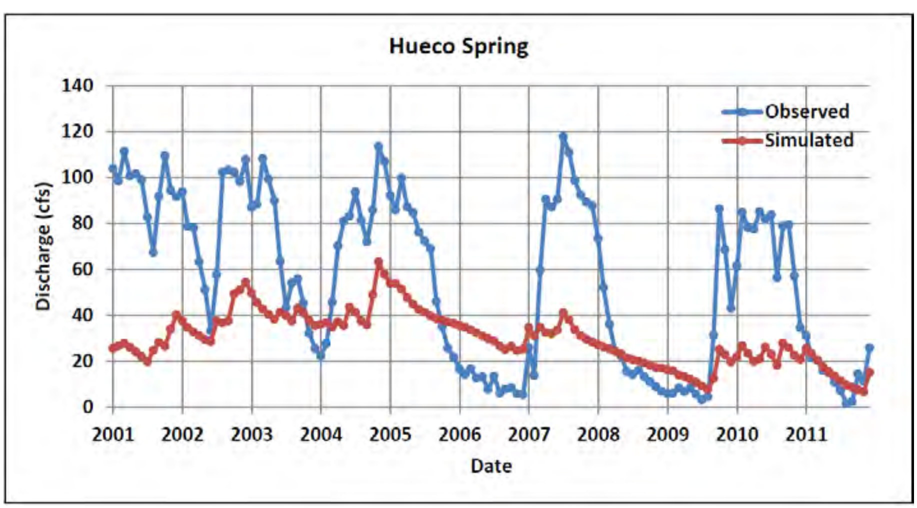


Figure 5.17 Observed (blue) and simulated (red) discharge at Hueco Springs for the years 2001-2011. Figure 4.3.1-3 from the Southwest Research Institute (SWRI) groundwater flow model of Edwards Aquifer (Fratesi et al., 2015). A takeaway point for the readers: In year 2010-2011, roughly 45 cfs of the actual spring discharge disappeared in the SWRI model. This equates to approximately 10.6 billion gallons of water, enough to provide water supply for 2,000 people for the entire year.

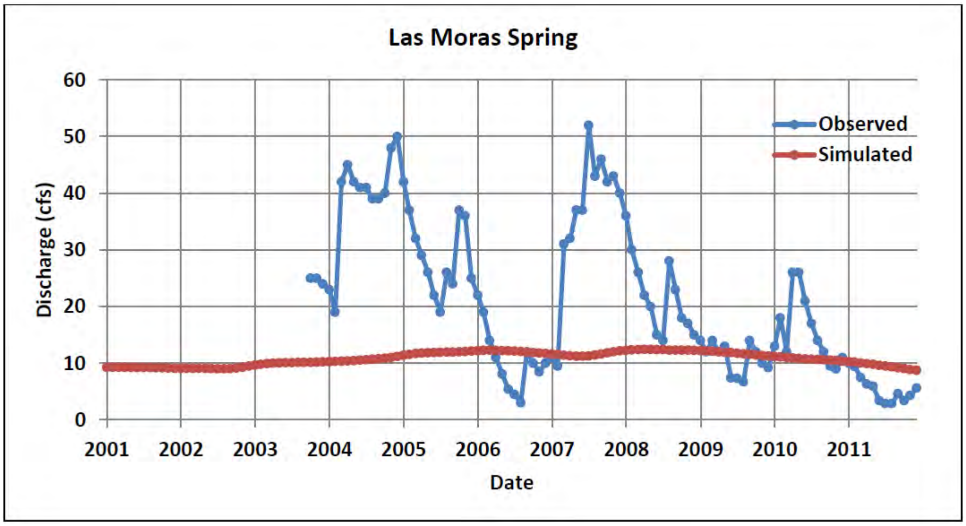


Figure 5.18 Observed (blue) and simulated (red) discharge at Las Moras Springs for the years 2001-2011. Figure 4.3.1-8 from the Southwest Research Institute (SWRI) groundwater flow model of Edwards Aquifer (Fratesi et al., 2015).

Since the SWRI model is not made publicly available, I was not able to review the model input and output files, or independently run the model and verify any results, statements, or figures in the Final Report relating to model parameters, geometry, initial and boundary conditions, calibration parameters, calibration goals, or any other quantitative aspects of the model and the modeling process. Nevertheless, based on what is presented in the Final Report, it is my best professional judgment that the finite-element groundwater model of the Edwards Aquifer developed by Southwest Research Institute cannot and should not be used in supporting groundwater resource management decisions or used for any of the applications listed in Section 1.1 Scope of Work of the Final Report. If EEA selects to continue work on the model trying to make it suitable as an alternative to their updated MODFLOW model (Liu et al., 2017), I believe that the associated effort would be more than substantial, possibly including radical changes in both the conceptual model and the design of the numeric model which would affect significant portions of the Edwards Aquifer. In other words, it would not be advisable to *throw good money after bad* (money spent on the 3-year modeling effort).

In contrast to my opinion, SWRI states the following on pages ii and iv of their report (Fratesi et al., 2015):

Currently, the EAA uses a finite-difference model developed in 2004 by the U.S. Geological Survey using MODFLOW (Lindgren et al., 2004) to perform these water-resource management analyses. There are recognized limitations and shortcomings in the 2004 MODFLOW model, including questions about the conceptual model on which the numerical model is based."

The alternative model successfully replicated the general response of the Edwards Aquifer. Seven of 14 of the target goals were met by the alternative model. In comparison, the 2004 MODFLOW model met 3 of the 14 target goals. The inability of the alternative model to match high discharge at Comal and San Marcos Springs led to the greatest discrepancy between simulation results and the target goals.

Since the main intention of this book is not to discuss hydrogeology or groundwater modeling at nauseam, I will let the readers make their own judgment, using their own common sense, if Figures 5.16 through 5.18 demonstrate a success. However, it would help various stakeholders if, for example, EAA made public any reviews or comments about their models from independent professionals. This includes any input from the members of the Groundwater Model Review Panel (GMRP) listed on page xiii of the modeling report by Liu et al., 2017.

Incidentally, I am aware of one additional member of GMRP whose name is not acknowledged in the SWRI report. It is not entirely inconceivable that this member was omitted because her/his review was not "greatly appreciated". Perhaps the "review comments and discussions" by this reviewer did not fit the expected or desired narrative? Perhaps they were dissenting? The highest court in the nation, the Supreme Court, whose rulings affect all Americans, does reveal dissenting opinions. Likewise, the EAA should inform the public of any unfavorable reviews of the SWRI's model.

In any case, and for the benefit of the Texans concerned with the welfare of their springs and their groundwater resources in general, it would be appropriate to bring a bit more transparency to the entire process of managing the Edwards Aquifer. This includes the question of who decided to drop the name of the fourth member of GMPR from the Acknowledgment section of the SWRI modeling report by Liu et al., 2017. Was it the SWRI project manager, or the EAA project manager, or some other leader in this serious case of groupthink?

Hoping to make it a bit more educational and interesting for the reader, I could not resist explaining one of the absurdities of the SWRI's groundwater flow model of Edwards Aquifer. It is illustrated with Table 5.1 of this book (Table 3.3.1-1 in Liu et al., 2017) and in photographs in Figure 5.19.

To the best of my knowledge, no hydrogeologists or groundwater modelers simulate karst springs with hydraulic conductivity (see Table 5.1) since this would be nonsensical. Springs, in general, are simulated with a flow (discharge) rate or some other computer program feature such as a drain or something similar. What is simulated with hydraulic conductivity is a model element (another term would be "model cell" or "node") representing the porous medium or rock in which the spring is located, not the spring itself. Below are two definitions of hydraulic conductivity from public sources which can help the reader understand what this is all about.

Table 5.1 Initial reference elevation, calibrated elevation and calibrated conductivity of springs and points of discharge. Table 3.3.1-1 in Liu et al., 2017.

	Initial Reference Elevation (ft, msl)	Calibrated Elevation (ft, msl)	Calibrated Conductivity (ft/day)
San Marcos Springs	573	570	1
Comal Springs	609	600	1
Hueco Springs	652	630	0.3
San Antonio Springs	670	685	2
San Pedro Springs	660	655	0.02
Pinto Springs	1150	1160	0.1
Las Moras Springs	1105	1105	1E-06
Medina River/Underflow	845	860	0.02
Leona Springs/Underflow	811/839	811/839	0.03
Nueces River springs	795	810	3

Water Basics Glossary by United States Geological Survey (https://water.usgs.gov/water-basics_glossary.html).

(Hydraulic conductivity is) The capacity of a rock to transmit water.

The Groundwater Project, a free web resource (https://books.gw-project.org/hydrogeologic-properties-of-earth-materials-and-principles-of-groundwater-flow/chapter/hydraulic-conductivity/):

The hydraulic conductivity proportionality constant, K, can be conceptualized as the relative ease of fluid passage through a porous material. It has direction and magnitude and is represented as a vector.

It has units of velocity (e.g., feet per day, meters/day). However, K is not a velocity, rather it represents the transmission properties of the porous material.

The hydraulic conductivity of 1E-06 ft/day (0.000001 ft/day) assigned to the SWRI's representation of Las Moras Springs in their model is a very low number. It is so low that it corresponds to an almost impermeable "stiff" clay ("stiff" here does not refer to any equation; rather, it is a description commonly used in geological and soil sciences when describing certain types of clay). Without knowing what SWRI really tried to accomplish by assigning such a small number to their model feature that represents Las Moras Springs (which can discharge up to 50 cfs as seen in Figure 5.18), the result is obvious. Using an analogy, it is as if SWRI covered the spring with a "stiff" blanket of clay and the spring just could not flow as much as it should. And the poor San Pedro Spring (Figure 5.16) could not flow at all in the same parallel universe even though it received a bit higher number of conductivity from SWRI. Note to the reader: one can manipulate different parameters in the model, not just hydraulic conductivity, to achieve desired results. This is generally referred to as "model calibration". It is not clear what else may have been done by the SWRI modelers to make the poor San Pedro Spring not flow at all in their model. In any case, the conductivity value of 0.02 ft/day given to whatever feature or the model cell/node that simulates the strong karst San Pedro Springs is nonsensical.

To put this cursory review exercise in another perspective, one can simply compare the SWRI model with the updated EEA model (Figure 5.15). In the updated EEA model, the lowest hydraulic conductivity is 1 ft/day, and the highest hydraulic conductivity representing conduit-dominated flow including locations of large springs is 48,500 ft/d or many, many orders of magnitude higher than the 0.000001 ft/day SWRI used in their model for San Pedro Springs. The two models represent two extremes of the "equivalent porous media" (EPM) surrogate modeling approach showing that absurdity sometimes has no limits. The two EPM models are separated by exactly ten orders of magnitude. To put it more vividly in terms of an equivalent distance, the two surrogate models are separated by

10 billion feet

Figure 5.19 Photographs from San Marcos Springs. *Left*: Spring discharge at Johnny Weissmuller Spring is mainly from a single 11-foot-long fissure at the bottom of the V-shaped crater. *Right*: The geyser of the taller of the two sand boils in the photograph is about 1-foot high. Photographs by Bridget Lewin, Texas State University. From LBG-Guyton Associates, 2004.

Another way of analyzing the improbable selection of model parameters by SWRI is to examine available information on discharge mechanisms of the powerful San Marcos Springs, the second largest in Texas. This group of closely spaced springs, all discharging into Spring Lake (see Section 5.10), has 13 known locations and areas of discharge. Two examples are shown in Figure 5.19, courtesy of Bridget Lewin, Texas State University.

According to LBG-Guyton Associates (2004), discharge from the 13 spring areas occurs as (1) discrete flow out of a defined orifice, such as a fissure (Figure 5-19 *Left*); (2) diffuse flow out of the rubble of angular blocks; and (3) strong sand boils or sand geysers out of sand plains composed of white and tan, fine-grained quartz and calcite sands and black organic materials (Figure 5-19 *Right*). The measured velocity of groundwater discharging from the John Weissmuller orifice was 2.79 feet per second (ft/sec) or 241,056 ft/day; the discharge rate was estimated at 15 cubic feet per second (cfs). Velocity of water discharging through unconsolidated sand sediments, which cover the conduits in Edwards Limestone, could not be measured and was estimated at 0.03 ft/sec (2,592 ft/day) in the areas of fascinating sand boils and geysers, with the total discharge rate of 142 cfs. None of these numbers could possibly be equated with the conductivity number of 1 ft/day given to San Marcos Springs by SWRI (Table 5.1).

A nice visual comparison between the USGS numeric model of the Edwards Aquifer by Lingren et al. (2004) and the reality is shown in Figure 5.20. Here are key points of the Johnson et al. (2010) report which compares the model results and quite a few field tracer studies performed by EAA: *Whereas groundwater flowpaths carried tracers southward, the model predicted that they would travel southeastward toward a simulated high T zone in eastern Bexar County that carries water to Comal and San Marcos springs. Few faults were inserted into the model near Panther Springs Creek because Lindgren et al. (2004) concluded that faults in the recharge zone would have little influence on groundwater flow. In fact, principal faults in the model separating the recharge zone from the artesian zone did not influence groundwater-flow directions because, as Figure 38* (Figure 5.18 in this book) *shows, the tracer test flowpath crosses the modeled recharge zone boundary faulting. Actual groundwater velocities varied from model predictions. The length of the line between modeled flowpath arrows represents one year of travel, a distance ranging from one to two km. Because dyes traveled as far as several kilometers a day, MODPATH and MODFLOW severely underestimated groundwater velocity.*

According to Johnson et al. (2010), Lindgren et al. (2004) were cognizant of the limitations of the model. They also recommended not using the model to simulate travel times of contaminants in groundwater. Whatever the case may be, the question remains as to the utility of a model that cannot accurately simulate either groundwater flow directions or groundwater velocities, especially if such a model is to be used to manage Edwards Aquifer. This includes permitting groundwater pumping and evaluating any related impacts this pumping may have on the flows of various springs and pumping wells of other groundwater users.

Generally, nearly all projects in hydrogeology require future projections, and the hydrogeologist is relied upon for expert opinion in this matter. Most commonly, the hydrogeologist must evaluate the efficacy of selected interventions in water supply development or hazardous waste remediation (particularly groundwater remediation). Examples include the installation and operation of new water supply wells or extraction wells associated with pump and treat remediation, the injection of chemical reagents for groundwater remediation (in-situ chemical oxidation), or the stimulation of contaminant biodegradation. Groundwater models are the best available means of simulating these interventions and most simply, determining if they will work. Modeling can also fill in the gaps between data that has been or will be collected at discrete time intervals thus helping the hydrogeologist better understand and simulate transient processes (Kresic and Mikszewski, 2013).

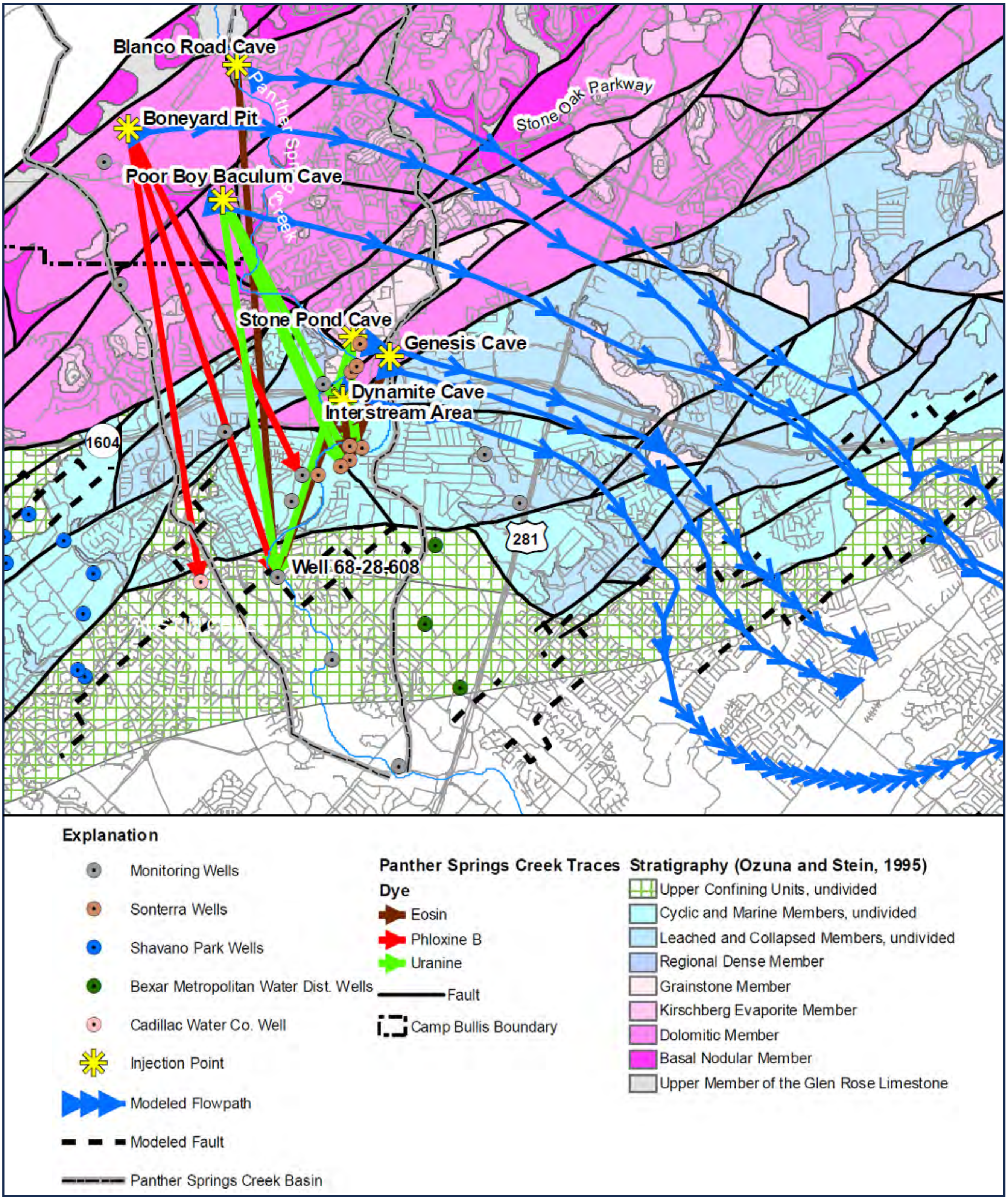


Figure 5.20 Tracer-test results compared with simulation using MODFLOW and MODPATH computer programs and the USGS model of the Edwards Aquifer by Johnson et al., 2004. Arrow marks on the modeled flowpaths (blue lines) denote 1-year travel times, the distance ranging from approximately 1 to 2 kilometers (0.6 to 1.2 miles). Dye travel velocity along the traced flowpaths (red and green lines), range from 52.5 ft/day to 16,338 ft/day. Figure 38 from Johnson et al., 2010.

5.2 The New Old Story, Painfully Familiar

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Texas State / Newsroom / Research & Innovation / 2024 / **Texas springs in crisis: New study highlights overwhelming increase in dry springs**

Texas springs in crisis: New study highlights overwhelming increase in dry springs

New research from The Meadows Center for Water and the Environment at Texas State University uncovers a concerning decline in the state's groundwater resources, finding that the number of dry springs has nearly tripled since the early 1980s.

Co-authored by Robert E. Mace, Ph.D., Meadows Center Executive Director, and Nohemi Galaviz, a Texas State undergraduate research assistant, the study revisits and builds upon the seminal work of Gunnar Brune's 1975 report, "Major and Historical Springs of Texas," and his subsequent 1981 book, "The Springs of Texas, Volume 1." As Texas' acknowledged expert on springs, Brune's publications cataloged the state's major and historical springs, forming the foundation of our knowledge today.

"For the first time in nearly half a century, we looked at the status of major and historical springs across the state to see if more springs had gone dry. Indeed, more—many more—have failed over the past 50 years," Mace said.

"The data speaks volumes about the growing demands on our groundwater resources and some of the consequences of meeting those demands," Mace said. "As groundwater use in the state continues to rise, the resulting decrease in springflow jeopardizes not only our groundwater and surface-water supplies but also the ecosystems that rely on these springs."

Jayme Blaschke | February 28, 2024

As explained by the non-profit organization Hill Country Alliance, whose mission "is to bring together a diverse coalition of partners to preserve the open spaces, starry night skies, clean and abundant waters, and unique character of the Texas Hill Country", Groundwater Conservation Districts (GCDs) are the only entities in place to protect Texas groundwater resources. The Texas Legislature, recognizing the need for groundwater management after multiple lawsuits challenging the Rule of Capture, adopted Senate Bill 1 in 1997 which allowed for the creation of GCDs. Districts are tasked with the development of groundwater management plans, the adoption of rules regulating the spacing and production of wells, and monitoring aquifer conditions.

GCDs are statutorily mandated to balance aquifer protection with the right of landowners to extract groundwater. As pointed out by Hill Country Alliance, *Ensuring our aquifers remain healthy and resilient given the diversity of seemingly competing interests is no easy endeavor*. More on GCD districts authority and challenges can be found at https://hillcountryalliance.org/wp-content/uploads/2023_HCA_ManagingGroundwater_Paper.pdf

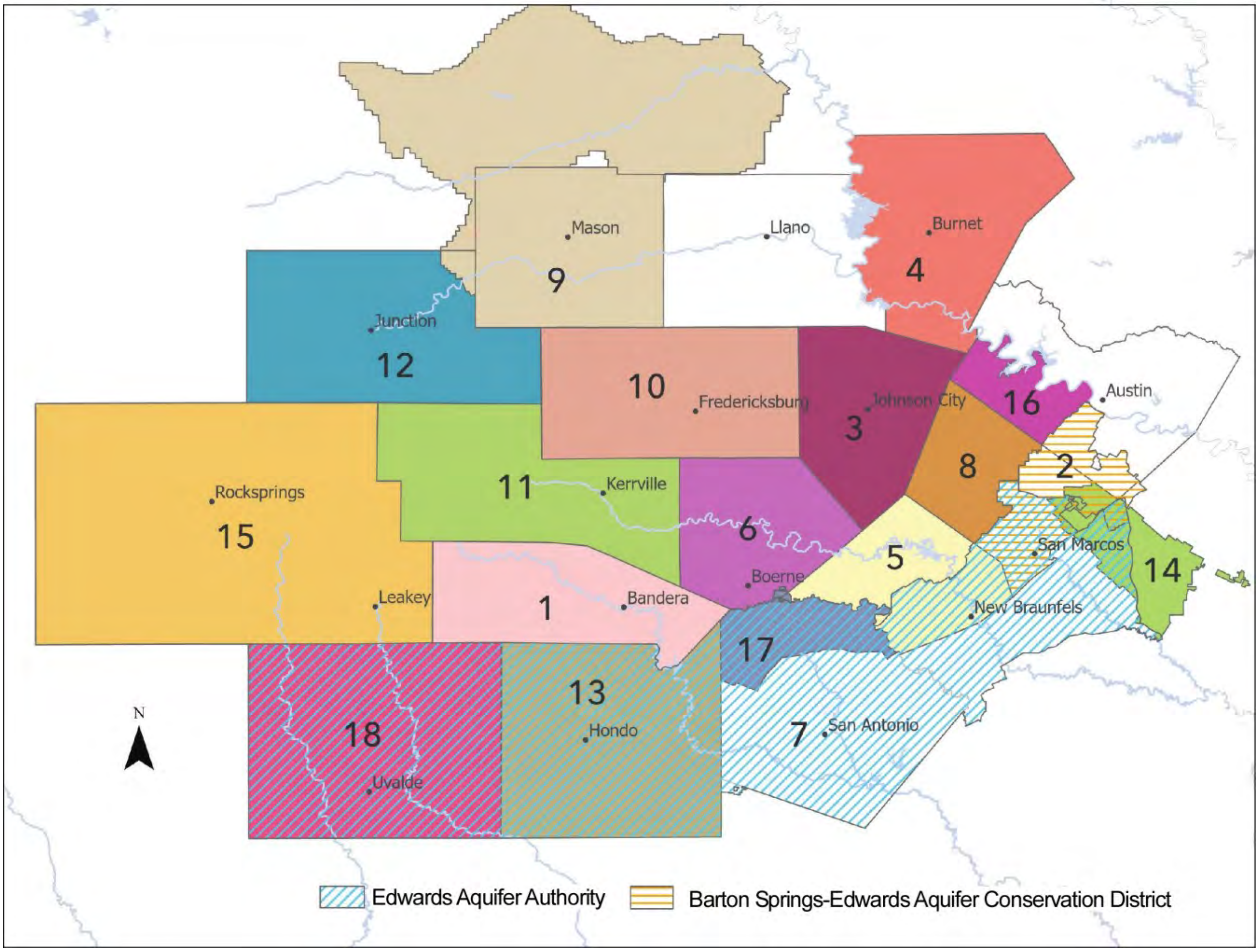


Figure 5.21 Map of Conservation districts in Texas Hill country. Courtesy of Hill Country Alliance. Available at https://hillcountryalliance.org/wp-content/uploads/GCDWebmap.pdf. **(1) Bandera County River Authority and Groundwater District** – Bandera County; **(2) Barton Springs/Edwards Aquifer Conservation District** – Travis, Hays, and Caldwell counties; **(3) Blanco-Pedernales Groundwater Conservation District** – Blanco County; **(4) Central Texas Groundwater Conservation District** – Burnet County; **(5) Comal Trinity Groundwater Conservation District** – Comal County; **(6) Cow Creek Groundwater Conservation District** – Kendall County; **(7) Edwards Aquifer Authority** – all or parts of Uvalde, Medina, Bexar, Comal, Hays, Caldwell, Atascosa, and Guadalupe counties; **(8) Hays Trinity Groundwater Conservation District** – parts of Hays County; **(9) Hickory Underground Water Conservation District** – all or parts of Kimble, Mason, Menard, McCulloch, and San Saba counties; **(10) Hill Country Underground Water Conservation District** – Gillespie County; **(11) Headwaters Groundwater Conservation District** – Kerr County; **(12) Kimble County Groundwater Conservation District** – Kimble County; **(13) Medina County Groundwater Conservation District** – Medina County; **(14) Plum Creek Conservation District** – parts of Hays and Caldwell counties; **(15) Real-Edwards Conservation and Reclamation District** – Real and Edwards counties; **(16) Southwestern Travis County GCD** – parts of Travis County; **(17) Trinity Glen Rose Groundwater Conservation District** – Northern Bexar County; **(18) Uvalde County Underground Water Conservation District** – Uvalde County.

Groundwater Management Areas (GMAs) follow the outline of major aquifers better and require GCDs within the boundaries to coordinate and cooperate in regional planning. These GMAs are directed to come up with "desired future conditions" (DFCs) for the aquifers: they must agree upon how much water can and should be pumped now and in the future and how that pumping will affect the future state of the aquifer. Most often, the DFC is an average aquifer drawdown measured in feet. Some GCDs measure their DFCs as specific springflow rates.

A complicating factor to groundwater management is that most major aquifers overlap and there are several minor aquifers that are relevant for regional planning as well. For these reasons, some GCDs are in more than one GMA and must participate in multiple distinct regional planning processes.

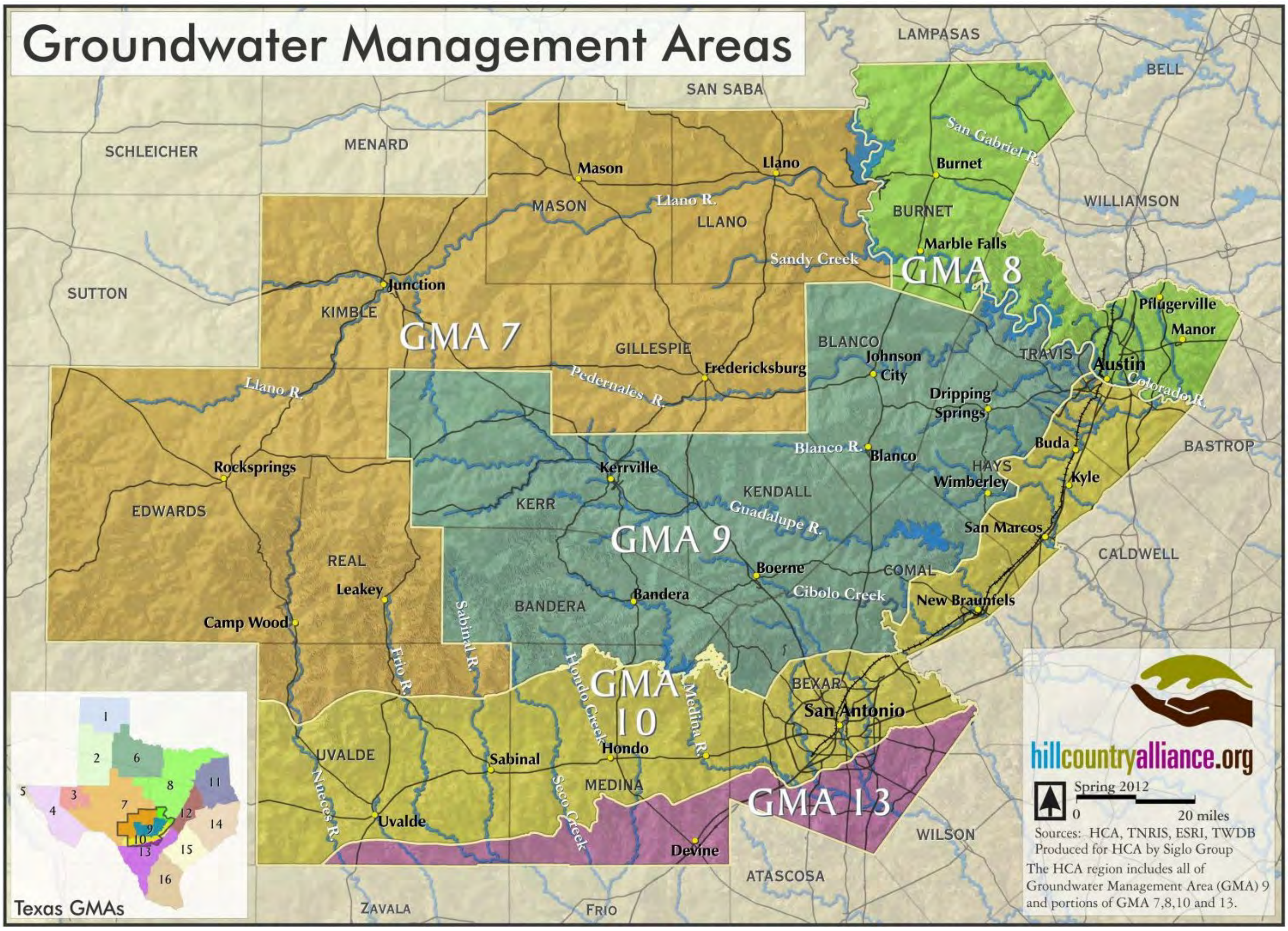


Figure 5.22 Map of Groundwater Management Areas in Texas Hill country. Courtesy of Hill Country Alliance. Available at https://hillcountryalliance.org/our-work/water-resources/groundwater-resources/

A non-profit organization, The Trinity Edwards Springs Protection Association (TESPA), has a mission to protect the Trinity and Edwards aquifers, the springs that flow from this interconnected system, and protect these waters for the people and wildlife who use and depend on them (https://www.tespatexas.org/).

The Watershed Association (https://watershedassociation.org/) is a non-profit organization located in the heart of the Texas Hill Country, "born out of a love for water." Their vision is "*For a future with clean, plentiful water flowing from Jacob's Well into Cypress Creek, a healthy ecosystem essential to the culture and economy of the Wimberley Valley. Over the past two decades, our broader mission has emerged to include fostering community awareness of the watershed and the community's responsibility to its watershed in the Wimberley Valley, across the Hill Country region, and throughout the state of Texas. At the heart of what we do is working to engage communities and provide experiences that reconnect people with nature. This principle runs throughout our six impact areas, which support implementing education, land conservation, and water policies to ensure water quality and availability for generations to come.*"

Hopefully, the work of organizations like TESPA, Hill Country Alliance, the Watershed Association, scientists like Mace and Galaviz, who are featured in the press release at the beginning of this section, and many others, will make more than just a dent in the armor of those that, collectively, can be characterized as profit- and special-interest-driven, and not concerned with the future of Texas groundwater resources and springs at all.

Following are quotes from the TESPA's webpage related to just one example illustrating the unfortunate mismanagement of Texas groundwater resources and the catastrophic failure to protect Texas springs which continue to dry up at what looks like an unstoppable pace.

Our work is far from over. The Hill Country is hot and dry right now. In this summer of 2023, Jacobs Well does not flow, again. Yet, development continues and investor-owned utilities like Aqua Texas continue to violate their groundwater permits. <u>Local groundwater conservation districts do their best to enforce and apply penalties while avoiding lawsuits that tight budgets cannot support</u> (emphasis added).

Our water means everything—our health, our economy, our connection to nature—everything. We must all stand together to ensure our water is managed sustainably. Now is the time to step up and take bold action. The situation is urgent, and YOUR voice is needed TODAY.

Aqua Texas failed to follow drought restrictions and Hays Trinity Groundwater Conservation District (HTGCD) rules and they failed to fix leaky pipes, wasting millions of gallons of our precious groundwater.

During the drought of 2022, Aqua pumped nearly 90 million gallons more than their permit allowed and they continue to pump. Aqua's noncompliance is unacceptable.

Aqua Texas has refused to settle its notice of alleged violation (NOAV) of the HTGCD rules and has failed to fix the leaky infrastructure.

Figure 5.23 A popular swimming hole for generations of Central Texans was in August 2023 down to a small pool of water. Photo by Michael Minasi. Courtesy of KUT News, Austin.

Aqua Texas is owned by a multi-billion-dollar company that has prioritized profits for its shareholders at our community's expense. It's time to hold them accountable to state and local rules and guidelines for responsible management of our water.

Now Aqua is suing the HTGCD in federal court, arguing that they should not have to comply with rules and regulations, or the limitations of their permit.

In the words of Charlie Flatten, General Manager for HTGCD:

"[The District] has never threatened Aqua's or the public's access to water...As is the case with every utility (corporate or local), Aqua is required to follow the rules that they agreed to in their permit. Some of those terms include adhering to a drought contingency plan if necessary. Aqua has not shown that they adhered to that plan in 2022. [The District's] lawful mandate is to protect the aquifer for ALL users. During emergency drought conditions, we must all conserve—and Aqua did not do that in 2022 and 2023."

Unfortunately, to no fault of their own, it is painfully obvious that various Groundwater Conservation Districts, Groundwater Management Areas, Boards, Authorities, and similar are, for the most part, underfunded, lack professional groundwater expertise, and have no real authority accompanied by strict legal enforcement, if not a mandate for criminal persecution. And yet, Groundwater Conservation Districts (GCDs) are the only entities in place to protect Texas groundwater resources? One thing that comes to mind when thinking of the most logical underlying reason for their tied hands is the following phrase "If you want nothing done—form a committee."

5.3 The Gunfight at Jacob's Well

Local investigative journalists and media have been covering the multiple murder attempts on Jacob's Well Spring life, with deep knowledge and passion as illustrated with just a few titles included here:

'It's heartbreaking': Jacob's Well stops flowing for sixth time in recorded history
KUT 90.5 | By Maya Fawaz; Published August 2, 2023 at 11:17 AM CDT

Utility company Aqua Texas 'ignored' pumping limits in 2022, threatening Jacob's Well
KUT 90.5 | By Maya Fawaz; Published August 15, 2023 at 10:38 AM CDT

Who's Killing Jacob's Well?
Texas Monthly | By Forrest Wilder; Published August 28, 2023

Jacob's Well Was Dry for Seven Months—One Company Just Kept Pumping
Utility giant Aqua Texas pumped 66 million gallons beyond its legal limit in 2023.
Texas Monthly | By Forrest Wilder; Published January 25, 2024

...Instead, the company has continued overpumping. New data analyzed by Texas Monthly shows that Aqua Texas continues to pump far more water from the Jacob's Well management zone than allowed by the Hays Trinity Groundwater Conservation District. In 2023, it overpumped by almost as much as it had in 2022, extracting 156 million gallons from two of its well sites near Jacob's Well, even though it was only authorized to pump 90 million. In all, the company pumped about 66.4 million gallons beyond its limit, or 74 percent more than its cap. (In 2022, it overpumped by 72.1 million gallons.)

We all know that, occasionally, a brave journalist or two, and their fearless editor (think *Watergate*, Carl Bernstein, Bob Woodward, and Ben Bradlee) can make a difference, a big difference. Unfortunately, the sad cases of Jacob's Well Spring and other Texas springs are almost always flying under the radar of most Texans, and certainly do not get any national attention that may help. The question then is who can help, if anyone? (The Texas system of the official groundwater management and protection is broken, as illustrated earlier.)

One answer is self-evident: attorneys and law firms. After all, the successful Sierra Club lawsuit did save Comal and San Marcos Springs, for now. But lawsuits take lots of money and lots of time, with an uncertain outcome, and usually make life of those that wanted to do something right completely miserable.

Another answer is—make a Hollywood movie. And not only one, make a trilogy! (Think *Godfather*). These movies can become blockbusters and can be set in the past, or present, or future, or all three. The title of the first one must be *The Gunfight at Jacob's Well*, because it is catching and it accurately conveys that it takes place in the Wild West (the parallel with *The Gunfight at OK Corral* would not hurt, on the contrary).

We also are witnessing how the Hollywood magicians can make any kind of fantasy look real, with artificial intelligence (AI) being just the latest available tool. So, the movie audience will be able to see how the Spring used to look before it was moved to a hospice care shown in Figure 5.23. There are plenty of photographs, video footage, and stories about the Spring's glorious days that could be easily recreated by the special effects and Computer Graphics (CG) folks in Hollywood (see Figures 5.24 through 5.26, and a quote below for examples).

"There are stories that there was once a 2-foot head on this where the water was bubbling out, almost like a fountain," he said. "You would try to swim down and it would push you back up." (from article by Maya Fawaz).

Of course, some scenes will be filmed at the location, for authenticity (GPS coordinates are 30^{o}02'04.07''N 98^{o}07'34.03''W). Spring is in Jacob's Well Natural Area, 3.6 miles northwest of Wimberley, via FM 2325, Jacobs Wells Road.

Figure 5.24 In 2021, the water was deep enough for visitors to jump into Jacob's Well. Photo by Michael Minasi. Courtesy of KUT News, Austin, Texas.

One suggestion to a daring Hollywood producer is to solicit the support of Mr. Robert Redford (note to younger readers: Mr. Redford is a Hollywood icon, one of our most famous actors, directors, and producers). Why Mr. Redford? Because he learned how to swim in Barton Springs in Austin, only about 40 miles from Jacob's Well, when he was a child. And because Mr. Redford is a true advocate for the environment and knows quite a bit about water wars in the Wild West (among other things, he directed *The Milagro Beanfield War*, a film that tells the story of a man's fight to protect his small beanfield and community against larger business and political interests. Access to water is the movie's central idea.)

Note to readers and all other potentially interested or concerned parties: What you are about to read, including everything related to a possible future movie entitled *The Gunfire at Jacob's Well* is a work of fiction. All similarities with actual events, characters, and any other circumstances associated with Jacob's Well in the State of Texas are unintentional and purely coincidental.

Some of *The Gunfight at Jacob's Well* movie characters are given: two young, brave, local investigative journalists; at least two ruthless executives of the main villain—a multi-billion-dollar company (this includes an option of revealing the names of one or two billionaires, the shadowy owners of the company), one or two tireless fighters for the springs from a non-profit organization, several corrupt local, state, and federal politicians (*Senator* seems the most appropriate title), an agency/district bureaucrat (not corrupt, but it is the producer's choice), and probably an attorney or two.

Equivalents to all these characters are easily defined regardless of when the movie takes place (in the past, present, or future): "local sheriff", "owner of 2,000,000 acres of land", "struggling small rancher", “schoolteacher”, “corrupt Senator” (this role is timeless, as demonstrated by about 93.7% cases worldwide), and such. I am sure the Hollywood producer/studio will have no trouble finding some successful western movies to draw from. This brings up the key question of the movie’s main heroes who will ensure its commercial success. Without suggesting any names to the producer and the director (it is none of my business), I know something for sure: one must be a male actor and one must be a beautiful actress because this is the formula that never fails.

I also am convinced that the main male hero must be a lone cowboy, very skilled with his two guns, because anything official will not cut it in the State of Texas.

A Federal Marshall is also a possibility. However, Texas and Federal Governments do not easily mix as everyone knows, so the movie may not be very popular in large parts of Texas, which would be counterproductive.

So, it must be a lonely cowboy, I am thinking from Missouri. Why Missouri? Because it is neutral (no conflicts of interest) and the Cowboy grew up next to a majestic spring where he learned how to swim and enjoy nature and life, and because he simply cannot stand to see that a beautiful spring is going to die, for no reason other than the greed and ruthlessness of some bad people. And because, when he was growing up, including during his most formative years, he saw that everyone else, in the State of Missouri, loves springs and does not want to hurt them in any way, period.

There are two options for the movie heroine:

(1) If the movie takes place in the Wild West of the past, it will be a beautiful young schoolteacher who learned how to swim in Jacob’s Well Spring. She now cannot gather the courage to go there and see how her beloved Spring is dying, all wild creatures that depend on it included.

(2) If the movie takes place in the Wild West of the present, I am voting for a beautiful hydrogeologist (unlike in the case of movie *The Dark Lagoon* which takes place in Florida, at Wakulla Spring; see Chapter 3.5). She earned her degree at a Texas university and has all the same attributes as the girl from the Wild West of the past (in option 1). I vote for the hydrogeologist to also be a brave cave diver who will dive deep into the Spring to bring evidence that it is still not completely dead, its beautiful soul is intact, and it still gives shelter to some amazing wild creatures (Figure 5.26).

Figure 5.25 Historic photo of Jacob’s Well near Wimberley, Texas. Copyright Jennifer Idol. All rights reserved, printed with permission.

Figure 5.26 Jacob's Well near Wimberley, Texas. Copyright Jennifer Idol. All rights reserved, printed with permission.

A scene or two will be filmed in Blue Hole Park in Wimberly, just a few miles from Jacobs Well. This beautiful park and the Cypress Creek that flows through it owe their very existence to Jacob's Well Spring. The swimming experience in the park is simply unforgettable (Figure 5.27) but it too may soon be a thing of the past.

Figure 5.27 Blue Hole Park, Wimberley. ©2021 Hill Country Alliance and National Wildlife Federation. From Faust et al., 2021.

At the end of the movie, the spring flows again, and the Cowboy (who is not lonely anymore) and the beautiful local Texan girl are embraced in a very long kiss (think Garry Cooper and Grace Kelley in *High Noon*) while the water of the spring gushes happily. This ending is if the movie takes place in the Wild West of the past.

For about 1.5 hours before the end, the plot of the movie is quite simple, as in many western movies of the past. There is at least one saloon fight, engagement of some firearms with one or two corpses being attended to by the happy local undertaker, lots of heart-warming melodrama (think *Shane*), and such. To keep the younger audience in the theater, rather than leaving it because of the potentially boring cliché (there are no special effects with explosions and no action heroes that defy laws of physics), the director can perhaps study several Mel Brooks movies and steal a scene of two (think *Blazing Saddles*).

Just before the end and the long kiss (which continues through the closing titles), there is of course the gunfight everyone was waiting for.

If the movie takes place in the Wild West of the present or the future, the sky is the limit. Everything is on the table and the main word will be from the special effects folks. But at the end, the spring also flows again, and there must be this long romantic kiss (which continues through the closing titles).

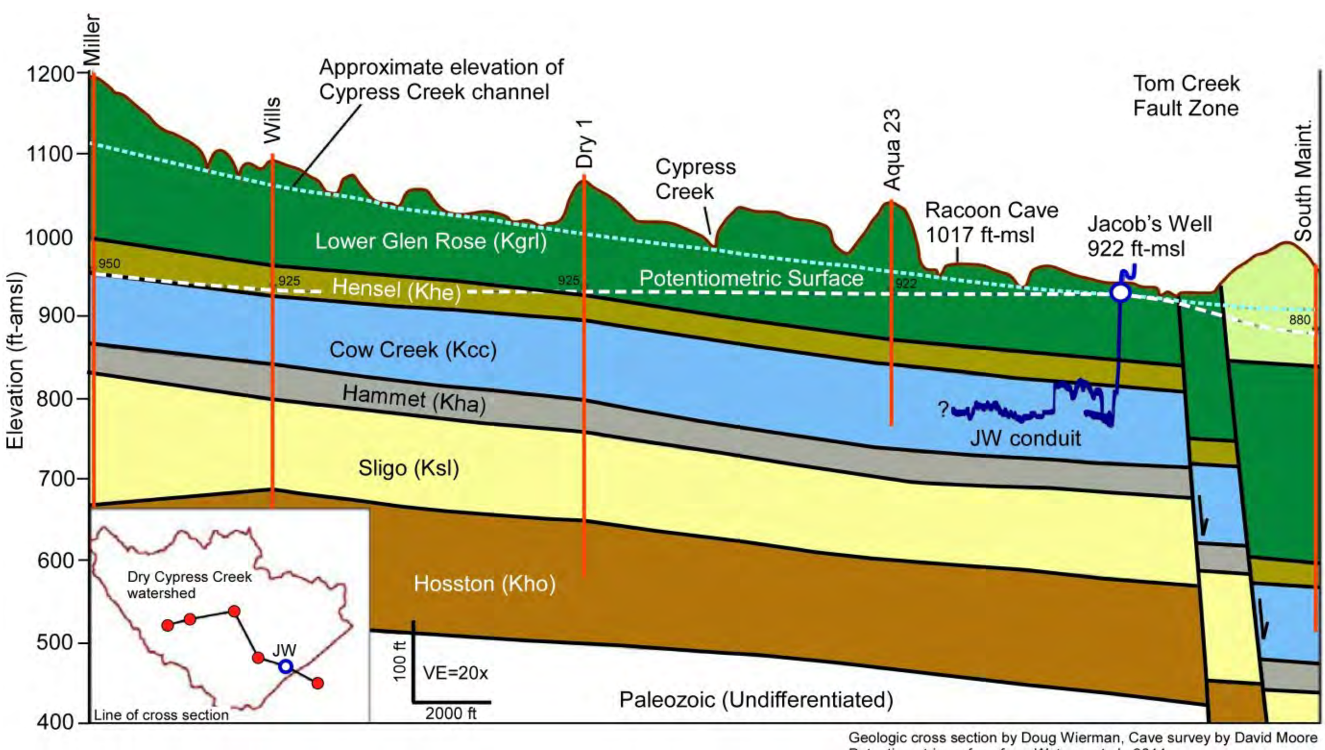


Figure 5.28 Geologic cross section through Dry Cypress Creek watershed. The potentiometric surface is for the Middle Trinity Aquifer. JW: Jacob's Well. From Gary et al., 2019.

Most importantly, however, the Wild West of the present/future will allow some scientific contents and advances in technology to creep in (e.g., see Figures 5.28 and 5.29), including an edge-of-your-seat deep cave diving scene which is a must (Figure 5.26).

Somewhere in the movie there is a scene where the main villain yells in rage, not so much at his high-powered attorney from a high-powered law firm in Dallas, but at this nuisance lawsuit in general. He yells: "This stupid graph is so stupid that I am out of my mind looking at it! These f.... lines are going up and down like crazy. Tear this nonsense apart!!!" (The main villain, a billionaire, is referring to a graph like the one shown here in Figure 5.29.)

The powerful attorney of course is not stupid (attorneys usually are quite smart) and knows that the graph may be the key evidence against his client. He therefore knows that he must confuse the expert witness he is going to question, maybe even by bringing up his character and/or personal beliefs along the way. This will show the jury that the expert witness does not know what he/she is talking about and is generally not trustworthy.

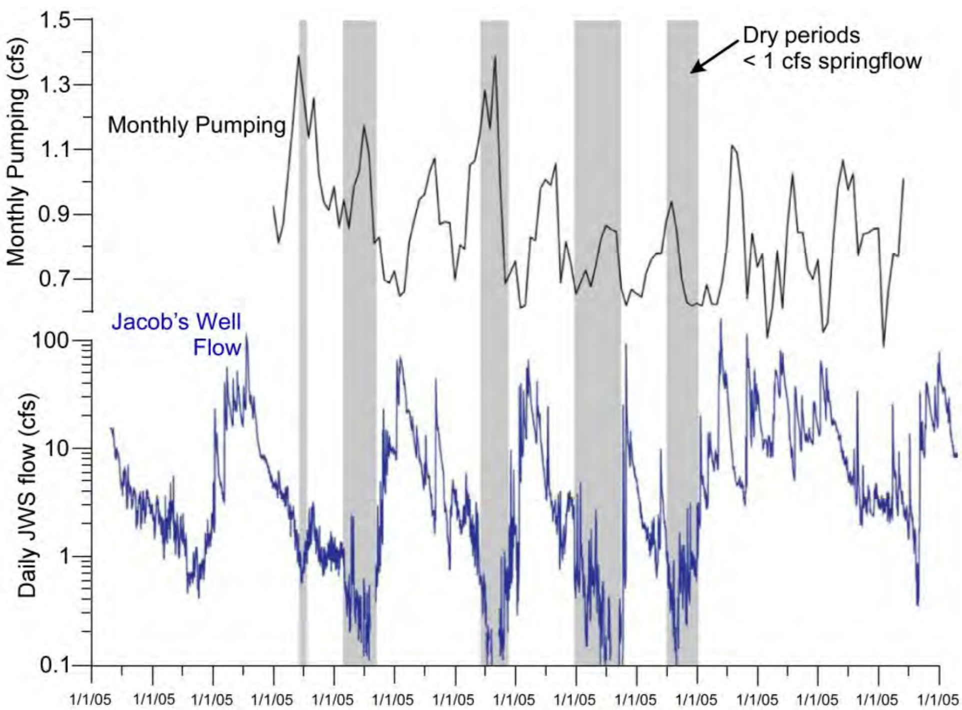


Figure 5.29 Hydrograph of mean daily flow of Jacob's Well from April 2005 to April 2019 and monthly pumping data from major public water-supply wells near to Jacob's Well. Jacob's Well has stopped flowing on four occasions during this period (2009, 2011, 2013, and 2014). Shaded areas indicate periods of drought with springflow less than 1.0 cfs. From Gary et al., 2019.

During the trial, the powerful attorney asks the expert witness:
"Isn't it true that water cannot flow up?"

The witness, with a little hesitation, answers:
"Well, yes, everyone knows that."

The attorney triumphantly exclaims (looking at the jury):
"But this line on your graph shows that water indeed is flowing up, and then down, and up, and down; the graph is incorrect, isn't it ?!"

The expert witness now is confused, and stares at the attorney in disbelief before answering:
"It is going up because the wells are pumping less, and it is going down because the wells are pumping more."

The attorney, triumphantly, looks at the jury and almost yells:
"So, it is going up and you just said it cannot do that!"

He then addresses the judge:
"No further questions your Honor."

Luckily, the attorney for the good side will be able to *redirect* the expert witness which means there is another chance to explain to the jury what the graph is all about. Unfortunately, there is no guarantee that the jury will be able to fully understand this whole thing and there may still be some jurors that will be more influenced by the convincing act of the high-powered attorney for the bad side, and the bad side will prevail in this lawsuit.

But this is a movie, and the good side will win at the end, with big help from the lonely Cowboy of the present-day Wild West who will take justice in his own hands (special effects included). The audience will also not be shortchanged for the romantic kiss, which continues through the closing titles (a friendly reminder: the kiss is between the modern-day Cowboy, who is not lonely anymore, and the hydrogeologist/brave cave diver).

5.4 The Standoff at Las Moras Springs (Sequel to The Gunfight at Jacob's Well)

An Iconic Texas Spring Was Dry for Months. Is Mother Nature or Man to Blame?

By **Forrest Wilder**, Texas Monthly, October 2023. This article originally appeared in the October 2022 issue of Texas Monthly with the headline "Gone With the Flow." Below are several excerpts setting the stage for the sequel (full article is available at https://www.texasmonthly.com/news-politics/why-did-las-moras-fort-clark-springs-dry-up/).

April 8 is significant to Travis Huey for two reasons.

It's the date when, in 2024, the narrow path of a total solar eclipse will pass over Brackettville, the small southwest Texas town where he lives. Huey owns the local newspaper, the Kinney County Post, and he's the president of the association that runs Fort Clark Springs, a private resort and historic site in Brackettville that has struggled to attract visitors in recent years. Huey has big plans for the fort that include drawing 5,000 visitors to the four-minute, eighteen-second eclipse.

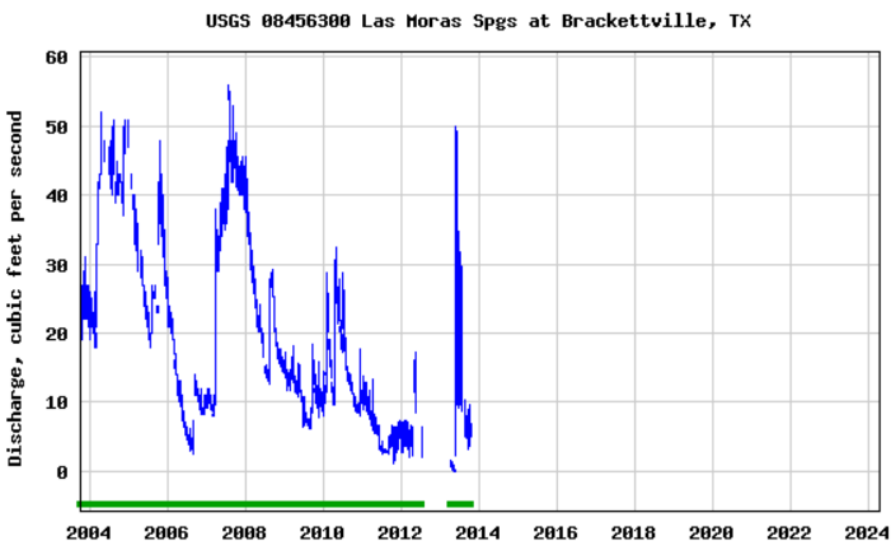
But April 8, 2022, complicated his plans. That's the day when Las Moras Springs, which typically pumps out 12 to 14 million gallons of cool, clear water a day—enough to fill two dozen Olympic size swimming pools—stopped flowing into the fort's swimming pool, the third-largest spring-fed pool in the state and Fort Clark's main attraction.

Before we get to the movie, here are some brief facts about the springs provided by the community of Fort Clark Springs (https://www.fortclark.com/las-moras-springs; GPS coordinates are 29°19' N, 100°25' W.)

Las Moras Springs, the ninth largest group of springs in Texas, is on the property of Fort Clark in Brackettville. The springs rise under artesian pressure from the Edwards and associated limestones and pass through a fault in the overlying formation, emerging at an elevation of about 1096 feet.

The springs fill a large walled-in area which spills into a 300-foot-long swimming pool, with excess flows diverted to a bypass channel around the pool. Just below the pool, both discharges combine and form the headwaters of Las Moras Creek.

Springflow rates vary in response to weather conditions and respond quickly to rains in the West Nueces River basin. In his work at the Texas Water Development Board, Gunnar Brune provides 51 flow rates for years between 1896 to 1978, and these ranged from a high of 38.8 to million gallons per day (mgd) in 1899 to lows of 3.6 and 2.6 mgd in 1964 and 1971. In those two years, the Springs dried up completely for a time. Beginning in 1998, the USGS recorded occasional field measurements of flow, and later a permanent gage was installed for continuous measurement. Real time flow data is available from the USGS (see Figure 5.30).



Las Moras Springs were used for thousands of years by prehistoric people. Projectile points as old as the Plainview type have been found, indicating a human presence at least 8,000 years ago. It was long a favorite site for diverse cultures and tribes that anthropologists have lumped together as "Coahuiltecan", and later for Comanche and Lipan Apache tribes.

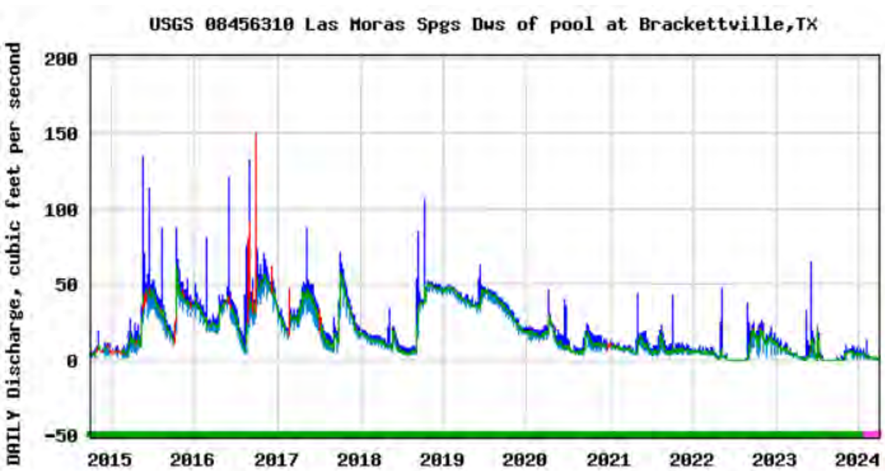


Figure 5.30 Discharge rate of Las Moras Springs recorded by USGS. As of 10-1-2014, site 08456300 Las Moras Springs at Brackettville, TX was moved approximately 600 feet downstream to site 08456310 Las Moras Springs downstream of pool at Brackettville, TX.

Spanish explorers began to camp at the Springs in the 16th century and gave them their name, which means "The Mulberries". In 1840 a cavalry unit drove Comanches from their village at the springs. At that time, many bison, antelope, and wild mustangs roamed the area (Brune, 1981).

As explained by Forest Wilder, Fort Clark was established in 1852 as a frontier military outpost along the San Antonio–El Paso Road, an important trade route that facilitated westward expansion into Indian Territory and guarded against a restive Mexico to the south. Black Seminole scouts served at the fort from 1872 until 1914, and one of the last horse-mounted cavalry divisions trained here during World War II. After the war, the fort was deactivated, sold to Brown & Root, the Texas construction behemoth, and later converted into a guest ranch. Today its sprawling grounds—all run by a homeowners' association—include a golf course, almost nine hundred homes, a motel, nature trails, an airport, an RV park, and more than thirty historic buildings, some of which date back to the fort's founding.

Disclosure: What you are about to read, including everything related to a possible future movie entitled *The Standoff at Las Moras Springs* is a work of fiction. All similarities with actual events, characters, and any other circumstances associated with Las Moras Springs in the State of Texas are unintentional and purely coincidental.

The plot of the movie and its main characters have little similarity with the movie *The Gunfight at Jacob's Well*. This is because the circumstances are quite complicated and convoluted: there is not a clear villain (ruthless multi-billion-dollar company) and poor, defenseless people trying something impossible, against all odds. Here, the fight is between neighbors, friends, and families, but it is still vicious as such fights usually are (think of once very popular TV series *Dallas*).

Figure 5.31 An aerial view of dry spring basin and swimming pool at Las Moras Springs in Brackettville, Texas. Photograph by Tamir Kalifa. Courtesy of Forrest Wilder, Texas Monthly.

The following however is similar: a dying spring; an uncompromising local investigative journalist; a ruthless and arrogant people in an official capacity (e.g., employees of the local/regional GCD/GMA) that favor, for an unknown reason (but soon to be revealed) only one party in the complicated standoff; a hired "expert" hydrologist (not hydrogeologist), and such. There are no attorneys (because there is no lawsuit yet), and the movie takes place in the Wild West of the present day.

The movie is, in essence, a drama involving the mysteries of human character: greed, revenge, passion, adultery (including in the spring at night, in a hot Texas summer, when it was still flowing), several vices, addictions, and other traits that may work in drawing audiences to see it. This probably is enough material for the producer/director/movie studio to embark on the project. Below are a few additional suggestions from the springs' point of view so to speak.

- The spring pool literary gasps for water. One can see the water level in it rhythmically drop and then rise in response to some nearby well(s) pumping from the aquifer as they are turned on and off. A special-effects scene shows how this mechanism works deep below ground, with some innovative approaches including mysterious shock waves moving through the earth's interior back and forth (perhaps annoying or frightening a subterranean creature such as a mole or something similar).
- Some fingers point to farmers and ranchers and their pumping wells, and some say this is an act of God.
- GSD does not want to do anything about the dying spring because it does not want to reduce existing pumping permits or deny new permit requests in fear of lawsuits (for which they don't have any budget or legal support from various state agencies supposedly caring for Texas' groundwater and springs).

- Years of mismanagement and infighting had left town businesses, including those relying on the Springs, with battered finances and no plans to survive, at no fault of the Springs in which they all learned how to swim (a few newcomers to the town excluded).
- Adultery is rampant between people that fell in love by the spring when they were young, but married someone else later and are now in seemingly different camps, which further complicates things.
- Most people at a town meeting learn that their own little town may soon be another Texas ghost town if the Springs finally die. They are reminded of the brutal destiny of Fort Stockton, some 200 miles northwest of here. The bustling desert town was once celebrating its springs and water abundance with an annual water carnival. And now the town is an afterthought, a random fuel or coffee stop for those on their way to somewhere else. (See the last section in this chapter on Texas springs called *The Miracle at Comanche Springs* for a glimmer of hope.)
- At the same town meeting, the hired hydrologist (not hydrogeologist) confirms that the dying of their springs is an act of God. The person that hired him then tells everyone in the room to "pray for rain".
- The town's favorite schoolteacher promptly informs everyone present that she will, as soon as the next day, start working with her first graders on a ritual rain dance that will, at the same time, honor the Native Americans and their lost wisdom.

Figure 5.32 The Fort Clark Springs swimming pool in 2018. Photograph by Wynn Myers. Courtesy of Forrest Wilder, Texas Monthly.

As much as I hate it, the climax of the movie involves the death of a completely innocent young person. Think of movie *The Last Picture Show* by director Peter Bogdanovich which also takes place in a desolate Texas town. Despite the tragic death, the movie was a huge success and was nominated for eight Oscars.

The tragic death at Las Moras Springs finally brings everyone in the town to their senses and the Spring happily flows again. Figure 5.32 is provided for the benefit of Hollywood special effects folks so they can create various scenes with the Spring flowing. (I am sure Mr. Myers, who took the photograph, has many more to share.)

5.5 The Mystery of Phantom Spring

This last movie in the trilogy on Texas springs will be something completely different (think English TV series *Monty Python's Flying Circus* from the 1970s). I of course fully understand that there is nothing funny about the death of yet another beautiful Texas spring. Telling the Texans and indeed the world about it in a different way that could be memorable and change something is the only motif behind thinking of *Monty Python's Flying Circus*.

In other words, making the movie about Phantom Spring absurd and improbable may work, just like with some Super Bowl commercials that stick in memory for a while and are a talk of the town.

Before we get to the movie, first some facts about Phantom Spring (also referred to as Phantom Lake Spring), based primarily on the materials available at an excellent webpage of ADM Exploration Foundation. An abundance of information, fascinating photographs and video footage are provided about a Spring cave diving expedition, the science behind it, ecology, biology, geology, and preservation of endangered species. Visiting this webpage is a must (http://www.admfoundation.org/projects/phantomcave2013/phantom2013.html).

Located six miles west of Toyahvale, Texas (GPS coordinates are 30º56’05.70’’N 103º50’58.77’’W), Phantom Spring and cave is owned by the Federal Bureau of Reclamation. Access to the cave is tightly restricted and requires a special scientific permit. No other access to the cave or the surrounding property is allowed under any circumstances. Only two permits are issued at a time due to concerns about overuse of the fragile ecosystem.

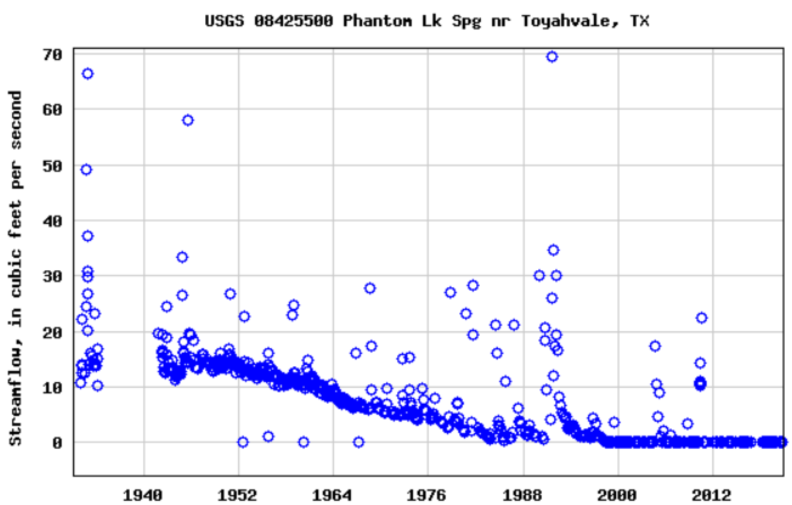


Figure 5.33 Hydrograph of discharge rate of Phantom (Lake) Spring for the period of record.

Phantom Spring was declared clinically dead in 1999 (see graph in Figure 5.33). Although one would never find a stamped, official death certificate listing the cause of death in any publication of various districts and agencies responsible for the well being of Texas groundwater and springs, there is little doubt in anyone’s mind what it was.

This quote is from the 2012 narrative available at the ADM Foundation website: “*In addition to groundwater extraction from municipalities and irrigation, these desert ecosystems are faced with the threat of hydraulic fracturing, also known as fracking. Serving as the primary method to extract petroleum and natural gas from deep shale formations, fracking activity is increasing at a rapid rate in Texas. More than 10 natural gas wells have been reported between Phantom Springs and the nearby town of Pecos. Over a well’s lifetime, it can require up to several million gallons of water. In addition to requiring large quantities of water, fracking fluid is composed of chemical additives including known carcinogens such as benzene, lead, and boric acid. Disposal of fracking fluid often consists of injecting this polluted brine into disposal wells around the area. Migration of fracking fluid poses one of the most common forms of groundwater contamination in areas with high natural gas activity*.”

Phantom Lake Spring is still the official home to five endangered species: Comanche Springs pupfish (*Cyprinodon elegans*), Pecos gambusia (*Gambusia nobilis*), Phantom tryonia (*Tryonia cheatumi*), Phantom springsnail (*Pyrgulopsis texana*), and diminutive amphipod (*Gammarus hyalelloides*). Comanche Springs located within the city limits of Fort Stockton went dry long time ago resulting in the loss of the pupfish from this locality. It is now only known from a group of springs around Balmorhea including Phantom Springs. Likewise, the Pecos gambusia was once more widely distributed, but today is only found in springs surrounding Balmorhea.

As part of their 2012 exploration, the ADM Foundation team laid down sediment traps, collected water quality data, and surveyed over 8,000 feet of the Spring cave. They also did dye tracing to determine where the water in Phantom Cave was traveling. A couple of days later, the dye came out in San Solomon Springs near Balmorhea. It is therefore postulated that, since the water is not discharging at Phantom Springs anymore, most if not all of it is now helping San Solomon Springs survive.

Figure 5.34 The mouth of Phantom Lake Spring after monsoon season of 2022. Photo courtesy of Texan by Nature. More photographs and extensive descriptions of six springs in the Balmorhea area are provided at https://texanbynature.org/projects/water-in-the-desert-the-story-of-san-solomon-springs/

Figure 5.35 Explorers Brett Hemphill and Curt Bowen illuminate the furthest reaches of Phantom Spring for videographer Andy Pitkin. Photo courtesy of ADM Exploration Foundation.

The big springs of Balmorhea and Fort Stockton are believed to have their source in an extensive network of fissures and solution passages in limestones of the Comanche series of Lower Cretaceous age, which are the oldest strata exposed near Balmorhea. The Comanche section includes, besides the limestones, interbedded calcareous shale and a basal unit composed of sand or sandstone.

Figure 5.36 Early Cretaceous limestone and dolomite of the Fredericksburg Group (equivalent to the Fort Terrett Formation) along IH-35 between Bakersfield and Fort Stockton, Texas. From George et al., 2011.

The limestones are mainly massive, thick-bedded, and very fossiliferous. They weather characteristically to dark-colored craggy or solution-rounded ledges and low rolling to hilly topography.

The uppermost limestone of the Lower Cretaceous series is well exposed near Phantom Lake Spring in a ridge that extends northwest from the spring along the south side of the Old Spanish Trail Highway. This limestone contains several deep, cavernous channels and crevices in this general vicinity, and from one of these crevices (Figure 5.34) emerges the water that feeds Phantom Spring (White et al., 1941).

The last movie in the trilogy on Texas springs, *The Mystery of Phantom Spring*, will not repeat anything that may further alienate that part of Texas public sick and tired of hearing who and what is killing their springs. And, since oil and gas are the royal family of Texas, there is not a chance that it will be presented in some questionable light here. Therefore, the movie will blame the Federal Government for the death of Phantom Spring. In the process, it will include many of the currently popular themes such as alien forms of life, war budgets in Washington, secret Government projects, and other confirmed but unsubstantiated shenanigans of the elected and non-elected Federal Government officials. This will secure the success of the movie in Texas as well as across the Nation.

Here are the key themes of the movie some of which will require the latest advances in CG and special effects by the skilled Hollywood professionals:

- The most secret part of Federal Government, closely connected with the Armed Forces, acquires vast tracts of land in west Texas, including around Phantom Spring, four years after the Roswell incident which happened in 1947 in the neighboring New Mexico. The public face of this purchase, the official owner of the land, is the Bureau of Reclamation.
- The reason for the purchase is discovery of an alien form of life in Phantom Spring. This form is not readily visible, but its presence can be detected with newly developed and very sensitive measuring devices.
- No access to the Spring or the surrounding property is allowed under any circumstances.
- A top-secret unit of the Navy special diving team nicknamed *Barracudas* is urgently dispatched to west Texas where it uncovers a vast network of submerged cave channels extending for hundreds of miles into New Mexico, all the way up to the Trinity Test Site where the first atomic bomb was detonated in 1945.
- Scientists working for another most secret part of Federal Government confirm that the alien form of life uses remnants of the nuclear energy released by the atomic explosion which penetrated deep into the aquifer. They also develop a working theory, yet to be fully confirmed, that the alien form of life demonstrates various kinds of intelligent activities including very dangerous ones, depending on the amount and velocity of the groundwater current feeding the Spring. This knowledge and reverse engineering will be used to develop a secret weapon for all branches of the Armed Forces.
- Alarming accounts by the locals describe ominous cloud formations lingering above the Spring, like those shown in Figure 5.37.
- A consensus between various scientists about which exact parameters of the groundwater flow are crucial for the super-intelligent and dangerous actions of the alien form of life is reached in 1952.

Figure 5.37 Phantom Spring. Courtesy of Tom Ilife, 2013.

- The agreed-upon solution for preventing the alien form of life from causing irreparable damage is to first slow down and then entirely stop groundwater from discharging at the Spring.
- The Department of Agriculture is contacted and helps secure participation of all ranchers and farmers in the general area of interest to increase their irrigated land and pump as much groundwater as possible. They are provided with many incentives to do so (the list can include any number of things and amounts of dollars.)
- The solution is working as demonstrated in Figure 5.33 and everyone involved is exhilarated because there are only rare signs of the damaging activity. The Spring finally stops flowing completely in 1999.
- The funding for the top-secret project is cut off entirely in 2002 because the Federal budget needs to support the anticipated foreign wars. In the movie, this is shown with some heart-breaking and controversial scenes.
- In 2007, something goes terribly goes wrong, and there is a flurry of construction activities at the Spring (Figure 5.38). The explanation to the public is that this action is needed to preclude livestock and human use and protect the endangered fish *refugium*.

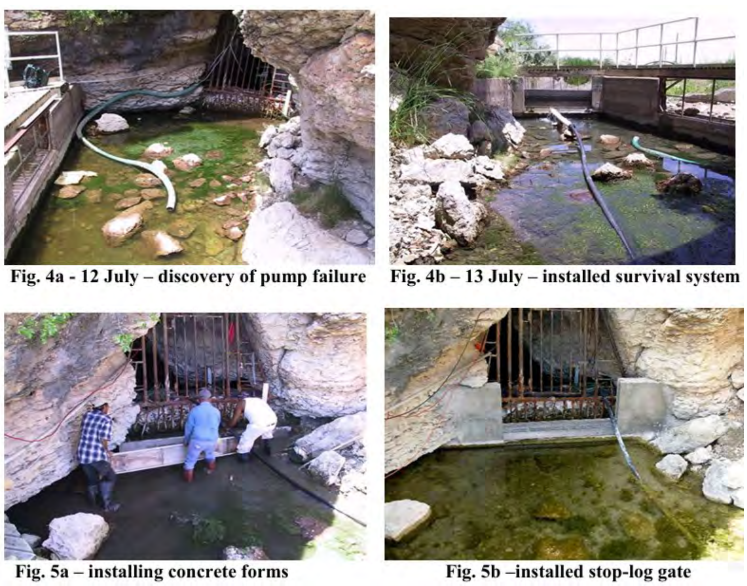


Figure 5.38 Official explanation about these photographs can be found in Karges (2007).

- The funding is reinstated, at minimal levels, in 2011 after several unexpected incidents including one in 2007.
- A small grant is provided to unassuming scientists to explore the Spring cave and collect samples of everything they see moving in water. In the process, amateur (non-Navy) cave divers, risking their lives, in 2012 and 2013 set a record: Phantom Spring Cave becomes the deepest underwater cave in the country at the time, at 493 feet deep. It also appears that many of the newly discovered submerged passages are engineered rather than natural, the conclusion supported by what looks like cut surfaces, sprayed with concrete (Figure 5.39).

The movie ends with a hint there may be a sequel. This includes a very sad possibility of having to drain San Solomon Springs (which are just down the road) as well to prevent a revival of the alien form of life, suspected of being able to cause irreparable damage to human health and the environment if supplied with enough groundwater of certain critical velocity.

Figure 5.39 Phantom Spring exploration in 2013. Courtesy of Tom Ilife, 2013.

5.6 San Solomon Springs

San Solomon Springs are in Balmorhea State Park four miles southwest of Balmorhea on State Highway 17, in Toyahvale. "Dive into the crystal-clear water of the world's largest spring-fed swimming pool in a cool oasis in the high desert. Swim, scuba dive, or just relax under the trees at this historic park in arid West Texas." (https://tpwd.texas.gov/state-parks/balmorhea).

In an old-fashioned, informative, and engaging USGS style of the past, White et al. (1941) describe the geology and groundwater resources of the Balmorhea Area in west Texas where the San Solomon Springs system is:

Balmorhea is the center of a thriving farming community, the lands of which are irrigated with water derived chiefly from large springs but partly from the storm flow of Toyah Creek. Balmorhea is situated near the foot of the Davis and Barrilla Mountains and along the southwestern margin of the Toyah Basin (see Figure 5.40). *The mountains and adjacent basin are drained by Toyah and Limpia Creeks.*

The group of springs around Balmorhea occur in the floor of the valley of Toyah Creek. They have been divided into artesian springs—Phantom Lake, Giffin and San Solomon Springs; and gravity springs—Toyah Creek, Saragosa, East Sandia and West Sandia Springs. The combined discharge of the springs during dry years is about 23,000 gallons a minute, of which the artesian springs supply more than 90 percent.

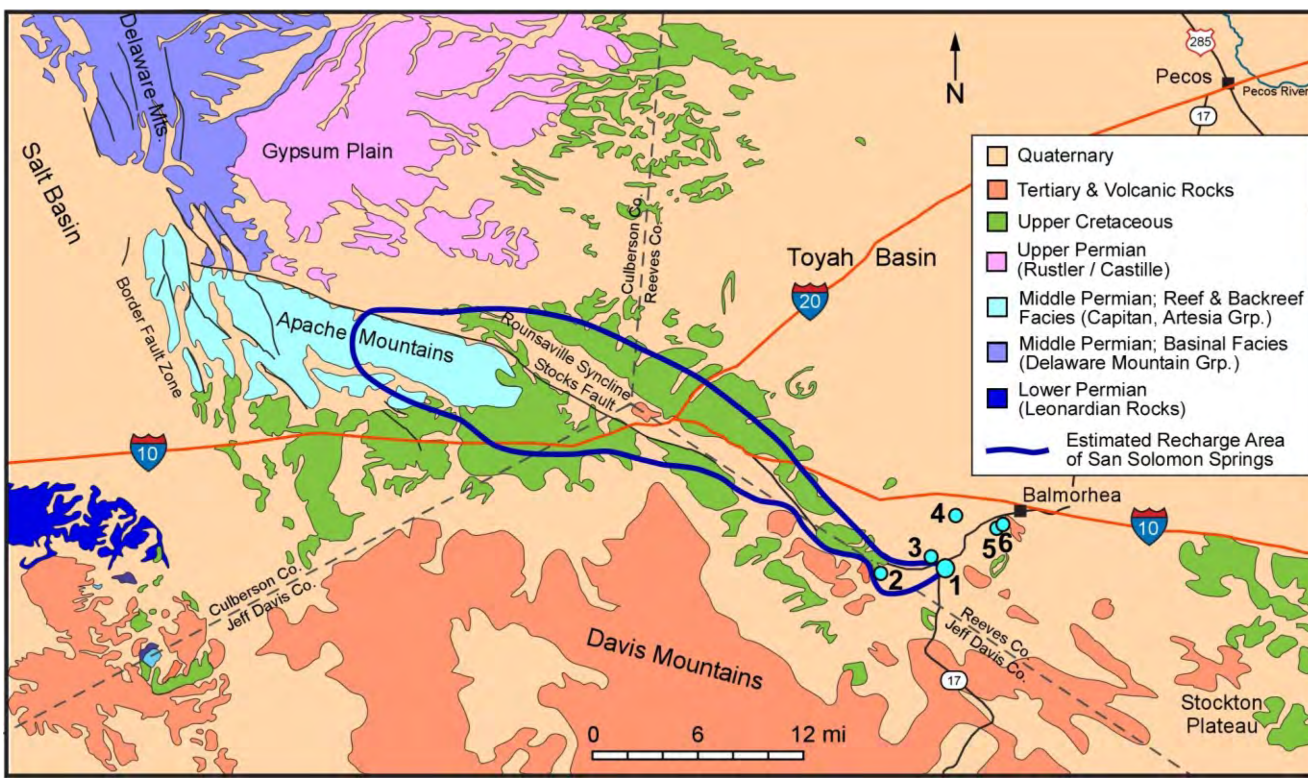


Figure 5.40 Hydrogeologic map of the San Solomon Springs system area. (**1**) San Solomon Springs; (**2**) Phantom Lake Spring; (**3**) Giffin Spring; (**4**) Saragosa Springs; (**5**) West Sandia Springs; (**6**) East Sandia Spring. Modified from Land and Veni, 2018. (Veni, 2013; based on Barnes, 1975; 1976; 1979; 1982.)

The underground reservoir which supplies the artesian springs is the fractured and cavernous Lower Cretaceous limestone. This limestone, about 500 feet thick, is underlain by impermeable rocks, probably of

Permian age, and is overlain by impermeable Upper Cretaceous strata that have a maximum thickness of about 500 feet. These are in turn overlain in the mountains by Tertiary lava and on the plains by gravel and other surficial deposits.

San Solomon and Giffin Springs rise from gravel deposits in the floor of the valley near Toyahvale, about 4 miles southwest of Balmorhea. The water originally came to the surface, forming a swamp of considerable size, which drained into Toyah Creek. San Solomon Spring now issues from gravel in the bottom of a large well-built bathing pool (see Figure 5.41). *The water is beautifully clear, and the discharge at all times is that of a good-sized creek. It is not surprising, therefore, that this spring is one of the leading scenic attractions of the region.*

Figure 5.41 Historic photograph of San Solon Springs swimming pool. Courtesy of Balmorhea State Park. Available at https://tpwd.texas.gov/state-parks/balmorhea/history.

The lowest discharge of San Solomon Spring recorded by the Geological Survey was 26.5 second-feet on April 26, 1923 (p. 121), and the highest was about 71 second-feet on October 7, 1932 (p. 131). The lowest recorded flow of Phantom Lake Spring was 10 second-feet on October 16,1931 (p. 142), and the highest 114 second-feet October 2 and 3,1932 (p. 127). The discharge of the Giffin Springs is relatively small, the smallest recorded daily flow being 2.9 second-feet March 4, 1925, and the largest between 6 and 7 second-feet in October 1932.

The temperature of Phantom Lake, San Solomon, and Giffin Springs is normally high. It was the same, 78° F., for all three in October 1931. After the increase in flow in September 1932 the temperature was 71° in Phantom Lake Spring and 74° in San Solomon Spring. On March 11, 1933, it was 77° in Phantom Lake Spring and 73° in San Solomon Spring.

As explained by Land and Veni (2018), Trans-Pecos Texas experiences an average annual precipitation of less than 300 mm; surface-water resources are scarce and brackish in this semi-arid region. Groundwater from wells and springs thus plays an important role in municipal, domestic and irrigation water supplies in the area (Sharp et al., 2003).

Figure 5.42 Historic photograph of San Solomon Springs swimming pool. Courtesy of Texas Parks and Wildlife Department. Available at https://texanbynature.org/projects/water-in-the-desert-the-story-of-san-solomon-springs/. Seeing the headwaters of San Solomon Springs as an attractive location for a park, the State Parks Board acquired the land in 1934. The Civilian Conservation Corps (CCC) arrived in July 1934, first building barracks, mess hall and a kitchen to support 130 to 200 men. The iconic double-wing swimming pool was built between 1935 and 1940. The pool is up to 25-feet deep, covers 1.3 acres and holds 3.5 million gallons of water. The largest spring, San Solomon Spring (singular) discharges into the pool.

The authors give an overview and compare early studies of the groundwater system in the Balmorhea area (such as White et al., 1941) with later studies that also benefited from groundwater isotope analyses, and deep drilling mainly for oil and gas. Notably, White et al. (1941) suggested that recharge to the springs originated via precipitation in the nearby Davis Mountains to the south and west. Water was thought to enter the Cretaceous-age Buda Limestone (which is stratigraphically above and not part of the Edwards-Trinity Aquifer) along the southwest limb of the Rounsaville Syncline (Figure 5.40) via seepage from the overlying volcanic aquifer, and from losing streams that flow across the syncline. Groundwater was then presumed to flow down dip, confined by lower permeability upper Cretaceous strata, and discharged from the San Solomon Spring Group where the upper Cretaceous units are displaced by faulting (LaFave and Sharp, 1987).

Harden (1972) and Couch (1978) suggested that groundwater originating in the Apache Mountains, which extend 40 to 80 km northwest of the Balmorhea area, might also contribute to San Solomon Group spring flow. LaFave (1987) tested this hypothesis and analyzed water chemistry and isotopic composition of the San Solomon area springs and groundwater sampled in the Davis Mountains. LaFave observed that the San Solomon Group spring waters are markedly dissimilar from Davis Mountains groundwater and have a distinctively different isotopic signature. However, he found a striking similarity between the spring waters and water samples collected from wells screened in the Capitan Reef Aquifer in the Apache Mountains to the northwest (Figure 5.40).

LaFave (1987) and LaFave and Sharp (1987) concluded that the San Solomon Spring Group is fed by two groundwater sources: a local source derived from precipitation on volcanic rocks of the Davis Mountains and recharged through nearby outcrops of the Buda Limestone; and a more distant source that originates in the thick, alluvial basin deposits in Wildhorse Flat and Lobo Flat in the southern Salt Basin to the west.

The springs of the San Solomon Springs group were used by Native Americans since prehistoric times; their irrigation canals were visible as late as 1898 (Hutson, 1898). The springs became known to European explorers and settlers in 1583 when Spanish explorer Antonio de Espejo made the historic discovery of San Solomon Spring (Castañeda, 1936). In 1849, the springs became known as Mescalero Springs for the Mescalero Apache who watered their horses there.

Mexican farmers called the springs "San Solomon Springs." They dug the first canals by hand, and then used the water to irrigate crops. They sold those crops to residents of Fort Davis. With plentiful water and the arrival of the railroad, a cattle ranching industry emerged in the 1880s. The Town's and Park's name comes from four men's surnames: E.D. Balcom, H.R. Morrow, Joe Rhea and John Rhea: Bal-mor-hea. These men formed an irrigation company in the area in the early 20th century.

In 1927, the Bureau of Reclamation dredged the springs and constructed a canal to better harness their flow. The State Parks Board acquired nearly 46 acres around San Solomon Springs in 1934. Civilian Conservation Corps Company 1856 built the park between 1935 and 1940.

One can read on the State Park's website (https://tpwd.texas.gov/state-parks/balmorhea/protecting-springs):

Water gushing from San Solomon Springs fills the pool at Balmorhea State Park, then flows downstream through cienegas and canals in the park and beyond. Not only does the water refresh hot, dusty Texans, it is also home to several rare and endangered species.

Texas Parks and Wildlife Department's mission is to protect the springs and this historic state park.

Oil and Gas Production

Oil and gas wells have dotted far West Texas over the last 50 years. But recent innovations such as hydraulic fracturing or "fracking" have changed how companies extract fuel from the ground.

As a result of these innovations, the Apache Corporation announced in fall 2016 it had identified a new area for pumping – the Alpine High Play. This play includes southern Reeves County, home to Balmorhea State Park.

Apache estimates it will have 2,000 to 3,000 well locations in this play, but possibly up to 5,000. Apache Corporation is not the only company operating in this area. Drilling may last for more than 20 years.

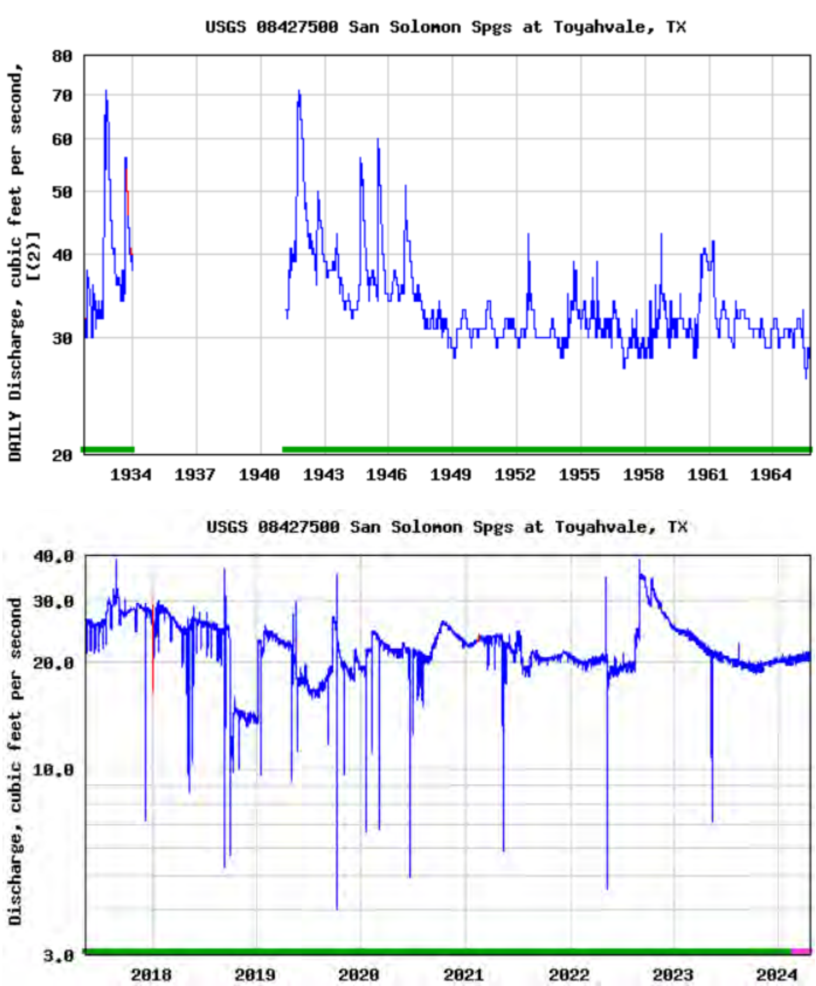


Figure 5.43 Hydrographs of daily discharge rate of San Solomons Springs. For period October 1931–September 1965 (top) the average is 34 cfs. For period October 2017–April 2024 (bottom) the average is 22 cfs.

Concerns

How might oil and gas production impact the springs?

One concern is that water use might diminish spring flows. Fracking to extract oil and gas requires 2 to 5 million gallons of water per well. Apache intends to reuse water as much as possible during the fracking process. It's undetermined how much water from the local area oil and gas producers will use.

Diminished spring flows or lower water quality would very likely harm the species that depend on the San Solomon Springs for survival. Either of these could also make the pool unsuitable for swimming.

Figure 5.44 Swimming pool fed by the main San Solomon Spring, Balmorhea State Park. Panels like the one in bottom left educate the park visitors about the springs and their importance.

Figure 5.45 Swimming pool in Balmorhea State Park fed by the main San Solomon Spring. It is the largest spring-fed pool in the world. Photos courtesy of Texas Parks and Wildlife Department, https://tpwd.texas.gov/state-parks/balmorhea

5.7 San Felipe Springs, and Goodenough Spring

The descriptions of San Felipe and Goodenough Springs is based primarily on the information provided by Gregg Eckhardt on his Edwards Aquifer website where there are numerous photographs of the springs as well (https://www.edwardsaquifer.net/index.html), and by Weinberg et al., 2018.

San Felipe Springs (centered at 29°22'N, 100°52' W), the third largest in Texas, are in Val Verde county on the outskirts of Del Rio. There are a group of ten or more springs that extend for over a mile along San Felipe Creek on the grounds of the San Felipe Country Club and on several ranches to the north (Figure 5.46). A groundwater divide near Brackettville separates this portion of the Edwards Aquifer from the central portion and the larger springs in San Marcos and New Braunfels.

In 1849, Captain S. G. French described San Felipe Springs and correctly noted they are the most western of a whole series of outflows from the Edwards. He wrote (French, 1850):

To the north of the road, and half mile distant, there is a beautiful spring of water, fifty feet in diameter at the surface, the sides of which incline towards a centre, like an inverted cone, and then, sinking in a cylindrical form to a depth of twenty-eight feet, through a soil of hard clay, afford a passage for the water to rise. The water comes to the surface with a slight ebullition, and flows off in a volume that would fill a cylinder two feet in diameter. This spring is the source of the San Felipe; as it flows on, the volume of its water is increased by other large springs, on either side; until it becomes a creek, when it empties into the Rio Grande, eight miles below the crossing, some thirty feet wide and several feet deep. Near its junction with the Rio Grande, its banks are shaded with large groves of pecan, maple, elm, and mulberry trees.

Hill and Vaughan (1896) give the following description of the springs:

The westernmost of the line of fault springs are the San Felipe springs near Del Rio. They break out at the edge of the Edwards Plateau, 2 miles northeast of Del Rio and about 5 miles from the Rio Grande. The pool is almost as large as that at the head of the San Antonio River. From the deep-seated rock at its bottom the water can be seen welling up in a great column, and has the same peculiar greenish-blue color as that of the other streams of this class. No trees surround it; it is alone - a fountain in the desert. The rocks from which it bursts - the Fort Worth limestones - have the same kind of joints and faults as are found at San Antonio and Austin. The outflow from the pool forms a bold, rushing stream that runs off to the Rio Grande, some 5 miles distant. The spring stream, in addition to running a mill and supplying the village with water, is partially utilized to supply 15 miles of irrigation ditch and to irrigate 5,000 acres, and can furnish water for the irrigation of several thousand acres more. Mr. Babb's measurements make a total discharge of 19 second-feet, or about 12,000,000 gallons per day.

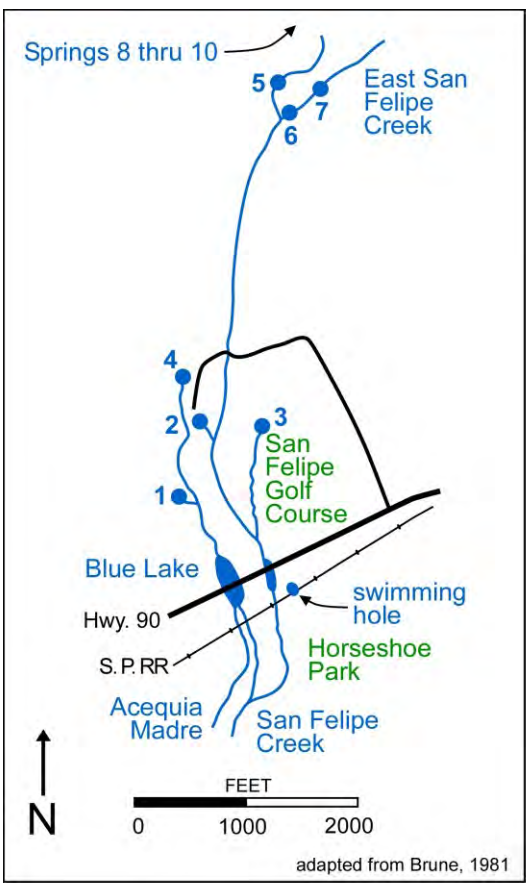


Figure 5.46 Map of San Felipe Springs based on Brune, 1981. Courtesy of Gregg Eckhardt (https://www.edwardsaquifer.net/sanfelip.html.)

On the website of Texas State Historical Association (https://www.tshaonline.org/handbook/entries/san-felipe-springs) there is following description from Brune (1981):

San Felipe Springs, the third largest springs in Texas, is a group of springs that extends two miles along San Felipe Creek northeast of Del Rio in Val Verde County. The water rises under artesian pressure through a fault in the rock. In 1590 Gaspar Castaño de Sosa stopped here; he was followed by other Spanish explorers *in the seventeenth and early eighteenth centuries. A mission was established in 1808 and followed by the settlement of San Felipe del Rio (now Del Rio) in 1834. The springs were also used by cavalry and stagecoaches in the 1800s. The springs are the sole water supply for the city of Del Rio and Laughlin Air Force Base. A historical marker is located at the springs. In 1977 the average flow was over 63,200 gallons per minute. The average flow from 1889 to 1977 was 41,080 gallons per minute. Amistad International Reservoir on the Rio Grande to the west has increased the flow of San Felipe Springs since its impoundment in 1968. It has provided additional recharge water and diverted part of the flow of Goodenough and other inundated springs to San Felipe Springs.*

Although much of the area downstream from the Springs is now urban, about 3,000 acre-feet per year are still delivered via the irrigation canals and used for agriculture. Swimming holes at Horseshoe Park and Lions Park are very popular cooling-off spots.

Figure 5.47 Spring #2, circa 1906 A very rare *Real Photo* postcard of Spring #2 before the municipal water supply pumphouse was added. Real Photo postcards were introduced in 1906 by Eastman Kodak and made it possible for anyone to have a postcard made using their own photograph. As such, they were usually produced in very limited numbers. The style of the back of the card dates it to pre-1907. Courtesy of Gregg Echardt https://www.edwardsaquifer.net.

Figure 5.48 *Left*: Postcard view of the pumphouse at Spring #2, circa 1930s (courtesy of Gregg Eckhardt). *Right*: City of Del Rio municipal water intake at Spring #2 in year 2000. Photo courtesy of Texas Parks and Wildlife. At the time, the spring was producing 90 million gallons a day (167 cfs) according to Texas Parks and Wildlife. There is currently no USGS gaging station at the springs or San Felipe Creek.

Figure 5.49 Blue Lake, early 1990s. Water leaving Blue Lake, which is fed by Springs 1, 2, and 4. Discharge from the Lake is split: water flowing to San Felipe Creek is running over the spillway on the right, and the Acequia Madre Canal is on the left. Photo courtesy of Gregg Eckhardt.

Historical Marker for the Canals System of Del Rio says:

Crude irrigation systems, drawing water from San Felipe Springs and Creek, were first devised by Indian and Spanish inhabitants of this area. Anglo-American settlers also saw the need for irrigation in this arid region, and about 1869 a group of landowners formed the San Felipe Agricultural, Manufacturing & Irrigation Company. Among early stockholders were W. C. Adams, Donald Jackson, Joseph Ney, Randolph Pafford, James H. Taylor, and A. O. Strickland. They dammed San Felipe Creek just below the Springs, and by 1871 had built canals diverting water to 1,500 acres of land.

Under an 1875 irrigation law, the company received a 99-year state charter which authorized the digging of two canals: five mile long "Madre Ditch", and mile-long "San Felipe Ditch", plus lateral canals. In 1876 the state inspector reported that the San Felipe Company had irrigated about 3,000 acres. Land grant provisions of an 1876 law awarded the Company 5,000 acres of state land for the total mileage of its canals.

In addition to promoting agricultural development, the work of the San Felipe Company stimulated the growth of Del Rio, since the irrigation canals provided water to the city as well. Today this vital water supply system is still in operation.

Historical marker located at Spring #3, says:

Oasis for explorers, soldiers, freighters - from 1542 onward. In 1675 priests named the 7 springs for King of Spain. In 18th century Comanches camped here on their war trail into Mexico. In 1808 a mission was established 3 miles downstream, on San Felipe Creek. By 1856-57 springs were on the 1470-mile San Antonio-to-San Diego mail route and on Chihuahua Road for wagons hauling silver and gold from Mexico to Indianola, then chief port on Texas coast. After settlers came in 1864, irrigation "Mother Ditch" was dug: soon Del Rio was founded.

Figure 5.50 San Felipe Springs that run alongside the 2nd hole of San Felipe Golf Course. Courtesy of City of Del Rio.

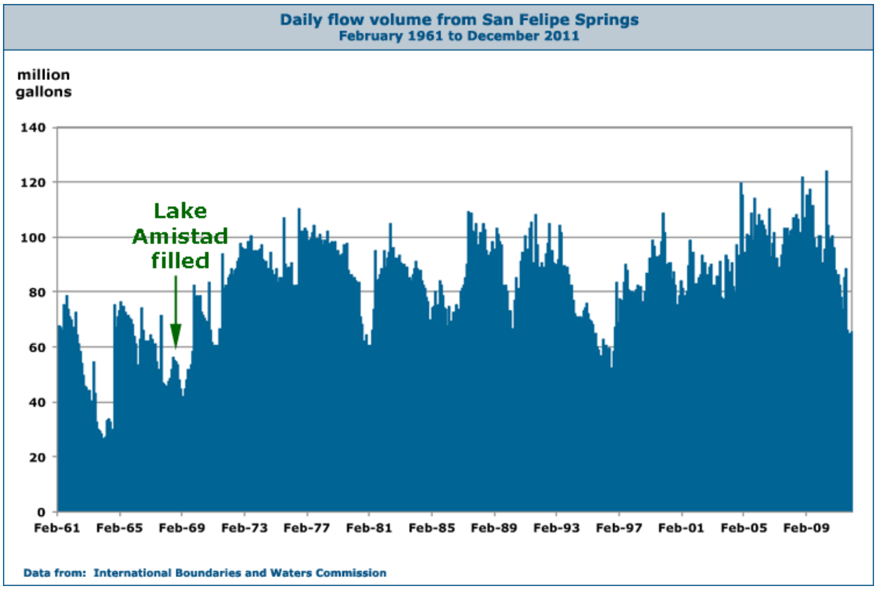


Figure 5.51 Daily flow volume from San Felipe Springs. Data from International Boundaries and Water Commission. Courtesy of Greg Eckhardt, The Edwards Aquifer Webpage. There is no USGS gaging station at the Springs or San Felipe Creek.

Goodenough Spring (historically also called Hinojosa Spring) is west of Del Rio in Val Verde County (GPS coordinates are 29°32′ N, 101°15′ W). It represents a major regional point of discharge from the Edwards Trinity (Plateau) Aquifer. Goodenough Spring was formerly the third largest spring in Texas. According to Weinberg et al. (2018), mean annual discharge was just under 100,000 acre-feet per year (138 cfs or 89 MGD) between 1921 and 1960, before Amistad Reservoir was constructed. This is nearly a quarter of the total modeled groundwater discharge to streams in Anaya and Jones' 2009 regional model, which covers 44,000 square miles of west-central Texas.

In the early 1900s John Kelly built a water wheel that pumped some of the Spring's waters to the top of a nearby bluff for irrigation (Figure 5.52). The opening was at the base of a limestone ledge on what is now the northeast side of Lake Amistad. The Spring was inundated in 1968 by the filling of the reservoir (Lake) and is now under about 150 feet of water. The flow has been reduced by the added pressure of the water column. Goodenough Spring is located on the U.S. side of the Rio Grande, along an east-west trending segment of a fault, and in an area with numerous northeast-southwest trending faults (Weinberg et al., 2018).

Figure 5.52 Goodenough Spring, early 1900s. Mr. John Kelly is pictured in the white shirt. The photo appeared in Grunnar Brune's 1981 *Springs of Texas* and was furnished to him by Mrs. R.C. Robertson through Claude C. Miller. Courtesy of Gregg Eckhardt. Available at https://www.edwardsaquifer.net/goodenough.html.

The source of water feeding the spring has been debated for years. Most current models assume that discharge from Goodenough Spring originates in Val Verde County and adjoining parts of Texas, and the International Boundary and Water Commission allocates 100 percent of the flow from Goodenough Spring to the United States. However, Thomas et al. (1963) note that Goodenough Springs "*discharge is not derived solely from local sources, for the fluctuations do not correspond with those of water levels in wells or of stream discharge in the adjacent Devils River basin*."

Reeves and Small (1973) noted that groundwater elevation contours indicated that "*much or all of the sources of these springs are to the north and northeast*," but "*it is also possible that an unknown quantity of water may be derived from sources to the northwest and west.*"

Stafford et al (2009) postulate a recharge source for Goodenough Spring in northern Mexico based on observed pre-inundation fluctuations in spring flow in response to precipitation events in Mexico at times when no rain fell on the U.S. side of the border.

The Edwards-Trinity (Plateau) Aquifer is the principal aquifer in Val Verde County. Groundwater in the aquifer generally flows from north to south and discharges to springs and streams draining to the Rio Grande. Groundwater quality data suggest that most recharge supplying major springs occurs through large fractures and sinkholes, and discharges through a system of conduits with minimal interaction with the aquifer matrix under normal flow conditions.

Water levels in wells across much of the southern half of the county were affected as Amistad Reservoir filled. Spring flows also increased in this area. Water levels in parts of the county outside the area influenced by Amistad Reservoir are very consistent over the period of record and do not exhibit any long-term decline in response to pumping or reduced recharge (Weinberg et al., 2018).

Figure 5.53 Goodenough Spring before it was inundated by Amistad Reservoir in 1968. Photo courtesy of Rene Barker and T.A. Small.

Figure 5.54 In 1941 the Grannis and Leurig families visited the Goodenough Spring site. At that time, Louis F. Leurig was publisher of the *Del Rio News-Herald* and the photo was provided by his son Louis pictured at right. Today Mr. Leurig's granddaughter Sharlene is a water sustainability expert who writes on Texas' springs and water issues. Photograph and text courtesy of Gregg Eckhardt. https://www.edwardsaquifer.net/goodenough.html.

5.8 San Antonio Springs, and San Pedro Springs

On The Edwards Aquifer Website (https://www.edwardsaquifer.net/) one can read the following early descriptions of the main San Antonio Spring, The Blue Hole, courtesy of Gregg Eckhardt:

Before Edwards wells were drilled, early explorers and travelers described The Blue Hole as a fountain spring, with water gushing many feet in the air. In 1857, Frederick Olmsted perceived the entire discharge of the Springs to come from The Blue Hole and he described the natural beauty of the site:

...*The San Antonio Spring may be classed as the first water among the gems of the natural world. The whole river gushes up in one sparkling burst from the earth. It has all the beautiful accompaniments of a smaller spring, moss, pebbles, seclusion, sparkling sunbeams, and dense overhanging luxuriant foliage. The effect is overpowering. It is beyond your possible conceptions of a spring. You cannot believe your eyes, and almost shrink from sudden metamorphosis by invaded nymphdom.*

Richard Everett in 1859 gave this description of San Antonio Springs, as well as of San Pedro springs, the other major natural discharge from the Edwards Aquifer in San Antonio:

Two rivers wind through the city [San Antonio], flowing from the living springs only a short distance beyond the suburbs. One, the San Antonio, boils in a vast volume from a rocky basin, which, environed by mossy stones and overhanging foliage, seems devised for the especial dwelling-place of nymphs and naiads. The other, the San Pedro, runs from a little pond, formed by the outgushing of five sparkling springs, which bear the same name. This miniature lake, embowered in a grove of stately elm and pecan trees, is one of the most beautiful natural sheets of pure water in the Union - so clear, that even the delicate roots of the water-lilies and the smallest pebbles may be distinctly seen.

Figure 5.55 The Blue Hole today, once the largest of the historic San Antonio springs (see also Figure 5.83). It is located on the campus of the University of the Incarnate Word toward the north side of the campus (see Figure 5.82). It can be reached from the intersection of Broadway and East Hildebrand Avenue. Photographer: James Hulse of Medina, Texas. Taken: December 30, 2022. Available on the historical markers webpage (J. Makali Bruton, the editor) at https://www.hmdb.org/m.asp?m=164134.

The historic marker at The Blue Hole Spring (29°28.132′ N, 98°28.06′ W) reads:

"*The Historic source spring of the San Antonio River, San Antonio Spring, has for centuries provided millions of gallons of crystal clear spring water daily to generations of Native Americans and early Texas settlers. The San Antonio River begins just south of this point, near the campus footbridge, where the Olmos Creek and the San Antonio Spring flow come together and, supplemented by hundreds of smaller springs along the way, begins the journey to the Gulf of Mexico. In the 19th century banker philanthropist George Washington Brackenridge purchased this property and established the first San Antonio Water Works. The concrete rim around the spring, which goes deep underground to the southern boundary of the Edwards Aquifer in the Olmos Basin, was added* *by Brackenridge to control the water flow. In time, however, the addition of wells and pumps south of the Brackenridge property made the Water Works less than lucrative. These wells and pumps also reduced the natural spring flow.*

This source of pure water attracted settlers from prehistoric and historic times, and these people have left rich archaeological resources for future study. The San Antonio Spring, Brackenridge Villa, and the five distinct Texas Archaeological Landmarks west of this spot are on the National Register of Historic Places as the Source of the River Archaeological District. These sites are protected by State and Federal law, with hefty fines and penalties for tampering with protected sites and/or removing prehistoric or historic artifacts. Look, please, and enjoy it as generations have done before you, but leave it as you found it for generations yet to come.

The San Antonio Springs are located mostly in the Incarnate Word community near Broadway and Hildebrand Avenue. There are several major spring outlets and thousands of small springs extending north into the Olmos Basin, and many still flow during wet times. The largest spring, known as The Blue Hole, and many of the smaller springs are now protected in a nature preserve called the Headwaters Sanctuary, established by the Sisters of Charity of the Incarnate Word in 2006. The Sanctuary consists of several acres surrounding The Blue Hole and about 50 additional acres of urban forest."

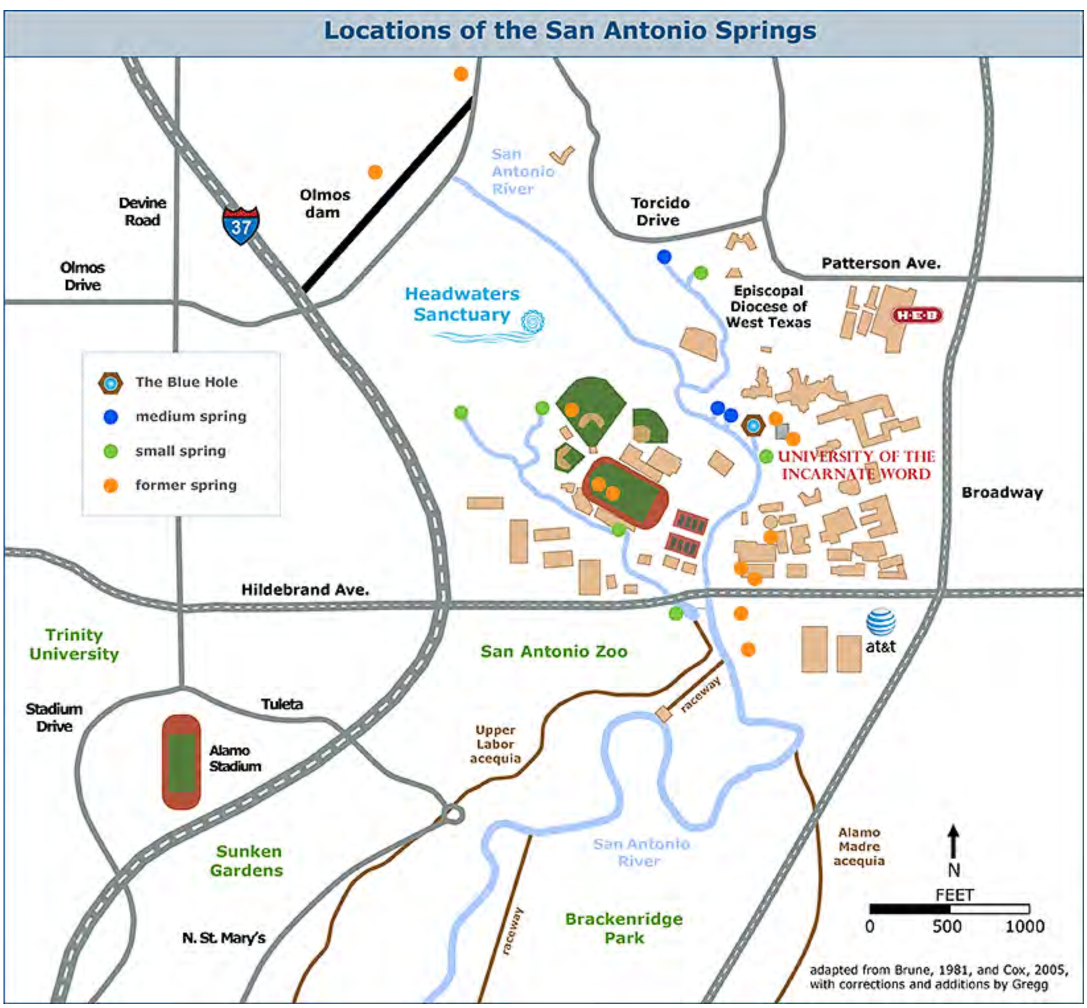


Figure 5.56 Map of San Antonio Springs. Courtesy of Gregg Eckhardt, The Edwards Aquifer Webpage (https://www.edwardsaquifer.net/saspring.html)

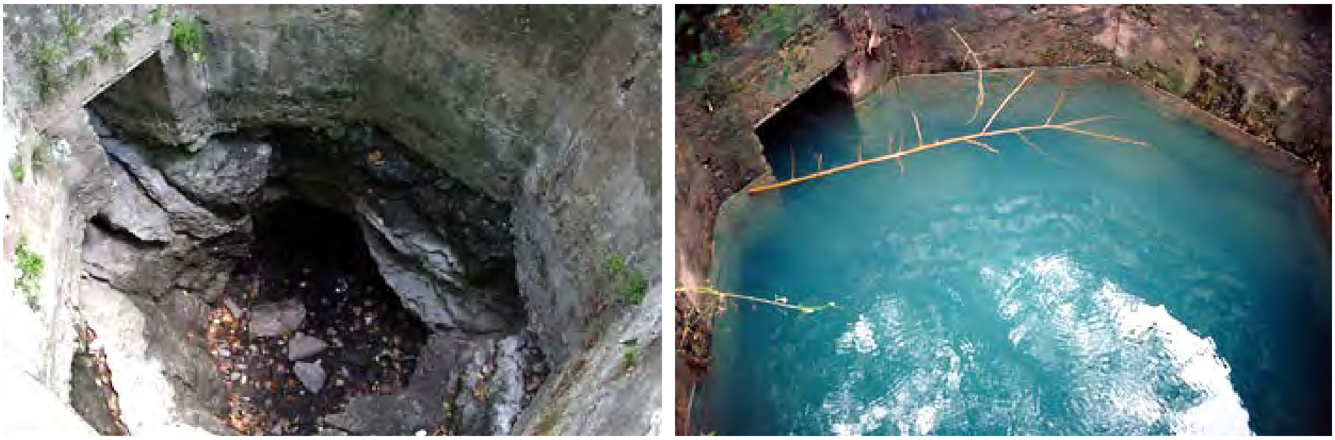


Figure 5.57 This is The Blue Hole, described by early explorers and travelers as a "fountain spring", gushing water many feet in the air. John Russell Bartlett described this chasm in 1850: "*The water rises in a cavity some six or eight feet in diameter and twelve or fifteen feet deep, and rushes out in an immense volume. The water of these springs unite with Olmos Creek, forming a river.*" Right photo: The Blue Hole on June 14, 1992, the day the Aquifer stood at its recorded high level of 703.3 feet, as measured by the J17 index well. On that record-setting day, The Blue Hole was a long way from being a "fountain spring". Discharge was still only a tiny fraction of what it must have been when Everett and Olmsted wrote their 19th century descriptions. Notice that you can see several feet below the surface to where the concrete wall ends. Photographs and caption courtesy of Gregg Eckhardt, The Edwards Aquifer Webpage (https://www.edwardsaquifer.net/saspring.html).

By the late 1890's, flows at San Antonio Springs had been drastically reduced by the drilling of numerous Edwards wells (see Figure 5.59) and a long drought. Brackenridge could not watch it happen, nor do anything about it, so he determined to dispose of his property. He wrote: "*This river is my child, and it is dying and I cannot stay to see its last gasps. It is probably caused by the sinking of many artesian wells. I have paid thousands of dollars for legal opinions on the question of stopping boring of the wells, but they all say I have no remedy - and I must go*." (Williams, 1921).

Brackenridge sold 280 acres including the San Antonio Springs to the Sisters of Charity of the Incarnate Word for $120,000, and in 1899 his Water Works Company donated 343.73 acres of land for the establishment of Brackenridge Park.

Figure 5.58 A group of young girls boating on the Incarnate Word campus near The Blue Hole, circa 1907. Courtesy of Gregg Echardt, The Edwards Aquifer Webpage https://www.edwardsaquifer.net/saspring.html

Figure 5.59 On the Edwards Aquifer Webpage, Gregg Eckhardt provides the following description of the photograph:

San Antonio began to rely on artesian wells for its water supply several years after the first large wells were drilled in 1891. These are two of San Antonio's first municipal water supply wells, drilled at Market Street for George Brackenridge, who owned the water system and had a contract to supply the city. The photo shows the tremendous amount of pressure that Aquifer water was under at that time. If we estimate the two men in the photo to be around 5 1/2 feet tall, then the column of water shooting up from the well is around 25 feet high! The effect of releasing all this pressure through wells was that springflows began to decline immediately and significantly. By 1896 there were approximately 40 wells in the San Antonio area. By around 1900 San Antonio Springs had been reduced to just a trickle in most years.

This photograph appeared in R. T. Hill & T. W. Vaughan's 1896 report on the geology and underground waters of the Edwards Plateau. Hill and Vaughan were the first geologists to recognize that wells such as these had impacted springflows. They were the first people to accurately describe the Edwards and how it works.

Although they never used the word 'aquifer', they referred to the Edwards as an artesian groundwater system, accurately described the catchment and transmission of water in the Aquifer, and recognized its large extent from Brackettville to Austin

Today, none of the San Antonio Springs flows except during periods of extreme rainfall. The San Antonio River is kept alive mostly by discharges of recycled water in Brackenridge Park, and by one artesian Edwards well inside the San Antonio Zoo.

The Blue Hole is still revered as sacred. Orchard (1983) reported that native peoples conducted ceremonies involving the placement of precious objects near the Springs or in the Springs themselves, and that tradition continues to this day.

San Pedro Springs (29^{o}26' 49.34"N 98^{o}30' 05.51"W) are in San Pedro Springs Park (San Pedro Springs Park (sanantonio.gov)) a few miles northwest of downtown San Antonio and the Alamo. It is located on land reserved for public use by the Spanish monarchy in 1729. Only one public park in America is older— Boston Common, which dates to 1630. San Pedro Springs Park was listed in the National Register of Historic Places in 1979.

People have gathered around the springs and the creek formed by them for some 12,000 years. Hunter-gatherers found water, food, and rock to carve weapons, and Spanish explorers first established their camps here in the late 17th century. In 1709, Fathers Antonio de San Buenaventura de Olivares and Isidro Felix de Espinosa named the waters "San Pedro springs." Historians agree that San Antonio’s earliest permanent settlement, a presidio and mission, were founded in 1718 near San Pedro springs, though its exact location is unknown. When the settlement was moved farther south in the 1720s, the springs continued to provide water to the new community. In 1731-34, the Spanish constructed an acequia to carry water to town for irrigation and household use.

As emphasized by Gregg Eckhardt, San Pedro Springs "... is one of the most important places in all of the southwest United States, and no web page of a few thousand words can begin to describe the pre-historic and historic significance of the Springs and surrounding Park." Nevertheless, visiting Gregg's website (Figure 5.60) is a must since he more than succeeds in describing the Springs, in the most exceptional manner. Below are a few paragraphs and photographs to give a flavor of what a visitor will have a pleasure of reading and seeing:

The Springs and a small natural lake just below the Springs were a favorite meeting place and campsite for native Americans for thousands of years. The bones of mastadons, giant tigers, dire wolves, Colombian elephants, and extinct horses have been found here, along with projectile points and stone tools. In early historic times, a band of Coahuiltecan Indians known as Payayas called the Springs and their village there Yanaguana.

After European settlement, the site was the social and recreational center of San Antonio for many decades, and a number of important old roads, including the Camino Real (King's Highway) radiated from this point. Early travelers would sometimes confuse these Springs with another major cluster of springs four miles to the northeast, San Antonio Springs. A nearby street, Calle del Camaron was named for the abundant crawfish that were found in the Springs and Creek. Limestone quarried from just northwest of the Springs provided stone for many of the town's early buildings.

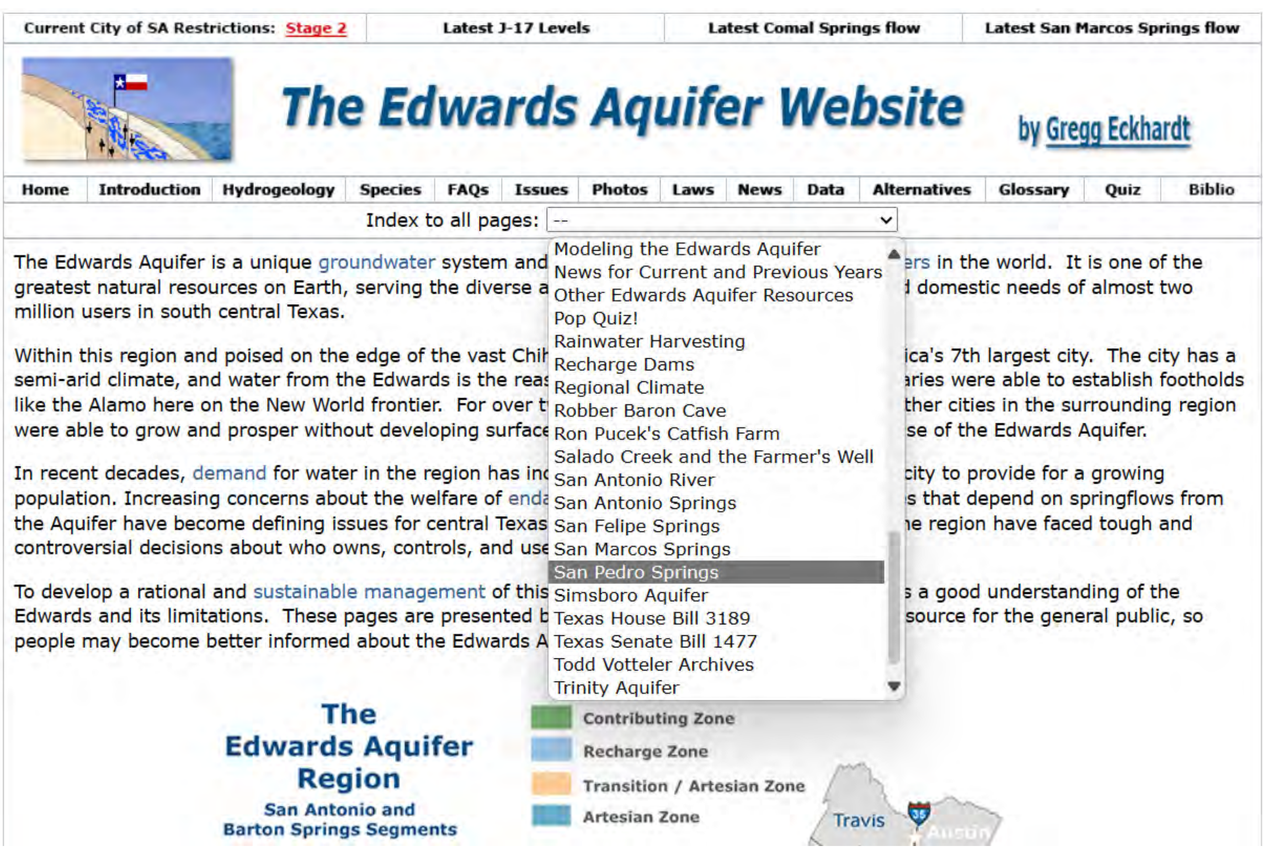


Figure 5.60 The Edwards Aquifer Website (https://www.edwardsaquifer.net/) has descriptions and sources of information for all notable springs, with the section on San Pedro Springs appropriately being the most extensive since this group of springs is one of the most important places in all of the southwest United States.

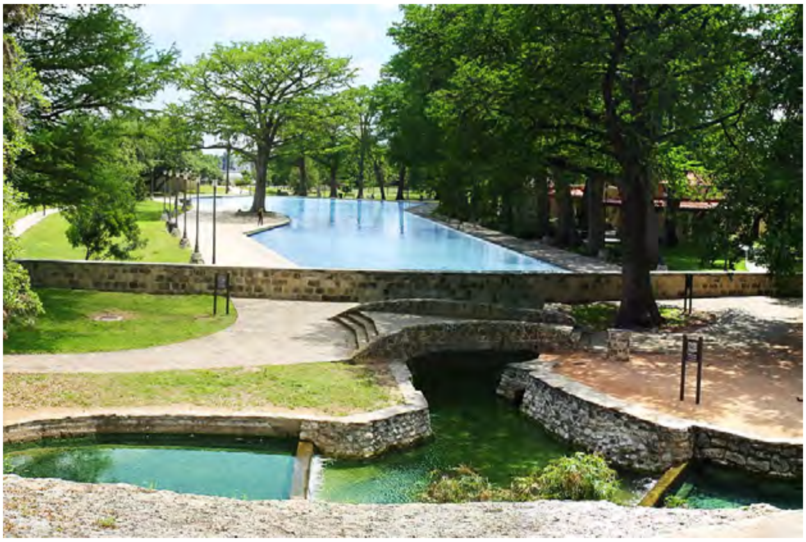


Figure 5.61 Pools of San Pedro Springs (in the front) when the springs are flowing, and the Park's swimming pool, which replaced the small natural lake south of the Springs in 1920s. The pool is fed by treated city water since the Springs do not have reliable flow and do dry up due to groundwater pumping from Edwards Aquifer. Photo courtesy of Gregg Eckhardt.

Figure 5.62 Children swimming in San Pedro Springs when they flowed after record rains in the spring of '92. A nearby sign commanded "NO SWIMMING". Photo courtesy of Gregg Eckhardt.

Since the mid-1990s, limitations on Edwards Aquifer pumping have been in place and world-class conservation efforts have been undertaken by the San Antonio Water System and residents. These measures have resulted in longer periods of springflow than have been witnessed in many decades. While the renovated Park still has plenty of fans, it has never regained its former prominence as San Antonio's most beloved playground. Many long-time residents have never even visited the park - most are completely unaware it even exists and know nothing of its history and importance to San Antonio. A group of volunteers is working to change that. The Friends of San Pedro Springs Park is a non-profit support group under the umbrella of the San Antonio Parks Foundation, and their mission is to help with the restoration and preservation of the Park, and to communicate its long history. Membership is open to the public, and details can be found at https://saparks.org/.

Gregg Eckhardt

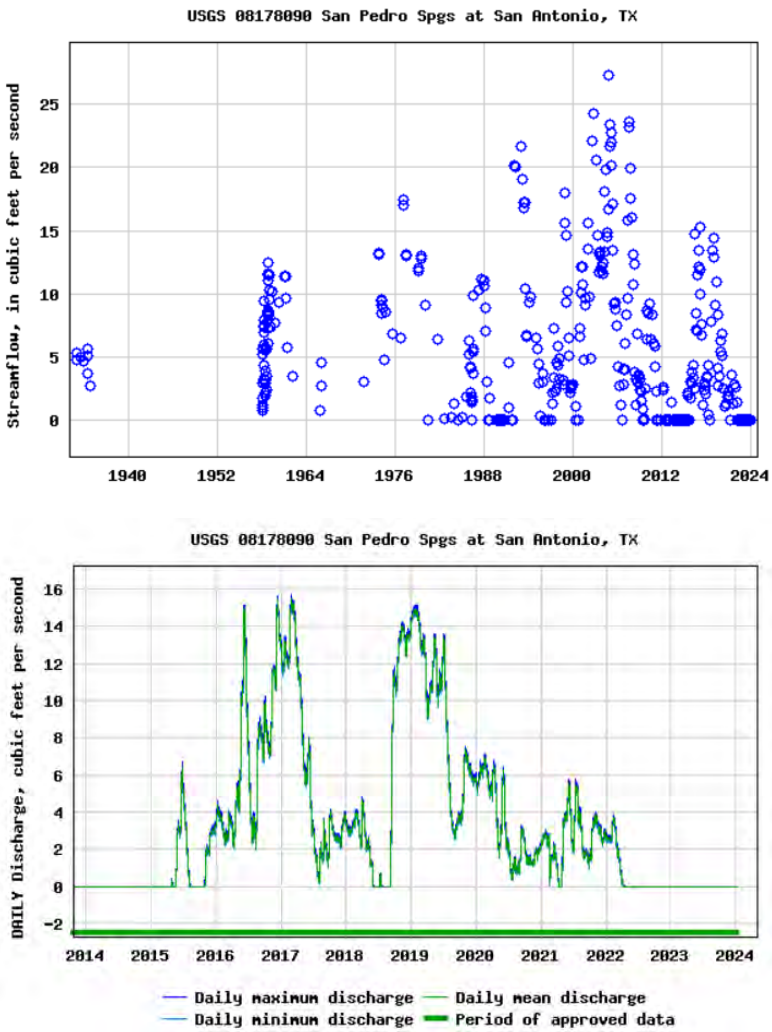


Figure 5.63 Discharge hydrographs of San Pedro Springs provided by USGS. *Top*: Field measurements for the period of record. *Bottom*: Available continuous daily recordings.

5.9 Comal Springs

Comal Springs of Central Texas (centered on 29°42'45.89"N 98°08'14.41"W) are in northwest New Braunfels, in Landa Park, a large park owned by the city. They are the largest springs in the southwestern United States and issue from various points along the base of an escarpment formed by the main Balcones normal fault in the area named Comal Springs fault. The seven major and many smaller spring outlets occur for a distance of 4300 feet along the fault (Figures 5.64 and 5.65). Many of the springs lie beneath Landa Lake or along its edge. Upthrown to the fault, Edwards carbonate rocks are exposed in Panther Canyon along the nature trail. The same rock layers are over 800 feet below the surface of Landa Lake.

The springs give rise to the Comal River, which runs for about three miles before joining the Guadalupe River and is known as the shortest significant river in the United States. The steady flow of water was developed for waterpower beginning in 1850s. Mills were built downstream of the springs, where the natural spring lake was enlarged by a low dam. The old mill buildings now host the annual Wurstfest celebration (https://www.beg.utexas.edu/texas-through-time/comal-springs.html).

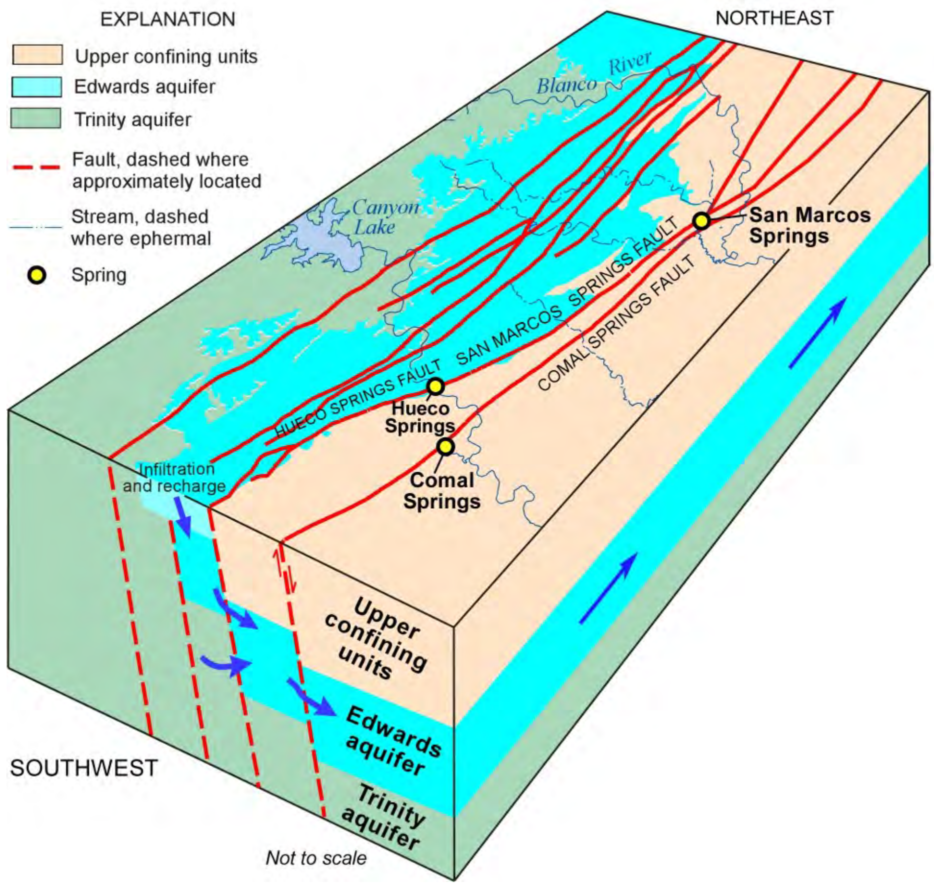
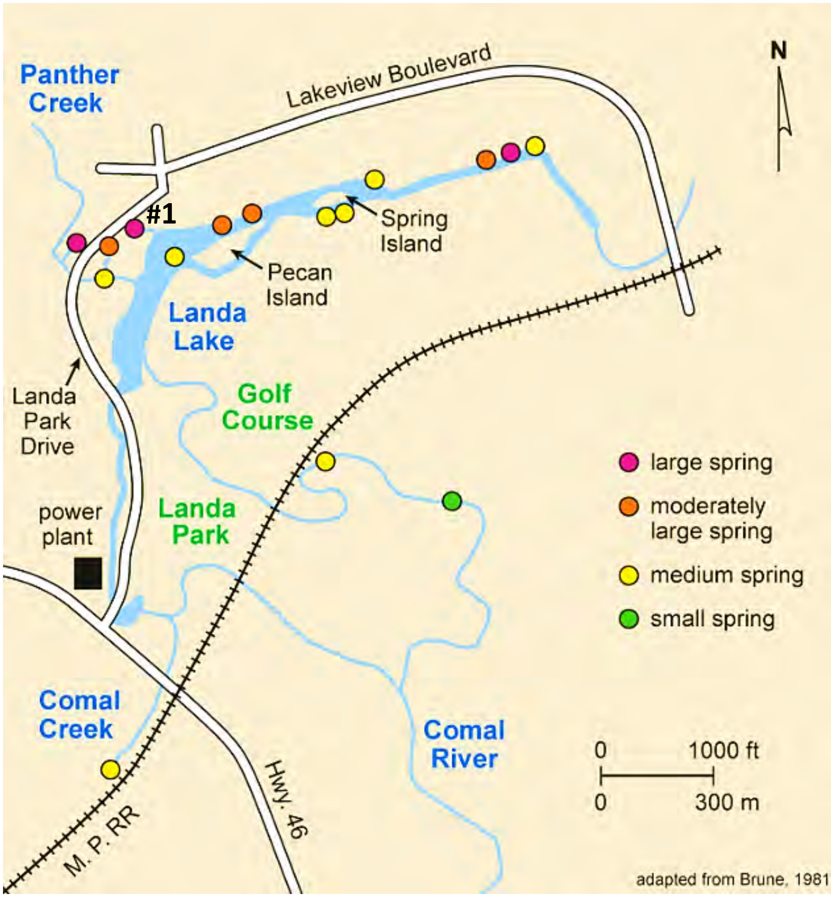


Figure 5.64 Idealized block diagram of the Edwards aquifer in the vicinity of Comal, Hueco, and San Marcos Springs, south-central Texas. Modified from Musgrove and Crow, 2012.

As explained by LBG-Guyton Associates (2004), discharge measurements by Ogden et al. (1985) and BIO-WEST (Ed Oborny, personal communications, 2003) indicate that during periods of normal to high flow only about one quarter of the total spring discharge (as measured at the USGS gage) is from the western group of large springs shown in Figure 5.65. The measurements also show that under conditions of lower flow, the contribution of this western group of springs, which are at higher elevations than the others, is reduced until these springs "go dry," at which point the lake springs are the sole components of total flow.

Discharge of springs in the lake is evidenced by small sand boils (geysers), saltation of sand grains, and areas where extensive clouds of gas bubbles can emanate from the lake bottom. Gas bubbles emanating from the bottom are considered evidence of groundwater discharge. The gas bubbles occur because the discharging groundwater is oversaturated with dissolved atmospheric gas. As Edwards groundwater rises from greater depths in the aquifer and discharges into the lake or individual springs, it depressurizes because of the decreasing hydrostatic head as it approaches land surface. As the water rises these gases come out of solution forming bubbles and bubble trains (LBG-Guyton Associates, 2004).

Regional flow paths originating in the western part of the Edwards Aquifer are generally understood to supply discharge at Comal Springs which have a small range of hydrologic and geochemical variability (Musgrove and Crow, 2012).



However, only a portion of the regional flow paths originating in the western part of the Edwards Aquifer are generally understood to supply discharge at Comal Springs (Musgrove and Crow, 2012). Groundwater from the up-thrown block of the Comal Springs Fault appears to be discharged from the western group of orifices at Comal Springs. The remainder moves eastward and discharges at San Marcos Springs (LBG-Guyton Associates, 2004).

Figure 5.65 Locations of Comal Springs. The largest spring, commonly referred to as Spring #1 (spring "l" in Brune, 1981; see photo in Figure 5.66), is in the westernmost group of three springs on the map. Courtesy of Gregg Eckhardt. https://www.edwardsaquifer.net/

Figure 5.66 *Left*: Spring #1, the largest in the Comal Springs group (GPS coordinates are 29°42'49.09"N 98°08'13.01"W). *Right*: TCU Seniors and Graduates happy to have seen the spring.

As explained by Edwards Aquifer Authority (EAA, 2024) and RECON Environmental et al. (2021), the Edwards Aquifer Habitat Conservation Plan (EAHCP) defines how federally listed species that live in the Edwards Aquifer and the Comal and San Marcos springs are protected. An Incidental Take Permit was issued by the U.S. Fish and Wildlife Service (USFWS), under the Endangered Species Act (ESA) to the Edwards Aquifer Authority, City of San Marcos, City of New Braunfels, Texas State University, and the City of San Antonio acting by and through the San Antonio Water System (collectively known as the EAHCP Permittees) to protect federally listed species from specific activities that can negatively impact them including threatening their very survival.

Figure 5.67 Landa Lake in Landa Park, owned by the City of New Braunfels, is formed by numerous springs discharging around the lake or directly into it.

Figure 5.68 *At three-miles long and a cool 70-72-degree temperature year-round, the spring-fed Comal River in New Braunfels provides a scenic, three-hour float. Tube gently along crystal clear waters amidst a scenic landscape with occasional strong currents. Easy float for families.* Text and photograph from *10 Of The Best Lazy Rivers To Go Tubing In Texas* by Colby Smith, Secret Houston, April 24, 2024. Photo credit: @garytray https://secrethouston.com/best-lazy-rivers-texas/

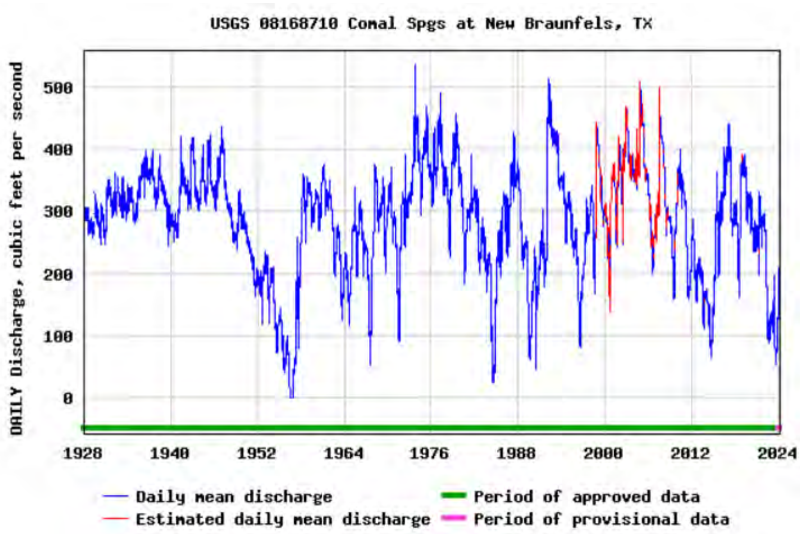


Figure 5.69 Hydrograph of Comal Springs daily discharge rate for the period of record. Average is 285 cfs.

Currently, the habitat protection measures in place through the EAHCP apply to six federally endangered species: the Texas Blind Salamander, Fountain Darter, Comal Springs Dryopid Beetle, Texas Wild-rice, Comal Springs Riffle Beetle, and Peck's Cave Amphipod; and one threatened species, San Marcos Salamander (see Figures 5.70 through 5.73). San Marcos Gambusia (*Gambusia georgei*) is now officially extinct and was delisted in October 2023. A federally listed species is classified as **endangered** if it is at immediate risk of extinction and **threatened** if it is at risk of extinction in the foreseeable future.

The primary threat to these aquifer dependent species is the intermittent loss of habitat from reduced springflows. Springflow loss is the combined result of naturally fluctuating rainfall patterns, natural discharges at other springs, and regional pumping and drawdown of the Edwards Aquifer.

As explained at the beginning of this Chapter 5, in 1991, the Sierra Club filed a lawsuit under the ESA that resulted ultimately in the creation of the Edwards Aquifer Authority (EAA). The Texas Legislature directed the EAA to regulate, among other things, pumping from the Aquifer, to implement critical period management restrictions, and to pursue a program "to ensure that the continuous minimum springflows of the Comal Springs and the San Marcos Springs are maintained to protect endangered and threatened species to the extent required by federal law" (EAA Act § 1.14(h)).

The following are among the major functions of the EAA as established by the EAA Act (EAA, 2024):

- Manage and control withdrawals of water from the Aquifer through the issuance of permits and the registration of wells.
- Protect the water quality of the Aquifer.
- Protect the water quality of the surface streams to which the Aquifer provides springflow.
- Achieve water conservation.
- Maximize the beneficial use of water available for withdrawal from the Aquifer.
- Protect aquatic and wildlife habitat.
- Protect species that are designated as threatened or endangered under applicable federal or state law.
- Provide for in-stream uses, bays, and estuaries.
- Protect water supplies.
- Protect the operation of existing industries.
- Protect the economic development of the state.

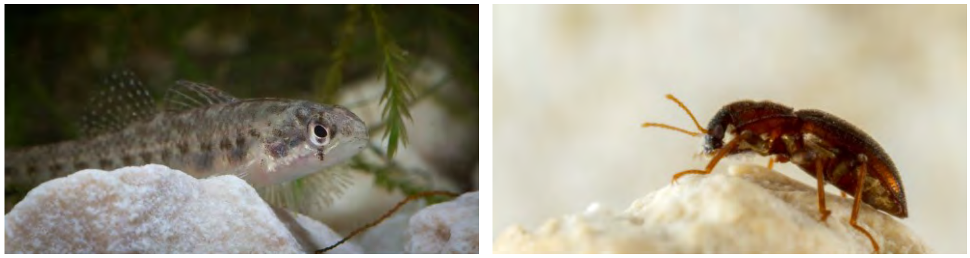


Figure 5.70 Left: Fountain darter (*Etheostoma fonticola*). Before being inundated by a small dam and lake, the main spring at San Marcos was described as emerging like a fountain from a limestone basin. *Right*: Comal Springs Riffle Beetle (*Heterelmis comalensis*). Courtesy of U.S. Fish & Wildlife Service.

Figure 5.71 *Left*: Comal Springs Dryopid Beetle (*Stygoparnus comalensis*).
Right: Peck's Cave Amphipod (*Stygobromus pecki*). Courtesy of U.S. Fish & Wildlife Service

Figure 5.72 *Left*: Texas Blind Salamander (*Eurycea* [formerly *Typhlomolge*] *rathbuni*).
Right: San Marcos Salamander (*Eurycea nana*). Courtesy of U.S. Fish & Wildlife Service.

Figure 5.73 Texas Wild rice (*Zizania texana*). *Left*: The upper stems of Texas wild rice can emerge above the water surface. The male and female flowers occur separately on side branches of a flowering stalk. The male flowers dangle lower down the flowering stalk than the rigid female flowers. Credit: Jackie Poole - Texas Parks & Wildlife Department. *Right*: Texas wild-rice roots underwater, and the stems bend, flowing parallel to the current. The leaves have a prominent main vein running down the middle of the blade. Credit: John Thomaides - Texas Parks & Wildlife Department.

5.10 San Marcos Springs

San Marcos Springs (centered on 29°53'35.44"N 97°55'53.94"W) in the City of San Marcos in southeast Hays County are the second largest spring group in Texas and form headwaters of the San Marcos River. The Springs (also known as Aquarena Springs) issue from the Edwards aquifer at the bottom of Spring Lake (Figure 5.74). The lake was built in 1848 at the site of a marsh formed by the springs to provide hydropower to a mill. The San Marcos River originates from the 15-acre lake and flows approximately 4 river miles south to its confluence with the Blanco River.

Sink Creek flows into Spring Lake from the east. Two connected dams control outflow from the lake on the western end. One of the earliest photographs of Spring Lake (Figure 5.75) was published by Taylor (1904). This view was presumably taken in the late 1800's or early 1900's (LBG-Guyton Associates, 2004).

Figure 5.74 Locations of larger San Marcos Springs. Courtesy of Gregg Echardt. https://www.edwardsaquifer.net/).

Figure 5.75 Spring Lake, San Marcos, Texas, showing power plant and western end of lake. Photographed about 1900. From Taylor, 1904 (Plate X in USGS Water Supply and Irrigation Paper No. 105). The lake was built in 1848 at the site of a marsh formed by the springs to provide hydropower to a mill (LBG-Guyton Associates, 2004.)

The springs at San Marcos Springs are all within Spring Lake. The names of the individual springs were given over the years by the glass-bottom boat guides at Aquarena Springs. There are no springs discharging at land surface and flowing to the lake as occurs at Comal Springs (LBG-Guyton Associates, 2004).

The thermally consistent water from the San Marcos River has long been noted and generally varies by less than 1 or 2°C in the headwaters at any time during the year. The stability of this stream, both in terms of flow dependability and thermal characteristics, is thought to have provided the appropriate ecological conditions necessary to allow the extreme endemism of the San Marcos River biota (Edwards et al., 1980).

A brief sketch of the earliest inhabitants and visitors to the San Marcos Springs and surrounding vicinity is provided by Brune (1975):

When the Spanish explorers discovered these springs in 1743, they estimated there were 200 springs. From 1755 to 1756 a mission was located there. The springs were an important stop on El Camino Real from Nacogdoches to Mexico. In 1840 Bonnell described them as "the most pleasant and delightful situation in the Republic." Power plants, gins, corn mills, and an ice factory used the water power. The springs were a stop on the Chisholm Cattle Trail from 1867 to 1895.

The city of San Marcos developed around the headspring area following early flooding and Indian attacks at the original site of the city several kilometers downstream from the headsprings. An early Federal fish hatchery was established near the springs (Jordan and Gilbert 1895). In the late 1920s the springs became a part of a privately owned resort hotel and later an amusement water park, Aquarena Springs, which operated between 1950 and 1996. The property of Spring Lake was purchased by Texas State University in 1994.

Since 2012, the Spring Lake is managed by The Meadows Center for Water and the Environment of Texas State University (https://www.meadowscenter.txst.edu/about.html). The Center offers glass-bottom boat tours, guided snorkel tours, guided stand-up paddling tours, nighttime light up kayak tours, scuba diving, and various educational and training programs.

Figure 5.76 Spring Lake in San Marcos, Texas is formed by San Marcos Springs which all discharge at the Lake's bottom. *Left*: Glass-bottom boat tours are one of the most popular offerings of The Meadows Center for Water and the Environment which manages Spring Lake. The A.B. Rogers' historic hotel, visible in the background, now houses offices for the Center's employees, as well as an exhibit that highlights endangered and threatened species. *Right*: Spring viewing platform.

According to LBG-Guyton Associates (2004), discharge from the identified spring areas within Spring Lake occurs as (1) discrete flow out of a defined orifice, such as a fissure (see Figure 5-19 *Left*); (2) diffuse flow out of the rubble of angular blocks; and (3) strong sand boils or sand geysers out of sand plains composed of white and tan, fine-grained quartz and calcite sands and black organic materials (see Figure 5-19 *Right* and 5.78). The measured velocity of groundwater discharging from the John Weissmuller orifice was 2.79 feet per second (ft/sec); the discharge rate was estimated at 15 cubic feet per second (cfs). Velocity of water discharging through unconsolidated sand sediments, which cover the conduits in Edwards Limestone, could not be measured and was estimated at 0.03 ft/sec (2,592 ft/day) in the areas of fascinating sand boils and geysers, with the total discharge rate of 142 cfs. Figure 5.79 shows discharge hydrograph for combined flow of all San Marcos Springs for the period of record.

Figure 5.77 Two western outlets of Spring Lake, San Marcos Springs in San Marcos, Texas. February 2015.

Figure 5.78 Sand boils at the bottom of Spring Lake, San Marcos Springs, marking strong discharge from the underlying limestone of Edwards Aquifer. Photo copyright Jennifer Idol, all rights reserved. Printed with permission.

Previous studies have hypothesized that discharge at San Marcos Springs might include notable contributions of recharge from nearby streams, including the Guadalupe River, Cibolo Creek, Dry Comal Creek, Sink Creek, Purgatory Creek, York Creek, Alligator Creek, and, in particular, the Blanco River (Guyton and Associates, 1979; Ogden et al, 1986; Johnson and Schindel, 2008). Results from a study by USGS (Musgrove and Crow, 2012) indicate that recharge from these local streams is not a major source of San Marcos Springs discharge.

Rather, discharge at San Marcos Springs is dominated by regional recharge sources and flow paths, even during wet hydrologic conditions when aquifer recharge is likely occurring from local streams. Geochemical modeling results using the program PHREEQC (Parkhurst and Appelo, 1999) indicate that the proportion of local stream recharge contributing to San Marcos Springs discharge increased from the dry period to the wet period, but even under wet conditions the proportion was less than 30 percent, and for most hydrologic conditions it was less than 10 percent (Musgrove and Crow, 2012; USGS, 2013).

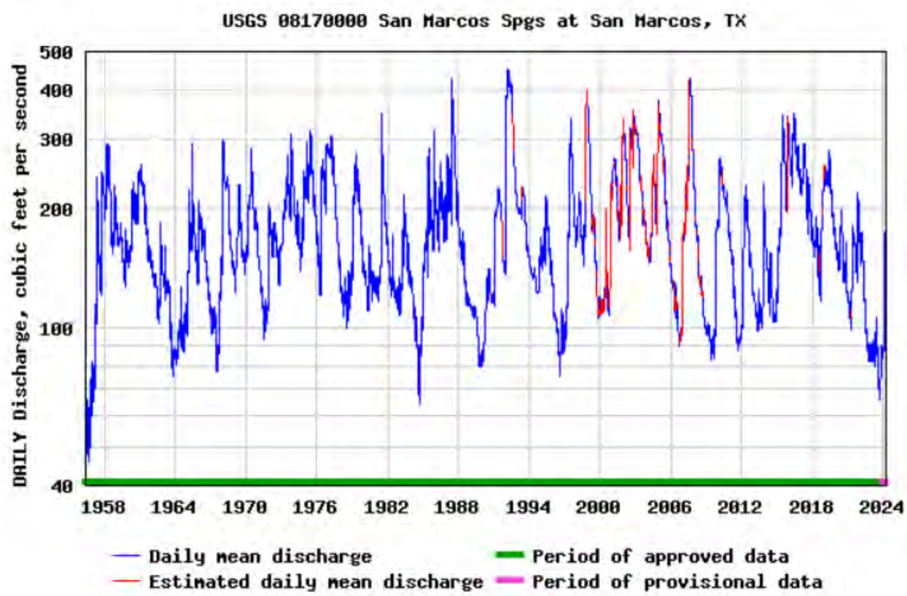


Figure 5.79 Daily discharge hydrograph of San Marcos Springs for the period of record. Average discharge rate is 173 cfs.

One of the best early descriptions of San Marcos Springs was that of McClintock, who described them as they were in 1846 (from Brune, 1981):

2 miles north of St. Marks we crossed the Blanco, a mountain torent of purest water, narrow and deep, there is the finest spring or springs, (for they are not less than 50 in a distance of 200 yds.) I ever beheld. These springs gush from the foot of a high cliff and boil up as from a well in the middle of the channel. One of these, the first you see in going up the stream. is near the center, the channel is here 40 yds. wide, the water 15 or 20 feet deep, yet so strong is the ebullition of the spring, that the water is thrown two or three feet above the surface of the stream. I am told that by approaching it in canoe, you may see down in the chasm from whence the water issues. Large stones are thrown up, as you've seen grains of sand in small springs, it is unaffected by the dryest season ... Great numbers of the finest fish; and occasionally an alligator may be seen sporting in its chrystal waters ... In the eddies of the stream, water cresses and palmettoes grow to a gigantic size. Great quantities of game in the neighborhood. It was a few months since, a favourite resort and camping ground for roving bands of Comanches.

5.11 Barton Springs

On the *Visit Austin* web page (https://www.austintexas.org/listings/barton-springs-pool/4687/), there is a description of Barton Springs (GPS coordinates centered on 30º15'49.16"N 97º46'16.52"W).

“Within Zilker Park's 358 acres lies one of the crown jewels of Austin - Barton Springs Pool. The pool itself measures three acres in size, and is fed from underground springs with an average temperature of 68-70 degrees, ideal for year-round swimming. Over the years, Barton Springs Pool has drawn people from all walks of life, from legislators who have concocted state laws there to free-spirited, topless sunbathers who turned heads in the 1970s. Robert Redford learned to swim at the pool when he was five years old while visiting family in Austin. Today, Barton Springs still attracts a diverse crowd of people and has seen record-setting numbers of visitors nearing 800,000 in recent years.

The Springs serves as home to the endangered Barton Springs Salamander, and is listed as a federally protected habitat. The pool is closed to the public from 9am to 7pm every Thursday to allow for the vigorous and methodical cleaning methods required to help maintain the pool area for wildlife and guests alike. Depths of the pool range from 0' to 18' with surrounding grassy areas for patrons to lounge upon. Adjacent to the pool bathhouse is Splash!, an educational exhibit where patrons can learn about the history and biology of Barton Springs and the Edwards Aquifer which feeds it."

Figure 5.80 Historic photograph of Barton Springs pool, Austin, Texas. Courtesy of Austin History Center, Austin Public Library.

Unfortunately, behind this upbeat description for the tourists and unsuspecting locals alike, there is a grim reality expertly described by Gregg Eckhardt on his web page (https://www.edwardsaquifer.net/barton.html). Below are only few of the alarming excerpts that may inspire some (or many) readers of this book to act and speak up for Barton Springs and all other springs in Texas.

Citizens have been fighting for decades against insensitive development that threatens Barton Springs. In the 1990s, residents overwhelmingly passed a Save Our Springs ordinance that would have implemented strict development controls. It was subsequently nullified by the state legislature, which passed a law allowing any development plat already on file to be completed without regard to the new controls.

In 2006, the United States Geological Survey published a Scientific Investigations Report that summarized water quality sampling performed from 2003 to 2005. Barton Springs was found to be affected by persistent low concentrations of atrazine (an herbicide), chloroform (a by-product of drinking water disinfection), and tetrachloroethane (a solvent).

In 2008, the fight to preserve Barton Springs was the subject of The Unforseen, a documentary co-produced by Robert Redford, who learned to swim there as a child. The movie uses the struggle over development in the Barton Creek watershed to illustrate the many clashes between private property rights and resource protection that are occurring across the country. The film drew great reviews, but some developers said it went too far and portrays them unfairly. Environmentalists said the movie is not hard enough on those who would develop lands at the expense of common resources like Barton Springs.

In January of 2019 the University of Texas at Austin released a study that showed 13 central Texas salamanders are in danger of `extinction due to overexploitation of groundwater. These include three at Barton Springs: the Austin Blind Salamander, the Jollyville Plateau Salamander, and the Barton Springs Salamander. The study relied on samples collected since the mid-1980s. In an interview for The Daily Texan, research fellow Thomas J. Devitt said urbanization has caused a decrease in the salamander populations. He said "Central Texas has some of the fastest-growing cities and counties in the nation, putting a strain on natural resources, especially water, and the environment. Overpumping of groundwater has caused (aquifer water levels) to drop and springs to stop flowing. This causes habitat loss for the salamanders."

In June of 2019 an environmental group, the Center for Biological Diversity, filed a lawsuit against the Fish and Wildlife Service, claiming federal officials are failing to protect the Georgetown and Salado salamanders. The group alleges the federal government has not taken steps to protect the habitats of the two salamanders since they were first listed as threatened in 2014.

Figure 5.81 Barton Springs pool, Austin, Texas. Courtesy of Austin Convention and Visitors Bureau.

Figure 5.82 A vintage publicity photo, undated but with a decidedly 1970s feel. Although Austin's natural beauty is mostly gone now, it still has plenty of willowy blondes and beatnik dudes in bug-eyed sunglasses. Text and photo courtesy of Gregg Eckhardt.

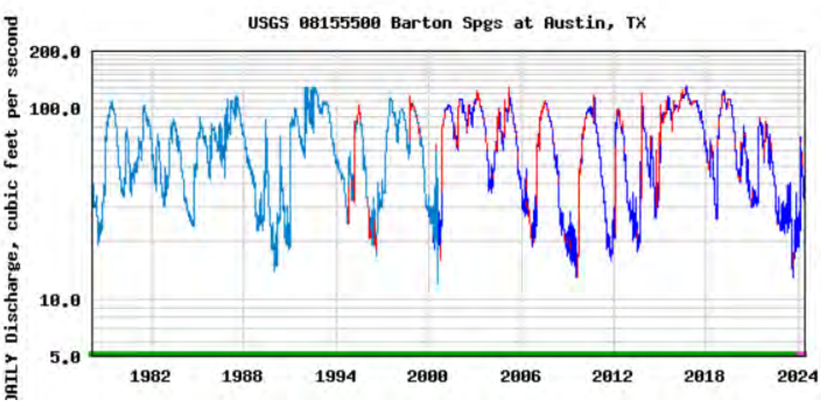


Figure 5.83 Daily discharge hydrograph of Barton Springs for the period of record. Average discharge rate is 63 cfs.

Today, Austin's natural beauty is a shadow of its former self, and the future of Barton Springs seems dim. Texas is struggling to find the right balance between protection of common resources and private property rights, and currently the pendulum is swinging strongly in favor of landowners, not residents.

Gregg Eckhardt

5.12 The Miracle at Comanche Springs

Here is a quote from a possible future (three or more years from now) news article that may appear in *Texas Highways.*

Historic Comanche Springs in Fort Stockton are flowing again. *Tens of thousands of visitors from Texas and around the country have descended to this small, long-forgotten Texas desert town to see the miracle with their own eyes—thanks to the generous support of an anonymous donor, these iconic historic springs have been fully restored to their unsurpassed former glory, again bringing joy and prosperity to the citizens of Fort Stockton. On Saturday night, an eagerly anticipated feature movie The Miracle at Comanche Springs will have a world premiere at the Fort Stockton Convention Center* (and so on and so forth...).

This article may also be poised to be widely cited by leading Texas and national newspapers and media including the Fort Worth Star-Telegram (newspaper published in the hometown of the suspected benefactor(s)), The Dallas Morning News, Houston Chronicle, The New York Times, Washington Post, CNN, CBS, NBC, Fox News, PBS, BBC America, Wall Street Journal, Los Angeles Times, USA Today, and many others:

The future miracle started unfolding sometime after an article entitled *Let It Flow: The Return of Comanche Springs* by Joe Nick Patoski, published in *Texas Highways* on January 22, 2020 (https://texashighways.com/travel-news/let-it-flow-the-return-of-comanche-springs/), was read by at least one member of an extremely wealthy Texas family of billionaires. A major Hollywood producer will be contacted by the billionaire(s), the future documentary and a feature movie will be made, and the rest will be history.

The essence of the 2020 *Texas Highways* article that will put everything in motion is illustrated with the following quotes:

Conservationists have a plan for how to enable the springs to go from an occasional to a year-round stream, and it involves paying landowners to curb their irrigation practices.

*... **Mace wasn't the only one** who thought there was a way to keep Comanche Springs flowing year-round. Sharlene Leurig, a Meadows Center fellow and CEO of Texas Water Trade, a nonprofit established in 2019 to utilize market solutions for water conservation and environmental flow, saw the potential, too. Together, Leurig and Mace started talking to community stakeholders, including the Middle Pecos Groundwater Conservation District and irrigated farming operations west of town, to develop strategies to permanently bring back Comanche Springs. They factored in the science, policy, and economics of a constant spring flow and came up with a plan.*

Texas Water Trade is launching a pilot program, hopefully later this year, to put a theory to test. The idea is to pay landowners collectively up to $1 million to suspend pumping a designated amount of groundwater for a year, calculated to be enough for Comanche Springs to theoretically maintain a healthy year-round flow that would fill the pool, the canals, and Comanche Creek. The Fort Stockton Convention and Visitor's Bureau has ponied up $50,000 for the program. The National Fish and Wildlife Foundation and the Cynthia and George Mitchell Foundation awarded a grant of $100,000.

All this started by the publication of Mace et al. (2020): *Comanche Springs, once the sixth largest spring in Texas, has a long and storied history, from mammoths sipping its brackish flow to hosting conquistadors and frontier forts to irrigating thousands of acres to being the focus of a key court decision. Unfortunately, due to pumping seven miles to the west, the springs started to fail in 1947 and stopped flowing in 1961 for 25 years. Along with the loss of Fort Stockton's natural swimming hole and the livelihoods of more than 100 families downstream was an ecosystem that supported several species now recognized as endangered, including the Comanche Springs pupfish. In 1986, the springs sprang back for a couple winters, disappeared, and then returned off and on in ensuing decades. Consistent winter flow over the past decade had posed the question: What would it take to bring flows back over the entire year? Therefore, the purpose of this study was to conduct a historical, hydrogeologic, policy, and economic review to inform residents, regulators, and policymakers on what it would take for Fort Stockton to call itself Spring City once again*.

Figure 5.84 *Left*: Looking west over Comanche Creek and Government Springs (circa 1910). *Right*: Looking toward the southwest across the natural pool (circa 1947). Postcards from the personal collection of Robert Mace. Available in Mace et al., 2020. (https://www.austingeosoc.org/news/2020/9/21/new-report-bringing-back-comanche-springs)

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Chapter 6 Grand Canyon, Arizona

6.1 Introduction

The Grand Canyon in northern Arizona is one the most famous national parks in the world (https://www.nps.gov/grca/index.htm). It is a prime international tourist destination, and a home or sacred place of origin for many Native Americans. Although the Colorado River, a primary source of drinking and irrigation water for 35 million people in the United States and Mexico, runs through the region, most communities in the area do not have rights or access to water from the river and are entirely dependent upon groundwater for all water uses. These groundwater-dependent communities include the Havasupai Nation, the Hualapai Nation, the towns of Tusayan, Williams, and Jacobs Lake, and the Grand Canyon National Park which is visited by as many as 6 million people each year. Additionally, groundwater discharge at spring sites sustains important ecosystems in the area (Tillman et al., 2021).

In January 1908, President Theodore Roosevelt exercised presidential right to make more than 800,000 acres of the Grand Canyon area into a national monument: “Let this great wonder of nature remain as it now is,” he declared. “You cannot improve on it. But what you can do is keep it for your children, your children’s children, and all who come after you, as the one great sight which every American should see.” Congress officially outlawed private development in the Grand Canyon in 1919, when President Woodrow Wilson signed the Grand Canyon National Park Act (https://www.history.com/this-day-in-history/theodore-roosevelt-makes-grand-canyon-a-national-monument).

Figure 6.1 Grand Canyon of the Colorado River, northern Arizona.

Figure 6.2 *The Grand Canon of the Colorado of the West and the cliffs of southern Utah*. Around 1910, the USGS produced a colored relief model of the Grand Canyon, which was later photographed. Available through the Library of Congress Web site as a raster image (https://www.loc.gov/item/98687193).

The Grand Canyon measures over 270 miles long, up to 18 miles wide and a mile deep making it one of the largest and deepest canyons in the world (Figures 6.1 and 6.2). As emphasized by the United States Geological Survey (USGS), the Grand Canyon tells one of the world's greatest geologic stories. Its distinctive features allow researchers to piece together the history of this unique location, one of America's treasures and a UNESCO World Heritage Site. Thinking of the geologic record as a book is helpful to understand each page of Earth's history, the story of which is provided by the USGS on an excellent webpage https://www.usgs.gov/geology-and-ecology-of-national-parks/geology-grand-canyon-national-park. USGS photographs of the Grand Canyon including many springs are provided by Billingsley et al., 2019.

The beginning of the story starts at the bottom of the canyon and moves forward in time as one gets closer to the rim (Figure 6.3). The three main rock layer sets in the Grand Canyon are grouped based on position and common composition into (1) Metamorphic basement rocks, (2) The Precambrian Grand Canyon Supergroup, and (3) Paleozoic strata. These three main sets of rocks were first described by the explorer and geologist John Wesley Powell during his expeditions of the Grand Canyon in the late 1860s and early 1870s.

The oldest rocks in the Grand Canyon, found at the bottom of the canyon, are primarily metamorphic, with igneous intrusions (the name given to when magma or lava enters or cools on top of previously formed rock). The intrusive igneous rocks here are called Zoroaster granite. The name given to this rock set (the combination of metamorphic and igneous rock of a certain age found at this location) is Vishnu Basement Rocks. Primarily schist (metamorphic) with granite (igneous), these rocks have visible crystals and are about 1.7 billion years old, from an era early in Earth history known as the Proterozoic. On Powell's expedition to explore and map the Grand Canyon, he named this part of the exposed rock "The Granite Gorge." This rock set tells the story of the creation of North America, when volcanic islands collided with the continental landmass, forming metamorphic rocks through intense heat and pressure. Volcanism continued after the collision and igneous intrusions continued after metamorphosis.

The middle rock set, the Grand Canyon Supergroup, is primarily sandstone and mudstone, both sedimentary rocks, with some areas of igneous rock. They are from the late Proterozoic, only slightly younger than the metamorphic basement rocks. These rocks do not contain many fossils, because they formed before complex life on Earth was common. The few fossils that are present include stromatolites, columns of sediment formed by cyanobacteria. The composition (sandstone) and presence of stromatolites indicate that this area was previously a very shallow sea. The rock layers in the Grand Canyon Supergroup have been tilted, whereas the other rocks above this set are horizontal. This is known as angular unconformity. The top of these sediment layers was then eroded away, forming the Great Unconformity.

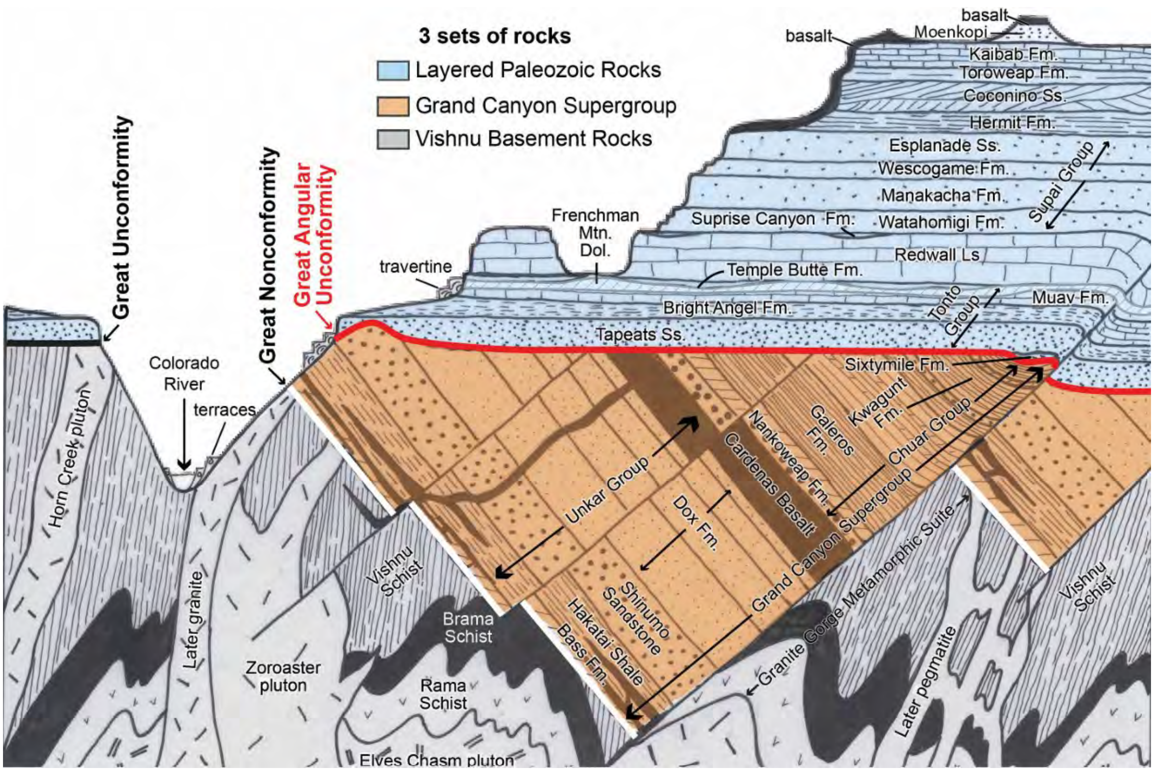

Figure 6.3. Stratigraphic column of rocks of the Grand Canyon region showing the three sets of rocks and major unconformities: Great Nonconformity (white line), Great Angular Unconformity (red line) and Great Unconformity (black line). Fm = Formation; Ss = Sandstone; Ls = Limestone. From Karlstrom et al., 2021.

Above the Great Unconformity are Paleozoic sedimentary layers, primarily sandstone and limestone (Figures 6.4 through 6.8). This set makes up most of the typical reddish and grayish-whiteish layers one often sees in images, and which come to mind when thinking of the Grand Canyon. The most common fossils are small sea creatures, such as brachiopods, bryozoans, coral, and crinoids, which indicates that the region was a warm, shallow sea when these sediments were deposited

The width and depth of the Grand Canyon make it truly remarkable and expose the rock layers explained above. After all the rocks were deposited, there was a period of uplift (where plate tectonics literally forced a section of the Earth upward), setting the stage for canyon formation. It provided a high enough elevation that water could flow downward, cutting through the rock as it went. The canyon was carved over millions of years by the

Colorado River. The canyon itself has formed much more recently than the deposition of rock layers, only about five million years ago (as opposed to the rocks, the youngest of which are a little less than 300 million years old (USGS, 2024).

Figure 6.4 *Left*: Kaibab limestone (white rock in the forefront) tops the Paleozoic sedimentary sequence at the Grand Canyon's South Rim. *Right*: Aerial view south toward a sinkhole in Kaibab Formation, west side of upper Mohawk Canyon drainage. Photo from Grand Canyon collection of Billingsley et al., 2019; USGS.

Figure 6.5 Cave in Woods Ranch Member of Toroweap Formation, Marble Canyon, south side of Tanner Wash, southeast of river mile 14.6. Photo from Grand Canyon collection of Billingsley et al., 2019; USGS.

Figure 6.6 Fractured Coconino sandstone, with typical crossbedding, as seen from Bright Angel trail below South Rim.

Figure 6.7 Aerial view northwest toward Redeye cave in north wall of Diamond Creek Canyon. Red sediment that fills the cave is Surprise Canyon Formation. The cave is in Mooney Falls Member of Redwall Limestone. From Grand Canyon collection of Billingsle et al., 2019.

Figure 6.8 Vishnu Basement Rocks exposed at the bottom of the canyon are the oldest rocks in the Grand Canyon. They are primarily metamorphic, with igneous intrusions, and are overlain by horizontal layers of Tapeats sandstone and Bright Angel shale which form an impermeable base of the R-aquifer (see Figure 6.9).

More on the fascinating geology of the Grand Canyon area including many color photographs and diagrams can be found in Graham, 2020, and Karlstrom et al., 2021. Here are few excerpts from the Executive Summaries that provide just a hint about these two outstanding publications:

Chapters of this report discuss the geologic setting, distinctive geologic features and processes within Grand Canyon National Park, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the previously completed Geologic Resources Inventory map data. Posters illustrate these data (Graham, 2020).

Grand Canyon National Park is all about time and timescales. Time is the currency of our daily life, of history, and of biological evolution. Grand Canyon's beauty has inspired explorers, artists, and poets. Behind it all, Grand Canyon's geology and sense of timelessness are among its most prominent and important resources.

*Grand Canyon has an exceptionally complete and well-exposed rock record of Earth's history. It is an ideal place to gain a sense of geologic (or deep) time. A visit to the South or North rims, a hike into the canyon of any length, or a trip through the 277-mile (446-km) length of Grand Canyon are awe-inspiring experiences for many reasons, and they often motivate us to look deeper to understand how our human timescales of hundreds and thousands of years overlap with Earth's many timescales reaching back millions and billions of years (*Karlstrom et al., 2021).

As explained by Bills et al., 2007; Graham, 2020; and Knight and Jones, 2022, the springs in Grand Canyon result from the complex relationship between caves and karst in the canyon. Smaller springs emerge from C-aquifer (Figure 6.9) which is defined as the saturated parts of the Kaibab Formation, Toroweap Formation, and the Coconino Sandstone, all of Permian age (Cooley et al., 1969). The C-aquifer is a water-table aquifer for most of its occurrence with depths to water that range from a few hundred feet to more than 1,500 feet.

Generally, the inter-crystalline permeabilities associated with the carbonate rocks that form most of the Kaibab and Toroweap Formations are negligible, but secondary permeability in the form of dissolution-widened joints and fractures coupled with a well-developed epikarst allows for recharge. The interstitial permeability found in the underlying Coconino Sandstone, although modest, is the largest found in any of the clastic units in the Grand Canyon Paleozoic section (McKee and Resser, 1945) and accounts for most of the storage that is present in the C-aquifer. The result is that perched saturated zones develop above the confining strata of the underlying aquitard composed of Hermit Formation and Supai Group. Groundwater then flows laterally to seeps at the base of the Coconino Sandstone along canyon or to extensional fault zones and fractures in the aquitard that allow the water to descend vertically and recharge the underlying R-aquifer (Knight and Huntoon, 2022).

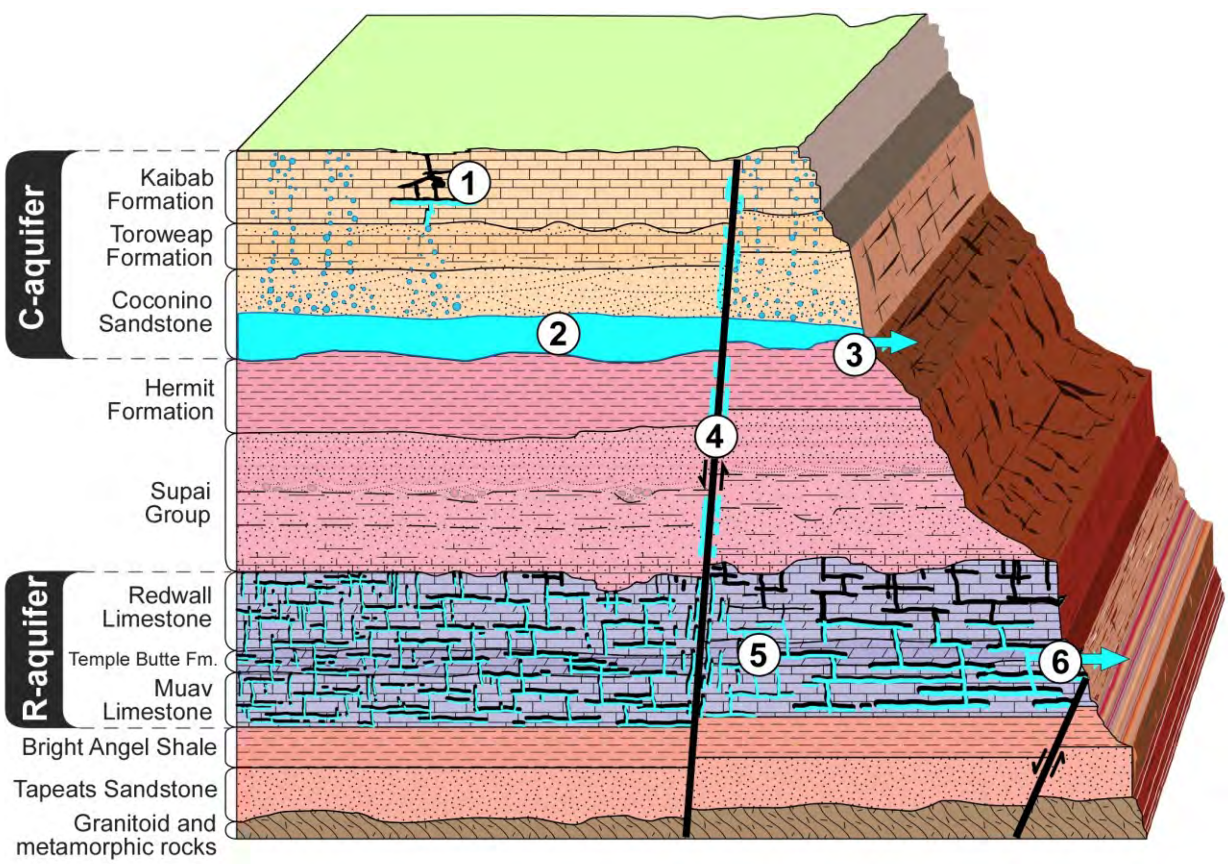

Figure 6.9 Conceptual block diagram of hydrogeologic units in Grand Canyon area. (1) Occurrence of recharge to C-aquifer can be widely distributed in space but is likely focused around areas of highly developed epikarst. (2) The majority of groundwater storage in the C-aquifer occurs in the Coconino Sandstone overlying the Hermit Formation confining unit. (3) Discharge from the C-aquifer occurs at springs exposed in canyon walls, or (4) as downward flow to the R-aquifer where substantial fracturing breaks the confining interval (aquitard). (5) Groundwater flow in the R-aquifer occurs via interconnected voids that have dissolved and widened over geologic time. (6) Discharge from the R-aquifer occurs at springs exposed in canyon walls near/at bottom of streams. Modified from Knight and Huntoon, 2022.

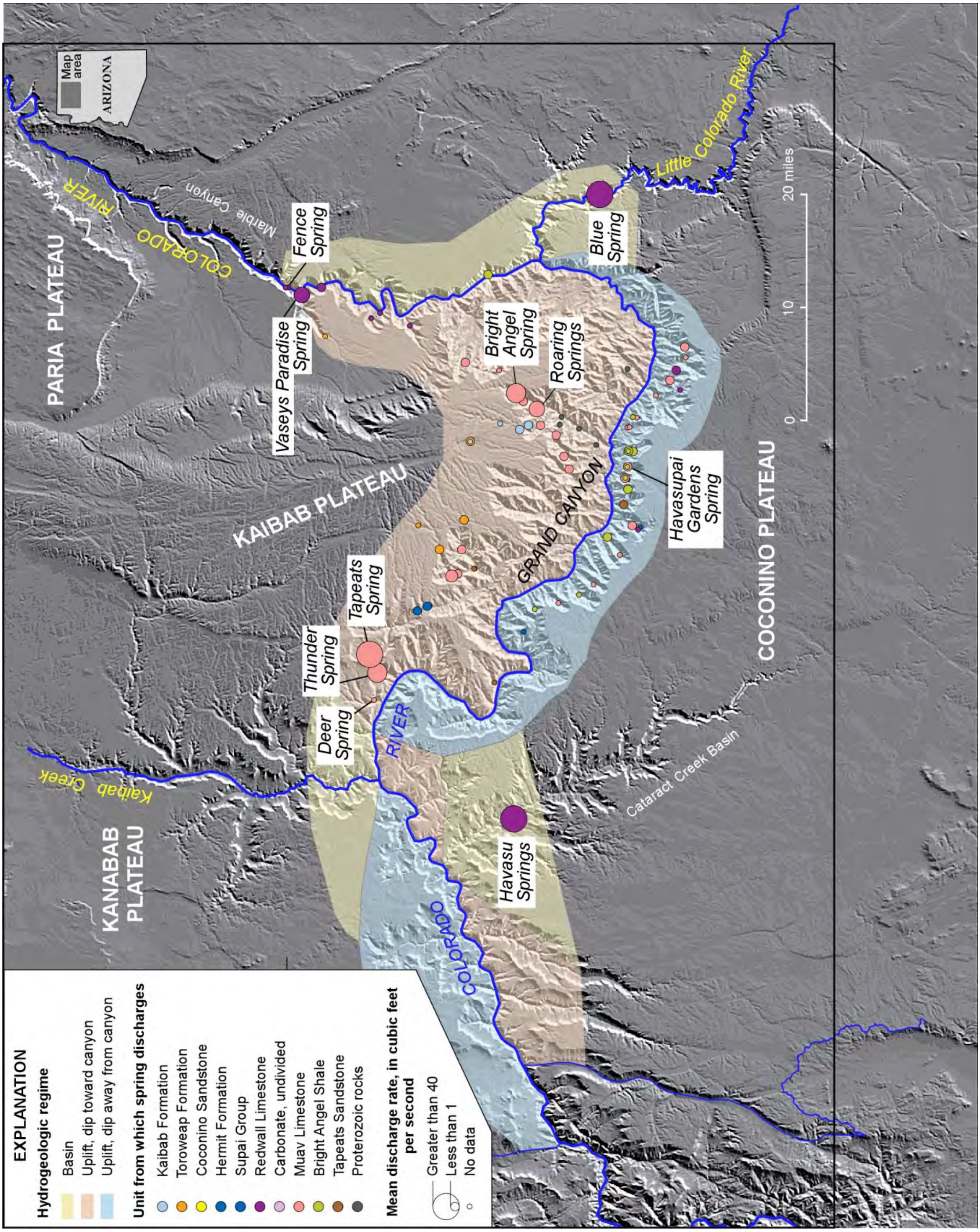

Figure 6.10 Map of the hydrogeologic regimes of springs discharging to the Grand Canyon and their designated geologic units. Symbol size indicates relative magnitude of mean discharge rate. Modified from Knight and Huntoon, 2022.

The larger springs emerge from the R-aquifer, which is composed of Redwall and Muav limestones. The Redwall-Muav aquifer is a confined aquifer for most of its occurrence with hydraulic heads of several hundred to more than 500 feet above the top of the aquifer in the western part of the Coconino Plateau and more than 2,000 feet above the top of the aquifer in the area near Flagstaff south of the Grand Canyon.

The Redwall Limestone (Figure 6.11) is named for the massive vertical cliffs forming red iron-stained walls in the Grand Canyon. The unit is composed almost entirely of highly soluble calcium and magnesium carbonate minerals. The Temple Butte Formation is a sandy dolomite containing thin sandstone and limestone beds. In the eastern Grand Canyon, it appears as thin, discontinuous lenses filling paleochannels no more than 100 feet thick in the upper surface of the Cambrian Muav Limestone. It gradually thickens to the west, reaching a maximum thickness of 650 feet west of the mouth of Grand Canyon (Beus, 2003). The Muav Limestone, as defined by McKee and Resser (1945), consists of the carbonate units in the Tonto Group. The base of the Muav Limestone is complex; the limestones that form the Muav Limestone intertongue with the underlying Bright Angel Shale of Tonto Group (Leighty, 2021).

Figure 6.11 Photograph of an entrance to a cave in the Redwall Limestone, Grand Canyon National Park. Note human figures for scale. NPS photograph by Dale Pate. From Graham, 2020.

Between the two aquifers lies a series of confining layers, or aquitards, with variable porosities and permeabilities. The Hermit Shale underlies the C-aquifer and generally acts as an aquitard, as do the interbedded sandstones and shales of the Supai Group. However, numerous intra-bed fractures, and larger fractures and faults, do allow for some vertical groundwater migration such that the unit is not an “aquiclude” (completely impermeable). Dye tracing tests on the plateaus confirm the hydraulic connectivity between the land surface and the R-aquifer, throughout the entire Paleozoic sedimentary rock sequence.

The Bright Angel Shale beneath the R-aquifer acts as a regional aquitard allowing only minimal water to flow from springs in the underlying Tapeats Sandstone or Precambrian basement rocks (Billingsley, 2000).

The incision created by the Colorado River has bisected these aquifers into separate flow systems on the north and south sides of the river. North of the river, the C- and R- aquifers are connected via faults and fractures on the Kaibab Plateau. Direct recharge of the C-aquifer on the Kaibab Plateau occurs from infiltration of precipitation water through the karstified surface including numerous sinkholes. Groundwater flowing from the C-aquifer to the R-aquifer feeds many large springs primarily located below the Kaibab Plateau, including the Roaring, Deer, Thunder, Tapeats, and Vasey’s springs (Huntoon, 2000b; Hill and Polyak 2010; see Figure 6.10).

Below the South Rim, Havasu Spring discharges into the Grand Canyon from the Coconino Plateau, an area twice the size of the state of Delaware. Blue Springs, the largest magnitude spring in Arizona and the largest spring adjacent to Grand Canyon National Park, is in the Little Colorado River area (Flynn and Bills 2002). These two springs discharge from the R-aquifer. The average flow of Blue Spring, one of dozens of outlets from the Redwall-Muav aquifer along the lower Little Colorado River, is about 95 ft^3/s, and the combined flow from all springs in this reach of the Little Colorado River is about 237 ft^3/s. Havasu Spring in Havasu Creek has a discharge of about 64 ft^3/s. Additional springs that discharge from the Redwall and Muav Limestones downstream to the mouth of Havasu Creek increase the base flow of the creek to about 71 ft^3/s. (Bills et al., 2007).

Metzger (1961) noted that most other springs and seeps along the south rim of the Grand Canyon that issue from the Redwall and Muav Limestones have small discharges. These springs typically are about 3,000 ft below the surface of the Coconino Plateau.

The R-aquifer is a typical karst aquifer; that is, the permeability in the aquifer is the result of dissolution of the host rock into interconnected voids and caves that have developed over geologic time. In contrast, the intercrystalline permeabilities of the carbonate rocks that compose the aquifer are negligible. Hydraulic gradients within karst aquifers dictate the development of the permeability architecture, which is hierarchical and organized in a down-gradient direction, towards large springs, much like a surface stream network (Knight and Huntoon, 2022).

There are two important characteristics common among springs discharging to the Grand Canyon from the R-aquifer: (1) the water discharges from the intensely karstified lower Paleozoic carbonates, and (2) faults are the dominant geologic factor on the locations of springs (Cooley, 1963). All springs in the region that have discharge larger than ~2 cubic feet per second (ft^3/s) are from fractures associated with faults, indicating that fractures not only provide the pathways for vertical circulation through the Paleozoic section, but also collect and transport water laterally to springs deep in the canyons (Knight and Huntoon, 2022).

As discussed by Graham (2020), based on GIS analysis of the USGS cave density map by Weary and Doctor (2014), Stortz et al. (2018) estimated that 70%–90% of the area within Grand Canyon National Park is considered karst. Within the National Park System, only Everglades National Park has karst area more than Grand Canyon National Park (Weary and Doctor 2014; Jones et al., 2017a). The park contains over 1,500 square miles of karst features, including a surficial karst system in the Kaibab and Toroweap formations, major cave development, and a deeper karst system in the Redwall and Muav limestones buried over 3,000 ft below the surface (Beus, 2003; Bills et al., 2016; Jones et al., 2017a).

Figure 6.12 shows karst features in a wider area around the Grand Canyon, courtesy of John Noll. Many other maps, photographs and schematic drawings describe the hydrogeology of Kaibab Plateau in detail on Mr. Noll's excellent web page at https://storymaps.com/stories/5779465a5cf7436f9be8150131a2bd45.

It is estimated that Grand Canyon may contain as many as 2,500 caves with several hundred caves having been documented. The Redwall Limestone hosts the majority of the park's caves, most of which are nearly inaccessible due to openings on vertical cliffs.

Caves in Grand Canyon National Park contain delicate cave speleothems (cave features), rare minerals, important archeological sites, and significant Pleistocene fossils. They also provide important habitat for many wildlife species from the endangered California condor to a number of different species of bats. Because of their importance and vulnerability, under the current park policy, *all caves* are closed to visitation, and may only be entered by scientists with research permits (https://www.nps.gov/grca/learn/nature/cave.htm).

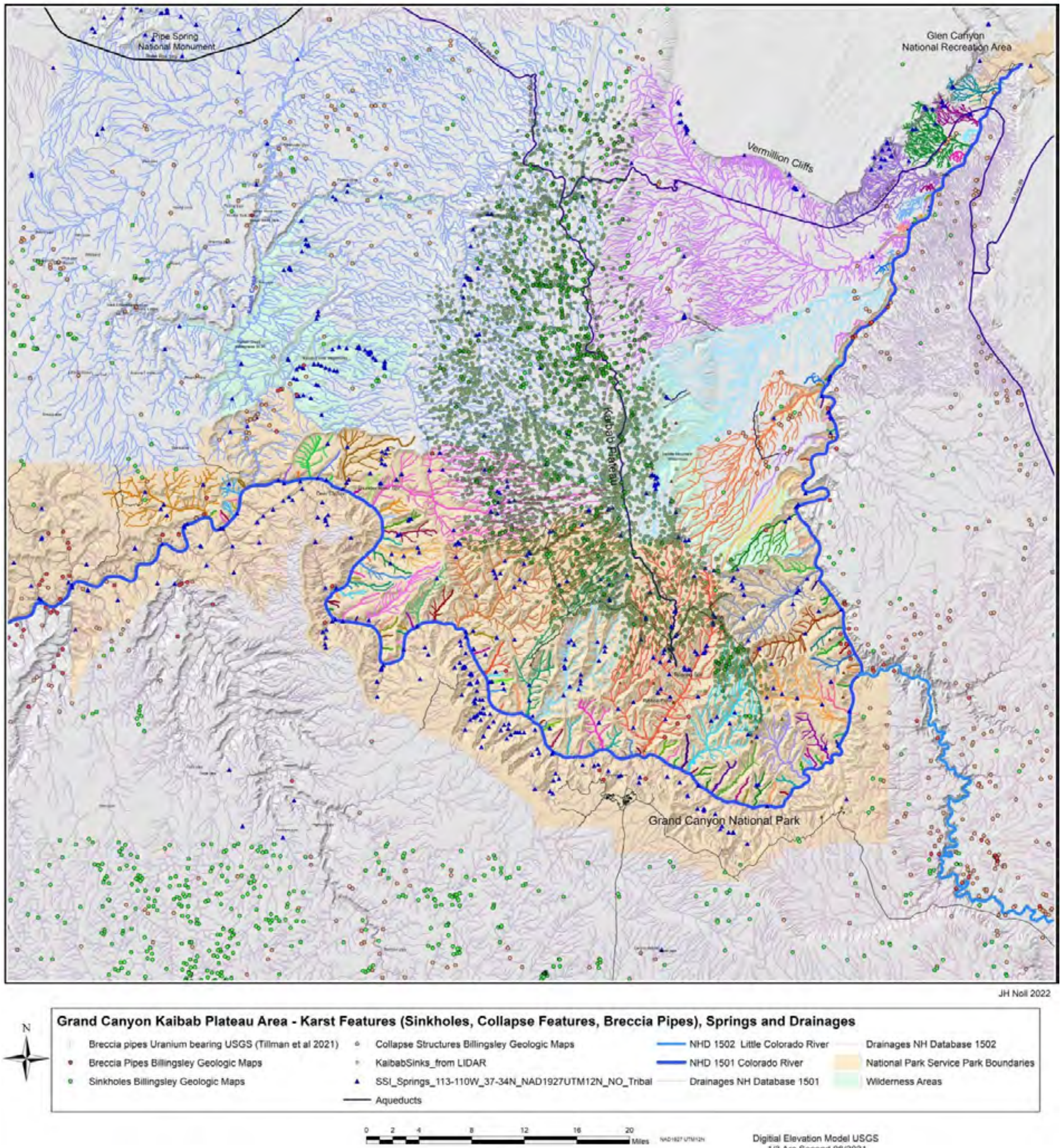

Figure 6.12 Map of extensive karst data from the USGS 30'x60' Geologic quadrangle maps. Mapped sinkholes are shown with green circles; collapse structures where there is surface dip in toward the center of the feature are shown with orange circles); and breccia pipes where collapse has progressed to brecciate the rocks at the surface are shown with red circles. The locations of karst features as defined by LIDAR imaging have been added ("grayed" green circles). LIDAR stands for Light Detection and Ranging and is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. These light pulses—combined with other data recorded by the airborne system—generate precise, three-dimensional information about the shape of the Earth and its surface characteristics. See the paper by Casey et. al. (2017) for more details on how karst was defined on the Kaibab Plateau using LIDAR imaging. Map and text courtesy of John Noll. From Hydrogeology of the Kaibab Plateau; A Brief Introduction by John Noll, April 2, 2022. Available at https://storymaps.com/stories/5779465a5cf7436f9be8150131a2bd45. John Noll is a geologist living in Flagstaff, Arizona with interests in the challenges of managing water resources in the arid southwest.

6.2 The Kaibab Plateau Springs

The largest springs that discharge from the Kaibab Plateau are the Tapeats, Thunder, Cheyava Falls Spring, and Deer Springs (See Figure 6.10 and Figures 6.13 through 6.15), which drain most of the plateau via the West Kaibab Fault Zone. The base flows from these springs are about 50 ft^3/s, although flood flows can be several times this amount (Johnson and Sanderson, 1968).

The huge outpourings of water at Thunder River, Tapeats Spring, and Deer Spring have attracted people since prehistoric times and today this little corner of Grand Canyon is exceedingly popular among seekers of the remarkable. Like a gift, booming streams of crystalline water emerge from mysterious caves to transform the harsh desert of the inner canyon into absurdly beautiful green oasis replete with the music of water falling into cool pools. Trailhead access can be difficult, sometimes impossible, and the approach march is long, hot, and dry, but for those making the journey these destinations represent something close to canyon perfection.

National Park Service

Figure 6.13 *Left*: Deer Spring. *Right*: Deer Creek Waterfall is a stop on most Colorado River Trips through the Grand Canyon. NPS Photos by Erin Whittaker, taken in August 2011; provided under https://creativecommons.org/licenses/by/2.0/#

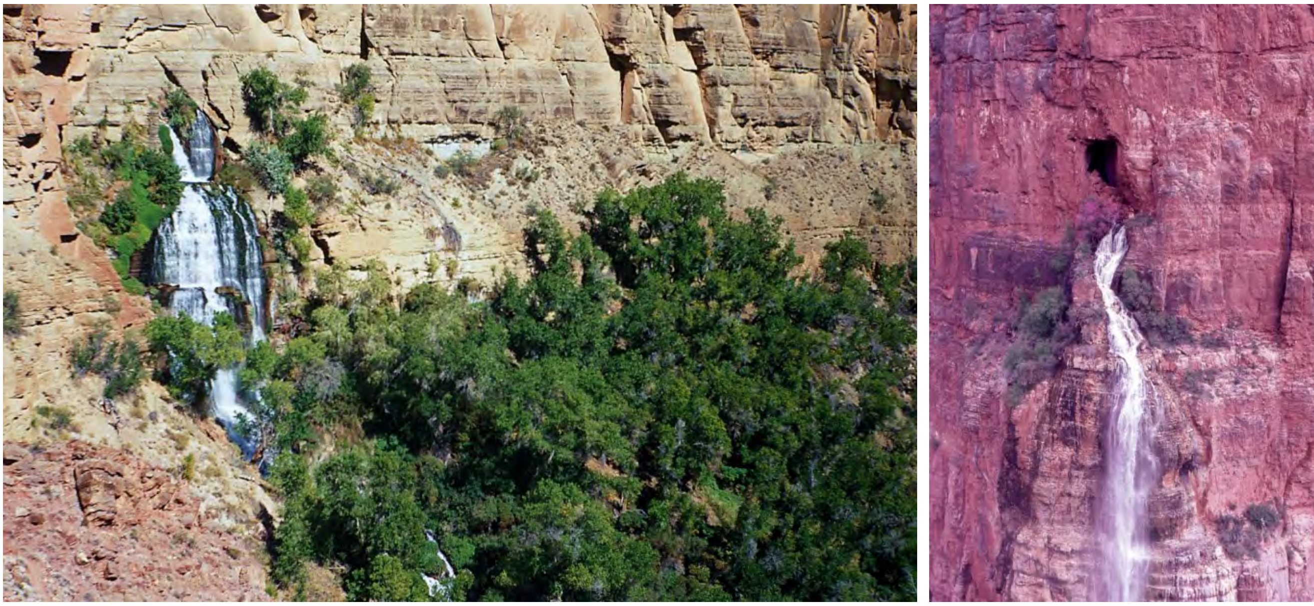

Figure 6.14 *Left*: View northeast toward Thunder Spring from Thunder River trail. Spring issues from fractures in Peach Springs Canyon and Kanab Canyon Members of Muav Limestone. *Right*: Intermittent Cheyava Falls Spring flow coming out of cave in Mooney Falls Member of Redwall Limestone, east wall of upper Clear Creek canyon. Photographs from Grand Canyon collection of Billingsley et al., 2019; USGS.

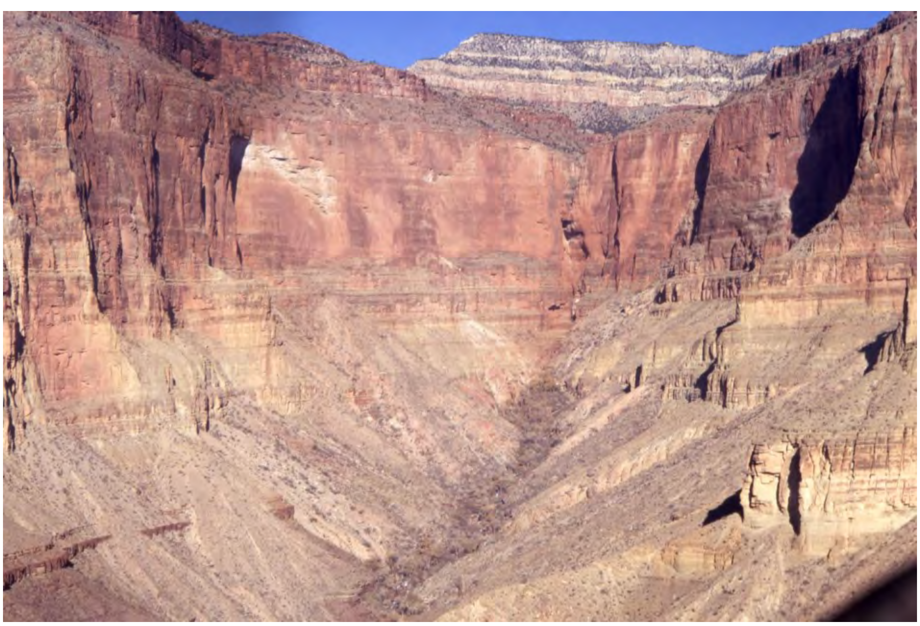

Figure 6.15 Aerial view north towards Tapeats Spring, north side of Tapeats Creek canyon. Spring issues from a cave in Peach Springs Canyon Member of Muav Limestone. Photograph from the Grand Canyon collection of Billingsley et al., 2019; USGS.

Bright Angel Creek springs and Roaring Springs (Figure 6.16) drain the south-central part of the Kaibab plateau via caves present on fractures or parallel to the Bright Angel Fault, which in turn is hydraulically linked to normal faults that trend along the axis of the Kaibab uplift.

Roaring Springs serves as the sole water supply for both the north and south rim developments in Grand Canyon National Park. In its current design, gravity plays a major role in the functioning of the waterline, creating sufficient pressure to flow water to Havasupai Gardens (formerly known as Indian Gardens) from the spring intake at an elevation of 5,200 feet. Water travels down along the North Kaibab Trail in the waterline, through Phantom Ranch. It crosses the Colorado River and reaches its lowest elevation of 2,400 feet before it ascends the canyon and enters the Havasupai Gardens pump houses at an elevation of 3,700 feet. From there, water is pumped up 3,300 feet in elevation to the South Rim through the borehole section of the waterline.

The only continuous streamflow records that exist for the Kaibab Plateau springs are daily measurements of the Bright Angel Creek (USGS station 09403000) from 1924 to 1974 and continuous measurements from 1991 to 1993 (Figure 6.17). These measurements serve as a useful proxy for spring discharge because the creek is fed by a series of karst springs including Roaring Springs.

Figure 6.16 Where the descending North Kaibab Trail meets the flatter bottom of Bright Angel Canyon, 5 miles from the North Kaibab Trailhead, Roaring Springs may be seen. Here, water gushes forth directly out of the cliffs, cascading over moss and fern to form Bright Angel Creek (which will be a constant companion all the way to the Colorado River). This large spring provides drinking water for every visitor and resident within Grand Canyon National Park. The water is delivered to the South Rim via a pipeline buried beneath the North Kaibab Trail (installed 1965-1970). NPS photos by Michael Quinn available at https://www.flickr.com/photos/grand_canyon_nps/albums/ under https://creativecommons.org/licenses/by/2.0/#. The park's new water bottle filling stations provide free spring water from Roaring Springs. Learn more about water bottle filling stations here: www.nps.gov/grca/planyourvisit/refilling_stations.htm.

The National Park Service (NPS) studies and design process has resulted in a decision that relocates the water intake to Bright Angel Creek near Phantom Ranch. This will create a second water source for the park with the South Rim, Havasupai Garden and Phantom Ranch receiving water from the new intake at Bright Angel Creek while Roaring Springs will continue to provide water to the North Rim, Manzanita and Cottonwood.

Moving the water source to Bright Angel Creek will enable additional streams and watersheds to feed into the water intake and provide more resiliency for future water conditions. The location will also reduce the pipe length and eliminate the portion of the current waterline that experiences the most frequent failures, an area north of Phantom Ranch known as "The Box". The new waterline will stretch nearly 3 miles from Phantom Ranch to Havasupai Gardens (formerly known as Indian Gardens). With this design, natural flow would be restored to Bright Angel Creek from Roaring Springs (NPS, https://www.nps.gov/articles/000/tcwl-design.htm)

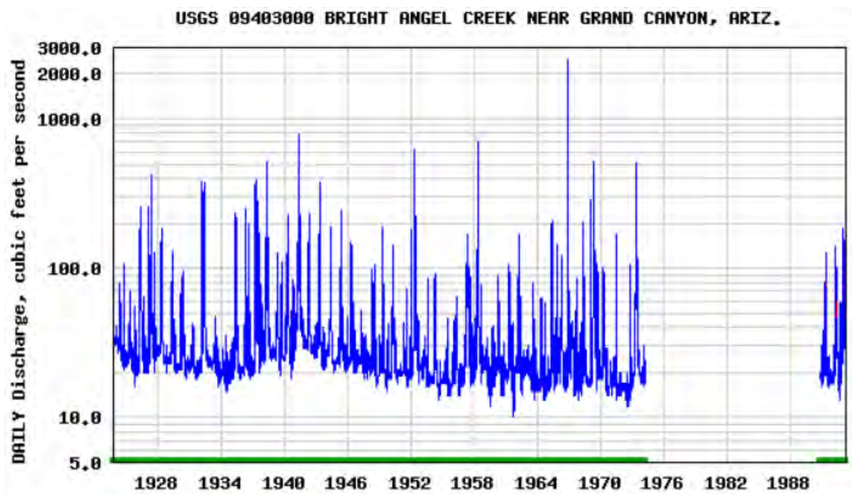

Figure 6.17 Hydrograph of the Bright Angel Creek flow rate for the period of record.

Figure 6.18 Bright Angel Creek. Photo courtesy of NPS.

Vaseys Paradise Spring, on the wall of Marble Canyon (Figure 6.19), is the most striking spring that drains the east side of the Kaibab Plateau. The water discharges from a cave dissolved along fractures parallel to the Fence Fault at the base of the Mooney Falls Member of the Redwall Limestone. Nearby submerged springs discharge water originating on the plateau directly from the Fence Fault into the Colorado River.

Figure 6.19 View west and upriver toward Vaseys Paradise Spring from river mile 32.2; Redwall Limestone in Marble Canyon. The Spring discharges from a cave more than 1.9 miles long. Photograph from the Grand Canyon collection of Billingsley et al., 2019; USGS.

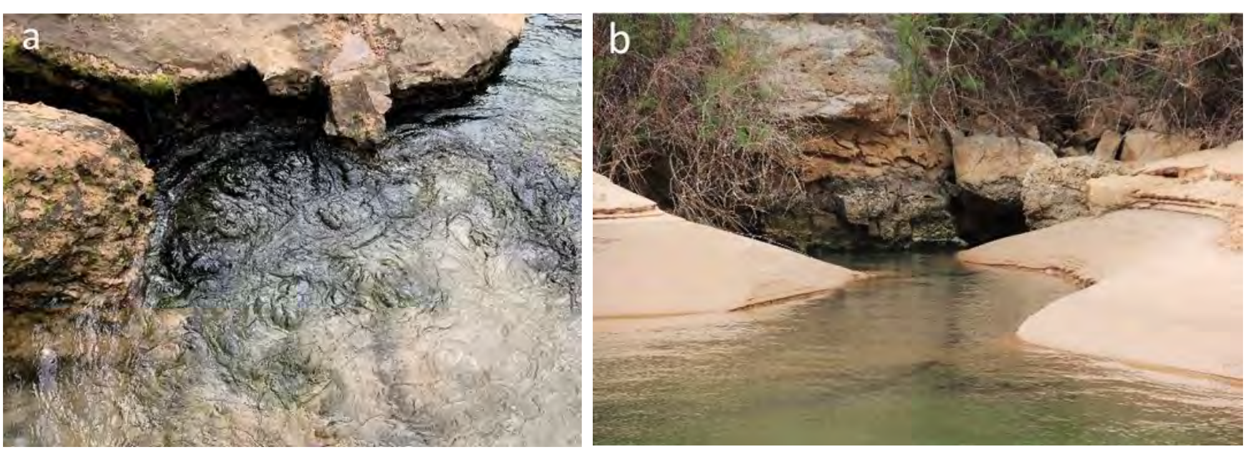

Figure 6.20 (a) Fence East spring bubbles up into the Colorado River. (b) Fence West emerges near river level and gets inundated by the river more easily than Fence East. Fence Springs are high discharge springs of the Redwall-Muav karst aquifer in Marble Canyon of eastern Grand Canyon (see Figure 6.10). Spring vents are in the fracture network of the river-crossing Fence fault, on its downthrown side, not along its main strand. Fence East Spring (~ 15.5 cfs) is artesian and emerges at the edge of the river; it is emergent at low river stage and covered at higher river stages. Fence West Spring has lower flow (~ 3 cfs) and emerges through both bedrock and alluvium near river level. Vents on opposite banks of the Colorado River within the Fence fault system have similar chemistries indicating the springs are connected hydrologically within the confined karst aquifer below the river. Stable isotope data fingerprint the recharge area for both springs to be the Kaibab Plateau, west of the river. Photos and text from Gibbon et al., 2022.

6.3 Havasu Spring

The Havasu Spring is on the Havasupai tribe reservation, surrounded by the Grand Canyon National Park. In order to maintain the pristine beauty of this isolated desert paradise, the Havasupai tribe limits the number of visitors allowed to visit the reservation. There is no day hiking permitted in the canyon. Any visitor must have a reservation and entrance fees are now paid in advance (see https://theofficialhavasupaitribe.com/).

As explained by Knight and Huntoon (2022), Havasu Spring is the primary point of discharge for groundwater from the Cataract groundwater system which underlies the Coconino Plateau (part of the greater Colorado Plateau) south of the Colorado River (see Figure 6.10).

The R-aquifer within most of the Cataract groundwater system is a classic basin-type karst system with a main discharge point at Havasu Springs on the floor of Cataract Canyon. The rocks that compose the R-aquifer, the Redwall Limestone and the Muav Limestone, are fully saturated under the lower reaches of Havasu Canyon. In contrast, the rocks are mostly dewatered where they are exposed along the South Rim of the Grand Canyon high above the Colorado River and dipping outward, away from the river and canyon wall. The narrow band along the South Rim to the east and west of Cataract Canyon is better described as an uplifted, outward-dipping karst system.

Although not exposed, the karstic character of the flow system supplying Havasu Spring can be readily inferred. The volume of water flowing from the spring reveals that it is fed by a cavern network dissolved in the Redwall Limestone that is analogous to the dewatered two-dimensional planimetric cavern networks exposed within the interior of the Eminence graben in the walls of Marble Canyon (Knight and Huntoon, 2022).

A major flood in 1993 coursed down the otherwise ephemeral Cataract Creek with losses of water into sinkholes that opened along fissures in the fault system 40 miles upstream from Havasu Springs (Melis et al., 1996). Within 2 years, the water quality at the spring freshened (concentration of total dissolved solids decreased), noticeably revealing that the flood waters had diluted the water in the R-aquifer and arrived. It is reasonable to infer that preferential dissolution enhancement of permeability within the R-aquifer aligned with the regional hydraulic gradient, and accounts for the hydraulic connection between the upstream fault zone and Havasu Springs.

The interior of the Cataract Canyon drainage basin is riven by a network of closely spaced, orthogonally intersecting, small-displacement normal faults that are well exposed in the Kaibab Formation at the surface. Approximately 20 percent of the surface area of the basin is internally drained by sinks along these faults, which may conduct available surface waters down through the C-aquifer directly to the R-aquifer (Melis et al., 1996).

Figure 6.21 Aerial view toward Havasu Springs area south of Supai village, Havasu Creek, Cataract Canyon. Esplanade Sandstone forms the rim and platform above Pennsylvanian group of strata. Photograph from the Grand Canyon collection of Billingsley et al., 2019; USGS.

A seepage investigation conducted from Havasu Spring to the mouth of Havasu Creek for the Havasupai Tribe showed that the creek loses about 14 percent of its flow from the spring to Havasu Falls and then gains 29 percent of its flow from Havasu Falls to the mouth (U.S. Geological Survey, unpublished data, 1995; from Bills et al., 2007).

The water from Havasu Spring is rich in magnesium, calcium, and high concentrations of bicarbonate. As it makes its way through Havasu Creek, these ions combine to form tufa and world-famous travertine dams and falls between the spring and the Colorado River. Taken together, the dissolved ions and tufa/travertine, reflect sunlight resulting in a more intense blue-green color (https://azgs.arizona.edu/photo/havasupai-falls). Havasupai literary means people of the blue-green waters.

The temperature of the water at the spring is about 70 °F and the discharge is fairly uniform at about 60 ft^3/s (Johnson and Sanderson, 1968). The water of the springs sustains a pristine natural environment and biota, some of which are endemic.

As discussed by Knight and Huntoon (2022), it is important to determine flow vectors to the R-aquifer, either in the subsurface or overland, that can be expected from contaminant sources including mined ore and waste rock stored on the surface and mine production water. Of particular concern are migration pathways to the swallow holes in the floor of Cataract Creek upstream from Havasu Springs. No quantitative work has been carried out in the form of dye traces to determine flow rates between Havasu Springs and the sinks in the floor of Cataract Creek in the fault zone 40 miles upstream. The transmissive character of the R-aquifer, particularly where it is fractured by highly conductive extensional faults, remains unquantified.

Figure 6.21 View southeast and upstream toward Havasu Creek spring flow, lower Cataract Canyon, just upstream of river mile 157.2. Photograph from the Grand Canyon collection of Billingsley et al., 2019; USGS.

Havasu Spring and Creek, and indeed the life on the Havasupai Tribe reservation as we know it are threatened by the uranium mining activities in the greater Grand Canyon area, as further discussed in Section 6.5, and in the Introduction to this book. Despite a decades-long fight to prevent the uranium mining and all its negative consequences, including lawsuits supported by many non-governmental organizations, the uranium mining at the Pinyon Plain Mine (previously known as the Canyon Mine) started in January 2024.

Figure 6.22 *Left*: Havasu Falls with travertine pools in the foreground, Havasu Canyon, part of the Grand Canyon area. Photo courtesy of David Price. *Right*: The confluence of Havasu Creek with the Colorado River (river mile 157) is a popular place for boaters to stop and admire the striking blue-green water of Havasu Creek. The turquoise color is caused by water with a high mineral content. At the point where the blue creek meets the turbid Colorado river there often appears a definite break. NPS photo by Erin Whittaker, August 15, 2011 (under https://creativecommons.org/licenses/by/2.0/#).

6.4 Blue Spring

Blue Spring is on the Navajo Tribal Land and hiking or camping is not allowed without prior permission from the Navajo Nation. The Blue Spring groundwater system is a basin-type karst system. It is the largest groundwater system that drains to the Grand Canyon, encompassing 27,000 square miles underlying the Little Colorado River drainage basin in Arizona and western New Mexico (Knight and Huntoon, 2022).

Blue Spring is a collective description of at least 36 individual springs on the floor of the Little Colorado River canyon within about 13 river miles of its confluence with the Colorado River. According to Cooley (1976), base flow upstream from Blue Spring is only about 5–7 ft^3/s. Blue Spring discharges at a constant rate of about 90 ft^3/s, which is almost half of the perennial flow at the mouth of the Little Colorado River. Cooley (1976) also recorded 60 ft^3/s contribution to streamflow from two unnamed springs just downstream from Blue Spring, 40–45 ft^3/s from other springs before river mile 10, and another 20 ft^3/s before river mile 3.1. In total, the springs of the Blue Spring groundwater system contribute 220 ft^3/s to the Little Colorado River (Cooley, 1976).

The large and steady discharge rate from the springs is consistent with the size of its catchment area. The water emerges at an average temperature of 70 °F and is turquoise in color owing to the spontaneous precipitation of calcium carbonate (Johnson and Sanderson, 1968). Deposits of calcium carbonate create a continuous series of travertine dams and rimstone pools between the springs and the Colorado River.

The Blue Spring is situated within an extensional rift zone riven by a dense set of generally north-south trending small displacements owing to normal faults. The regional dip of the Paleozoic strata is very gentle toward the southeast and a structural low near or upstream from Cameron, Arizona. The result is that the floor of the Little Colorado River cuts ever deeper into the Paleozoic section in the downstream direction along this reach. Most of the water emerges from a few major springs in the Mooney Falls Member of the Redwall Limestone, which discharge from saturated caves and dissolution-widened fractures associated with faulting (Knight and Huntoon, 2022).

Work by Cooley (1976) demonstrated that most of the Blue Spring water is derived from the C-aquifer underlying the Little Colorado River Basin. In Cooley's (1976) conceptual model, the water circulates laterally through the C-aquifer downstream within the basin until it is intercepted by the north-trending extensional faults oriented subparallel to the East Kaibab Monocline west of Cameron. It circulates downward within the fault zone to the R-aquifer where it then follows dissolution-widened fractures and caves in the Redwall Limestone that developed along the faults, emerging at the downstream springs.

Groundwater circulation rates through the fault zone that supplies the Blue Spring groundwater system are likely to be exceptionally fast given the expected karstic permeabilities. However, those rates have not been quantified.

Figure 6.23 View southwest toward three main springs of Blue Spring on southwest side of Little Colorado River; springs issue from Mooney Falls Member of Redwall Limestone. Photo dated January 26, 1970; from the Grand Canyon collection of Billingsley et al., 2019; USGS.

Figure 6.24 View southeast toward Blue Spring jetting out of Moony Falls Member of Redwall Limestone on southwest side of Little Colorado River. Photo dated May 2, 1970; from the Grand Canyon collection of Billingsley et al., 2019; USGS.

Figure 6.25 View east toward normal blue Little Colorado River spring water flowing over travertine dam deposits, just upstream of Big Canyon. Photo dated January 26, 1970; from the Grand Canyon collection of Billingsley et al., 2019; USGS.

Figure 6.26 Confluence of Little Colorado River (turquoise color) and Colorado River. Screenshot from a video *Virtual Tour—Grand Canyon, AZ Dams Threaten the Little Colorado River*, produced by EcoFlight in cooperation with the Grand Canyon Trust. https://www.grandcanyontrust.org/little-colorado-river-dam-proposals.

Figure 6.27 *Left*: First large spring about 1 mile upriver from Blue Spring, Mooney Falls Member of Redwall Limestone level, east side of Little Colorado River. Photo dated January 26, 1970; from the Grand Canyon collection of Billingsley et al., 2019; USGS. *Right*: Second large spring about 1 mile upriver from Blue Spring, Mooney Falls Member of Redwall Limestone level, east side of Little Colorado River. Photo dated November 29, 1975; from the Grand Canyon collection of Billingsley et al., 2019; USGS.

Figure 6.28 View north toward Curtain Spring, travertine spring deposits that cover Mooney Falls Member of Redwall Limestone, east wall of Little Colorado River, about a half mile upstream of Blue Spring. Photo dated January 26, 1970; from the Grand Canyon collection of Billingsley et al., 2019; USGS.

6.5 Uranium Mining Threats

High-grade uranium ore was discovered in geologic features called “breccia pipes” (Figure 6.29) in the Grand Canyon region during the late 1940s and became the subject of intense exploration during the 1970s (Otton and Van Gosen, 2010). Historical uranium mining of breccia pipes in northern Arizona has left a legacy of abandoned mines, mine waste, and waste rock exposed at the surface, allowing subsequent remobilization of minerals and radionuclides and contamination of both surface water and groundwater systems in the region. Although the advent of stricter environmental regulations and improvements in mining practices reduced the potential for environmental contamination, secondary permeability in fractured and karstified rocks provides pathways for dispersing remobilized radionuclides.

Today, Indigenous communities on the Colorado Plateau continue to bear the brunt of America’s sordid past when it comes to uranium extraction. More than 500 abandoned uranium mines remain in need of careful assessment and cleanup on Navajo Nation lands alone, where a recent study found that over a quarter of 781 Navajo women tested had elevated levels of uranium in their bodies, as did newborn babies. The Navajo Nation banned uranium mining on its 27,000-square-mile reservation in 2005, but the abandoned mines remain (Reimondo, 2020).

As explained by the U.S. Geological Survey (Tilousi and Hinck, 2024), growing public concern that uranium mining activities could have adverse environmental, cultural, and social impacts prompted a withdrawal of approximately one million acres of Federal lands from future mineral extraction to study the potential effects of uranium mining (Alpine, 2010) and to prepare an environmental impact statement (Bureau of Land Management, 2011). In 2012, the former Secretary of the Interior, Ken Salazar, closed the Federal lands in the Grand Canyon watershed to new mining claims under the 1872 Mining Law until the year 2032 (Bureau of Land Management, 2012; U.S. Department of Interior [DOI], 2012

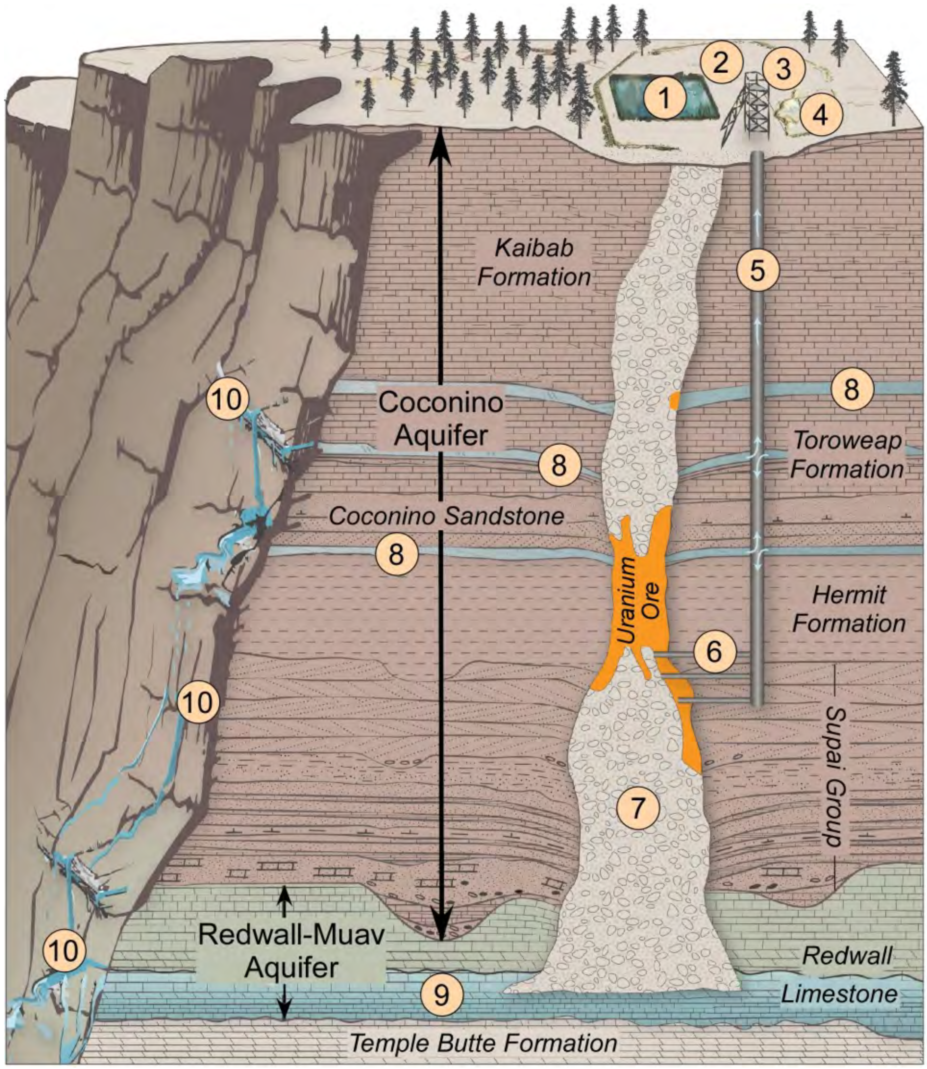

Figure 6.29 Lithology and mine features at breccia-pipe uranium mining sites in the Grand Canyon region. From Reimondo, 2020. (1) Containment pond; (2) Ventilation shaft; (3) Mine headframe; (4) Waste rock, ore pile, and top soil storage; (5) Mine shaft; (6) Horizontal shaft ("drifts"); (7) Breccia collapse feature; (8) Perched aquifer; (9) Regional aquifer; (10) Seep or spring. Potential water flow in mine shaft is shown with blue arrows. Generalized and modified from the USGS report Site Characterization of Breccia Pipe Uranium Deposits in Northern Arizona and Uranium Mine Conceptual Model. Graphic by Stephanie Smith, Grand Canyon Trust. Available at https://www.grandcanyontrust.org/Canyon-Mine-Report.

This designation did not exempt Red Butte and the surrounding area from renewed mining operations at the Pinyon Plain Mine (Winters, 2016). The mine is located fewer than 9 miles south of the south rim of the Grand Canyon and is very likely within the drainage area of the Havasu Springs and Creek.

Energy Fuels, Inc. changed the name of the mine to Pinyon Plain Mine in 2020; it had previously been known as the Canyon Mine since at least the 1980s (U.S. Department of Agriculture, 1986). Pinyon Plain Mine development has been completed and the mine operation (extraction of uranium ore) by Energy Fuels, Inc. started in January 2024. The Havasupai Tribe did not stand a chance in the cruel continuation of what the newcomers to their ancestral lands have been doing to them ever since the U.S. Government seized most of their territory by executive order in 1882.

As descendants of the original peoples who have lived in the Grand Canyon for centuries, the Havasupai have long and deep connections to water, plants, animals, and geology throughout the Colorado Plateau. Historically, many Pai Tribes inhabited the land around the Grand Canyon, including the Havasupai, Hopi, Hualapai, Southern Paiute, Yavapai-Apache, and Zuni. Important geographical landmarks included the Grand Canyon, the San Francisco Peaks, Bill Williams Mountain, and Red Butte. The Havasupai Tribe lived at the rim of the Grand Canyon and the Colorado Plateau in the winter and spent summers farming in the bottom of the Grand Canyon (Hirst, 2006). When the U.S. Government seized most of their territory by executive order in 1882, the Havasupai were locked into 519 acres within the Havasu Canyon along Cataract Creek; their village, known as Supai (Figure 6.30), is only accessible by foot, horse, or helicopter.

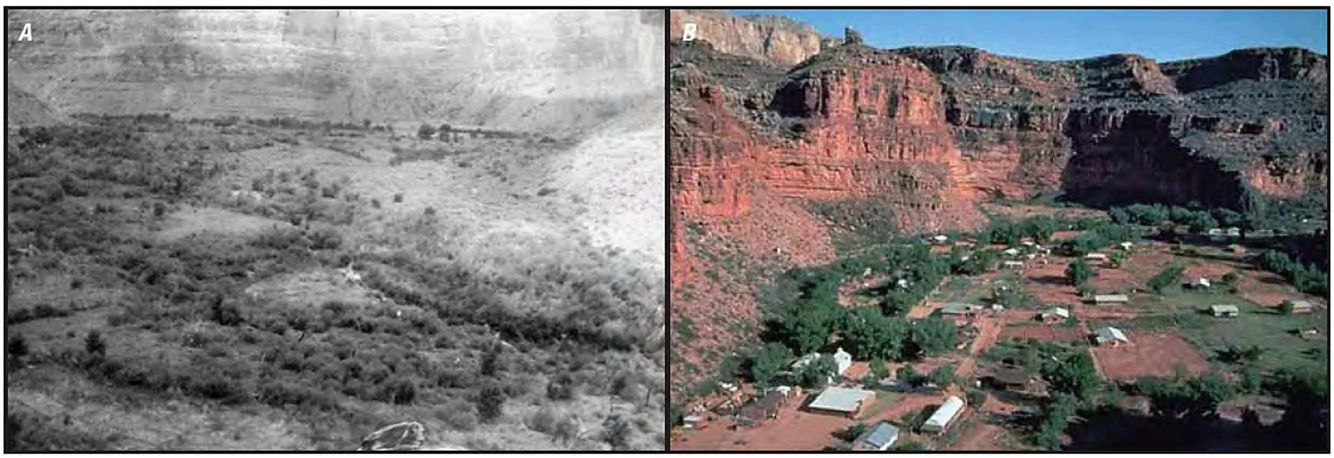

Figure 6.30 Area of Havasupai village, known as Supai, within the Havasu Canyon. *A*, Supai in 1893 (Coupland, 1893). *B*, Supai in 2016 (photograph courtesy of National Park Service).

The Havasupai's indigenous territory includes the Grand Canyon National Park, which is home to sacred trails, prayer areas, mountains, and burial sites. In 2022, the Havasupai successfully petitioned the name change of Indian Gardens to Ha'a Gyoh (Havasupai Gardens), honoring their ancestors and reclaiming their historical connection to the Grand Canyon (National Park Service, 2022; Fonseca, 2023; see Figure 6.31).

The Havasupai Tribe has spoken out against mining at the Pinyon Plain Mine through lawsuits, injunctions, and protests. They have voiced concerns to the U.S. Government and the international community that uranium mining may cause death and destruction to their waters and to the existence of their life and traditional practices (U.S. Congress, 2019). In 2012, the Havasupai believed that the DOI heard their voices when enacting the 20-year mining withdrawal, which meant that for two decades there would be no new uranium mines on Federal land on the north and south rims of the Grand Canyon (DOI, 2012); however, existing permitted mines, including the Pinyon Plain Mine, were grandfathered into this withdrawal. The Havasupai have continued to oppose the opening of the Pinyon Plain Mine through partnerships with nongovernmental organizations including the Sierra Club, Center for Biological Diversity, and the Grand Canyon Trust. Federal courts have ruled against their appeals to stop mining at the Pinyon Plain Mine (United States District Court for the District of Arizona, 1990, 2015; United States Court of Appeals for the Ninth Circuit, 1991, 2017, 2022; Winters, 2016).

Water is essential to Havasupai identity and its importance is passed from elders to Havasupai children through oral stories (for example, see Tikalsky et al., 2010). The Havasupai note that the people's existence and belief systems are at risk of serious effects that cannot be mitigated if the water becomes contaminated from uranium mining (Tilousi, 2019). The Pinyon Plain Mine is above a primary aquifer, the Redwall-Muav aquifer or R-aquifer, on the Colorado Plateau (Pool et al., 2011).

Figure 6.31 The Bright Angel Trail, one of the most popular trails in the Grand Canyon National Park, levels out as it approaches Havasupai Gardens (formerly known as Indian Gardens), 4.5 miles and over 2,000 vertical feet below the South Rim. This destination is a green oasis within the canyon, home to the Havasupai People until they were forced to leave when the National Park was established. This oasis is now threatened by the uranium mining at the Pinyon Plain Mine.

As masterfully explained by Reimondo (2020; https://www.grandcanyontrust.org/Canyon-Mine-Report):

Uranium mining is inherently dangerous for land, water, and people. Once uranium is exposed to oxygen, a never-ending battle with Mother Nature begins to keep the radioactive element from finding its way into water, soil, plants, wildlife, and the bodies of human beings.

The inherent dangers posed by mining uranium are only amplified in the Grand Canyon region, a place of complicated hydrogeology. Exactly what direction(s) groundwater flows and how quickly it gets from one point to another is a complex question that too often lacks a definitive answer. Rock layers adjacent to the Grand Canyon are highly fractured, meaning that even would-be "confining layers," or dense rock through which water wouldn't typically flow, can still have places that allow contaminated water to move downward to precious groundwater aquifers and to sources of seeps and springs inside the walls of the Grand Canyon.

One way to visualize the complex nature of the region's hydrogeology is to imagine a pipe system designed by Dr. Seuss where water can flow in multiple directions from one spot, sometimes very quickly, sometimes taking thousands of years, and no two places look the same.

These complexities and unknowns matter a lot when it comes to uranium mining. If we don't know exactly where groundwater flows, and how quickly it gets there, we can't properly weigh the risks of allowing a mine to move forward. If we don't understand groundwater flow, we also don't know exactly where to monitor for contamination. That means it is also possible we simply would not know groundwater was contaminated until contamination was detected in a critical water supply, like Havasu Creek. Worst of all, even if contamination were detected, it would be, at best, extremely expensive to manage and, at worst, likely impossible to reverse. And while a mining company might move on to other places or lines of business, the people, plants, wildlife, and economies that rely on the Grand Canyon landscape for water and other life-sustaining resources, will pay the price of uranium mining for many lifetimes.

Ultimately, the unknowns, the risks, and the consequences for people, cultures, the natural world, economies, and critical water supplies are all too high. Conversely, as the Grand Canyon Trust outlined in a January 2019 report, "Uranium Mining in the Grand Canyon Region," the need to mine the uranium deposits near the Grand Canyon is low and the ever-growing costs of the legacy left behind by past uranium mining are bad enough. No matter how many times uranium-mining companies make promises that their operations are safe, even "overly regulated," the facts show that they are neither.

If the R-Aquifer becomes contaminated, and we must abandon our ancestral home of Supai Village, we will leave the blue-green waters of Havasu Creek behind and consequently will cease to be the Havasuw baja. While we may still breathe air, we, the People of the Blue Green Water, will have become extinct.

Havasupai Vice-Chairman Edmond Tilousi

According to Bills et al. (2010), at least fifteen springs and five wells in the region contain concentrations of dissolved uranium that exceed the U.S. Environmental Protection Agency maximum contaminant level for drinking water (30 µg/L) and are related to mining processes. Most of the groundwater samples represent conditions at the end of a groundwater flow path from areas of recharge to location of discharge (springs). Affected groundwater, if any, may not have flowed yet to the points sampled in this study.

The Pigeon Mine sump had a single reported value of 170 µg/L in 1986, and the Hermit Mine sump concentrations ranged from 3,310 to 36,600 µg/L (the highest reported value of any sample type in this study) in 1989−90. These high concentration mine shaft and sump waters may be sources of dissolved uranium for nearby spring sites if mine water is entering the regional groundwater flow system.

The results of hydrogeologic studies performed by Jones et al. (2017a) show that strong groundwater flow connectivity exists between the shallow groundwater system in the C-aquifer and the deep, regional karst system of R-aquifer which feeds all the largest springs in the Grand Canyon area including Havasu Spring.

Uranine injected into sinkhole in Kaibab plateau at the land surface was detected in tributaries to Bright Angel Creek downstream from Roaring Springs which discharge from the R-aquifer at thousands of feet of lower elevations, three months following injection. In addition, it stayed in the system for two more months. The timing and locations of the detected dyes indicate that the vertical connection between C and R aquifers occurs along fractures with high transmissive properties. However, the downward movement of groundwater along these vertical conduits and horizontal flow within the two aquifers is extremely complex (Jones et al. 2017a).

To further understand the complexities of the deep karst aquifer, Jones et al. (2017a) analyzed spring discharge at Roaring Springs, chosen because it is the sole water source for the park. Spring discharge hydrographs allow for the determination of aquifer water storage and discharge distributions over time because discharge can be directly measured at the spring.

Discharge analysis demonstrated a connection between the R-aquifer and surface recharge and characterized the vertical flow patterns through over 1,000 m (3,000 ft) of lithostratigraphic units, as well as horizontal flow patterns in the perched C-aquifer (Jones et al. 2017a). According to Jones et al., the hydrograph data for the deep karstic R-aquifer "indicate a complex, unknown history of transit time, flow paths and residence times" (Jones et al. 2017a, p. 16).

And yet, various "environmental impact statements" and related studies by government agencies and other entities interested in uranium mining in the Grand Canyon area virtually all are based on an extremely limited number of true groundwater monitoring locations, such as shallow and deep monitoring wells, sometimes only one or two, or none. This practice would be unacceptable at any potential groundwater contamination site, anywhere in the country, regulated by any regulatory agency, at any level of government.

Figure 6.32 White Mesa community members participate in the 2019 White Mesa spiritual walk, an annual protest walk organized by Ute. Mountain Ute tribal members are concerned about the uranium mill's impacts on groundwater, air quality, and public health. Photo by Tim Peterson, from Reimondo, 2020; https://www.grandcanyontrust.org/Canyon-Mine-Report)

6.5.1 The Voices of the Profession

Las Vegas Sun
UNLV prof to Congress: Mining contaminates Colorado River By Mary Manning
Tuesday, July 21, 2009 | 4:13 p.m.
The Associated Press contributed to this report.
https://lasvegassun.com/news/2009/jul/21/unlv-professor-congress-uranium-mining-contaminate/

Restarting uranium mining near the Grand Canyon poses a contamination risk to the Colorado River, serving more than 25 million people in western states, a UNLV hydrology professor told a congressional committee today.

David Kreamer, a UNLV professor, said that assuming renewed uranium mining would have little or no effect on the river and surrounding springs is "unreasonable" and cannot be supported by past investigations and research.

Kreamer and his students have been conducting studies on springs in the Grand Canyon for 25 years and he told the House Natural Resources Committee's parks subcommittee that past mining activities have polluted a spring that feeds the Colorado River and that pollution is expected to continue if more mining occurs.

Kreamer said his research found uranium levels three times above the Environmental Protection Agency's recommended limit on water supplies in Horn Creek, a canyon creek that runs into the Colorado. He said that the uranium polluted the creek's water from mining that stopped more than 10 years ago.

Public Comment of Prof. David K. Kreamer regarding Application of Pinyon Plain Mine (formerly known as Canyon Mine) for an Individual Aquifer Protection Permit (APP) No. 100333, LTF 84446

"My background is that I have been a professor of hydrogeology at the University of Nevada, Las Vegas for over 30 years in the Department of Geoscience, and previously taught in the Department of Civil Engineering at Arizona State University, and the Department of Hydrology and Water Resources at the University of Arizona (where I also received my Ph.D.). I am the co-author of the 3rd edition of the textbook "Contaminant Hydrogeology", am completing a 5th edition of the textbook "Applied Hydrogeology" and have authored or co-authored more than 75 professional publications, including the recent, peer-reviewed, "Review: The Distribution, Flow, and Quality of Grand Canyon Springs, Arizona (USA)" in the journal Hydrogeology (Tobin et al., 2018). My full Curriculum Vitae is available upon request. I have testified before the U.S. Congress on this issue, and recently addressed the General Assembly of the United Nations on related groundwater issues. I have served as a Board Member for the National Ground Water Association, Division of Scientists and Engineers, and as President and Board Member of the Universities Council on Water Resources. I currently serve as the President of the International Association of Hydrogeologists (IAH), the largest international groundwater association in the world, with thousands of members in over 130 countries, many national chapters and regional Vice-Presidents, and Commissions and Networks that address specific groundwater challenges. IAH is a scientific, educational, and charitable organization that was established in 1956. https://iah.org/

Key points regarding serious shortcomings in hydrogeological interpretation in the Individual Aquifer Protection Permit Application (APP) include:

- No basic water balance is presented in the application or supplementary material, that would indicate the impact, or the location and severity of groundwater withdrawals or water quality changes associated with mine operations. A basic, quantitative groundwater balance is a basic framework for evaluation of groundwater supply to wells or springs, or potential contamination.
- It is asserted by the applicants that surface infiltration is low. Surface infiltration has not been fully measured or characterized at the site, and an assumption of low infiltration conflicts with geologic field conditions and historical evidence.
- Previous assertions that the C-aquifer contains little groundwater is a repeated misrepresentation and shown to be false by multiple lines of evidence.

- Statements that there are no major geologic structural features near the mine that could affect vertical migration of mine water or its movement toward the Grand Canyon are a misrepresentation of previous studies and investigations.
- A hypothetical inferred groundwater divide north of the mine has been represented as fact, rather than supposition and major potential pathways of groundwater flow from the mine site to the canyon have not been included in the APP.
- Groundwater "age" is misrepresented in the application as opposed to the more accurate "average groundwater residence time."
- The propensity for dissolution and mobilization of high concentrations of uranium into groundwater as a likely result of mining operations is ignored, and placed in a misleading context, considering only pH and not anticipatable, changing redox conditions.
- Inappropriate groundwater equations are used for analysis of the hydraulic properties of groundwater at the site.
- Numerical groundwater flow modeling by the mine's consultants, that indicates groundwater movement from the mine area to the Grand Canyon springs, is not presented.
- Water quality similarities between groundwater at the mine site and Grand Canyon springs, a piece of evidence supporting hydrogeologic connection and communication, is not presented or evaluated.
- The groundwater monitoring system is inadequate to access excursion of contaminated groundwater from the site and does not follow U.S. EPA guidance.
- The period of groundwater monitoring and reporting after mine closure is inexact and is insufficient to capture long term impacts.
- Post-closure subsidence of the mine is a real, unaddressed possibility, allowing additional fracturing and new vertical pathways for contaminant movement.
- The APP application has not reported consideration of recent hydrogeological findings from the field area in recent literature.
- Impacts on Grand Canyon springs (both quantity and quality) are only considered for a few large-discharge springs, not the overwhelming number of smaller discharge seeps and springs where impact would be greatest."

Professor Kreamer went into great detail explaining all the key points, providing extensive backup and references to many professional and scientific publications including by the United States Geological Survey. In doing so, Dr. Kreamer also delivered a thorough lecture on Hydrogeology 101 to the personnel at the Arizona Department of Environmental Quality (ADEQ) responsible for the responses to public comments. This includes very basic concepts such as how to determine directions of groundwater flow based on observations at monitoring wells.

After receiving these and many other public comments, ADEQ did what most agencies usually do when the train has already left the station. For one, the Agency was not going to acknowledge their fundamental lack of understanding of hydrogeology and the nature of groundwater flow and the contaminant fate and transport in complex hydrogeologic environments such as the Grand Canyon.

So, the authors at ADEQ went through the motions and answered various comments but did not answer some of the most critical ones. Some questions were answered in the most amazing way. So amazing that, while reading them carefully, I felt as if I was pulled into a parallel universe, straight into a huge black hole. There also is no question that the authors at ADEQ did succeed in pulling some other people into a huge black hole; after all, the

Individual Aquifer Protection Permit was granted by the Agency and the uranium mining at Pinyon Plain Mine (formerly known as Canyon Mine) commenced in January 2024.

Although it is unlikely that we will ever understand everything that contributed to the permit approval, it is hard not to mention one of the most powerful rockets, faster than the speed of light, that the Agency fired straight into the black hole for the purpose of this approval. The design of the rocket is described on page 31 of 118 of the *Summary and Response to Public Comments, Energy Fuels Resources (USA) Inc. (EFRI) Pinyon Plain Mine Permit # 100333 LTF # 84446* authored by the Arizona Department of Environmental Quality, Aquifer Protection Program (APP) available at https://static.azdeq.gov/wqd/pinyonplain/2022_indpermit_rs.pdf :

R-AQUIFER MONITORING WELL

Commenters asserted that the R-aquifer well on-Mine is not adequate for monitoring the R-aquifer for a variety of reasons including its location relative to the Mine. Several commenters expressed concern that the R-aquifer monitoring well is not adequate because the groundwater flow direction is not known.

ADEQ Response

From a hydrogeologic standpoint, the R-aquifer monitoring well at the Mine is essentially immediately below and downgradient of any potential release from the shaft or workings. The thickness, age difference, and hydraulic separation of the C-aquifer and R-aquifer, at the Mine, make the R-aquifer monitoring well an appropriate monitoring point for the low probability potential of leakage and impact above the AWQS. Additionally, the proximity of the R-aquifer monitoring/supply well to the breccia pipe makes it an appropriate monitoring point for detection of a potential release.

Based on my professional judgment, this statement by ADEQ is nonsensical from a hydrogeologic standpoint and contrary to the entire professional and academic practice of groundwater science and engineering in any porous media and type of aquifer, not just in karst.

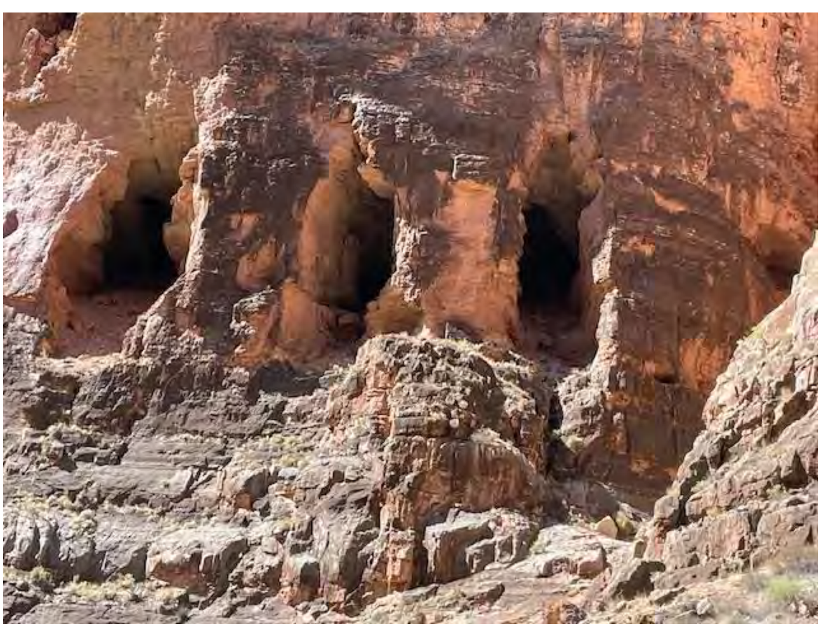

Figure 6.33 Redwall limestone, main member of the R-aquifer. Question for ADEQ and others interested: Do you think that one monitoring well in the R-aquifer is sufficient? Photo courtesy of David Kreamer.

Namely, ADEQ believes that one (emphasis added) well in the highly karstified R-Aquifer, which is known to have very complicated hydrogeologic characteristics and local and regional flow directions (see Figure 6.34 for an example), is sufficient to determine, with reasonable accuracy, the directions of groundwater flow and fate and transport of any contaminant reaching the R-aquifer.

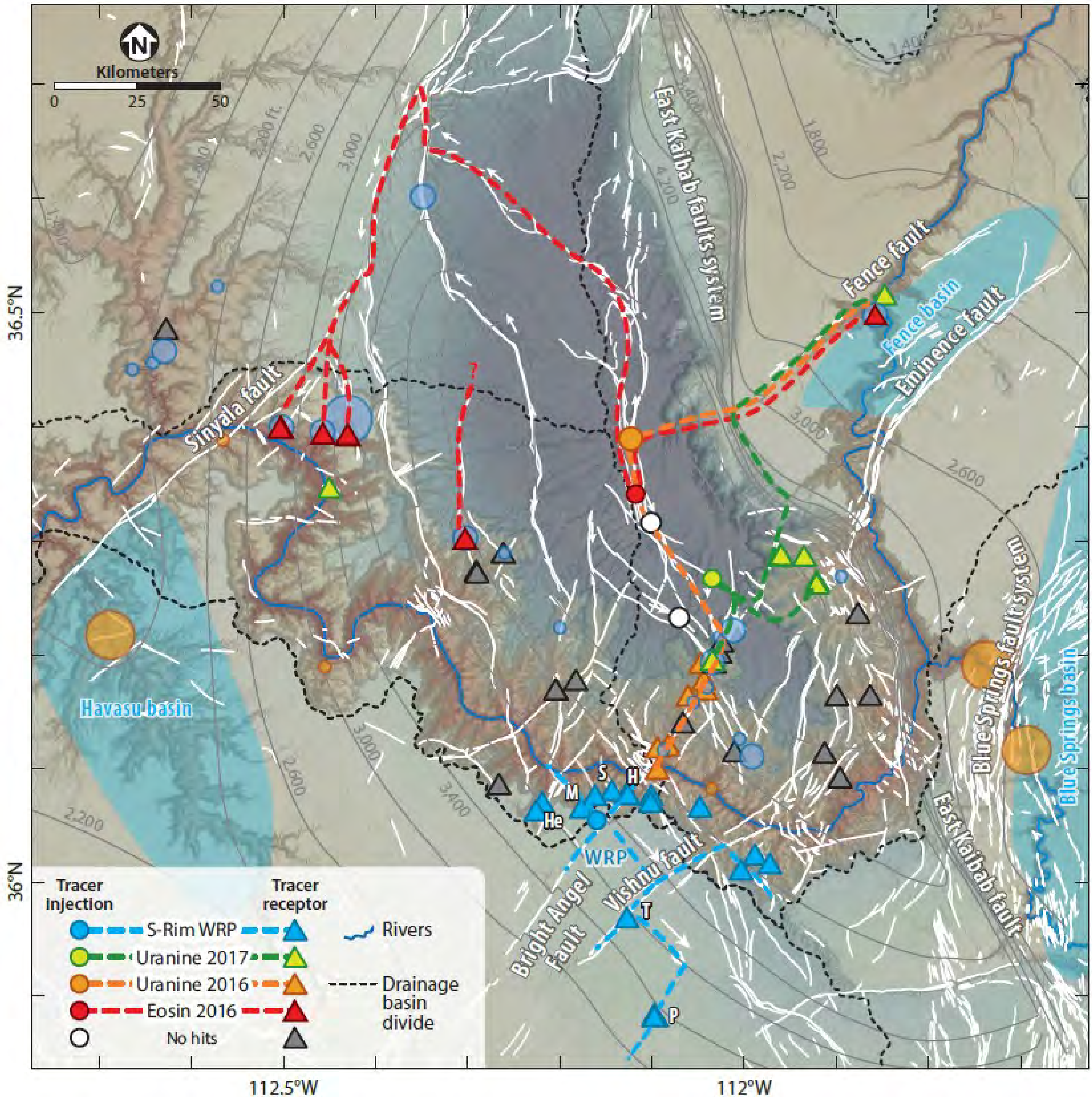

Figure 6.33 N-Rim dye tracer studies (Jones et al., 2018; Tobin et al., 2021) injected various dye tracers into sinkholes (*dots*); some reached detector locations (*triangles*) within weeks to months. On the S-Rim, pipeline water injected at the WRP along the Bright Angel fault is hypothesized to be affecting S-Rim springs and groundwaters based on using stable isotopes as time-averaged natural tracers (Curry et al., 2023). NW-trending faults mapped by Maxon (1968) may convey water to Hermit, Monument, Salt, Horn, and other S-Rim springs as well as to Tusayan and Pinon Plain Mine wells. Structure contours (in feet) are drawn on the top of the Bright Angel Shale aquitard (adapted from Huntoon 2000). Fence, Blue Spring, and Havasu sub-basins on either side of the Kaibab uplift are in synclinal or graben depressions and are discharging from the upper Redwall, with the R-M aquifer filled; most other springs are discharging from the Muav, with the aquifer mostly drained. Data are in Supplemental Table 1. Abbreviations: H, Horn; He, Hermit; M, Monument; N-Rim, North Rim; P, Pinon; R-M, Redwall-Muav; S, Salt; S-Rim, South Rim; T, Tusayan; WRP, Water Reclamation Plant. Copyright 2014 by L.J. Crossey, K.E. Karlstrom, B. Curry, C. McGibbon, C. Reed, J. Wilgus, C.J. Whyte, and T. Darrah.

Provided below are excerpts from a press release by the University of New Mexico that was picked up by many newspapers and media in the West, including New Mexico Sun: https://newmexicosun.com/stories/657306825-a-new-look-at-grand-canyon-springs-and-possible-threats-from-uranium-mining):

A new look at Grand Canyon springs and possible threats from uranium mining

By New Mexico Sun, Mar 25, 2024

A new research paper published in Annual Reviews of Earth and Planetary Sciences sheds light on the significance of Grand Canyon's springs and groundwater, as well as the potential threats posed by uranium mining. The paper, titled Hydrotectonics of Grand Canyon Groundwater, emphasizes the importance of sustainable groundwater management and the need for better monitoring to address uranium mining threats.

Lead author Laura Crossey discussed the findings of the research, noting the role of faults as fluid superhighways that connect different aquifers. She stressed the importance of understanding these "hydro-tectonic" concepts in managing and protecting the Grand Canyon's springs and groundwater wells.

The paper also addresses the timely issue of uranium mining in the region, particularly the Pinyon Plain mine near the Park's South Rim Village. Karlstrom expressed concern over the lack of consideration for recent scientific findings in the permitting process, stating, "Tribes claim the permitting is ignoring recent peer-reviewed science and risks to culturally significant features."

The authors of the paper advocate for caution and oppose mining in the sensitive region due to the significant risk of contamination, especially of the Havasupai springs that supply water to the Havasupai Village. The paper serves as a comprehensive summary of the science surrounding Grand Canyon groundwater, urging state and federal agencies to prioritize the protection of this unique and vital ecosystem.

The paper in question authored by Crossey et al. (2024) is available at https://doi.org/10.1146/annurev-earth-080723-083513. Figure 6.33 is from it, illustrating the complexity of groundwater flow in the Grand Canyon area including the hydraulic connectivity of water flow between the ground surface and the springs discharging from the R-aquifer, throughout the entire thickness of both the C- and R-aquifers and any intervening fractured aquitards.

Back to ADEQ's most powerful rocket and the huge black hole. Many people with common sense, living in this universe, did resist in being pulled into the huge black hole in the parallel universe, as illustrated with the following press release:

Center for Biological Diversity

For Immediate Release, June 27, 2024
Contact: Sandy Bahr, Sierra Club Grand Canyon Chapter: (602) 999-5790, sandy.bahr@sierraclub.org
Taylor McKinnon, Center for Biological Diversity: (801) 300-2414, tmckinnon@biologicaldiversity.org
Kelly Burke, Wild Arizona, (928) 606-7870, kelly@wildarizona.org

17,000 Petition Signatures Delivered to Gov. Hobbs Urging Her to Shut Down Pinyon Plain Uranium Mine

PHOENIX— Local and national public-interest groups, as well as Havasupai Tribe members, delivered more than 17,000 petition signatures to Gov. Katie Hobbs today urging her to use her authority to close the Pinyon Plain uranium mine that threatens the waters of the Grand Canyon and the Havasupai Tribe.

This comes after the groups, scientists and many others sent a letter to the governor in January outlining the threats posed by this mine and asking for her assistance with its closure.

"The Havasupai Tribe, other Tribal leaders, and those who care about protecting Grand Canyon and its waters have fought the Pinyon Plain uranium mine for decades because it threatens the waters of Grand Canyon and the Havasupai," said Sandy Bahr, director for Sierra Club's Grand Canyon (Arizona) Chapter. "Gov. Hobbs can and should help shut down this mine as once the mine contaminates the groundwater, there is no way to clean it up. The best way to protect Grand Canyon and the people who depend on its waters is to move forward with closure of this mine."

The Pinyon Plain mine, which began extracting uranium ore on Jan. 8, is seven miles south of Grand Canyon National Park and inside the newly designated Baaj Nwaavjo I'tah Kukveni – Ancestral Footprints of the Grand Canyon National Monument. Although President Biden's national monument designation permanently bans new mining claims and development inside the monument, it exempts preexisting claims with valid existing rights like the Pinyon Plain uranium mine.

"Neither industry nor regulators can guarantee that the Pinyon Plain uranium mine won't irretrievably damage aquifers that feed Grand Canyon's precious springs," said Taylor McKinnon, Southwest director at the Center for Biological Diversity. "That's not a risk worth taking. At the Center we stand with the Havasupai Tribe asking Gov. Hobbs to close the mine now."

The petitions delivered to the governor by groups including the Sierra Club, Center for Biological Diversity, National Parks Conservation Association, Wild Arizona, Chispa Arizona, and HaulNo!, along with Tribal members, request that she "do everything [she] can to help protect the waters of Grand Canyon, the new national monument, and these waters that are essential to the existence of the Havasupai people. This mine should be closed before it creates irreversible harm."

"State Aquifer Protection Permits issued to Pinyon Plain mine relied in part on analyses employing scientific representations that were already shown to be inaccurate when the mine pierced a shallow aquifer," said Kelly Burke, executive director of Wild Arizona. "With as much as 10 million gallons per year being pumped from the mine shaft, ore extraction and stockpiling well underway, and recent geohydrological science pointing to real cause for concern for the waters, wildlife and the Havasupai people of Grand Canyon, it's clear Gov. Hobbs needs to move now to close Pinyon Plain mine."

"Several lines of recent scientific evidence indicate a potential threat of uranium mining near the Grand Canyon to the quantity and quality of springs in the canyon," said David Kreamer, professor at the University of Nevada Las Vegas and president of the International Association of Hydrogeologists.

The governor has not responded to the groups' January letter asking her to close the mine. They hope the petition signatures from thousands of Arizonans and people around the country who care about the Grand Canyon will catalyze Gov. Hobbs to action.

The hope is that all beautiful springs, the landscape, and the wildlife of the greater Grand Canyon area will be as protected as the National Park itself, the beauty of which is illustrated with the photographs that follow.

Figure 6.34 This view is looking towards the northwest at the Colorado River. Geikie Peak is on the left. Scorpion Ridge is in the center with the side canyon of Tuna Creek on the right. NPS photo.

Figure 6.35 The Redwall Limestone is very hard stone, which causes it to break down at harsh angles, creating pillars such as these. NPS Photo by Kristen M. Caldon. Redwall Limestone (thickness: 500-800 ft) forms distinct red cliffs about mid-level in the canyon. It was deposited 340 million years ago, during the Paleozoic Era - Late Early to Middle Mississippian Period. Although its name implies that the Redwall Limestone is a red rock, it is in fact a gray stone. It gains its reddish appearance from the rocks above. Both the Supai Group and the Hermit Formation are red in color due to their high iron oxide content. Over time, rain has continually washed these eroding red sediments over the Redwall, staining it red. The Redwall Limestone contains thousands of caves. Limestone is a water soluble rock, meaning that it can be slowly dissolved by water, eventually resulting in caves of various sizes. Many animals, such as the California condor, now make these caves their homes, just as giant Shasta ground sloths made them their homes 11,000 to 20,000 years ago. Text and photo courtesy of NPS.

Figure 6.37 Supai Group's 800-foot rock layers as seen along Hermit Trail. NPS Photo by Kristen M. Caldon. The rocks of the Supai Group are red sandstones and siltstones, deposited 315-285 million years ago during the Paleozoic Era- Early Pennsylvanian Period. Supai Group rocks are primarily non-marine, meaning that they were not deposited in the ocean. Instead, the Supai Group was primarily deposited along a coastal low-land plain. At times it was swampy while at other times it was dry and sandy. Plant fossils and high-angle aeolian (wind-blown) sand dunes reveal these two different environments. The red color in the Supai Group rocks comes from iron oxide, which is perhaps better known as rust. It is this mineral that also stains the Redwall Limestone below. Note numerous vertical fractures crossing the sediment layers.

Figure 6.38 The Royal Arches are a seep and large alcove on River Mile 41.5 in Marble Canyon, Grand Canyon National Park. Large alcoves of this kind are often formed in arid climates by salt wedging. Salt wedging is an erosional process where saline groundwater emerges, (in this case on a cliff face), and undergoes evaporation, leaving salt crystals that grow in cracks and pores and spall out pieces of rock. Photo and text courtesy of David Kreamer.

Figure 6.39 *Left*: Pumpkin Spring in the Grand Canyon is a highly mineralized travertine spring located at River Mile 213. Its orange color makes it look like a Pumpkin from river level. It is known to have some of the highest aqueous concentrations or arsenic of any of the springs of the Grand Canyon. *Right*: Travertine Falls, at River Mile 230.5, is a large travertine cone with water issuing to river level from a spring some distance above. It is a site of great cultural and spiritual significance to the local Native American communities. Photos and text courtesy of David Kreamer.

Figure 6.40 Large dissolution features in the Redwall Limestone below the Bridge of Sighs, River Mile 35.9, Grand Canyon National Park. Photo courtesy of David Kreamer.

Figure 6.41 Travertine pools ("Beaver Falls") on Havasu Creek, Havasupai Tribe Reservation, Grand Canyon. The entire ecosystem supported by the Havasu Springs and the Creek are now under threat because of the uranium mining interests and operations of the Pinyon Plain Mine. Photograph courtesy of the Havasu Tribe. Available at https://www.facebook.com/HavasupaiTribeTourismOfficial

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Chapter 7 The West

7.1 Introduction

Except for the four springs in Montana which drain the karstic Madison aquifer (see Section 7.4), all other first-magnitude springs in the West issue from the vast Pacific Northwest basaltic and volcanic rock aquifers shown in Figure 7.1. The basaltic Snake River Plain aquifer in south central Idaho, not shown in Figure 7.1, also hosts some of the largest springs in the country(see Chapter 4).

Although karst (carbonate) aquifers do abound in the West (Figure 7.2), their individual extent and other hydrogeologic and recharge characteristics do not provide for the emergence of large springs such as those in the Ozarks, Florida, or Texas. Rather, the springs draining carbonate rocks in the West are generally much smaller, with a few being of second magnitude. Many springs, however, have played and continue to play an important role in supplying local communities with drinking water and providing irrigation water for ranches and farms.

What all large, first-magnitude cold-water springs in the West have in common is that less than a handful (either individually or as a group) have been the subject of a thorough hydrogeologic study focused on a spring. Instead, most large springs in the West seem to be an afterthought, sometimes only briefly mentioned in the context of general water availability studies about the alarming decline of groundwater (aquifer) levels across the region, and the various negative impacts of extensive groundwater withdrawals by irrigation and, to a lesser extent, public water supply wells.

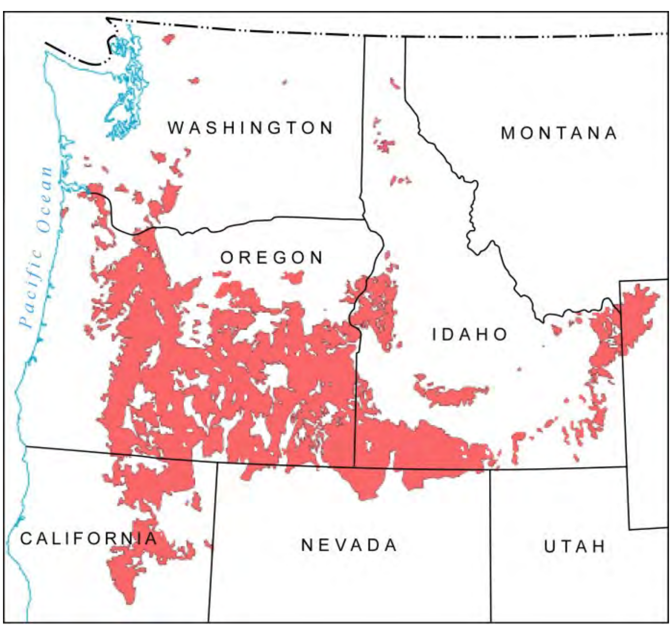


Figure 7.1 Pacific Northwest basaltic-rock aquifers. From Whitehead, 1994; Ground Water Atlas of the United States, U.S. Geological Survey. https://pubs.usgs.gov/ha/730h/report.pdf

Mysteriously, not a single first-magnitude spring in the west, outside Idaho, has an established USGS or a State Agency gaging station for a systematic long-term daily monitoring of discharge rates and water quality parameters. Sometimes, in occasional reports on other water resource topics, the discharge rates of large springs in the West are estimated from the monitoring data for surface streams into which they discharge, but even this is an exception. One complicating factor that contributes to this lack of systematic monitoring of large springs is that they often do not have a well-defined orifice or a short spring run that can be easily gaged (Figure 7.3).

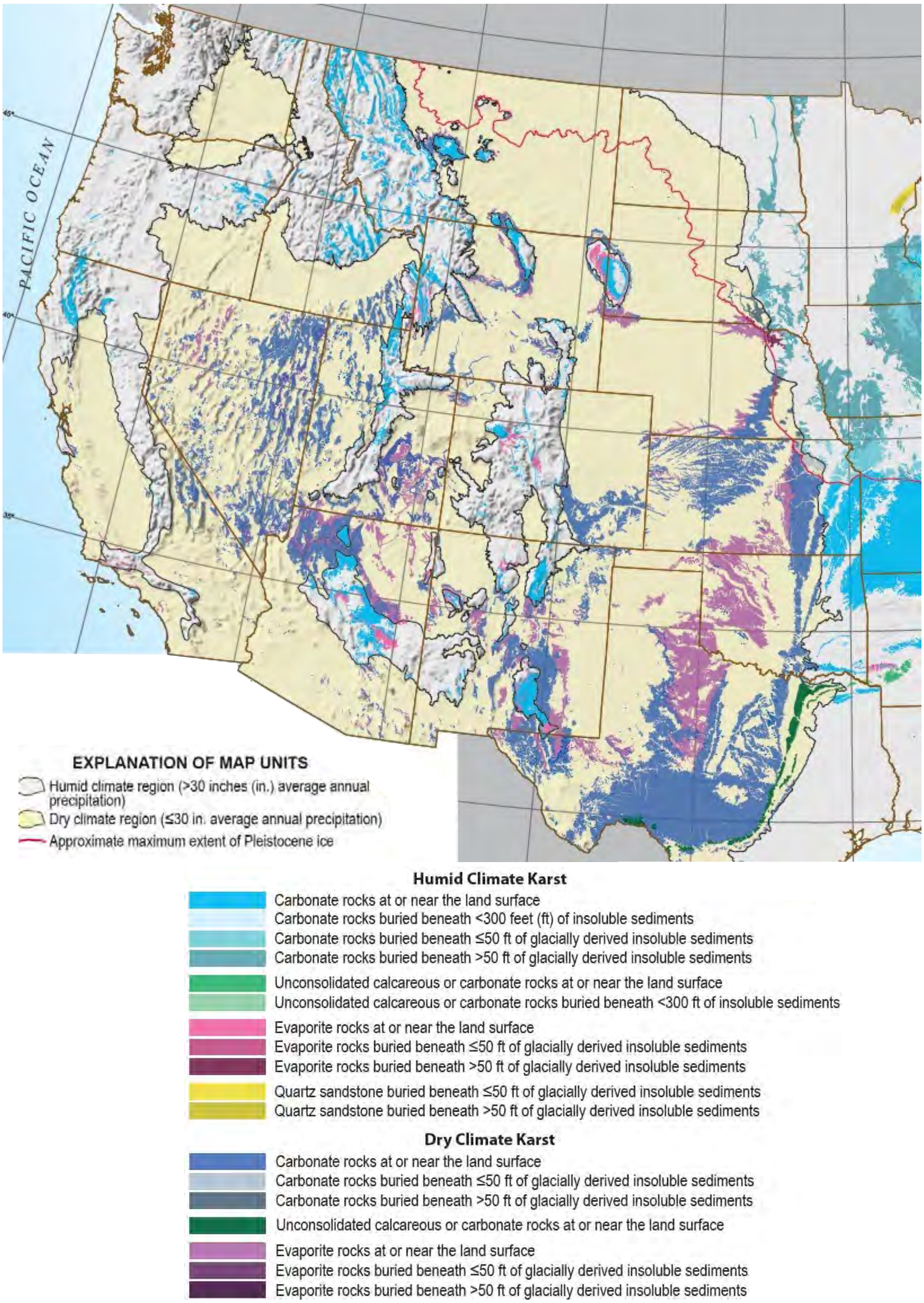
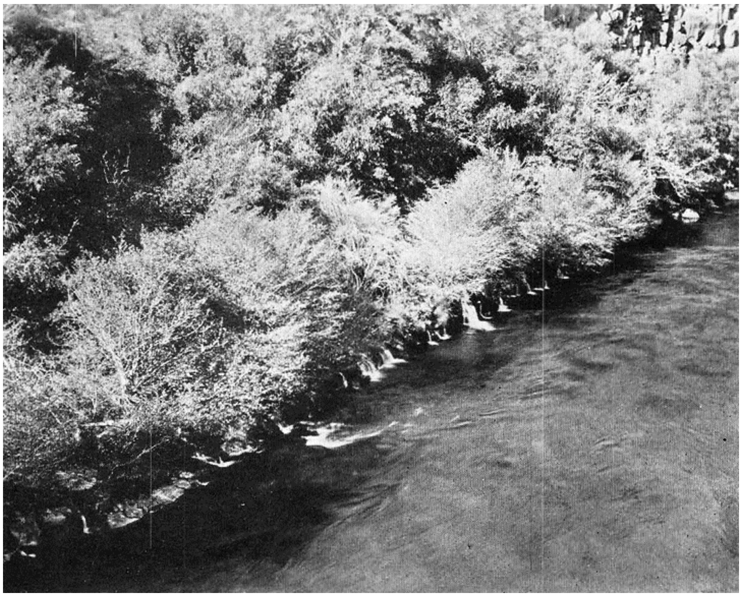


Figure 7.2 Distribution of karst and potential karst areas in soluble rocks in the western part of contiguous United States. The eastern United States and a large part of the Pacific coastal zone are considered to be humid. Locally, areas of the Rocky Mountains and the Sierra Nevada are also classified as humid regions, with higher effective precipitation amounts mostly due to orogenic effects. From Weary and Doctor, 2014; USGS.



Probably the most telling fact about the lack of a wider interest in large cold-water springs in the West by various government agencies at different levels, is that only a small number of public parks (National, State or regional) have been established because of a spring, unlike in the cases of Florida, the Ozarks, and Texas. Sometimes, this is explained by arguments that some of the large springs are privately owned or are not easily accessible.

Figure 7.3 Springs issuing from Pelton basalt in the west wall of Deschutes Canyon, central Oregon. From Sterns, 1931.

Many large cold springs in the West are beautiful, in equally beautiful surroundings, support diverse wildlife, and provide crystal-clear water to some of the most pristine surface water streams, that are often hailed as "the best trout-fishing rivers" in the Nation.

7.2 Oregon

In his seminal work *Large Springs in the United States,* published in 1927, Oscar Meinzer of USGS lists 16 first-magnitude springs in Oregon making it the state with the most such springs in the country; Idaho's Snake River Basin had 15, Florida (together with adjacent parts of Alabama and Georgia) had 11, the Ozark region of Missouri and Arkansas had eight, Sacramento River Basin in California had seven, "Balcones fault belt" in Texas had four; Montana had three, and northern Alabama had one, for a total of 65 first-magnitude springs in the country at that time (Meinzer, 1927; table on page 4). Meinzer describes several more notable cold springs and provides a map of large springs in Oregon which is used as the basis for Figure 7.4 in this book.

Since the Meinzer's publication, there have been no other books describing first-magnitude or other large springs in Oregon in detail, and no permanent gaging station for a long-term systematic monitoring was established by USGS or another agency at any of them. Instead, some of the springs were briefly mentioned in various publications on groundwater resources in Oregon which typically include sporadic measurements of their discharge rates and/or estimates (e.g., Stearns, 1931; Caldwell and Truini, 1997; Caldwell, 1998; Gannett et al., 2001, 2007, 2012, and 2017). Although Oregon has many large, beautiful springs, there is not a brochure or any other official publication by an Oregon agency, including those responsible for promoting tourism, that would inform both the Oregonians and out-of-state visitors about this treasure.

Below is an excerpt from a report entitled "*2021 Review of the Deschutes Basin Groundwater Mitigation Program; 5 Year Review*" by the Oregon Water Resources Department that illustrates the sad state of affairs with the studies of springs in Oregon (DGWSA stands for Deschutes Groundwater Study Area; ODFW for Oregon Department of Fish and Wildlife; OWRD for Oregon Water Resources Department; DEQ for Oregon Department of Environmental Quality).

Stakeholder Comments: Stakeholders raised concern with regard to other spring systems in the DGWSA. ODFW suggested that OWRD implement a program to monitor key spring complexes to determine ecological impacts to springs resulting from groundwater pumping. Department Response: ODFW, DEQ, and OWRD have discussed cooperatively combining efforts to obtain funding for a study aimed at identifying impacts to the springs within the DGWSA, and to understand whether any impacts are the direct result of the mitigation program.

Oregon Water Resources Department

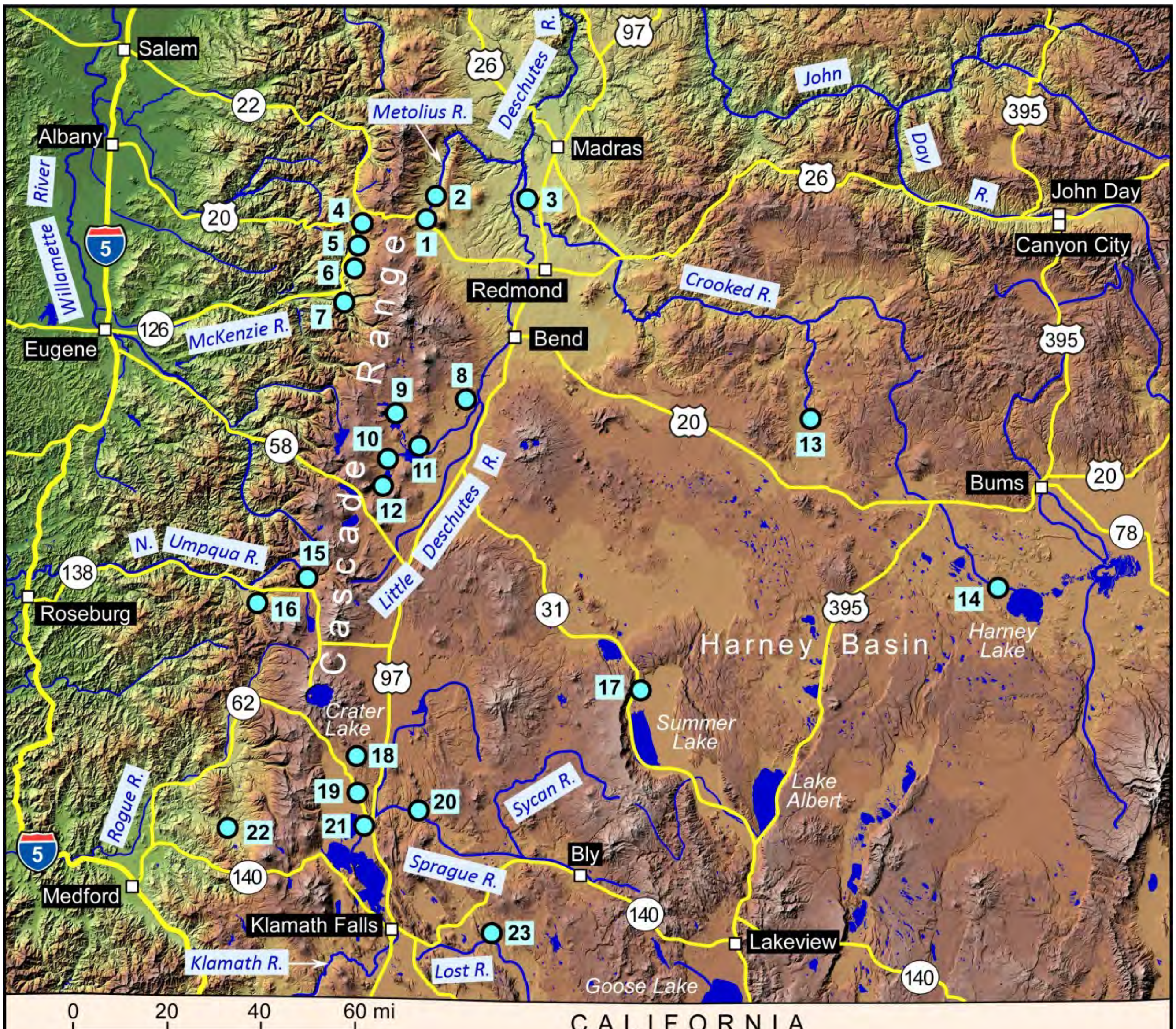


Figure 7.4 First magnitude and other large springs in Oregon. Spring locations are from Meinzer, 1927. (1) Metolius Springs (also called Black Butte by Meinzer); (2) Heising; (3) Opal; (4) Clear Lake; (5) Lower Falls; (6) Ollalie Creek; (7) Lost Creek; (8) Spring River; (9) Little Lava Lake; (10) Sheep Bridge; (11) Fall River; (12) Davis Creek; (13) Gilchrist; (14) Double O; (15) Spring River; (16) Clearwater River; (17) Ana River; (18) Wood River; (19) Beetles Rest; (20) McCready; (21) Spring Creek; (22) Big Butte; (23) Bonanza.

The following excerpts from an article entitled *Race to the bottom: How big business took over Oregon's first protected aquifer* by Emily Cureton Cook, published on March 16, 2022, at https://www.opb.org/, illustrate the alarming situation with the groundwater in Oregon in general, where drying of springs is "just" a collateral damage.

In Malheur County's Cow Valley, state regulators have ignored known issues with overpumping groundwater, leaving the region at risk of economic and ecological damage that will be difficult to reverse.

More than six years after media reports and a state audit exposed the agency for failing to protect stable groundwater supplies across the state, policies and practices enabling overpumping have not substantially changed.

In 2019, Green Alpha II LLC acquired about 3,300 acres with Crow's water rights for $8.1 million. The company is part of a vast network of entities controlled by Homestead Capital, a private equity firm based in San Francisco and founded by former directors from Goldman Sachs and J.P. Morgan. Corporate filings and property records show the Homestead firm controls more than 50 similarly-named companies with title to thousands of acres of farmland across the U.S.

Farley and his brother spent years challenging the company's application to transfer water rights around, before reaching a settlement agreement in 2019. Farley said the family ended their protest because it was expensive to pay lawyers, and it seemed futile to challenge the state's approval where groundwater problems were already so well-known.

Oregon law since 1955 has called on regulators to maintain reasonably stable groundwater levels, but the valley's water table has been shrinking farther and farther below the surface, dropping about 33 feet in Farley's lifetime. About half of that decline has happened in the last 10 years alone.

"This is not reasonable," Farley said. "This is abuse."

State records suggest that once Cow Valley's water table drops more than 32 feet total from pre-farming levels, it won't naturally discharge to springs and creeks anymore. With a projected decline of more than 30 feet already, groundwater in the valley may soon be nearing a point of no return that will end surface connections. In 1959, Oregon's water managers explicitly endorsed allowing this to happen to capture water deep underground for irrigators, calling any natural flow to springs and creeks "losses."

A large part of this groundwater, which is not now being put to beneficial use, could be utilized if the water table were lowered sufficiently to reduce these losses," reads the 1959 order from the state engineer.

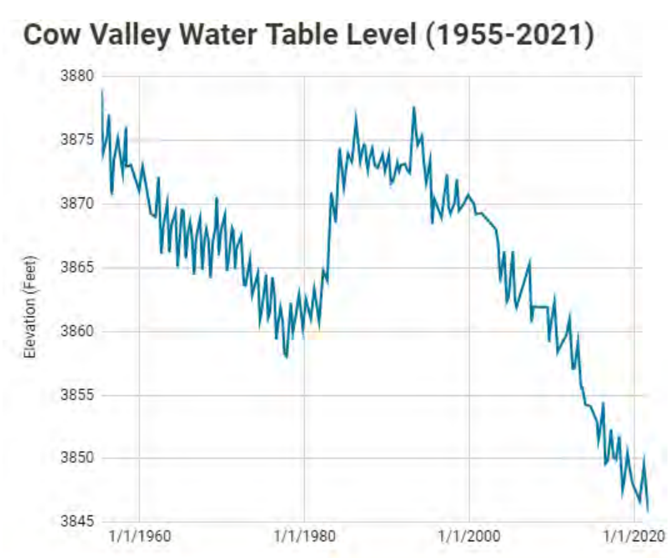


Figure courtesy of Emily Cureton Cook, OPB.

This strategy has not been updated, meaning more legal leverage for people with the deepest wells, likely death for groundwater dependent ecosystems, and financial ruin for people who can't afford to race to the bottom of aquifers.

Policies of the Oregon Water Resources Department don't directly address climate change, according to agency director Tom Byler. "Our state water laws were born out of concepts that were put into place in the 19th century," he said in a September interview. "The whole idea setting up the system of laws around the use of water is for people to use water."

In contrast to the groundwater resources, segments of quite a few spring-fed streams in the Oregon mountains have been protected in one way or another, for example as parts of the U.S. Forest Service lands. This includes designation of segments of the Deschutes, Metolius, Crooked, McKenzie, and Klamath Rivers as National Wild and Scenic Rivers under the Wild & Scenic Rivers Act, October 2, 1968 (the drainage areas of these five rivers host most large springs in Oregon; see Figure 7.4):

> *It is hereby declared to be the policy of the United States that certain selected rivers of the Nation which, with their immediate environments, possess outstandingly remarkable scenic, recreational, geologic, fish and wildlife, historic, cultural or other similar values, shall be preserved in free-flowing condition, and that they and their immediate environments shall be protected for the benefit and enjoyment of present and future generations. The Congress declares that the established national policy of dams and other construction at appropriate sections of the rivers of the United States needs to be complemented by a policy that would preserve other selected rivers or sections thereof in their free-flowing condition to protect the water quality of such rivers and to fulfill other vital national conservation purposes.*

Figure 7.5 The Crooked River in Central Oregon offers excellent hiking opportunities with spectacular geologic formations and waterfalls. A portion of the designated Wild and Scenic segment provides expert Class IV-V kayaking/rafting during spring runoff. The section of river from the Ochoco National Forest to Opal Springs flows through scenic vertical basalt canyons. Photo Credit U.S. Forest Service. https://www.flickr.com/photos/forestservicenw/36380358043/in/album-72157683485449304/

https://www.flickr.com/photos/forestservicenw/23635464210/

Figure 7.6 Dillon Falls, a part of the Deschutes River in the Deschutes National Forest in Central Oregon. The Deschutes River provides much of the drainage on the eastern side of the Cascade Range on its way to its confluence with the Columbia River. The Deschutes was an important resource for thousands of years for Native Americans and in the 19th century for pioneers on the Oregon Trail. It features ruggedly beautiful scenery, outstanding whitewater boating, and a renowned sport fishery for steelhead, brown trout, and native rainbow trout. Photo courtesy of U.S. Forest Service – Pacific Northwest Region.

https://www.flickr.com/photos/forestservicenw/23302851104/

Figure 7.7 View of the Horn of the Metolius River in the Deschutes National Forest in Central Oregon. Photo courtesy of U.S. Forest Service – Pacific Northwest Region. Nestled in a forested valley on the east side of the Cascade Mountain Range in central Oregon, the Metolius River gushes full-grown from the spectacular springs at its headwaters and is one of the largest spring-fed rivers in the United States. Its clear, cold, and constant waters support nationally renowned blue ribbon flyfishing along with whitewater boating.

https://www.rivers.gov/rivers/image/klamath-river-0.

Figure 7.8 The Klamath River, Oregon. Photo credit Bob Wick, BLM (under Creative Commons License). The Klamath River is one of only three rivers that bisect the Cascade Mountain Range. Beginning in Oregon's high desert interior, it cuts through the Cascades and the Klamath Mountains before entering the Pacific Ocean in northern California. This creates a wide diversity of habitats supporting an abundance of fish and wildlife. Steep, boulder-strewn rapids in Hell's Corner shown here testify to the Native American name for the river, "Klamet," meaning "swiftness."

Figure 7.9 The McKenzie River originates at Clear Lake in the central Oregon Cascades and flows south and west through the Willamette National Forest. Recent volcanism, including three distinctive lava flows, has shaped the river into pools, dramatic waterfalls, and cascading whitewater. These features provide for exceptional whitewater boating, hiking, and fishing. Photo credit U.S. Forest Service.

Unfortunately, many Oregon rivers and the groundwaters that maintain their baseflows are under an increasing threat because of the excessive pumping for agriculture and irrigation. This is the main reason why some of the Oregon groundwater basins now have groundwater mitigation programs. These programs, developed by the Oregon Water Resources Department, seem to have various challenges judging from the numerous public comments such as this one included in the 2021 Review of the Deschutes Basin Groundwater Program:

I am writing to comment on The Deschutes Basin Ground Water Mitigation Program.

I feel the program has some real problems that should be mitigated. We know that aquifer is shrinking and ultimately this is bad for water quality, wildlife and even use. The unfortunate thing is that the majority of all water is consumed by Agriculture for nearly worthless water-loving crops like alfalfa. At some point, we need to determine whether the public's water (and the public owns all water in Oregon) should be wasted on such use. Most of the Deschutes River is covered by the State Scenic Waterway Act which states that the best uses of the river are for recreation, fish, and wildlife. As Oregon courts have stated, this is not occurring.

The first is the idea that all water is the same. Replacing cold groundwater with warm polluted irrigation water is not equivalent in water quality.

Second, averaging flows misses an important point. Sometimes the water is extremely low and detrimental to fish and other aquatic life. Timing of flow is critical. The lowest flows should be the limiting factor not the averages. (https://www.oregon.gov/owrd/WRDReports/ORS_540_155_Legislative_Report.pdf)

Third, there are many exempt wells. Monitoring of use is supposed to occur but does not. At the very least, there should be no future exempt wells. And perhaps some form of monitoring of existing wells should be put into place.

Finally recharge is assumed, but the state does not know how much really is occurring, not to mention if it is mostly irrigation water, it may be polluted.

I hope the state will identify and rectify these problems.

Sincerely;

As can be seen in Figure 7.4, most large springs in Idaho are along the eastern and western slopes of the Cascade Range which is a north-south trending zone of compositionally diverse volcanic eruptive centers with deposits extending from northern California to southern British Columbia. Prominent among the eruptive centers in the Deschutes Basin are large stratovolcanoes such as North, Middle, and South Sister, and Mount Jefferson, all of which exceed 10,000 ft above sea level in elevation. The Cascade Range is primarily a constructional feature, but its growth has been accompanied, at least in places, by subsidence of the range into a north-south trending graben (Lite and Gannett, 2002; Allen, 1966).

A few large springs issue around the perimeter of Harney Basin which is part of the larger High Lava Plains east of the Cascades.

Most of the geologic features in the area of large Oregon springs are the result of about 30 million years of volcanic activity related to a north-south trending volcanic arc, the most recent manifestation of which are today's Cascade Range volcanoes. Volcanic and tectonic activity over the past 8 to 10 million years in the Basin and Range (to the southeast of the Cascades) and High Lava Plains (to the east) has also helped shape the present landscape. Most of the important rock water-bearing units in the area were formed within the past 7 million years (Lite and Gannett, 2002).

The next major surge in volcanic activity occurred between 7 and 4 million years ago. That volcanic activity produced the Deschutes Formation, a sequence of highly permeable lava flows, pyroclastic deposits, volcanoclastic deposits, and sediment more than 2,000 ft thick (Smith, 1986). Many of the springs within the Cascade Range are associated with these lava flows.

Figure 7.10 Roaring Springs on the South Fork of McKenzie River emerge from a 150-foot-long fracture from a single lava flow. Photo copyright Gordon Grant; all rights reserved.

Roaring Springs of the McKenzie River (Figure 7.10), Paulina Springs near the head of Indian Ford Creek, and springs at the head of Fall River are good examples. Paulina Springs (which discharges about 10 ft^3/s) is one of several springs that discharge from the toe of a Cascade Range lava flow. The head of Fall River (nearly 100 ft^3/s) appears to issue near the boundary of a young drainage filled by lava flows (Lite and Gannett, 2002). Two basalt units within the Deschutes Formation, the Opal Springs basalt and Pelton basalt, are well known for their large springs that discharge to the Crooked and Deschutes Rivers (Stearns, 1931; Sceva, 1968).

The surfaces of the young volcanic deposits are commonly fractured and brecciated, including presence of lava tubes (Figure 7.11), which makes them extremely permeable. Much of the precipitation in the Cascade Range percolates through these rocks to recharge the groundwater flow system. The large number of springs and lack of incised surface-water drainages in the Cascade Range, high seepage loss from canals near Bend, and high streamflow loss south of Bend demonstrate the permeable nature of the deposits (Gannett et al., 2001).

Figure 7.11 O-Deschutes Lava Tube. Photo courtesy U.S. Forest Service – Pacific Region. Taken on July 19, 2022.

As explained by Gannett et al. (2007), the upper Klamath Basin, which spans the California-Oregon border, occupies a broad, faulted, volcanic plateau between the volcanic arc of the Cascade Range and the Basin and Range geologic province. It consists of internally drained Silver Lake, Summer Lake, and Goose Lake Basins to the east, and the Pit River Basin to the south. Most of the basin is semiarid, but the Cascade Range and uplands in the interior and eastern parts of the basin receive on average more than 30 inches of precipitation per year.

The basin once also contained two large lakes, Lower Klamath Lakes and Tule Lake, each of which covered areas of 100 to 150 square miles, including extensive marginal wetlands. These two lakes have been mostly drained, and the former lake beds are now cultivated.

Figure 7.12 Sprague River Valley from Knot Tableland, looking southeast. Photograph by Kenneth Lite, USGS.

Groundwater flows from recharge areas in the Cascade Range and upland areas in the basin interior and eastern margins toward stream valleys and interior subbasins. Large amounts of groundwater discharge in the Wood River subbasin, the lower Williamson River area, and along the margin of the Cascade Range.

Much of the inflow to Upper Klamath Lake can be attributed to groundwater discharge to streams and major spring complexes within a dozen or so miles from the lake. This large component of groundwater buffers the lake somewhat from climate cycles. There are also groundwater discharge areas in the eastern parts of the basin, for example in the upper Williamson and Sprague River (Figure 7.12) subbasins and in the Lost River subbasin at Bonanza Springs (No.23 on the map in Figure 7.4).

The Oregon Water Resources Department has documented declining groundwater wells in the Klamath Basin since 2001 due to the increasing reliance of farmers on groundwater with more frequent and prolonged droughts that have had a great impact on the availability of surface water for irrigation. For example, in 2021, due to an extreme drought and declining populations of endangered Lost River and shortnose sucker fish in Upper Klamath Lake, the federal Bureau of Reclamation – which controls the Klamath Project – cut off water to irrigators to keep lake levels sufficiently high for the fish to survive. The main supply canal that provides water from Upper Klamath Lake to the Klamath Project remained closed that summer, and only a handful of irrigators got any surface water for their crops (Holly Dillemuth, Jefferson Public Radio, Oct. 23, 2021 9 a.m.), available at https://www.opb.org/article/2021/10/23/klamath-basin-farmers-irrigation-water-crops-groundwater-wells/),

What all this means of course is that many springs fed by the Basin's groundwater are in jeopardy.

The following descriptions of some of the notable Oregon springs shown in Figure 7.4 mostly are based on the materials presented by Meinzer, 1927; Sterns, 1931; and Peterson and Grah, 1972 ("*Geology and Origin of the Metolius Springs, Jefferson County, Oregon*") since, as explained earlier, there is a lack of more recent, readily available comprehensive hydrogeologic studies focused on springs.

7.2.1 Metolius Springs

As described by Peterson and Grah (1972), the Metolius Springs (Figure 7.13), referred to as Black Butte Spring by Meinzer (No.1 on the map in Figure 7.3), are situated in timbered country in the southwest corner of Jefferson County about 30 miles northwest of Bend and Redmond. The area is easily reached by several roads that leave U.S. Highway 20 between Santiam Pass and Sisters. The shortest route is a paved road from a well-marked junction about 10 miles east of Santiam Pass or 9 miles west of Sisters, which trends northeast for about 4 miles to the springs and continues northward to a loop road that parallels the Metolius River and provides access to famous fishing resorts and popular recreation area. The U.S Forest Service has built a parking lot, rustic trail, and viewpoint structure from which visitors can see the river begin.

The Metolius Springs rise from two groups of orifices about 200 yards apart at the northern base of Black Butte. The water bubbles out of bouldery valley fill at a chilly temperature of 48°F, and the two flows join within a short distance to make up the headwaters of the Metolius River. Total flow from the springs consistently measures from 45,000 to 50,000 gallons per minute (gpm; 120 to 134 cfs) year-round. In its 35-mile course northward and eastward to the Deschutes River, the Metolius gains an additional 600,000 gpm (1,605 cfs) from springs and tributary streams that drain the east flank of the Cascades (Peterson and Grah, 1972).

Near the springs the Metolius Valley is about 3 miles wide and nearly flat. Its elevation is approximately 3000 feet above sea level. Immediately to the south is Black Butte (Figure 7.14), a symmetrical volcanic cone towering more than 3000 feet above the valley floor to a total elevation of 6346 feet.

On the east is Green Ridge, a north-trending fault scarp which rises 2000 feet above the valley. On the west 10 miles distant are the snow-covered volcanic peaks of Mt. Jefferson, Three Fingered Jack, and Mt. Washington.

Figure 7.13 One of two Metolius Springs (44°26'05"N 121°38'17"W) which form headwaters of the Metolius River. Water bubbles out of ground near willows in the center of picture. Courtesy if U.S. Forrest Service – Pacific Region.

Two larger springs downstream of the headsprings are shown in Figure 7.14. Heising Spring (No.2 on the map in Figure 7.3; not shown in Figure 7.14) is the largest among other springs discharging into the Metolius River. It enters Jack Creek just before its confluence with the Metolius River and provides a stable flow of cold water and abundant fish-spawning gravel in its 0.3 km length. It flowed 128 cfs on March 26, 1912, and 90 cfs on November 24, 1925 (Meinzer, 1927).

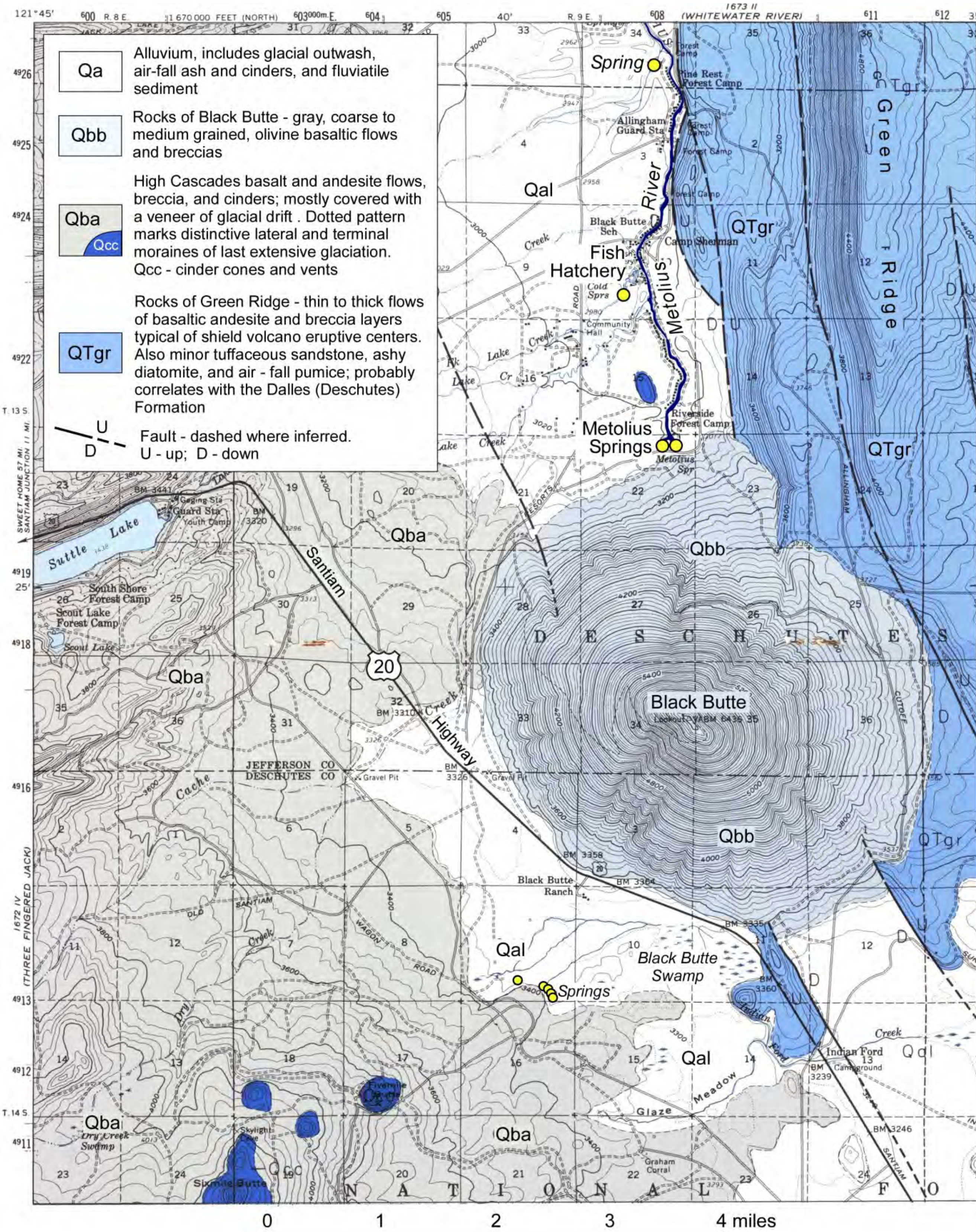


Figure 7.14 Geologic map of Metolius Springs and vicinity, Oregon. Annotated for clarity. From Peterson and Grah (1972).

An interesting narrative provided by Peterson and Grah (1972) attempts to explain the origin of Metolius Springs "... which may best be understood by looking at the geologic map in Figure 7.14 and pretending momentarily that Black Butte is not there. Visualize the remaining geologic and topographic features. This gives a fairly accurate picture of the way the area looked prior to the formation of Black Butte.

With Black Butte gone, the Metolius Springs do not exist. Instead, the headwaters of the Metolius River extend to Black Butte Swamp or even farther south and west. Here, water from rain and melting snow in the High Cascades enters the valley in the form of small streams and as subterranean seepage through glacial outwash and porous zones of lava. Since drainage eastward is prevented by the southern extension of the Green Ridge escarpment, the upper Metolius River waters are channeled northward along the base of Green Ridge.

Now restore Black Butte to the present scene and it is apparent that Black Butte covers the ancestral course of the Metolius River. The water that once flowed on the surface as a river now percolates downward through the permeable sands and gravels of the ancient channel beneath the volcano and surfaces again at the lowest point just north of Black Bute, i.e., at Metolius Springs.

Black Butte Swamp plays an important role. The valley fill at which it is composed laps against the southern base of Black Butte and acts as a sump or container for the water migrating from the extensive drainage area to the southwest. An important feature is its elevation about 300 feet higher than the Metolius Springs. The collection basin that it forms acts as a standpipe and tends to keep a constant hydraulic head on the water from the springs, thus insuring their constant flows. More water enters Black Butte Swamp than surfaces at the spring. This excess is removed by Indian Ford Creek, which follows a circuitous route east and then south past Sisters." (Peterson and Grah, 1972).

Figure 7.15 Metolius River downstream of the headsprings. Photo taken on May 24, 2011.
Courtesy of U.S. Forest Service – Pacific Region.

In contrast, James and Manga (2000), based on natural tracers' study involving the isotopes of helium, carbon, oxygen, and hydrogen, conclude that large, cold springs in the central Oregon Cascades are recharged near the Cascades crest up to 50 km from the springs, and discharge water that is a few years old. The authors also show that deeply circulating groundwater advectively transports geothermal heat and magmatic volatiles to several of the springs such as the Metolius Spring and Lower Opal Springs. "Based on topographic considerations alone, the Metolius River appears to discharge water derived from Black Butte. But a tracer analysis of the water indicates that the spring discharges water derived from much farther to the west, in the high-elevation Cascade Range." (James and Manga, 2000.)

> *Three of the western tributaries of the Deschutes have their sources in giant springs, Metolius, Spring and Fall rivers, and of these three the Metolius is the largest and longest. It flows from the north base of Black Butte, full-bodied and icy cold, and after winding northward through beautiful pine forests, swings around the north end of Green Ridge through a canyon of great depth and majestic grandeur, joining the Deschutes just north of the mouth of Crooked River.*
>
> Lewis A. McArthur, Oregon Geographic Names

Figure 7.15 The "Big Springs" on Metolius River. Photo by Bobcat. Courtesy of OregonHikers.com. To reach the springs, start from Lower Canyon Creek Campground at the end of Forest Road 430. Go towards Wizard Falls Fish Hatchery along the East Metolius River trail #4020. Gushing springs ("Big Springs") issue from the left bank, about 1/3 of a mile from the starting point. Available at https://www.oregonhikers.org/field_guide/File:The_big_springs,_West_Metolius_River.jpg

7.2.2 Deschutes River Springs

The observations made by Meinzer almost 100 years ago (in 1927) still hold true today since, as discussed earlier, none of the large Oregon springs has had a long-term systematic monitoring or was a subject of a thorough, textbook, hydrogeologic investigation and study: "The magnitude of the Deschutes River springs, as in other regions, depends on their grouping, which is based on insufficient information, and would necessarily be somewhat arbitrary even if complete information were available." The springs contributing significant flow to the Deschutes River, upstream from its confluence with the Metolius and Crooked Rivers, that were tentatively recognized as springs of the first magnitude by Menzer, are **Little Lava Lake, Sheep Bridge, Davis Creek, Spring River,** and **Fall River Springs** (see Figure 7.4).

The stream that is considered to form the head of Deschutes River rises in **Little Lava Lake** (No.9). This lake, which, according to the United States Forest Service map, has an area of about 80 acres, has almost no surface inflow and is, therefore a large spring pool. North of this spring is an area of exceedingly permeable lava and volcanic debris which has rather copious precipitation but virtually no surface drainage. The water that falls in this area is largely absorbed and percolates underground to Little Lava Lake (Figure 7.16) or other large springs. In its underground course the water appears in a number of lakes that have no considerable surface intake and no surface discharge. One of these is Lava Lake, which discharges into Little Lava Lake underground.

Figure 7.16 Headwaters of the Deschutes River at Little Lava Lake in the Deschutes National Forest. Photo by Donald Graham. Courtesy of U.S. Forest Service – Pacific Region.

A summary of the discharge measurements of Deschutes River recorded at a gaging station at a point about 6 miles below Little Lava Lake, above Snow Creek and other important tributaries is provided by the United States Geological Survey. The record, which covers the period from June 1922, to September 1924, shows a discharge ranging from 52 to 213 cfs, averaging 95 cfs.

Sheep Bridge Springs (No.10). A large flow of water enters Deschutes River from springs about 4 miles below the mouth of Quinn River, in the vicinity of the so-called Sheep Bridge. The water issues from coarse glacial morainal debris, but its true source is undoubtedly the underlying basalt. On November 19, 1925, the discharge of the north vent was found to be 38 cfs and that of the south vent 51 cfs. On August 30 the water from the north vent had a temperature of 40° F, and that from the south vent 38° F. On the east side of the river there are several springs with a temperature of 45° F, and a combined discharge of about 50 cfs. According to Meintzer, this temperature, which is a few degrees above the normal for the region, suggests that the water of the eastside springs comes largely from the leaky Crane Prairie Reservoir. This reservoir lies less than 2 miles upstream from the springs. During the summer its water is much warmer than normal groundwater. The total spring inflow to the river at the bridge is about 300 cfs. The flow of the entire group of Sheep Bridge Springs, according to estimates based on seven sets of measurements, has ranged from 278 to 348 cfs and averaged 323 cfs.

Davis Creek Springs (No.12). Davis Creek, which is about 6 miles long, rises in a group of springs that issue from the base and margin of a bed of barren recent andesitic lava which in this vicinity fills the ancient valley and has formed the dam that has given rise to Davis Lake. These springs are the outlet of an underground stream that rises in Davis Lake. At several places on the lava, it is possible to hear the water running underground, and cold air issues from crevices in the lava at these places. On November 17, 1925, the largest single spring was discharging 54 cfs and had a temperature of 48° F. This temperature, which is about 10° F above the average of springs in this region, furnishes additional evidence that the springs are fed from Davis Lake, where the water warms up somewhat during the summer. Other large springs enter Davis Creek from the north. On November 20, a spring entering about 1 mile below the head discharged 79 cfs and another a little farther downstream discharged 68 cfs. The temperature of both was 39° F. Davis Creek, although generally receiving all its water from springs, fluctuates considerably in discharge. It has been measured from time to time at Graft's ranch, near its mouth, but only during 1924 has a complete year of record been obtained. In that year its minimum flow was 174 cfs and its average flow was 203 cfs (Meintzer, 1927).

Spring River Springs (No.8). Spring River rises in a group of springs, about 1 mile west of Deschutes River and 10 feet above the river. All the water of this group issues from three main vents in an area of about 100 square feet. On August 28,1925, these springs were discharging about 125 cfs. The temperature of the water from all vents on that date was 45° F. The springs issue from basalt, the water probably being collected at this place by a lava tube or lava tongue. Spring River has been measured at intervals for nearly 20 years at a point near its mouth. Its discharge varies, much more widely than that of Fall River, ranging from 142 to 299 cfs and averaging 197 cfs in the 22 measurements.

Fall River Springs (No.11). Fall River heads in a group of springs, the largest of which issue from crevices in basalt. The discharge from the two vents at the fish hatchery on November 21, 1925, was found to be 103 cfs. The temperature of; the spring water on that date was 41° F. The operator of the fish hatchery stated that the temperature does not vary throughout the year. From the head springs Fall River flows about 6 miles in a fairly straight course to the falls and thence tortuously to its mouth. Measurements made of this stream near the falls from time to time since 1912 indicate a remarkable regularity of discharge. In the 10 measurements recorded below the flow ranged only from 113 to 126 cfs and averaged 119 cfs.

Meinzer describes three more groups of springs in the Upper Deschutes River basin that were estimated to be of second magnitude at the time. **Snow Creek**, the uppermost tributary of Deschutes River, rises in large springs about 2 miles south of Little Lava Lake. It flows nearly parallel to the Deschutes and not more than half a mile from it for almost its entire course of about 6 miles. Its flow, measured during the summer months of 1922-1924 at a gaging station near its mouth, is nearly constant and averages about 28 cfs. It showed little reduction even during the low-water year of 1924, when the discharge of Little Lava Lake decreased notably.

Cultus River has its source in a group of large springs. Its discharge, as measured at a gaging station less than a mile below the springs, has ranged from 43 to 70 cfs and averaged 54 cfs. The Cultus River Springs have a variation in discharge similar in character to that of Little Lava Lake but much less in degree.

Quinn River is a short stream that is supplied entirely by springs at its head. The discharge as measured during the summer months of 1922-1924 at a gaging station just below the springs has ranged from 8 to 36 cfs and averaged 18.4 cfs. Thus, these springs fluctuate in discharge even more than Little Lava Lake (Meinzer, 1927).

7.2.3 Opal Springs

Hundreds of springs occur in the Crooked River Canyon, and many of them are so close together that they issue as sheets of water. The largest are Opal Springs (No. 3 on the map in Figure 7.4). The following description of Opal Springs is provided by Sterns (1931). The springs discharge on the east bank of the Crooked River (Figures 7.16 through 7.20). They receive their name from the polished siliceous pebbles that occur in the springs. Many of the pebbles are translucent or transparent chalcedony that have a polish which could not be improved by a lapidary. A few of the tiny pebbles are shaped like cabochon opals ready for setting. People come from long distances to gather these natural polished gems, and a few have been mounted in jewelry. The pebbles have been derived from siliceous veins in the Clarno formation and appear to have been polished by rubbing against one another in the spring water. Opal Springs has a mean annual discharge of about 300 cfs, and on August 25, 1925, the water had a temperature of 54° F. The water discharges in a small pool at the level of the river, but a considerable amount breaks out of the coarse talus about 4 feet above the river and tumbles into the pool.

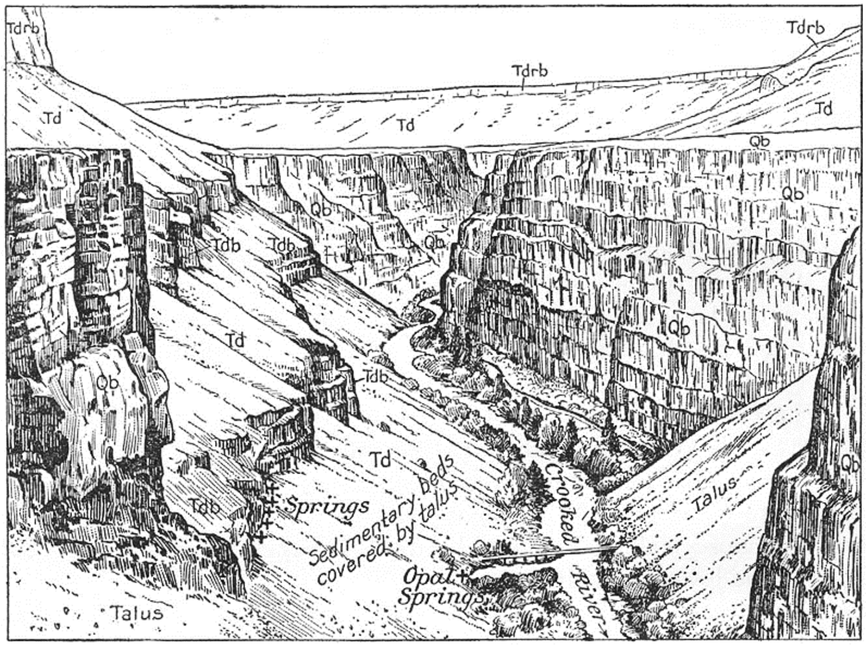


Figure 7.16 Geologic sketch of Crooked River Canyon near Opal Springs looking South. Qb, Basalt flows (intra-canyon basalt); Tdrb, basalt flows (rim-rock basalt) overlying fluviatile deposits; Tdb, basalt flows interstratified with fluviatile deposits; Td, partly consolidated sand, silt, gravel, tuff, and beds of diatomaceous earth constituting fluviatile deposits. From Sterns, 1931.

Figure 7.17 Opal Springs (shown with yellow arrow; GPS coordinates (44º29'26"N 121º17'53"W) are in the Crooked River Canyon, short distance downstream from the Opal Springs Hydropower Dam. View is looking North. Google Earth Map; satellite image by Landsat/Copernicus acquired on April 9, 2015.

The Crooked River at Opal Springs is flowing near the contact of the sedimentary beds of the Deschutes formation with the intra-canyon basalt (see Figure 7.16). The basalt forms a vertical cliff about 350 feet high at the west edge of the river. The east bank consists of a steep talus slope rising to a vertical cliff of interstratified basalt 105 feet above the river. A steep slope broken by another vertical cliff formed by interstratified basalt at an altitude of 2,345 feet rises above this lower cliff of basalt to the rim-rock basalt. Numerous springs issue from the basal contact of the bed of basalt 105 feet above the river. The talus slope extending from this bed to the river is covered with water-loving vegetation, indicating that the talus is saturated with water, although most of the water from the visible springs is collected in a flume and used for the development of power.

The numerous springs flowing into the river from the talus at the river's edge is additional proof that considerable water is finding its way into the talus, probably a short distance back from the outcrop of the inter stratified basalt. Moreover, a shallow cut made in the talus slope from the river near Opal Springs to the interstratified basalt contains numerous seeps and small springs that come from the base of the basalt cliff 105 feet above the river. The water is groundwater that has been perched in the basalt because of the impermeable sediments underneath it.

It is probable, from analogous situations with other large springs, that the accumulation at this place of 300 cfs of water is due to an elaborate system of drainage buried by a lava flow. However, it is impossible to state with certainty whether Opal Springs are supplied by water that has found its way to its present outlet from the water-bearing bed of basalt 105 feet above it or from another similar bed of basalt below the river (Sterns, 1931).

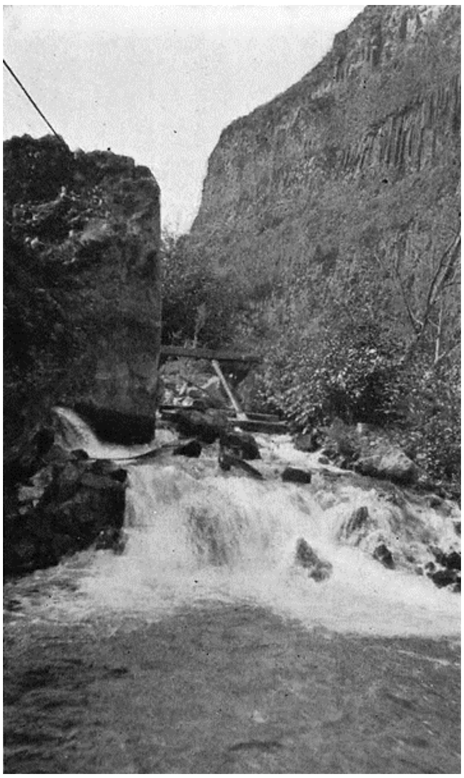


Figure 7.18 Opal Springs in the Crooked River canyon, August 26, 1925. From Sterns, 1931.

Figure 7.19 Opal Springs. Photographs courtesy of Deschutes Valley Water District.

The fact that all the springs downstream to the Metolius River along the Crooked and Deschutes Rivers issue from the Pelton basalt proves beyond question that it is a great aquifer. The only way to determine whether this bed supplies the water in Opal Springs is to drill near the spring and determine the depth to the underlying lava (Sterns, 1931).

As described by Deschutes Valley Water District (https://www.dvwd.org/aboutus.html), Opal Springs, along with Wells #1, #2 and #3 (combined, referred to as the Opal Springs Aquifer) are the sole source of supply of domestic water for approximately 4400 customers. They are located 5 miles southwest of Culver at the bottom of the 850 foot deep Crooked River canyon, less than 150 feet from the river.

Opal Springs flows approximately 108,000 gallons per minute (289 cfs) at 53.8 degrees Fahrenheit with no seasonal variation. There has been no detectable change in flow, temperature or pH since the spring was first tested in 1925. The quality of Opal Springs water is outstanding. No volatile organic or synthetic compounds (herbicides or pesticides) have been detected by water testing. Various inorganic compounds are found in the water but are far below the maximum allowable amount. The Opal Springs aquifer has yet to show radiation from WWII nuclear testing, placing the age of the water flowing from the spring at least 70 years old.

Analysis shows conclusively that Opal Springs is a groundwater source, not in any way influenced by surface water. Currently, there is no filtration or treatment of Opal Springs water, of any kind. Periodically, every reservoir receives a measured application of chlorine for safety, which is the only chlorinating being done. There are several bottling plants in Culver bottling Opal Springs water. The taste, clarity, and purity of Opal Springs water make it a popular bottled product.

The initial water rights to Opal Springs were 3.0 cubic feet per second (cfs). The current water rights are not to exceed 27.150 cfs. If all pumps were activated, 23.500 cfs would be withdrawn from Opal Springs, less than 10% of the total spring flow.

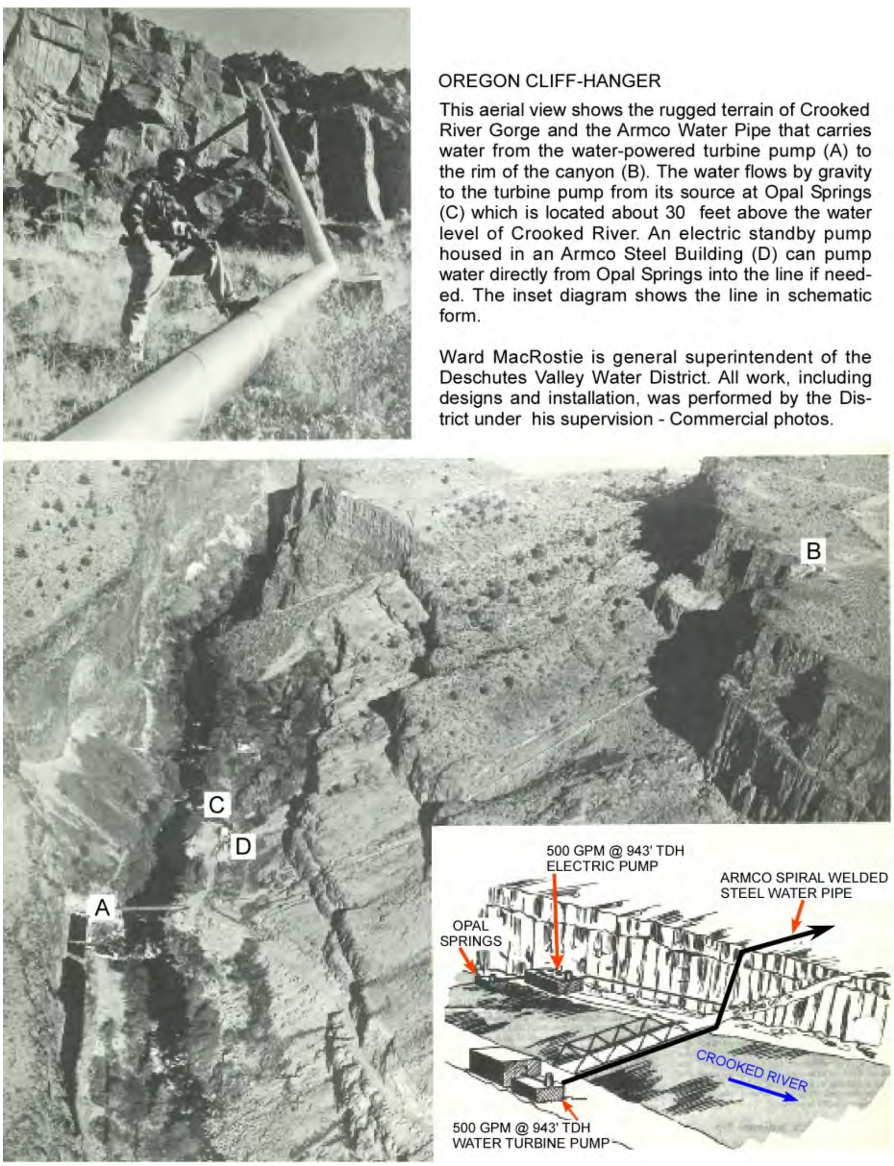


Figure 7.20 Historic photographs and schematic of public water supply facility at Opal Springs. Courtesy of Deschutes Valley Water District.

The fascinating history of Opal Springs and its development as a source of reliable water supply is provided at https://www.dvwd.org/history.html (also see Figure 7.20). Here are several interesting points:

- Drinking water in the area was in scarce supply because much of the surface water was contaminated, causing Typhoid fever outbreaks. Many homesteaders purchased small tracts of land in the east foothills, where they dug wells to sell and haul water. In the Culver area, water was provided by a well 1,000 foot deep, producing only 12 gallons per minute.
- Seeing a need for domestic water, Earl Thompson, an engineer, acquired a homestead on Opal Springs. He designed the Thompson Water Engine that would lift the pure, cold water 850 feet to the canyon rim. Pipes were laid starting at the canyon rim; thus, the domestic water situation was overcome, and water was first delivered through these pipes to Culver on August 22, 1916.
- In the early 1920's, Thompson put in a water powered turbine pump at Opal Springs and another larger pipeline was put up the canyon. A 6" steel pipe was installed to the reservoir at the top of the canyon – providing all of Culver, Metolius and surrounding farms with metered water, at a cost of about $10.00 per month.
- In 1963, Thompson was awarded The Elmer A. Sperry Award for Advancing the Art of Transportation for design and development of the first notably successful automatic automobile transmission.

7.2.4 Springs of McKenzie and North Umpqua Rivers

According to Meinzer (1927), a number of large springs are found in the lava-covered region on the west slope of the Cascade Mountains in Oregon, five of which are apparently springs of the first magnitude. The first-magnitude springs are **Clear Lake**, **Lower Falls**, **Olallie Creek**, and **Lost Creek Springs**, which discharge into McKenzie River, a tributary of the Willamette, and **Spring River**, which discharges into the North Umpqua (see Figure 7.4). The following descriptions of these five springs are from Meinzer (1927) who obtained some of the information from H.T. Stearns, K.N. Philips, and B.E. Jones, all from the United States Geological Survey.

Clear Lake (No.4) is near the head of McKenzie River. It is a beautiful green lake about a mile long and is reported to be 190 feet deep at one place. A gaging station is maintained at the outlet of the lake. On September 5, 1926 the discharge was approximately 200 cfs, all of which rose in the bottom of the lake except about 20 cfs that issued from Great Spring, 100 feet from the east shore of the lake, and about half a cfs that entered through a tributary creek. According to Mr. Stearns of USGS, the lake owes its origin to a basalt flow that entered the valley of McKenzie Eiver and formed a dam in the valley. On September 5, 1926, the temperature of the water of Great Spring was 39° F., and that of the lake was 50° to 52° F (Meinzer, 1927).

Spring at Lower Falls of McKenzie River (No.5). A beautiful spring pool occurs at the foot of the Lower Falls of McKenzie River. This pool discharges about 250 cfs of water at times when there is no surface flow in the river above the pool. A few springs issue from crevices in the basalt about 10 feet above the water surface, but most of the water rises in the pool below the water level. Mr. Stearns reports that the spring is due to a recent basaltic lava flow that entered the gorge of the McKenzie and flowed down it. In normal stages the entire river sinks into this basalt, and the water reappears about 1.5 miles farther down the gorge in the spring pool.

Olallie Creek Springs (No.6). The entire flow of Olallie Creek, a tributary to McKenziee River, at low stages comes from springs about 1.5 miles above its mouth, which issue from basalt. The information in regard to these springs was furnished by Jones, who examined them in July, 1926.

Nearly all the water comes from three spring areas. Two of these are on the creek about a quarter of a mile apart and have a difference in altitude of 30 to 40 feet. Their combined flow was estimated at about 60 cfs. The third spring issues at somewhat lower altitude, at the head of a branch a quarter of a mile long that discharges into the creek a short distance below the other two. It also discharges approximately 60 cfs. The flow of the creek below the spring branch was 137 cfs, according to a measurement by Jones on July 20, 1926. Practically all the water came from these three springs and several smaller springs in the same locality.

As the flow of streams in this region was exceptionally low in the summer of 1926, the discharge of these springs was probably also below the average. It appears, therefore, that the Olallie Creek Springs may be regarded as a spring of the first magnitude.

Figure 7.21 Lost Creek Spring. Photo copyright Gordon Grant; all rights reserved. Printed with permission.

Lost Creek Spring (No.7; see Figure 7.21) rises chiefly from one large irregular pool at the end of a basalt flow. The water flows northeastward through Lost Creek into McKenzie River. The temperature of the water on September 7, 1926, was 42° F. According to measurements made by Jones 3 miles below the spring, the flow was 175 cfs on August 9,1926, 172 cfs on September 6, and 166 cfs on September 22. This spring owes its origin to the burial of an ancient stream channel by a lava flow (Meinzer, 1927).

Spring River (No.15), which is only a mile or two long and discharges into North Umpqua River, forms the outlet for two large springs which may together be regarded as a spring of the first magnitude. The two springs are less than a mile apart. The western one, which is somewhat the larger, issues from the base of a lava bed about 100 feet thick. The water is clear and had a temperature of 40° F. on July 29, 1926. In the bed of the stream where the spring issues Stearns observed waterworn cobbles, which suggest that the water issues from the bed of an ancient river that was buried by the lava flow. The eastern spring issues from the same lava bed. Its water on the same day had a temperature of 42° F. This slightly higher temperature may be due to relatively warm water from nearby Thirsty Creek that may percolate to the spring.

Evidently, the water of Spring River is the underground drainage of a large area of permeable rocks in the Cascade Mountains, to the southeast. The flow of Spring River below both springs was 177 cfs on May 20, 1926, and 174 cfs on July 17, 1926, according to measurements made by Phillips.

7.2.5 Klamath River and Interior Basins Springs

The upper Klamath River Basin and other basins on the eastern flank of the Cascade Range are unique in that groundwater discharge composes a large proportion of the total streamflow. This is attributable to the substantial regional groundwater system that exists in the permeable volcanic terrane. Some major streams in the basin, such as the Wood River and Spring Creek, are virtually entirely groundwater fed.

For decades, hydrologists have recognized that much of the water flowing into Upper Klamath Lake originates as groundwater that discharges to tributary streams within 12 miles of the lake, or directly to the lake (Bureau of Reclamation, 1954, p. 150). Groundwater discharge to streams is not constant but varies seasonally and from year to year in response to climate cycles. In most large spring complexes, such as the headwaters of Spring Creek or the Wood River, discharge variations due to longer-term, decadal climate cycles are larger than seasonal variations. Basin wide, climate-driven groundwater discharge variations exceed 450 cubic feet per second (cfs), a rate that equates to an annual volume of 326,000 acre-feet (Gannett et al, 2007).

Several springs contribute flow to the Lost River subbasin in the sediment filled Langell, Yonna, and Poe valleys. Bonanza Spring (No. 23 on the map in Figure 7.4), near the town of Bonanza, is a major contributor of baseflow to the river as are a series of springs adjacent to the river near Olene Gap. Discharge measurements of Bonanza Springs show considerable temporal variation. The largest measurement, 118 ft^3/s in October 1958, occurred after a 15-year period of wetter-than-average weather. The smallest measurement, 38 ft^3/s in January 1992, occurred late in a drought that started in the mid-1980s. Overall, the pattern of spring discharge follows the general pattern of precipitation, reflecting drought cycles and a general drying trend since the late 1950s. Unfortunately, no measurements are available from the very dry period in the early 1940s. Bonanza Springs discharge is affected by climate, groundwater pumping, and artificial manipulation of the stage of the Lost River (Grondin, 2004). Discharge from the main spring can cease entirely during the irrigation season in dry years. Most measurements after 1960 were made well after the irrigation season (December to April), so the system should have mostly recovered from the seasonal effects of pumping and diversion. Present information is insufficient, however, to determine precisely how much of the variation in spring discharge is natural and how much is related to pumping (Gannett et al, 2007).

7.2.5.1 Wood River Springs

Wood River rises in spring pools a few miles north of Fort Klamath. These pools are fed largely by two groups of springs about 1,500 feet apart. On November 7, 1925, they discharged 208 cfs. The temperature of the water was 42° F at the north group of springs and 48° F at the south group. The water of the spring, known for its beauty, is clear and intensely blue. The water bubbles up from glacial gravel and pumice at the foot of an andesite fault scarp which trends north (Meinzer, 1927).

The property of the headwaters was donated by the Oregon Board of Forestry in 1954 for creation of the Jackson F. Kimball State Recreation Site, named for Jackson F. Kimball, an early day Klamath Basin lumberman and advocate of good forestry practices (https://stateparks.oregon.gov/index.cfm?do=park.profile&parkId=166).

Jackson F. Kimball State Recreation Site is a pristine site. Here stream flows from the pine forest run into open meadow land laced with picturesque quaking aspen surrounded by the southern Cascade Mountains. Wood River offers fine fishing that can be accessed from the park by canoe. The park offers primitive camping next to the headspring which is named Kimbal Lagoon (Figure 7.22).

Figure 7.22 Kimball Lagoon – headwater spring of Wood River in Jackson F. Kimball State Recreation Site. Photo by Jan Hazevoet, available at File:Jackson F Kimball State Park.jpg - Wikimedia Commons. Licensed under Creative Commons Attribution 2.0 Generic license.

7.2.5.2 Ana River Springs

Ana River Springs (No.17 on the map in Figure 7.4) form Ana River, the principal feeder of Summer Lake, which it enters from the north through a channel about 5 miles long. There are five vents close together that are at times flooded by water impounded by a dam. They issue from Pliocene lake beds at the north end of the great fault valley occupied by Summer Lake. The origin of the springs has not been fully determined, but as suggested by Waring (1908), the water probably comes from permeable lava rock and is brought to the surface through the agency of the fault. A temperature of 66° F, reported by Waring, suggests a deep origin of the water (Meinzer, 1927).

According to Brown (1957), about 1915 a small dam was constructed across a narrow part of the Ana River ravine between the two main clusters of springs. This old dam is reported to have raised the water depth of 20 or 30 feet over the orifice of the upper springs. The dam fell into disrepair and was out of use by 1920. The new dam was constructed in 1922-23. The main spring orifices are now drowned in the reservoir. Reports on the pre-reservoir appearance of the orifices agree that the water issued from irregularly shaped, but generally vertical, shafts in the lake beds. Longtime residents of the area pointed out that Buckhorn Springs, which rise farther east on the Carlin Ranch, are similar in appearance to the now submerged Ana Springs. The waters of Buckhorn Springs arise through a circular pipelike vertical conduit which terminates in an elliptical-shaped orifice in the lake bed (Brown, 1957).

On July 27, 1925, Mr. S. Mushin, of Lakeview, Oregon measured these springs and found them to be discharging cfs. Ana River has been measured from time to time for the last 22 years at a point below the lowest of the large springs. In the 29 measurements recorded in the following table the flow has ranged from 106 to 165 cfs. The discharges of 106 and 109 cfs were measured at times when a diversion dam constructed just above the measuring section had raised the water to a height of 30 or 40 feet above the bed of the stream. The minimum measured before this dam was constructed or thereafter when the water was not impounded behind the dam was 114 cfs. The flow of the springs in the 27 measurements exclusive of these two has, therefore, ranged from 114 to 165 cfs and has averaged about 135 cfs.

Figure 7.23 Riparian habitat on the upper Ana River. Photo by highdesertbruin, provided under Creative Commons license (Attribution-Share Alike 2.0 Generic), available at Ana_River_habitat,_Summer_Lake,_Oregon.jpg.

The measurements show that in addition to small seasonal variations there has been a moderate secular fluctuation due to a cycle of relatively wet and dry years. From a maximum measured flow in 1904 there was a persistent decline to 1920, followed by a partial recovery in the next five years (Meinzer, 1927).

The Ana River meanders through and supplies the water that maintains the Summer Lake Wildlife Area wetlands owned and maintained by The Oregon Department of Fish and Wildlife (Bureau of Land Management owns some of the adjacent land). The 60-acre Summer Lake reservoir is owned by the Summer Lake Irrigation District. The wildlife area is located in central Lake County along State Highway 31, 100 miles southeast of Bend and 75 miles northwest of Lakeview.

Summer Lake Wildlife Area was established in 1944, with primary objectives of protecting and improving waterfowl habitat and providing a public hunting area. It is now a popular destination for hunting, wildlife viewing and environmental education due to its geographic setting, the abundance of wildlife, and species diversity. Ana Reservoir (with a boat ramp) at the north end of the wildlife area provides good fishing opportunities, picnicking, and camping. (https://myodfw.com/summer-lake-wildlife-area-visitors-guide)

7.3 California

As a rule, the large springs in the basaltic and other volcanic-rock aquifers region of Northern California (see Figures 7.1 and 7.24) fluctuate much less than the large limestone springs of Florida, Missouri, and Texas. In this respect they have a distinct family resemblance to the large springs in the volcanic rocks of Oregon and Idaho. For example, Fall River Springs, the largest spring group in California, in the early 1900s had an average discharge of about 1,400 cfs and in a period of more than two years of continuing record, their discharge did not depart from this average more than 10 or 15 percent (Meinzer, 1927). Since then, the excessive diversion for irrigation and hydropower of Fall River and other surface streams in the area prevents any reliable estimates of what large springs are discharging during different seasons and years as no permanent gaging station at a spring exists.

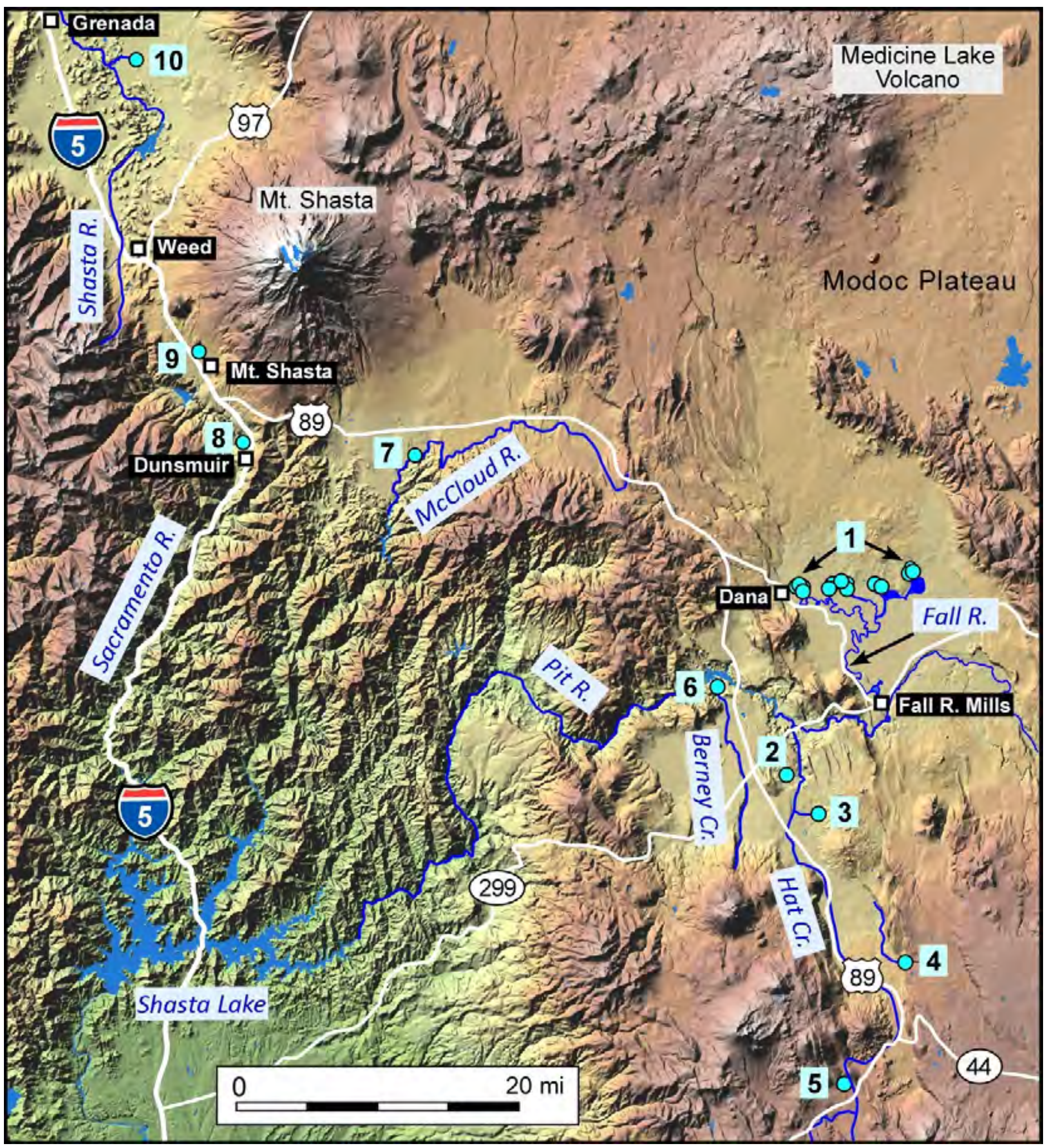


Figure 7.24 Notable springs in volcanic terrains of Northern California. (1) Fall River Springs; (2) Crystal Lake Sp.; (3) Rising River Sp.; (4) Lost Creek Headwater Sp.; (5) Big Spring; (6) Berney Falls Springs; (7) Big Spring on McCloud River; (8) Mossbrae Falls Springs; (9) Big Spring (Mt. Shasta City Park); (10) Big Spring (Shasta River watershed). Shaded relief map courtesy of USGS.

7.3.1 Fall River Springs

Nearly all the water of Fall River comes from numerous large springs that occur in a belt about 10 miles long (Figures 7.24 and 7.25) at the south margin of an extensive lava field in the southwestern portion of the vast Modoc Plateau which extends to parts of Oregon and Nevada. The Modoc Plateau is a volcanic table land (elevation 4,000 6,000 feet above sea level) consisting of a thick accumulation of lava flows and tuff beds along with many small volcanic cones. Occasional lakes, marshes, and sluggishly flowing streams meander across the plateau. The plateau is cut by many north-south faults. The province is bound indefinitely by the Cascade Range on the west and the Basin and Range on the east and south (California Geological Survey, 2002).

Only a small amount of direct runoff is supplied by Bear Creek, which flows into Fall River from the northwest. The following measurements were made by the U.S. Geological Survey near the mouth of the river prior to 1912: September 9, 1901, 1,447 cfs; September 16, 1902, 1,543 cfs; September 11, 1903, 1,510 cfs; September 23, 1910, 1,470 cfs. A gaging station was established on this river near its mouth with Pit River on January 19, 1912, and daily records of discharge were obtained until August 10, 1913, when the station was discontinued. During this period of nearly 19 months the discharge ranged between 1,240 and 1,590 cfs and averaged about 1,400 cfs, indicating that the springs do not fluctuate greatly. Owing to the deficient precipitation in 1912 and 1913, there was a general decline in discharge-during the period, but with some fluctuations (Meinzer, 1927).

The gravity diversions from Tule River in 1927 had a capacity of about 500 cfs, and there were numerous small pumping plants along the banks of Fall River. Beginning October 23, 1922, the Pacific Gas & Electric Co. diverted practically the entire flow of Fall River at a point about 1 mile northwest of Fall River Mills.

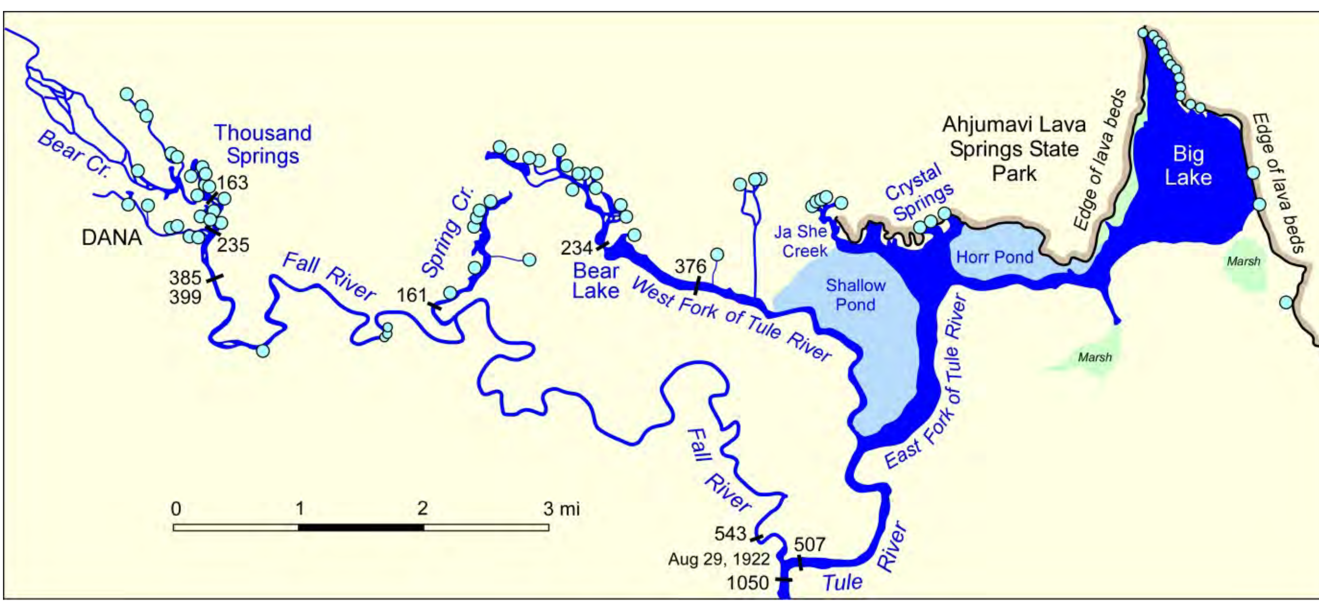


Figure 7.25 Springs (blue circles) and spring branches of the Fall River Springs complex. Flow measurements, in cubic feet per second, by E.A. Garland, of the Pacific Gas & Electric Co., in August and September 1922. From Meinzer, 1927; modified, updated, and simplified for clarity.

In 1922, the springs at the head of Fall River had a combined flow of 385 cfs, according to one measurement, and 399 cfs, according to another. This flow was made possible chiefly by five groups of springs, which yielded 163, 44, 54, 51, and 14 cfs. The springs that yielded 163 cfs are regarded as forming the head of Fall River. Spring

Creek, which is a spring-fed body of water a little over a mile long, had a discharge of 161 cfs. The springs at the head of Fall River and those on Spring Creek together produced a flow of 543 cfs, or approximately half of the total discharge of Fall River before confluence with Tule River.

The springs at the head of the West Fork of Tule River (nowadays called Little Tule River) had a total flow of 234 cfs, as measured just above Bear Lake. One of the most remarkable features is Bear Lake, or the "Big Hole," into which the springs at the head of West Fork discharge. Here the stream widens to about a quarter of a mile and, according to soundings that have been made, reaches a depth of about 100 feet. There is no visible inflow, but at the time of measurement the quantity of water increased by 142 cfs, as shown by the flow of 234 cfs just above the hole and a flow of 376 cfs less than a mile below it.

As stated by Meinzer, in comparison to the springs on Snake River, it would be logical to consider that there are on Fall River three springs of first magnitude and many smaller ones. The three springs of first magnitude are those at the head of Fall River, which discharge about 385 to 399 cfs; those at the head of the West Fork of Tule River, including Bear Lake, which discharge about 376 cfs; and Spring Creek, which discharges about 161 cfs.

Figure 7.26 Fall River valley. Mt. Shasta, covered with snow, is visible in far distance. Photograph copyright Michael Wier, all rights reserved. Printed with permission.

Although not measured by Garland or discussed by Meinzer, it follows that springs forming the East Fork of Tule River, located in what is now Ahjumavi Lava Springs State Park (Figure 7.25; see also photographs in Figures 7.27 and 7.28) had a combined flow of 100-130 cfs and could also be classified as a first-magnitude spring group.

The source of the large quantity of water discharged by these springs is discussed by Waring (1915; from Meinzer, 1927): They all rise at the southern border of an extensive lava field and were at the time considered to be the outlet of Tule or Rhett Lake at the northern border of the State. “The water may, however, be furnished by the precipitation on the lava fields to the north, for much the greater part of the water that falls on these fields sinks into the crevices and caverns in the rock, and there is very little direct surface run-off. A continual flow of 1,500 cfs would be furnished by an annual run-off of about 1 cfs per square mile, or 13 inches a year in depth of water over an area of 1,500 square miles. This is not excessive for the region under consideration, where the annual precipitation is 20 to 40 inches, for it represents both a normal run-off and the amount that usually sinks into the ground. There is an area of nearly 2,000 square miles of lava beds extending from northeast to northwest of Dana, and the topography of this area is favorable to the theory that it may furnish the water of the springs at the head of Fall River. The temperature of the water, 53° to 54° F., indicates that it is of essentially surface origin." (Meinzer, 1927).

According to Mariner et al. (1998), isotope values for the large discharge cold springs of the Fall River Valley are similar to values of cold springs and wells on Medicine Lake Volcano indicating that it is possible for these waters to recharge on Medicine Lake Volcano. However, the authors emphasize that this does not constitute proof that the waters discharged by these large discharge cold springs recharge on Medicine Lake Volcano.

Figure 7.27 Springs in Ahjumawi Lava Springs State Park. Photographs Copyright Michael Wier, all rights reserved. Printed with permission.

Informational billboards in Adjumawi Lava Springs State Park proclaim that the large discharge cold springs, which are a prominent feature of the park, are fed by underground streams from Tule Lake. The source of this "information" appears to be MacDonald (1966) and is apparently based on the difference in elevation between

Tule Lake and the Fall River-Adjumawi area, and that large quantities of water have been observed to flow into the subsurface at Tule Lake without showing up again. However, chemical and especially isotopic data show that it is impossible for a significant amount of Tule Lake (Tule Lake Sump) water to be present in the large-discharge cold springs that feed the Fall and Tule rivers. Isotope data from waters of large-discharge cold springs between the Fall River Valley and Lassen Peak (Rose et asl., 1966) are virtually identical to values from the large-discharge cold springs of the Fall River - Ahjumawi Lava Springs State Park (Mariner et al., 1998).

Three eastern groups of springs, those forming Ja She Creek, the Crystal Springs, and many smaller springs that discharge into Big Lake, are part of the Ahjumawi Lava State Park (https://www.parks.ca.gov/?page_id=464; see Figure 7.25). All other springs of Fall River are privately owned and without public access.

"Where the waters come together...." is a translation of the California Native Americans' word Ahjumawi, which is also the self-describing word used by the Pit River Tribe members who still inhabit the area.

Figure 7.28 Flow of water from the spring-fed Ja-She Creek entering East Fork of Tule River. Photo courtesy of Garrett Costello, Symbiotic Restoration. https://www.symbioticrestoration.com/

The Park is in remote northeastern Shasta County and can only be reached by boat. Power boats are allowed to access Ahjumawi, but larger power boats are not recommended due to shallow access points to the park. There are no public roads to it and private motor vehicles are prohibited within. Visitors can launch into Big Lake at a PG&E public boat launch known as "Rat Farm". It is reached from McArthur by turning north off Highway 299 on to Main St., continuing past the Intermountain Fairgrounds, crossing over a canal and proceeding 3-miles north on a graded dirt road ending at a dirt launch ramp. PG&E owns five miles of the south shore of Big Lake, 2 miles along the east shore of the Little Tule River, and most of the inundated area. A levee on this shoreline protects the reclaimed McArthur Swamp, owned by PG&E, from inundation. Much of the northern shoreline is in Ahjumawi Lava Springs State Park.

Figure 7.29 Big Lake, Ahjumawi Lava Springs State Park. Photo courtesy of Marina Marcelli.

The large volumes of spring water inflow maintain Fall River water temperature at near optimum ranges for trout production, even during mid-summer. At the Island Road Bridge, mid-summer temperatures are generally in the low to mid 50s ^{o}F and, near Glenburn and the Pit No. 1 Intake, in the low to mid 60s ºF. Big Lake is used primarily for waterfowl hunting and supports a warm water fishery year-round and a trout fishery during the general trout season. Horr Pond supports a similar sport fishery, including largemouth black bass, and brown bullheads. The Tule River supports bass, bullheads, and trout for anglers each year, and the Little Tule River contains self-sustaining populations of rainbow and brown trout. (https://fallriverconservancy.org/the-river/).

Preserved within the Park are lava flows broken by great faults and deep cracks, lava tubes and craters. Freshwater springs flowing from the lava are prominent along the shoreline. Oak, pine, and juniper forests and slopes of rabbit brush and sagebrush are part of the great variety of vegetation in the area. Abundant wildlife populations can be seen in all seasons. A great variety of birds, including bald eagles, ospreys, and great blue herons nest or travel throughout the park.

7.3.2 Hat Creek Basin Springs

Detailed discussion on the geology and hydrogeology of the Hat Creek Basin (Figure 7.30) is provided by Marcelli et al. (2023). Four high-volume spring complexes, each discharging >3 m^3/s or >100 cfs (Crystal Lake, Rising River, Lost Creek Headwaters Spring, and Big Spring; see Figures 7.24 and 7.31) are in the Hat Creek Basin and contribute to the Creek's flow before it joins the Pit River. In the conceptual model of groundwater flow for the Basin, young, permeable, laterally connected, basin-filling basalt flows in the valley bottom accumulate water from the adjacent and southern uplands. These young basalt flows efficiently transmit groundwater from Lassen Peak in the south to the Pit River in the north.

Hat Creek flows over a leaky, compartmentalized aquifer system with at least three distinct segments separated by geologic structures. The two downstream compartments are characterized by losing stream reaches upstream and gaining reaches downstream. The authors hypothesize that the pattern of streamflow gain followed by streamflow loss occurs across structural boundaries created by faults and at unconformities between volcanic units with contrasting transmissivity.

Figure 7.30 Hat Creek valley looking north. Mount Shasta, covered with snow, is visible in far distance. Photo courtesy of Marina Marcelli.

The upstream-most Big Spring compartment gains 4.2 m^3/s at its downstream boundary near the fault at Big Spring, increasing streamflow by a factor of 5. The Sugarloaf compartment (which extends from the fault at Big Spring (ca. river km 61) to the groundwater-flow barrier north of Sugarloaf Peak (ca. river km 42) likely regains streamflow lost in its upstream reaches at a groundwater-flow barrier between river kms 48 and 42. In the Rising

River compartment, near river km 15, Hat Creek almost goes dry, but gains around 14 m^3/s between river kms ~14 and 8. Similar patterns of streamflow gains and loss at groundwater-flow barriers can be found at other locations in the Shasta-Lassen Peak-Medicine Lake volcano study area (SLMSA) south of the Pit River (Marcelli et al., 2023).

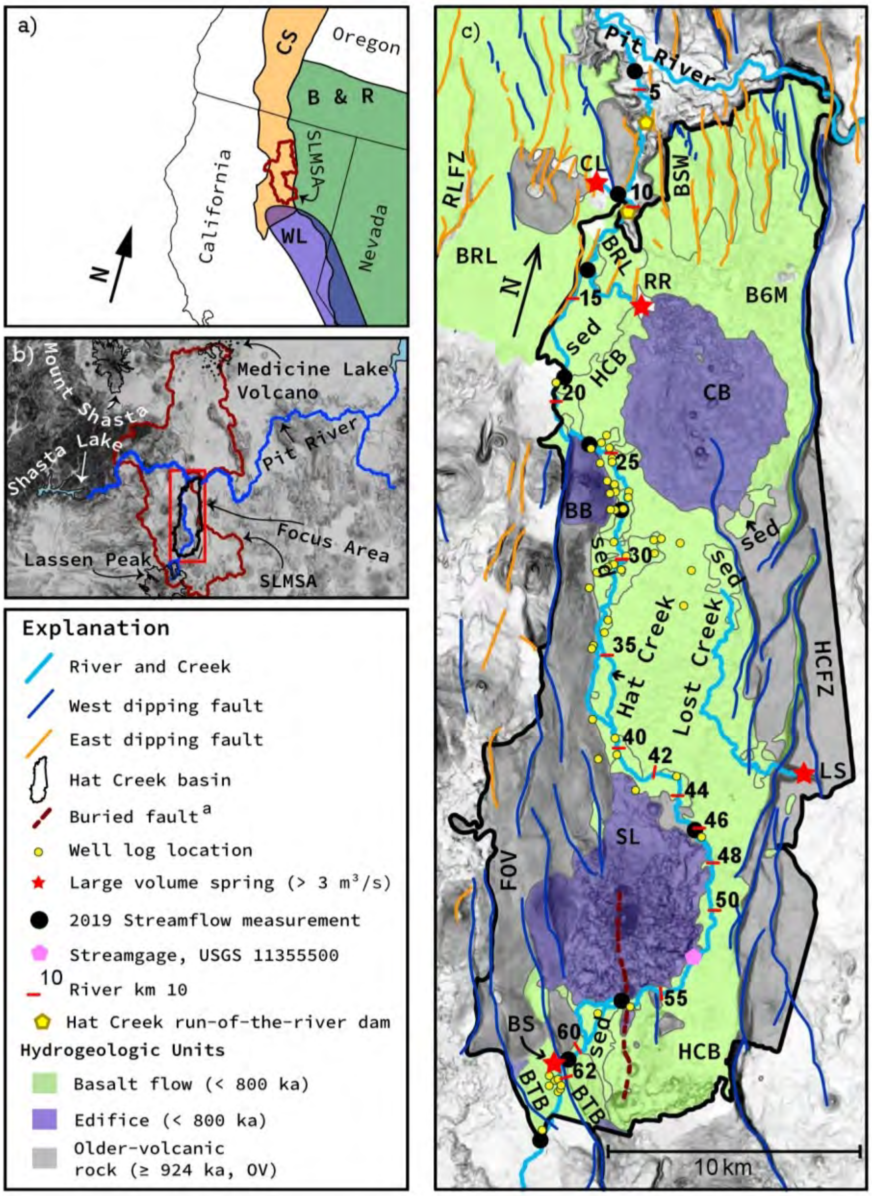


Figure 7.31 Geology of the Hat Creek focus area. (**a**) The Basin and Range extensional province (B&R), Cascade Range (CS), and Walker Lane Fault Zone (WL) intersect in the Shasta-Lassen Peak-Medicine Lake volcano study area (SLMSA, red/brown outline). Modified from Langenheim et al. (2016) and from US Geological Survey physiographic divisions of conterminous USA (Fenneman and Johnson 1946). (**b**) Geographic setting of SLMSA and the Pit River drainage basin. Box on the right indicates the location of the Hat Creek focus area (**c**).

Abbreviations

HCB–Hat Creek Basalt; BTB–basalt of Twin Bridges; BRL–basalt of Rocky Ledge; BSW–basalt of Sam Wolfin Spring; B6M–basalt of 6 mile hill; BB–andesite of Brown Butte; CB–basaltic andesite of Cinder Butte; SL–Sugarloaf Peak; BS–Big Spring; LS–Lost Creek headwater spring; RR–Rising River Spring; CL–Crystal Lake Spring; sed–sediment; RLFZ–Rocky Ledge fault zone; HCFZ–Hat Creek fault zone.

(**c**) Conceptual geologic map of the Hat Creek focus area. Volcanic rocks are grouped into three units. Green identifies basalt flows and Holocene sediments. Purple area depicts high-elevation volcanic edifices. Faulted-older volcanic units that form the valley and are exposed in adjacent uplands are in gray. Informal names of volcanic units are based on Muffler and Clynne 2015. Labels include HCFZ: Hat Creek fault zone, RLFZ: Rocky Ledge fault zone. Fault dip direction was established with a LiDAR derived slope shade map, US Geological Survey Quaternary Fault and Fold Database of the United States (US Geological Survey 2018), and geologic mapping. Legend footnote: [a] Clynne and Muffler (2017).

Hat Creek is considered a world-renowned fishing destination. The Hat Creek route takes visitors through a highly pristine riparian corridor lined with Ponderosa pine, Oregon and black oak, and willow species. The creek is crystal clear and shallow in some places, allowing clear views of the substrate and occasional obsidian flakes and points.

Fig 7.32 Big Spring on Hat Creek in June of 2019, in the early middle of the dry season. This is the spring near one of West Dipping faults just south of Sugar Loaf Peak (see Figure 7.31). It was the spring responsible for the 5-degree Celsius temperature drop in Hat Creek in the afternoon temperature profile. Text and photo courtesy of Marina Marcelli.

7.3.3 Mount Shasta Springs

As described by Blodgett et al. (1988), Mount Shasta in northern California (Figure 7.33) is one of the largest and highest stratovolcanoes in the Cascade Range. Future events that may be hazardous to life and property in the vicinity of Mount Shasta include volcanic activity and debris flows caused by nonvolcanic events, such as glacial melt and precipitation. The lower flanks of Mount Shasta consist of a broad, smooth apron of fans of pyroclastic-flow, debris-flow, and fluvial deposits; all these deposits are porous and highly permeable. Streams that originate on Mount Shasta enter three river systems—the Shasta, the Sacramento, and the McCloud rivers. Many streams draining the flanks are intermittent, and flows disappear into the volcanic and fluvial debris on the flanks and at the base of the volcano.

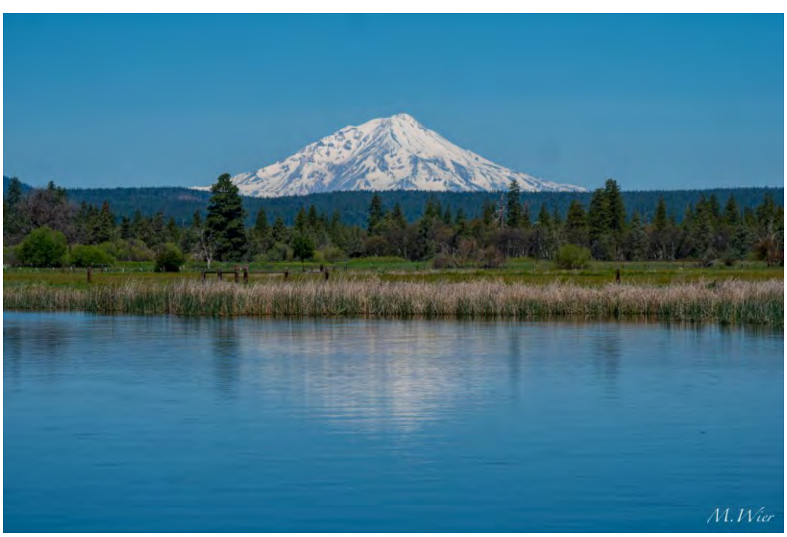


Figure 7.33 View of Mount Shasta from Fall River. Photo copyright Michael Wier, all rights reserved. Printed with permission.

Groundwater, which is generally abundant, is found on all sides of Mount Shasta and generally flows away from topographic high points toward the Shasta, the Sacramento, and the McCloud rivers. The communities of Weed, Mount Shasta (city), Dunsmuir, and McCloud depend on groundwater as their major water supply. The difference of volcanic and fluvial deposits in the area causes wide variations in groundwater properties; no single aquifer can be identified. Primary sources of groundwater include fracture joints in andesite deposits near Mount Shasta (city), sand and gravel beneath vesicular lava flows near McCloud, and lava tubes of the Plutos Cave Basalt, the most prolific aquifer in Shasta Valley. Poor sources of groundwater are the pyroclastic flow assemblages located on the southwest flanks of the mountain and fluvial deposits in the Whitney Creek drainage. Those areas where streams have high rates of streamflow losses are considered major recharge areas.

There are many small springs and three large springs with the same name on the flanks of Mount Shasta: Big Springs on McCloud River (#7 on the map in Figure 7.24; about 616 ft^3/s was measured at one time). Big Springs near City of Mount Shasta (#9; 20 cfs), and Big Springs, located about 6 mi SE of Grenada (#10; 36 cfs). The Springs serve as the main source of water for the communities of Mount Shasta, McCloud, Dunsmuir, and Weed.

Yields from wells that supplement water supplies for Mount Shasta (city) as well as for domestic use range from 0.01 to 8.0 ft^3/s. Water levels in wells fluctuate from less than 1 to almost 27 feet during the year. Seasonal fluctuations are caused by variation in rainfall and snowmelt, discharge by pumpage for irrigation, and thickness and areal extent of the aquifer. The quality of well and spring water generally is suitable for most uses, with chemical properties of a mixed cation bicarbonate type. The quality of all groundwater used for drinking purposes meets standards of the U.S. Environmental Protection Agency. Water sampled at Mount Shasta Sulphur Springs near the summit was found to be similar to water sampled from acid sulfate springs at other volcanoes high in sulfate and low in chloride, very acidic, and with an average temperature of about 78 °C.

Figure 7.34 Big Springs on McCloud River, California. Photo copyright Bill Tuthill; all rights reserved.

Mount Shasta's rain-shadow effect causes a great range in precipitation and runoff; mean annual precipitation is about 53 inches at McCloud on the south side of the mountain and about 18 inches near Yreka, located north-northwest of the mountain. Streams located south and east of the mountain have the highest flows in terms of unit runoff; those located in Shasta Valley have the lowest runoff. The McCloud River near McCloud has the least fluctuation in flow throughout the year probably because a large part of the flow is derived from springs.

In 2007, California Trout convened a group of scientists to design an initial baseline study of Mount Shasta springs—data which was needed to help make policy decisions. The scope of the Mount Shasta Springs study included taking water samples from 22 springs on Mt. Shasta. Springs at high, middle, and low elevations, in the three watersheds (Shasta, Upper Sacramento and McCloud) were sampled. The water samples were analyzed for a full suite of general water quality and geochemical parameters. A subset of the samples was also analyzed for oxygen and hydrogen isotopes. The purpose of the sampling was to determine the elevation at which spring water originates on the mountain, as well as if any of the springs may be related. The information collected from the study informed the development of a vulnerability rating for the springs sampled. The rating analysis assumed that Mount Shasta spring waters could be vulnerable to land use (water quality), development (water use), and climate change (variability). The purpose of the vulnerability rating was to assist with water management decisions (https://caltrout.org/mountshastasprings).

The Big Springs on the McCloud River (#7 on the map in Figure 7.24) is estimated to be discharging approximately an average of 200 cfs, which is a considerable percentage of the total flow of McCloud River. It discharges directly into the river , emanating from a deeply eroded escarpment on the Hearst Property. The only access to the spring is via boat (Figure 7.34). An isotope sample is not available for this spring, but water of Muir Fall Spring, located several thousand feet upstream (Figure 7.35) was analyzed and the results indicate a residence time of 14 years. It may be reasonable to expect that McCloud Big Springs and Muir Falls Springs are potentially sourced from the same aquifer (Aqua Terra Consulting and SGI Environmental, 2010; California Trout, 2010).

Figure 7.35 Muir Springs on McCloud River. Photo courtesy of Aqua Terra Consulting, and SGI Environmental.

Mt. Shasta Big Springs (#9 on the map in Figure 7.4) is in the Mt. Shasta City Park and is known as the headwaters of the Upper Sacramento River. With a discharge elevation of 3,567 feet and a calculated recharge elevation of 8,170 feet, it has one of the largest elevation differences of the springs sampled. The tritium sampling of this spring indicated the water to be more than 50 years old (Aqua Terra Consulting and SGI Environmental, 2010; California Trout, 2010).

The land, which ultimately became the Park, was once part of the hunting ground for the Wintun, Maidu, and Okwanuchu Native American tribes and was first crossed by explorers around 1841. Big Springs once contained a waterwheel and was the city's first source of energy (1901) for generating power to light the local community (https://www.msrec.org/headwaters-spring).

7.3.4 Burney Falls Springs

Burney Falls (#6 on map in Figure 7.4) are on spring-fed Berney Creek which flows into Lake Britton, a man-made reservoir on Pit River. The creek originates from springs and small lakes at the foothill of Mt. Burney, a volcanic cone to the south. Numerous spring vents are also visible along the falls' escarpment, pouring fourth from interflow zones between two basalts. During drier times, Burney Creek commonly sinks into its bed, disappearing well upstream of Burney Falls, only to reappear as seepage into the creek bed above the falls and as springs in the rock face of the falls. In the summer, the farthest upstream spring is about ¾ mile from the lip of the falls. The Burney creek bed is usually dry from that point on upstream (Wopat, 2015). The 129-foot-high falls, recognized as a National Natural Landmark, are in McArthur-Burney Falls Memorial State Park. Burney Falls was named after pioneer settler Samuel Burney who lived in the area in the 1850s. The McArthurs were pioneer settlers who arrived in the late 1800s. Descendants were responsible for saving the waterfall and nearby land from development. They bought the property and gave it to the state as a gift in the 1920s (McArthur-Burney Falls Memorial State Park).

The Park experiences extremely high visitation beginning in April and continuing through October. Most weekends all summer the park will fill to capacity and entrance into the park is subject to closure due to limited parking availability. Visitors should expect traffic delays on State Highway 89 for up to an hour prior to entering the park due to the increased visitation experienced at this park. It is illegal to park along Highway 89 outside of the park for a mile either direction.

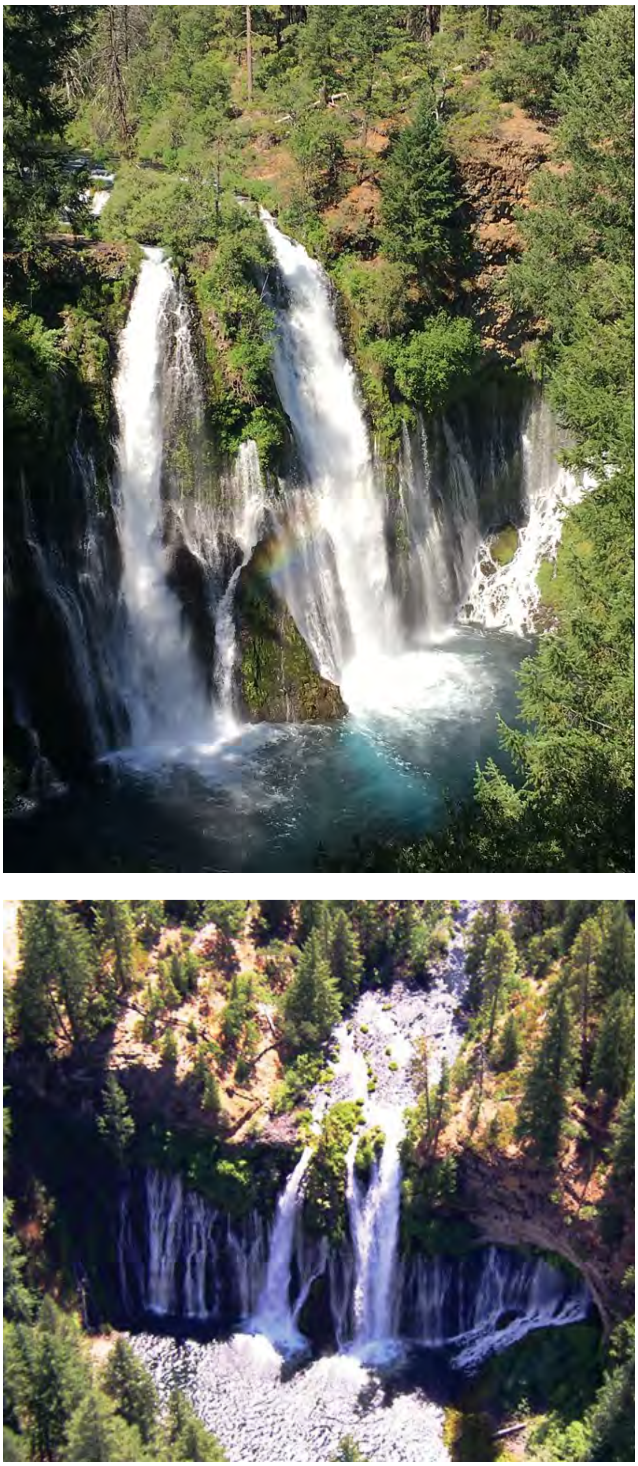


Figure 7.36 Two views of Burney Falls (#6 on map in Figure 7.4) Top photo courtesy of Marina Marcelli. *Bottom* photo credit: Dennis Heiman, Sacramento River Watershed Program; CGS_SR230_McArthurBurneyFalls_MemorialSP_lr.pdf

7.3.5 Mossbrae Falls Springs

Mossbrae Falls near City of Dunsmuir (#8 on the map in Figure 7.24) is a series of springs that issue from the cliffs above Upper Sacramento River and then rain down into the water. One access to the falls is via a mile-long illegal and dangerous hiking trail on the Union Pacific Railroad active railway. Mossbrae Falls was a tourist destination when railroad tracks were first constructed through the river canyon. Visitors arrived by either riding the train to the Shasta Springs train stop, or by hiking the rail tracks on foot from Dunsmuir. Through the years as the number of hikers and rail traffic has increased, it has become a growing concern for residents and visitors. In 2017, Dunsmuir City Council approved to make a proposal to key property owners to construct a trail.

The City of Dunsmuir is still raising money to create a public trail connecting the Hedge Creek Falls Trail to Mossbrae Falls. When completed, the Hedge Creek Falls trail will be extended another 0.6 miles, becoming one mile long. The new trail will feature a pedestrian bridge over the Sacramento River and a raised trail along the Sacramento. Union Pacific has agreed to grant the right of way to build the trail; the only thing that is missing is the $3 Million in funding needed to make this trail project a reality (https://www.ci.dunsmuir.ca.us/mossbrae-falls-trail/).

One of the most enchanting aspects of Mossbrae Falls is the lush green moss that drapes over the rock formation. This creates a captivating curtain-like effect, adding to the falls' ethereal beauty.

Figure 7.37 Mossbrae Falls near City of Dunsmuir, California. The waterfall is named for the profusion of moss on the hillside at the site, together with *brae*, which means "a steep bank or hillside" in Irish and Scots. Photo by Pinecar at English Wikipedia, released in public domain. Available at https://commons.wikimedia.org/wiki/File:Mossbrae_falls.jpg.

7.4 Montana

The locations of four large springs in Montana described by Meinzer in his seminal work on large springs in the United States (1927) are shown in Figure 7.38, together with three other notable, non-thermal springs: Blaine, Armstrong, and Nelson Springs. What they all have in common, except possibly for Armstrong and Nelson Springs, is that they drain a deep-seated carbonate Madison Aquifer which is recharged in the highland areas and plunges below a series of thick, less permeable sediments that extend into the Northern Great Plains, with most of the discharge from the system occurring in eastern North Dakota and in the Canadian Province of Manitoba.

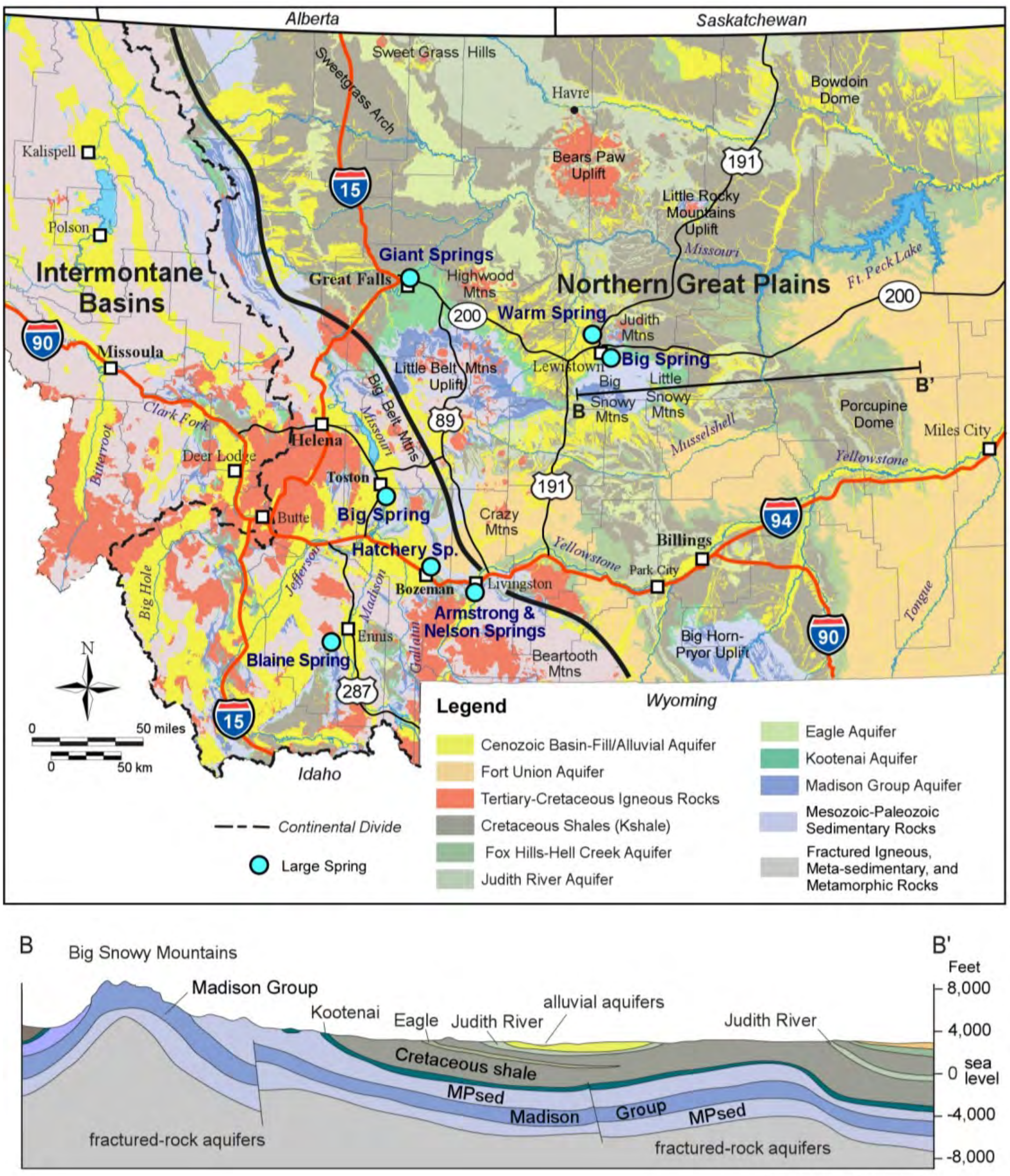


Figure 7.38 Locations of large springs in Montana. Aquifer map and cross-section from John I. LaFave, 2024: Principal Aquifers of Montana. MBMG Special Publication 122: Geology of Montana, vol. 2: Special Topics; available at https://mbmg.mtech.edu/pdf/geologyvolume/LaFavePrincipalAquifersFinal.pdf

As discussed by LaFave (2024), the Madison Group aquifer consists primarily of the Mission Canyon Limestone. The thickness of the Mission Canyon ranges from 300 to 600 ft (Miller, 1981). In central Montana, the Madison Group crops out mainly along the northern flanks of the Little Belt and Big Snowy Mountains. It is also prominently exposed along the northeast flank of the Pryor Mountains in the Big Horn-Pryor Uplift, and in narrow exposures in mountain ranges in southwest Montana (Figure 7.38). The Madison typically dips downward steeply away from the mountain fronts and decreases in slope with distance from them. It is deeply buried (5,000–8,000 ft below the surface) under most of eastern Montana. The limestone is relatively impermeable; however, where fracturing and karst features are well developed, there is the potential for large well yields and fast advective flow paths. The permeability and well yields are variable; in places closely spaced wells have very different reported yields.

In Cascade county, near Great Falls, the Madison is about 350 ft below the land surface; however, it is exposed about 25 mi to the south–southeast along the north flank of the Little Belt Mountains (Smith, 2008). More than 900 wells (roughly 75 percent of all Madison wells statewide) use the Madison aquifer, mostly between the Little Belt Mountains and the Missouri River near Great Falls. Several streams lose flow to the Madison aquifer in outcrop areas, and groundwater moves from the mountain recharge areas, in the Little Belt Mountains, towards the Missouri River, including the largest spring in Montana, and one of the largest springs in the country, the Giant Springs near Great Falls (see Figures 7.39 through 7.43; Feltis and Shields, 1982; Madison, 2016).

Chlorofluorocarbons (CFC) age dating of Madison aquifer water at Giant Springs and a nearby Madison well returned an apparent age of 23 and 26 years respectively, suggesting that flow rates between the Little Belt Mountains (recharge area) and the Springs and the Missouri River (discharge area) could be as much as 15 ft per day (LaFave, 2012).

Four of the largest springs in Montana, which drain the Madison, supply water for fish hatcheries: Giant Springs in Cascade County near Great Falls, Big Spring in Fergus County near Lewistown, Hatchery Spring in Gallatin County near Bozeman, and Blaine Spring in Madison County near Ennis all have a consistent flow of relatively low-TDS water with very similar water chemistry despite the geographic distance between them (LaFave, 2024).

7.4.1 Giant Springs

The Giant Springs were discovered by Captain Clark, of the Lewis and Clark Expedition. On June 18, 1805, Clark described Giant Springs as "*the largest fountain or Spring I ever Saw, and doubt if it is not the largest in America Known, this water boils up from under th rocks near the edge of the river and falls imediately into the river 8 feet and keeps its Colour for ½ a mile which is emencely Clear and of a bluish Cast*."

On June 29, Lewis and Drouillard hiked six miles from their upper portage camp to visit the spring after hearing Clark's description. They found it "*much as Capt. C; had discribed & think it may well be retained on the list of prodegies of this neighbourhood towards which, nature seems to have dealt with a liberal hand*." (National Park Service, https://www.nps.gov/places/giant-springs.htm).

As explained by Cassius A. Fisher of USGS in 1909, "*According to measurements made by E. T. Nettleton* (in 1892) *the flow of these springs is approximately 638 cubic feet per second, an amount which, converted into gallons, is the equivalent of over 400,000,000 gallons every twenty-four hours a veritable underground river. The fact that the water of Giant Springs issues from rocks at the water's edge and in the bed of the river renders it* *difficult to measure their exact flow. In order to ascertain this amount, measurements were taken of the total flow of Missouri River above and below the springs; the difference between these two measurements is assumed to be the quantity furnished to the river by the springs. It is readily seen from the above figures that these springs rank among the largest in the United States. The water, which boils up with considerable force, is clear, blue, and relatively pure, containing no more dissolved salts than the average well water of the region. It has a temperature of about 50° F.*

No spring deposits occur in the immediate vicinity of Giant Springs, and the water is not generally regarded as possessing therapeutic value. It is not utilized at present, but is allowed to flow into the river. There are, however, a few improvements, such as sidewalks, etc., which make it possible for tourists to view the springs from the most advantageous points."

Figure 7.39 Giant Springs. Photo by Alex Wiles, National Park Service.

Unfortunately, no similar measurements were conducted since or made publicly available to the best of author's knowledge. However, based on various accounts over the years, the spring discharge rate does not seem to change significantly from season to season and is always described as powerful. Whatever the case may be, Giant Springs likely belongs to the group of 5-10 largest springs in the country.

Hydrogeologically, it is a unique spring draining deeply seated karst aquifer developed in Madison Limestone. This ascending spring emerges from the large joint planes in a medium to coarse grained Kootenai sandstone which overlies Morrison Formation and Madison Limestone (Figures 7.40 and 7.41). For a short distance on either side of the main spring there are smaller springs flowing from the joint planes. In the bed of Missouri River, there is another large spring which is only apparent during low water seasons. The spring recharge area is 30-40 miles to the south where the Madison Limestone outcrops on the Little Belt Mountains.

As discussed by LaFave (2012), samples from Giant Springs and a nearby Madison well were analyzed for environmental isotopes to determine apparent groundwater age and residence time. Chlorofluorocarbons (CFC's) and tritium were detected, and the results returned "CFC ages" of 23 and 26 years, respectively. The ages are consistent with the tritium values of 10.1 and 10.2 TU. Radiocarbon dating of samples from the well and Giant Springs returned values of close to 50 percent modern carbon (47.48 and 49.38 PMC, respectively), reflecting that half of the DIC is derived from atmospheric CO_2 with modern ^{14}C activity, and half from the carbonate ($CaCO_3$) that has no ^{14}C activity.

Figure 7.40 The vertical fractures in Kootenai Sandstone at Giant Springs State Park near Great Falls, Montana. Giant Springs is located on the crest of the Sweetgrass Arch—a gentle fold that was tectonically active during deposition of Paleozoic and Mesozoic sediments. The aquifer is the Madison limestone, which is only 400 feet below the surface. The fractures are extension fractures and are open. They provide an easy conduit for groundwater in the Madison aquifer to rise to the surface and be discharged in and next to the Missouri River. Text and photo courtesy of Dr. David Baker.

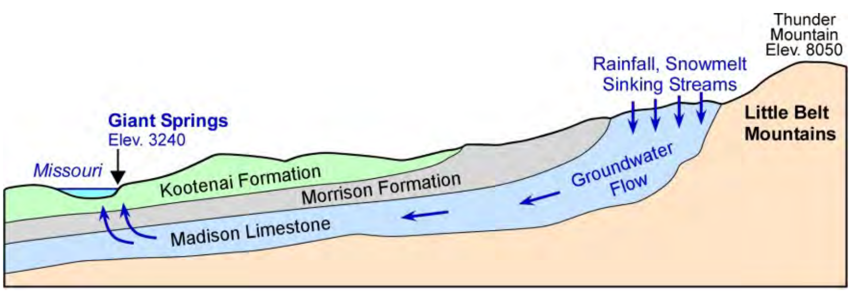


Figure 7.41 Schematic cross-section between Giant Springs and its recharge area in Little Belt Mountains. Courtesy of Giant Springs Bottled Water Company.

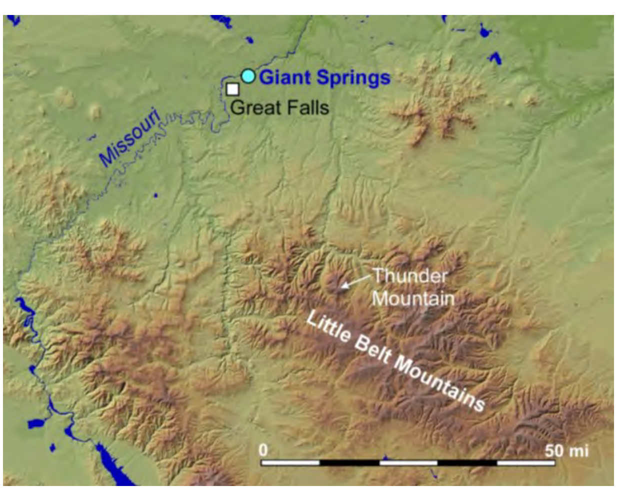


Figure 7.42 Main recharge zone for the portion of karstic Madison Aquifer drained by Giant Springs is in its outcrop areas on Little Belt Mountains. Bands of limestone bluffs break up uniform expanses of evergreen forest. Streams, which often have losing reaches, have carved beautiful, exposed escarpments and palisades. There are also numerous caves. Color shaded relief map on the left courtesy of USGS. Photo on the right courtesy of U.S. Forest Service.
https://www.fs.usda.gov/detail/hlcnf/home/?cid=fseprd499908#main_content

Giant Springs is in Giant Springs State Park, the most visited state park in Montana The springs are a source of the Roe River (only 201 feet long, before it empties into the Missouri River), once listed as the shortest river in the World by the Guinness Book of World Records before Guinness eliminated the category. The park hosts a trout hatchery, established in 1928, which uses about 15,000 gallons of water per minute by diversion from the springs. Water temperature is constantly 54 degrees Fahrenheit. A drinking water bottling company uses water sourced directly from the springs via a protected intake.

Figure 7.43 Drone photo of Giant Springs. Courtesy of Giant Springs State Park. https://fwp.mt.gov/stateparks/giant-springs/

On the Park's website, one can read the following: "Located just outside of Great Falls and encompassing nearly 14 miles of Missouri River shoreline, Giant Springs State Park has something for everyone. The park provides opportunities for hiking, biking, picnicking, photography, fishing, hunting, boating, and bird watching. Visit the Giant Springs Fish Hatchery and take a walk through the visitor center or feed the fish in the show pond.

If you are looking for something a little more active, Giant Springs provides excellent fishing opportunities along the Missouri River as well as a separate fishing pond. Take a walk, go for a run or ride your bike along the park's 30+ miles of paved and dirt single-track trails, which range in difficulty from beginner to expert. The trails are all part of the larger River's Edge Trail System, which consists of nearly 60 miles of trail around the Great Falls area. Whether you come to picnic, hike the trails, fish the Missouri, or simply admire the springs, Giant Springs State Park has exciting opportunities for the whole family!" (https://fwp.mt.gov/stateparks/giant-springs/).

7.4.2 Big Spring, Lewistown

The following description is from the Lewistown's website (https://enjoylewistown.com/big-spring-creek).

"Big Spring Creek originates seven miles southeast of Lewistown where it bubbles out of the ground from one of the world's largest fresh water springs. Historically known as a sacred site to Native American tribes, and later recorded as a valued resource for Lewistown's early settlers, Big Spring Creek remains one of Lewistown's best kept secrets. This artesian spring emerges from the Madison-Limestone aquifer formation on the north slopes of the Big Snowy Mountains and pumps from 50,000 to 64,000 gallons per minute (equivalent of 110 to 134 cfs) of 52-degree water, all year round. From here, Big Spring is diverted in part, and serves as a state fish hatchery in which thousands of brown, rainbow and cutthroat trout are raised annually.

From it's origin near the state fish hatchery, the creek runs almost thirty miles before joining the Judith River, a main tributary of the Missouri River. The creek flows through and under the City of Lewistown for a few city blocks, via a man-made channel.

Big Spring Creek is a stream of extraordinary beauty and is a superb fishery, known for its year-round, red-ribbon fly-fishing. Montana Fish, Wildlife & Parks maintains six seasonal public fishing access sites along Big Spring Creek. Lewistown is one of the few towns of its size where you can often catch rainbow and brown trout from within the city limits.

Swimming, tubing and kayaking are among the many popular recreational activities available along the creek, especially during the hot, summer months. The 25+ mile City trail system meanders along the creek for many miles, providing scenic exercise and wildlife-viewing opportunities.

Figure 7.44 Big Spring near Lewistown, Montana. Photo by Mike Cline taken on 16 August 2015, licensed under the Creative Commons Attribution-Share Alike 4.0 International license. Available at https://commons.wikimedia.org/wiki/File:Big_Spring_Creek_Lewistown_Montana_29.JPG

Aside from the world class fly-fishing and recreational opportunities, Big Spring is the main water source for the City of Lewistown, providing crystal clear, mineral-rich water to 6,000+ city residents, with little purification needed. This crystal-clear mineral water is also bottled and shipped throughout the country.

The largest cold-water trout hatchery in the state, Big Springs Trout Hatchery is located seven miles southeast of Lewistown next to Big Springs, the originating point of Big Spring Creek. The public can view fish in the hatchery raceways but are encouraged not to feed or bother them.

Big Springs Trout Hatchery began in 1922 with help from the City of Lewistown and the local Rod & Gun Club. During the 1930s, the federal government created "New Deal" programs to provide employment. Several of these programs, including the Works Progress Administration built rock-walled ponds and bridges, as well as planted willow trees for the hatchery and spring area. The original hatchery is now known as the Upper Unit.

The trees and natural rock boundaries provide a rustic, scenic backdrop for the adjacent park, which is maintained by the City of Lewistown.

The park offers wildlife viewing of deer, small mammals and a variety of birds, and includes a picnic area, shelters, restrooms, volleyball and baseball fields. The perfect spot to spend an afternoon with family and friends, the highlight of this beautiful picnic spot are the springs and trails which follow the creek as it begins its journey to town.

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Figure 7.45 Trout Hatchery at Big Springs. Photo courtesy of Montana Fish, Wildlife & Parks.

Additions have been made throughout the years, including inside and outside raceways, houses and garages. In 1959 an additional hatchery site called the Lower Unit was developed ½ mile up the road, which includes 30 outside raceways. The Lower Unit originally received water directly from Big Springs Creek, which caused water quality problems when the water became muddy due to rain and floods. In the early 1970s a canal and pipe system was constructed, which allowed the Lower Unit to get water directly from Big Springs, eliminating the water quality problem. The hatchery raises five different strains of Rainbow Trout as well as Brown Trout, Kokanee Salmon and Chinook Salmon. Big Springs Trout Hatchery stocks fish ranging from 2-12" into Montana waters." (https://myfwp.mt.gov/fwpPub/landsMgmt/siteDetail.action?lmsId=39753636).

7.4.3 Warm Spring, Lewistown

Warm Spring is located 15 miles northwest of Lewistown on the Denton Highway (driving directions: 9.5 miles north of Lewistown on US Highway 191, turn left at State Highway 81 and drive about 5 miles, turn right at the Warm Springs sign). It is the principal source of Warm Spring Creek, a tributary of Judith River.

According to Meinzer (1927), the first reported discharge measurement of the spring was 140 cfs in 1907, followed by 180-190 cfs in 1923. The water was used in part by the Barnes-King Development Co. for power in mining and milling operations, and some of the water was also used for irrigation. Today, the spring is on a private ranch owned by Vanek Family since 1940 and feeds a large 5,000-square-foor pool of water at constant temperature of 68°F (20°C). "*On a typical summer day, you can find folks of all ages swimming, picnicking, playing volleyball or horseshoes, and fishing in Warm Spring Creek. You can relax in the shade of one of many willow shoots that surround the spring. Warm Springs charges $4 for age 14 and over, $3 for ages 6- 13 and age 5 and under are free. Sorry no dogs allowed!*" (https://enjoylewistown.com/exploring-lewistown-montana/wide-open-places/warm-springs).

The fascinating history of Warm Spring and its surroundings is described by Marie Vanek in *Heritage of One of Nature's Wonders, Gigantic Warm Springs* available on the Montana History Portal at Heritage of One of Nature's Wonders: Gigantic Warm Springs | Montana History Portal (mtmemory.org); here are couple of excerpts:

As early as 1840 individual members of the Metis Indians penetrated the area to help the traders and trappers in their ventures into a beautiful valley affording as fine a grazing and agricultural district as could be seen in the territory. Trappers found many kinds of animals to trap and hunt, to use for food. They found an unusual wide stream of warm water fed from an unusual warm spring that never froze over in the winter that flowed the length of this valley of abundant grass as far as the naked eye could see. Here was an opportunity to explore the mountain ranges for the treasures that were to be had for those that were willing to brave the wild unexplored territory.

From article by Ed. Degnar "about 1872, the Judith Cattle Pool, owned by various rich mining men of Butte and Helena, was located on Warm Spring Creek and the Judith Basin country, which H.P. Brooks as foreman and wagon boss of the Two Bar Wagon and Horseshoe Bar Ranch, trailed 5,000 head of Spanish cross bred California and Texas long horn steers and turned them loose along the Judith River. They were very hardy cattle, died only by accident or starvation. They could out smart the best cattlemen, and would strike fear in the hearts of the bravest cowboys who ever handled them. They were high strung animals. They could smell a change in the weather, or water for many miles when thirsty. These longhorns were turned loose in the Warm Spring-Judith River area country to roam".

Figure 7.46 Photo from an article by Elizabeth Hawley *Guide to the Best Gigantic Warm Springs Experience* published in Pocket Montana, updated on March 13, 2024. Available at https://pocketmontana.com/things-to-do/outdoor-activities/hot-springs/gigantic-warm-spring/

Several opinions on the spring's origin and the unusually high (for non-thermal springs in Montana) water temperature of 68°F are provided by Meintzer (1927) and Calvert (1909). In the light of newer, now widely accepted understanding that this first-magnitude spring drains the deeply seated Madison limestone aquifer, the opinion by Calvert that the temperature is not result of recent magmatic activity, seems right on target:

If the spring does represent the last phase of such activity, however, it would seem highly improbable that it should be the only one in the entire district whose temperature is noticeably above the average. Likewise, it would seem strange that not even this spring is depositing lime. In fact, field analysis of its waters shows that they contain no more than the average of carbonates for that region. It might also be argued that the temperature is a result of recent faulting, and the fact that the spring is directly on a fault line gives weight to that assumption. However, numerous other faults, apparently contemporaneous, occur in the region, and since springs near them are not affected as regards temperature, it would seem that some other cause should be sought to account for the exceptional temperature of the water of Warm Spring. A much more probable theory regarding the elevated temperature of the spring water is that it has come from a considerable depth.

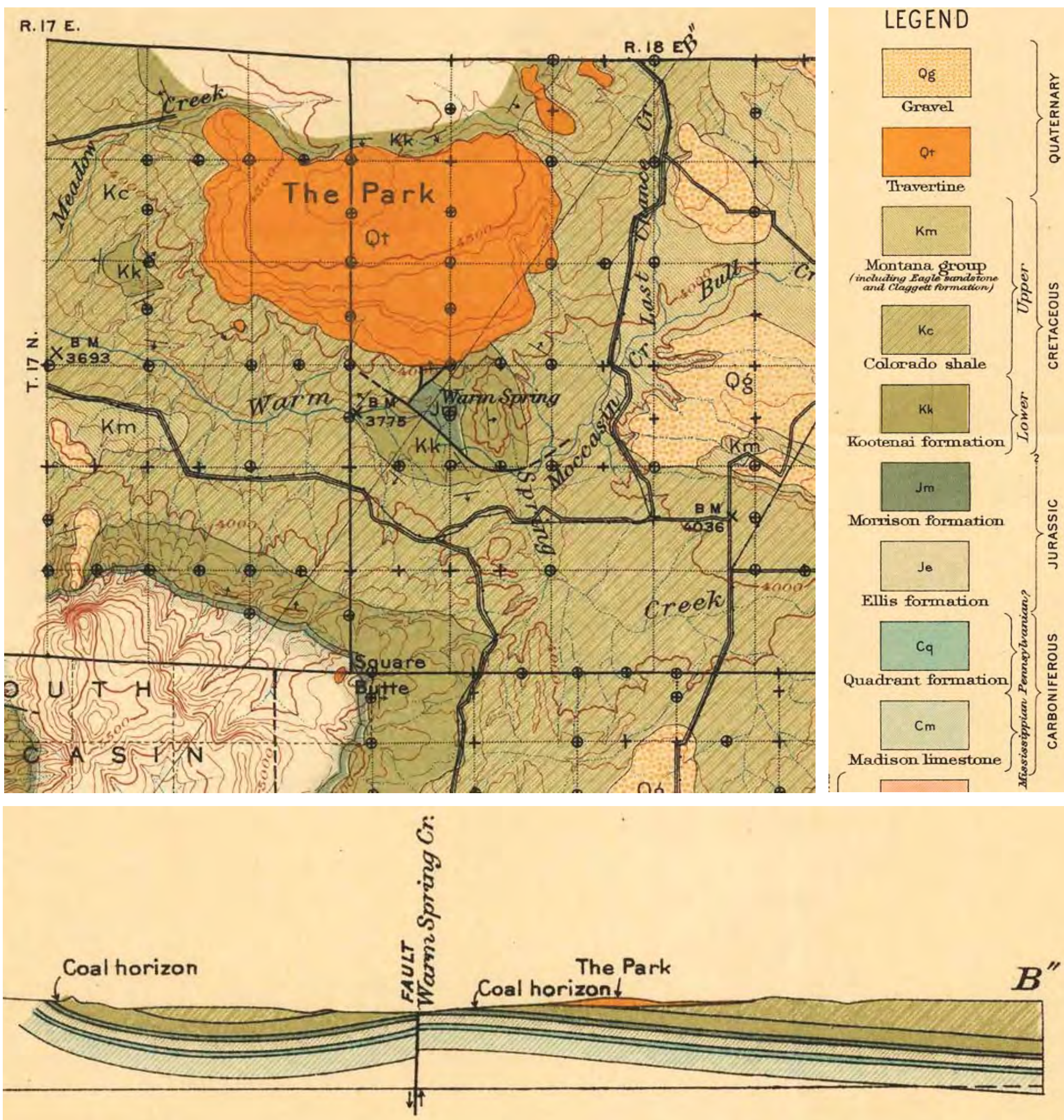


Figure 7.47 Geologic map and cross-section of the Warm Spring area. From Calvert, 1909 (portion of Plate 1).

7.5 Nevada and Utah

All large springs in Nevada and many in Utah are issuing from the Basin and Range carbonate-rock aquifers.. Although the Basin and Range Province is primarily structural, faulting has been accompanied by widespread volcanism which, together with the complicated tectonics and the related deep groundwater circulation, is the main reason for countless thermal springs in the Basin as well.

The Great Basin comprises the entire northern portion of the Basin and Range physiographic province. It contains parts of southwestern Oregon, southeastern Idaho, western Utah, and nearly the entire state of Nevada. "Basin" in the name reflects the fact that all groundwater is internally drained and does not discharge to the ocean.

Within the Basin and Range province, the Earth's crust has been stretched up to 100% of its original width. As it expanded, the crust thinned and cracked, creating large faults. Along the trending faults, mountains were pushed up, and valleys carved below creating a distinctive alternating pattern of ranges and valleys which are typically 10 to 20 miles across.

The geology, topography, and dry climate create impressive features and landscapes. These include pediments, alluvial fans, bajadas, bolsons, inselbergs, playas, mud flats, salt flats, lakes, sand dunes, and canyons, many of which are in various national and state parks and national monuments (National Park Service, https://www.nps.gov/articles/basinrange.htm).

The carbonate-rock aquifers store a large amount of water and lie below basin-fill aquifers and in ranges adjacent to them. They are viewed as a potential future source of water in this dry climate environment, including for ever-expanding urban centers such as Las Vegas.

As explained by USGS (Thiros et al., 2014), the Basin and Range carbonate-rock aquifers cover an area of about 92,000 square miles, mostly in Nevada and Utah (see map in Figure 7.49). The carbonate-rock aquifers consist of thick sequences of Paleozoic limestone and dolomite interbedded with shale, sandstone, and quartzite. A regional assessment of the availability of groundwater in both the basin-fill deposits and carbonate rocks is presented in Heilweil and Brooks (2011).

In Nevada and Utah, carbonates and other sedimentary rocks were deposited on the continental shelf of the ancestral coast of North America between 570 million and 280 million years ago. The layers of ancient marine sediments have a cumulative thickness of as much as 40 thousand feet. All the sedimentary rocks in this sequence, where deformed and fractured, may transmit some groundwater flow, it is the carbonate-rock layers, because of their brittleness and dissolution by flowing water, that are the principal aquifers (Dettinger, 1989). Due to tectonic forces (faulting and folding), these carbonate aquifers have complex shapes and are connected to aquifers of other rock types. Some of the blocks may be highly productive aquifers, whereas others may transmit only moderate quantities of water or impede flow altogether. Regional groundwater flow, through both the carbonate-rock aquifers and basin-fill aquifers, is from the areas of recharge (rain and snow on the mountain ranges) towards the areas of discharge (springs, playas; see Figures 7.50 and 7.51).

An example of one of the many threats facing springs and groundwater resources in the Great Basin is the fight by locals in Spring and Snake Valleys in Nevada and Utah to protect their water from the relentless thirst of Las Vegas. Various environmental and citizens groups challenged a proposed northeastern expansion of Southern Nevada Water Authority (SNWA) water supply wells and a 300-miles long pipeline.

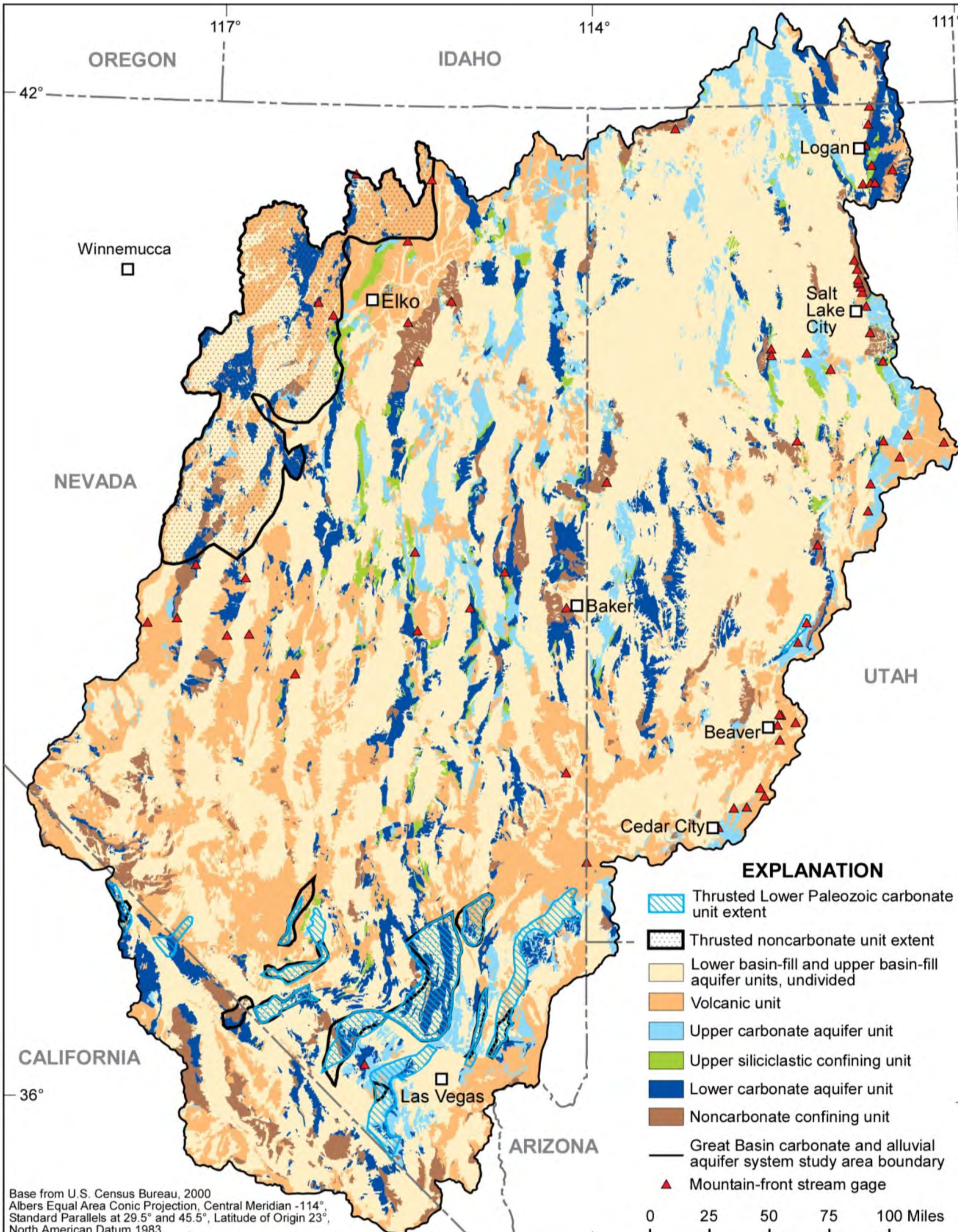


Figure 7.49 Surficial hydrogeologic units of the Great Basin carbonate and alluvial aquifer system. Modified from Sweetkind et al. (2011).

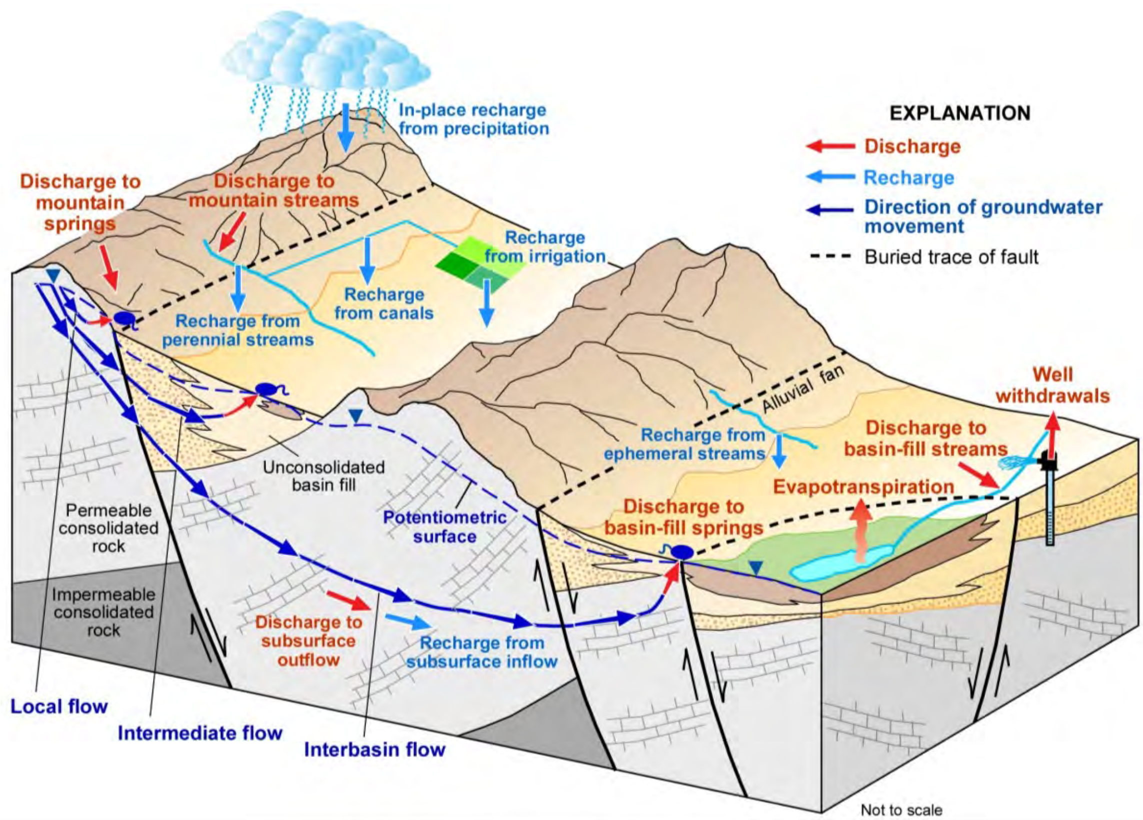


Figure 7.50 Schematic diagram showing conceptualized groundwater flow in the Great Basin carbonate and alluvial aquifer system. Modified from Sweetkind et al. (2011).

Figure 7.51 Clay Spring emerges in South Snake Valley (basin) in Utah and helps water Burnbank Meadows, large wetlands and wet meadow complex, and Pruess Lake fishery. In the first decade of 2000s it was threatened, together with other springs in the valley, by a proposed expansion of the Southern Nevada Water Authority (SNWA)desperately looking for additional groundwater sources for the exploding population of Las Vegas. More detail is provided in the text. Photo courtesy of Gretchen Baker.

In addition, the state of Utah initiated a comprehensive groundwater monitoring program in the area and completed a report summarizing likely impacts of the proposed large-scale pumping from the Snake Valley aquifer on its water resources (Kirby and Hurlow, 2005). The Utah Association of Counties petitioned the federal government, requesting that four agencies of the Department of Interior, including the Bureau of Land Management and the Bureau of Indian Affairs, file protests against the plan. In 2013, the Utah Governor Gary Herbert decided not to sign a controversial water-sharing agreement with Nevada, despite the pressure from Utah's neighbor and the threat of a lawsuit; the two states negotiated for years over the division of water from the Snake Valley aquifer, which straddles the border and is home to small ranching and farming communities.

The conclusions of the Utah Geological Survey assessment of likely impacts of the proposed water diversion from Snake Valley are as follows (Kirby and Hurlow, 2005):

- Wells proposed by the Southern Nevada Water Authority will likely adversely affect groundwater conditions in nearby Utah.
- The total drawdown of groundwater near Garrison in western Millard County could be greater than 100 ft (31 m).
- The proposed pumping may change or reverse groundwater flow patterns for much of the east-central Great Basin in Utah and Nevada. The effects may eventually propagate eastward and impact discharge at important regional springs in Wah Wah Valley and Tule Valley.
- Discharge of agriculturally and ecologically important springs will decrease.

Clay Spring (Figure 7.51), which originally attracted some of the first settlers in Snake Valley, the Clay family, is just one of the many springs in Snake Valley and the adjacent Spring Valley that could be affected by the proposed large-scale groundwater pumping, such as the one shown in Figure 7.52. The photograph illustrates the contrast of a spring ecosystem that supports a variety of wildlife including migrating birds, deer, elk, pronghorn, small mammals, and aquatic organisms, with the surrounding dry Great Basin desert. A small drawdown in groundwater near this area could reduce or eliminate spring flow and result in the disappearance of these important oases. (https://www.protectsnakevalley.org/page0.html).

Figure 7.52 A spring in Spring Valley (which is adjacent to Snake Valley) that may be affected if the proposed expansion of Southern Nevada Water Authority is revived. Photo courtesy of Gretchen Baker.

Figure 7.53 shows the results of a regional groundwater flow study in southern Nevada. The total rate of flow in carbonate-rock aquifers is estimated to be about 77 thousand acre-feet per year (approximately 108 cfs; note that one acre-foot-year equals 0.0014 cfs). The main discharge is at two large groups of springs, Ash Meadows and Muddy River Springs, or through the basin-fill sedimentary aquifers that partly fill valleys, while the rest flows out of Nevada into adjacent states, mostly California (Dettinger, 1989). It is interesting that, due to a very low recharge (large portions of Nevada and Utah are desert terrains), the entire groundwater flow in this vast area is less than the average flow of many individual first magnitude karst springs in Florida or the Ozarks.

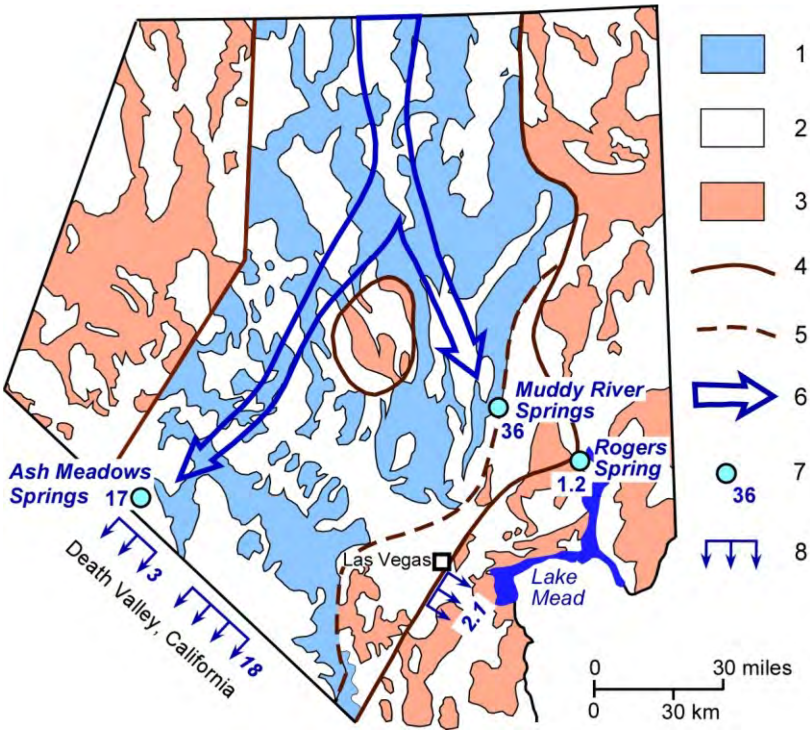


Figure 7.53 Components of regional groundwater budget within Central Corridor in southern Nevada. (1) Carbonate rock outcrops within Central Corridor; (2) Basin fill; (3) Areas underlain by thin or isolated carbonate rocks, or carbonate rocks that may contain poor-quality water; (4) Boundary of Central Corridor; (5) Western limit of rock sequences containing salt-bearing minerals and overlying carbonate rocks. Groundwater east of this line is generally poor quality; (6) General direction of regional groundwater flow; (7) Spring with the annual discharge in acre-feet per year or AFY (one AFY equals 0.0014 cfs); (8) Regional groundwater outflow to Death Valley and California, in acre-feet per year. Modified from Dettinger, 1989.

7.5.1 Ash Meadows Springs, Nevada

Ash Meadows is drained by Carson Slough, a through-flowing tributary of the Amargosa River, which terminates in Death Valley. The boundaries of Ash Meadows are poorly defined, but the name is generally applied to the gently sloping terrain, watered by numerous springs, within the southeastern part of the Amargosa Desert, part of the greater Mojave Desert. The western boundary of Ash Meadows corresponds to the western limit of the low salt meadows in the Carson Slough bottomland. Fairbanks Spring defines the northern limit, and Bole Spring is approximately the southern limit. As thus defined, Ash Meadows lies wholly in Nevada (Dudley and Larson, 1976).

Figure 7.54 Ash Meadows area from above. Courtesy of Ecoflight, 2023.

Groundwater discharges from the Ash Meadows groundwater flow system at dozens of springs and seeps in the Ash Meadows National Wildlife Refuge (Figure 7.54). The refuge includes about 21,850 acres of desert uplands and spring-fed oases. The springs and seeps in the Refuge are an area of major discharge of groundwater that flows beneath the eastern part of the Nevada Test Site toward Death Valley in California (Nichols et al., 1997; USGS).

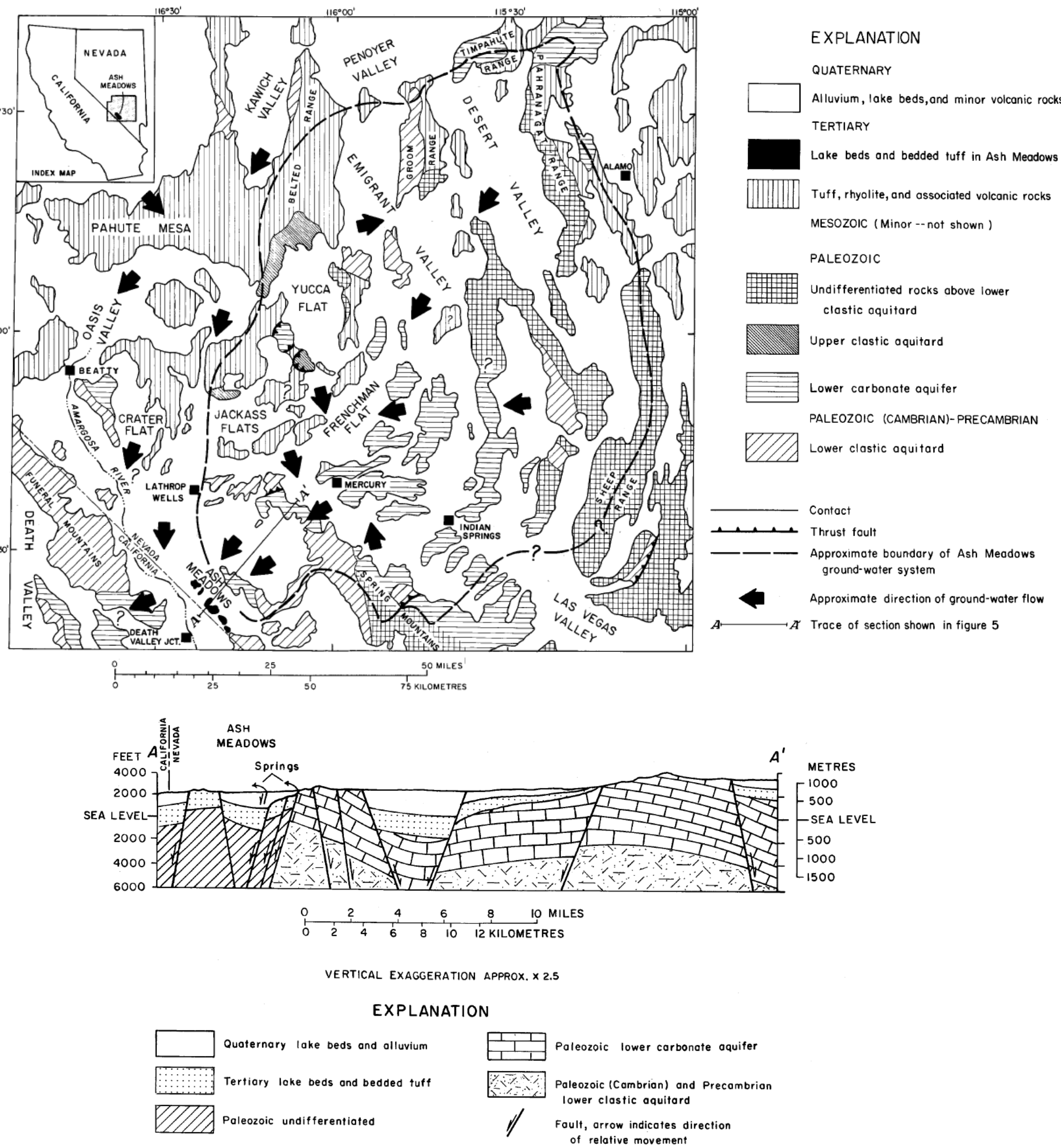


Figure 7.55. Top: Generalized hydrogeology and boundary of the Ash Meadows groundwater system. Adapted from Carlson and Willden, 1968; Denny and Drewes, 1965; and Winograd and Thordarson, 1975. Bottom: Generalized geologic section along flow path approaching Ash Meadows. Modified from Winograd and Thordarson, 1975. From Dudley and Larson, 1976.

The highly transmissive lower carbonate aquifer is widely distributed beneath the ranges and basins lying to the northeast of Ash Meadows. Recharge to the aquifer moves through fractures and fault zones, which form a conduit system so permeable that it acts as a gigantic drain for about 4,500 mi^2 (Winograd and Thordarson, 1975). The flow system encompassed by this area (Figure 7.55) discharges at the numerous springs in Ash Meadows and is therefore known as the Ash Meadows groundwater system. Walker and Eakin (1963) estimated the natural spring discharge of the system to be about 17,000 acre-ft per year (about 23.5 cfs).

Between the altitudes of 2,325 ft and 2,175 ft, in the 1970s, dozens of springs and small seeps discharged a total of about 11,000 gal/min (24.5 cfs). About 3,000 gal/min (6.7 cfs) of that was from Crystal Spring alone (Dudley and Larson, 1976; see Figure 7.56).


Figure 7.56 *Left*: Crystal Spring at Ash Meadows National Wildlife Refuge (NWR). Photo by Mason Voehl, courtesy of Amargosa Conservancy (https://www.amargosaconservancy.org/explore/discover-ash-meadows-national-wildlife-refuge/). *Right*: Ash Meadows NWR Crystal Spring Boardwalk leads to a beautiful Caribbean-blue spring pool. This spring produces 2,800 gallons of water per minute (6.25 cfs), is approximately 15 feet deep, and the water stays a constant 87°(F) 30°(C). The length of the boardwalk is approximately 0.9 miles round-trip and there are benches, viewing area complete with scopes and colorful informational panels along the way. The boardwalk is wheelchair accessible, but no bicycles are allowed. Photo by Rod Colvin, U.S. Fish & Wildlife Service.

Ash Meadows National Wildlife Refuge (https://www.fws.gov/refuge/ash-meadows) can be reached from Las Vegas by taking US-95 North to NV-373 South at Lathrop Wells/Amargosa Valley, and continuing on NV-373 South to Death Valley Junction and turning on State Line/Belle Vista Road to Spring Meadows Road (dirt road) to the South Entrance.

Figure 7.57 Ash Meadows wetland. Photo by Alan Nyiri, U.S. Fish & Wildlife Service (USFWS).

As written by Adamas Weitzenfeld and Jennifer Heroux in a story for the USFWS entitled "Galapagos in Mojave Desert": *Despite being located in the hottest and driest corner of the United States, Ash Meadows National Wildlife Refuge is home to the second greatest concentration of endemic species in North America. In just under 24,000 acres live 26 species found nowhere else on Earth. That's because approximately 10,000 years ago, as the climate warmed, aquatic species survived by seeking refuge in receding and fragmenting wetlands. Isolated for millennia, the survivors evolved into new species in separated "islands of water" scattered across a sea of desert. Nearly all of Ash Meadows' endemic species live in or around its 50 springs and seeps.*

The story of this wetland's conservation begins thousands of years before the United States existed. Countless generations of the Nuwu and Newe's ancestors seasonally cared for the land known as Koieechee and Qwaiuhwuzzah. In the 19th century, Anglo-American settlers arrived and re-named and re-imagined the land as Ash Meadows. Nonetheless, the Nuwu and Newe continued to live and gather at Ash Meadows until the mid-1900s when large agricultural endeavors displaced them. Driven more by profit than stewardship, the landowners drained and mined the marshes, bulldozed and plowed mesquite meadows, straightened and piped spring outflows, and introduced bullfrogs and bass, thus imperiling endemic species and the original caretakers' relationship to the land.

Figure 7.58 Endanegerd and Federally protected Devil's Hole pupfish, one of the world's rarest fish. Photo by O. Feuebacher, U.S. Fish & Wildlife Service.

*Though a 1976 U.S. Supreme Court ruled in favor of federal water rights to protect the Devils Hole pupfish from dropping water levels (*caused by groundwater pumping for irrigation; author's note*), this landmark decision did not fully protect Ash Meadows' other endemic species. Soon after, a land development company purchased the land from the farmers to build a 50,000-person resort community. The proposed community would have paved over rare habitats and consumed three times the annual discharge of all 50 springs. In 1984, the efforts of conservationists paid off again, and the Nature Conservancy successfully acquired and transferred the land to the care of the U.S. Fish and Wildlife Service. On June 18 it became Ash Meadows NWR.*
https://www.fws.gov/story/ash-meadows-galapagos-mojave-desert

Figure 7.59 *Left*: Kings Pool is one of many freshwater springs at Ash Meadows National Wildlife Refuge (NWR). Visitors can view the spring by walking along the boardwalk at the Point of Rocks trail. Photo by USFWS, https://www.fws.gov/media/kings-pool-ash-meadows-refuge. *Right*: Big Spring at Ash Meadows NWR. Photo by Kate Bloomfield, USFWS.

Ash Meadows National Wildlife Refuge was named after the galleries of ash trees described in expedition notes from 1893. This desert oasis, a very rare and unique ecosystem, is recovering and playing an important role in global conservation efforts. The refuge strives to promote conservation management and awareness through environmental education, outreach programs, volunteerism, and visitor services programs (https://www.fws.gov/refuge/ash-meadows).

U.S. Fish & Wildlife Service lists the following top reasons to visit Ash Meadows:

- The largest remaining oasis in the Mojave Desert.
- An internationally recognized wetland and designated Ramsar site.
- Home to relict species of desert fish that have existed here since the Pleistocene.
- The highest concentration of endemic species in the United States.
- Four endangered fish species and eight threatened or endangered plant species.
- Diverse habitat including dune fields, alkali seeps, and groves of mesquite and ash trees.
- Spring systems fed by fossil water that originated from the last ice age.
- Three points of interest with wheelchair accessible boardwalks, restrooms, interpretive signs, views, and picnic areas.
- Opportunities for education, photography, wildlife observation, and hunting.

AMARGOSA CONSERVANCY

THE FIGHT TO SAVE ASH MEADOWS, DEATH VALLEY, AND THE AMARGOSA VALLEY

https://www.amargosaconservancy.org/news-blog/the-fight-to-save-ash-meadows/

Included here are several excerpts from this very recent (summer of 2023) and desperate call for action:

Canadian mining company Rover Critical Minerals (then named Rover Metals) in summer of 2023 submitted an application to the Bureau of Land Management (BLM) seeking to conduct a lithium exploration project that included drilling up to 30 boreholes to a depth of 300 feet on the northern boundary of the Refuge.

The looming prospects of exploratory drilling and open-pit mining illuminated the reality that despite 40 years of protected status and management under the U.S. Fish and Wildlife Service, Ash Meadows remains highly vulnerable to impacts from beyond its designated borders. And beyond Ash Meadows, the rural communities of this corner of the Mojave desert also came to the realization that their lives and livelihoods revolved around the sustainable conservation of groundwater. Consensus quickly formed around the notion that *left unchecked, mineral exploration and industrial mining on unprotected public lands posed a potentially existential threat to communities whose lifeblood is the flow of groundwater ferried by the Amargosa River.*

A coalition including the Timbisha Shoshone Tribe, 24 nonprofit organizations, local governments, and concerned citizens led the fight against this project over the summer and raised the alarm. As a result of public pressure and litigation filed by the Amargosa Conservancy and the Center for Biological Diversity, the BLM rescinded their approval of Rover Metals' initial project application on July 19th, 2023. The BLM also required the company to conduct a full National Environmental Policy Act review and to submit a full Plan of Operations.

At the time of this writing (summer of 2024), the destiny of Ash Meadows is still in peril.

7.5.2 Muddy River Springs (Warm Springs), Nevada

The Muddy River Springs, also commonly referred to as Warm Springs, are in the northwestern end of Moapa Valley, and include a network of springs and seeps that form the headwaters of the Muddy River (Figure 7.60). Over time, this area has been home to the Anasazi and the Southern Paiute Indian tribes, outlaws, prospectors, Mormon settlers, and others (Beck et al., 2006; Baxter and Haworth, 1996; U.S. Fish and Wildlife, 1991). The availability of water has provided past and current inhabitants with the resources necessary to sustain life in a desert setting. In addition, nearby entities, such as the Moapa River Indian Reservation, the Moapa Valley Water District (MVWD), and the Nevada Power Company (NPC), use water obtained from surface streams fed by the springs (Beck et al., 2006).

The Warm Springs area is home to the Moapa Valley National Wildlife Refuge. The refuge was established in 1979 solely to protect and secure the riparian habitat of an endangered native minnow, the Moapa dace (Moapa coriacea; Figure 7.61). It was the first National Wildlife Refuge created for the purpose of protecting an endangered fish species.

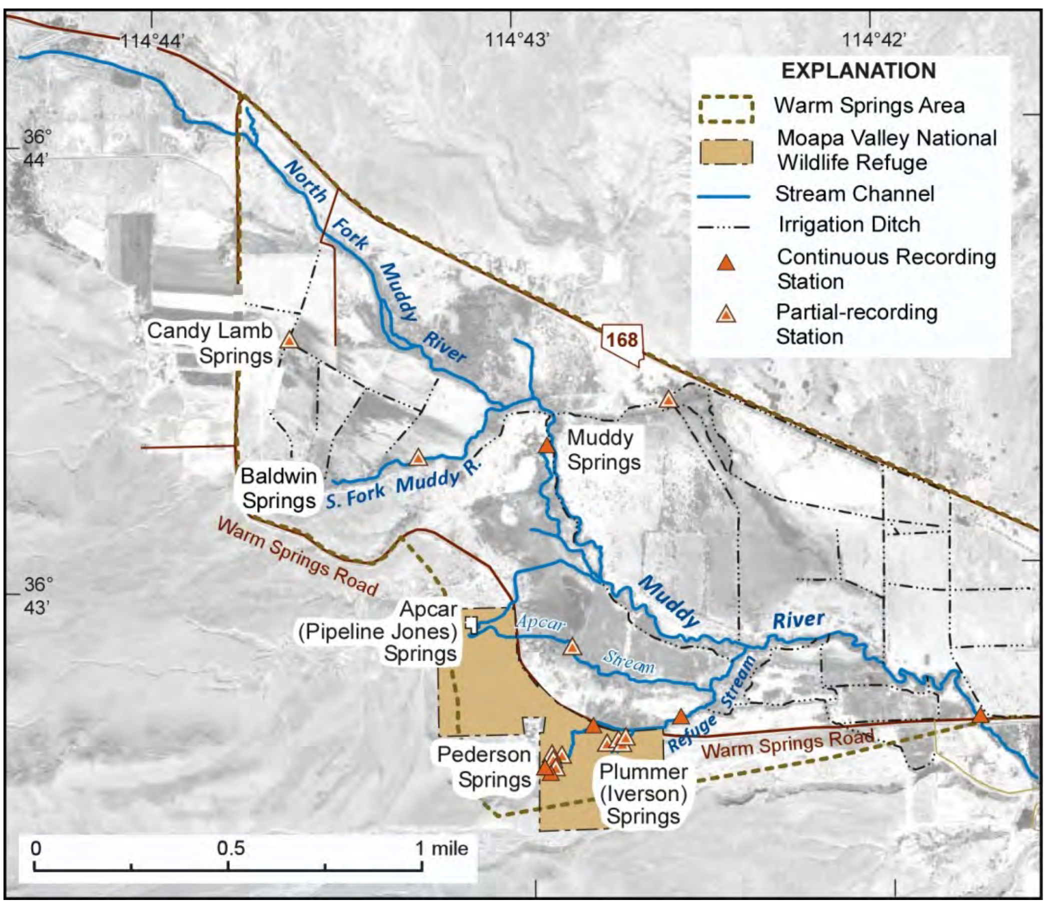


Figure 7.60 Location of major spring groups, and U.S. Geological Survey monitoring stations on August 17, 2004, in the Warm Springs area near Moapa, Nevada. Modified from Beck et al., 2006.

The Moapa Valley NWR is in the Warm Springs area of the upper Moapa Valley in northeastern Clark County in southern Nevada. It lies just south of State Highway 168 and the Muddy River, between Interstate 15 on the east and U.S. Highway 93 on the west. The refuge is bounded on the North by Warm Springs Road, on the south by Battleship Wash, and on the east and west by private property. It is approximately 60 miles northeast of the city of Las Vegas and 9 miles west of the town of Glendale.

Dace habitat on the refuge consists of stream channels supported by six springs, three of which are within refuge boundaries (Apcar, Pederson, and Plummer Springs; see Figures 7.60 and 7.63).

Figure 7.61 Moapa Dace (front center) and Springfish. Photo by Mark Hereford, USGS. The Moapa dace is one of six endemic species at Warm Springs. These endemic species are native and can only be found in this region of Nevada and nowhere else on earth. Of all the sensitive species at Warm Springs, the Moapa dace is the most imperiled. Listed as an endangered species in 1967 under the Federal Endangered Species Preservation Act, the preservation and population recovery of the Moapa dace has received the highest priority in the management of Warm Springs, and the U.S. Fish and Wildlife Service considers the recovery of the Moapa dace to be essential in this region.

Stable flows from the refuge's springs (see Figure 7.62) fill meandering channels downstream that provide ideal habitat for dace, Virgin River chub and other species of endemic fish and invertebrates. The spring bank and riparian plant communities provide habitat for southwestern willow flycatcher as well as a rich diversity of migratory and resident songbirds, colonial nesting species, and other native wildlife. The springs are thermal in nature and have an average annual water temperature of 90 degrees Fahrenheit at their points of discharge.

Before the refuge was established, dace populations were in peril due to habitat destruction and modification. Competition with introduced species such as mosquitofish, shortfin molly, and tilapia also contributed to the dace's decline. However, as more and more habitat is restored (Figure 7.63) and non-native species are removed, the fish has begun to rebound. Population surveys show an increase in numbers in recent years. As of February 2024, there were 1,935 dace in the Muddy River system. Biologists say that there needs to be a stable population of at least 6000 to ensure the security of the species (https://www.fws.gov/refuge/moapa-valley).

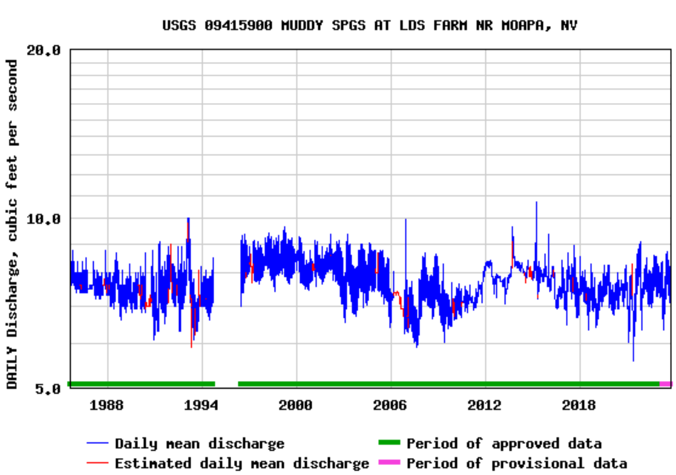


Figure 7.62 Discharge rate, in cfs, of Muddy Springs at gaging station Church of the Latter-Day Saints (LDS) farm near Moapa, Nevada.

The Warm Springs are near the southern boundary of the White River groundwater flow system developed in carbonate rocks of Paleozoic age and sedimentary rocks of Tertiary age. Carbonate rocks form complex aquifers whose extents and thicknesses are largely unknown (Prudic et al., 1995). Discharge from the springs and seeps of the Warm Springs area is believed to be the largest and most southerly outflow from this groundwater system. Recharge is primarily from precipitation in the high mountain ranges in east-central Nevada (Eakin, 1966).

Figure 7.63 *Left*: Restored Pederson Spring. *Right*: Confluence of three spring runs coming from Plummer Springs. Photographed June 9-10, 2004 by D. Beck. From Beck et al., 2006.

The fascinating history of the Muddy River Springs water resources development is described by Beck et al. (2006, Appendix A; see also Figures 7.64 and 7.65). Below are a few interesting points.

The first known dwellers in the area were the Anasazi and the Southern Paiute Indians (Baxter and Haworth, 1996). Little is known about the Anasazi in southern Nevada. By the early 1800s, the Paiutes had sizable populations along the Muddy and Virgin Rivers. Although most of these riverine and desert groups were primarily foragers and hunters, the Paiutes were known to also have irrigated crops, such as corn, squash, melons, and wheat, along the banks of the Muddy River (Mozejko, 1981). In addition to using the river as a source of irrigation and drinking supply, the Paiutes also used it for ceremonial rites, which are still practiced today within the Moapa Paiute Indian Reservation (Phil Swain, Moapa Band of Paiutes, oral communication., 2004).

The first known ranch in the Warm Springs area was started in 1871 with several cattle and horses rustled by a fugitive bank robber from Texas. He built a rock house just north of the current Church of the Latter-Day Saints (L.D.S.) Recreation Area (Baxter and Haworth, 1996). He called the ranch Stone Cabin Springs and worked it until his death in 1882.

Past and present owners of large tracts of land and various springs include Francis Taylor, who established Warm Springs Ranch. Billionaire Howard Hughes, after seeing the Warm Springs area during a test flight, purchased the entire Warm Springs Ranch. Although he owned the Ranch for nearly 8 years, Hughes reportedly never set foot on it; (Baxter and Haworth, J., 1996). The Church of the Latter-Day Saints (L.D.S.), Desert Oasis Warm Springs Resort, Frederick Apcar, the Federal Government (the land is managed by the U.S. Fish & Wildlife Service), Clarvid Lewis, were all owners along with other private ranchers and farmers.

Farming and ranching continue today within the Warm Springs area, but land usage has dropped significantly since its peak in the mid-1970s.

In December 1997, the Nature Conservancy and U.S. Fish and Wildlife Service signed an agreement for cooperative management of the Moapa Valley National Wildlife Refuge. The endangered Moapa Dace have increased in Refuge streams as UFWS and Conservancy staff and volunteers have restored stream habitat by removing excess vegetation, digging out years of accumulated pea gravel, and restoring natural pools, riffles, and the natural substrate. The Conservancy has played a key role in developing cooperation between public agencies and private landowners to control the invasion of tilapia, an exotic fish, which has appeared as an emergency threat to dace and other native fish in the Muddy River.

Today, the Conservancy is facilitating a broad-based scientific consensus on the conservation and restoration priorities for the Muddy River under the auspices of the Clark County Multiple Species Habitat Conservation Plan. The Conservancy has provided leadership in the acquisition process, as well as technical and contractual services to the transactions (The Nature Conservancy - Muddy River/Meadow Valley Wash Project (archive.org).

Figure 7.64 View of the Francis Taylor Mansion built in the 1950s in the Warm Springs area. The pool is fed by a spring. Photographed in July 2004 by D. Beck. From Beck et al., 2006.

Figure 7.65 Swimming pool fed by a spring in the recreation area of the Latter-day Saints Church property in Warm Springs near Moapa. Photographed in June 2004 by D. Beck. From Beck et al., 2006.

For years, Warm Springs , together with the precious Moapa dace and all other endemic species that live nowhere else on Earth, were threatened by the proposed Coyote Springs development upgradient of the springs. The development is envisioned as a man-made oasis, entirely relying on pumping of groundwater for nearly 160,000 homes, a golf course, and all other excesses that go with it, on more than 40,000 acres in the middle of the desert (see Figure 7.66 for a likely outcome of such a development). Below are excerpts from a press release of the Center for Biological Diversity, illustrating the (temporary?) victory for those that were opposed to the development.

Figure 7.66 After an initial "bounty" (top), the bottom cartoon shows the likely outcome of developing a brand-new city on more than 40,000 acres in the middle of the desert, entirely relying on pumping of groundwater for nearly 160,000 homes, a golf course, and other wonders of modern American life. Cartoons courtesy of Marin Kresic.

Nevada Supreme Court Affirms Protecting Water for Wildlife - Center for Biological Diversity

For Immediate Release, January 25, 2024
Nevada Supreme Court Affirms Protecting Water for Wildlife

CARSON CITY, *Nev.*— The Nevada Supreme Court ruled today that the state has a right to manage groundwater for the preservation of senior water rights and the public interest, including wildlife.

Today's decision in the Lower White River Flow System case will help determine the future of water management in the driest state in the union. The Center for Biological Diversity was a co-respondent in the case.

"This is a monumental victory for the conservation of water resources in a time of escalating climate change and drought," said Patrick Donnelly, Great Basin director at the Center. "Nevada's animals are already under stress from the lack of water resources, and our victory will help ensure that industry and developers don't leave wildlife high and dry."

The case centers around an aquifer that sustains the Muddy River in Clark County, Nevada. This spring-fed oasis provides habitat for an endangered fish called the Moapa dace. The Muddy River is also a source of drinking water for Las Vegas.

Coyote Springs, a proposed city of a quarter-million people in the desert 50 miles northeast of Las Vegas, applied for groundwater rights to pump water that scientists say would deplete the springs the Moapa dace relies on for survival.

The state engineer, Nevada's water czar, ordered a pump test and extensive hydrologic investigations. He then ruled that there was a finite supply of water available in the aquifer and that excessive pumping would impair senior water rights and harm the Moapa dace.

In its ruling today, the court overturned a district court ruling in *Sullivan et al. v. Lincoln County et al.*

The court also remanded the case back to the District Court Judge Bita Yeager for a ruling on whether the state's order was based on substantial evidence. This is a distinct set of legal criteria from today's ruling, which evaluated whether the state had the power to issue the order.

"We've been fighting for this little fish for more than 15 years, and we're not backing down an inch," said Donnelly. "We'll continue to press our case and we won't rest until we can pound the nails into Coyote Springs' coffin."

7.5.3 Rogers Spring, Nevada

Rogers Spring is in Lake Mead National Recreation Area operated by the National Park Service (GPS coordinates:36°22′40″N, 114°26′37″W). It is situated right beside Northshore Road (Hwy 167), 51 miles north of the visitor center and about one hour drive from Las Vegas.

As described by NPS (2024; https://www.nps.gov/lake/learn/nature/rogers-spring.htm), Rogers Spring and other smaller springs such as Corral Spring and Blue Point Spring in the "North Shore Complex" comprise one of the terminal discharge areas for the regional carbonate-rock aquifer system of eastern Nevada and western Utah. Groundwater discharge from these springs along the Rogers Spring Fault totals approximately 1,000 gallons per minute, with temperature ranging between 82 and 90°F. Due to the importance of the springs from both an ecological and recreational standpoint, the National Park Service remains vigilant in protecting these water features from potential adverse effects associated with nearby, large-scale ground water pumping from the regional carbonate-rock aquifer (see Figure 7.66).

The prevailing theory suggests that much of the recharge water that enters the carbonate-rock aquifer occurs in the high mountain ranges around Ely, Nevada, located 250 miles north of Lake Mead. As this groundwater flows south through the carbonate rocks, it encounters several faults along the way, including the Rogers Spring Fault, which has caused the older carbonate rocks (primarily limestone and dolomite) to be displaced against younger evaporite deposits of the Muddy Creek and Horse Spring formations. Here, the lower permeability of these evaporite deposits, along with high subsurface water pressure, forces the ground water in the carbonate rocks to flow upward along the fault and emerge at the surface as Rogers Spring (Figures 7.67 and 7.68).

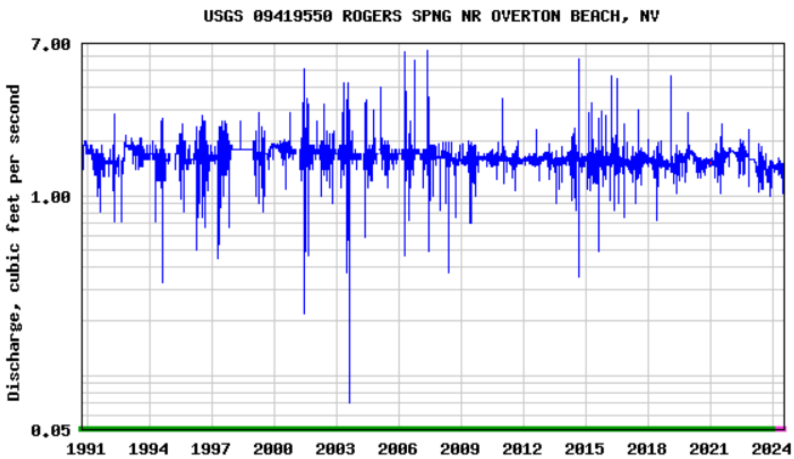


Figure 7.66 Discharge rate hydrograph of Rogers Springs. Average is 1.8-1.9 cfs, with a slightly declining trend since late 1990s, likely due to large-scale pumping in the area.

Figure 7.67 View of Rogers Springs with Lake Mead in the background. NPS Photo by Andrew Cattoir.

Rogers Spring and Blue Point Spring both share a colorful history. One story involves a 1903 project to build a canal to divert water from both springs to 500 acres of farmland located several miles south of St. Thomas. During this effort, several industrious men used a horse team, scraper, homemade ditcher and shovels to construct a channel to connect both springs. They tested the channel and discovered that the water flowed only a short distance before soaking in. Undaunted, they lined the ditch with clay to prevent leakage, and when that failed, they borrowed $3,000 and took several months mixing cement by hand and again lining the ditch. Eventually, they were successful in transporting the water to the intended land. However, the project ultimately failed due to economic reasons. The men involved evidently drank the spring water while working on the project. Unfortunately, this water acted as a natural laxative, and they lost a considerable amount of weight. Subsequently, the channel discharging water from Blue Point Spring became known as "Slim Creek." (NPS, 2024)

Figure 7.68 Rogers Spring footbridge. Photo courtesy of NPS. Available at [Photo Gallery (U.S. National Park Service) (nps.gov)]

7.5.4 Utah Springs

The official database maintained by the Utah Geospatial Center contains 16,719 springs (Figure 7.69), which is about sixteen times more than the official number of 1,114 Florida springs in the Florida Department of Environmental Protection Geospatial Open Data. In comparison, other states with more than 1,000 officially recognized springs include Missouri (4,451), Nevada (4,406), Kentucky (2,899), Texas (1,891), and Virginia (1,638). California's Geoportal database of combined spring, seeps, and Areas of Conservation Emphasis (ACE) has 63,890 entries, but it is not entirely clear what they represent and how many springs are in it. In addition, the California Portal is not as friendly as, for example, the Missouri springs Geographic Information System (GIS)—one cannot simply plot or visualize online the distribution of springs in California. Apparently, this is because there are "Too Many Records" when attempted to do so, as indicated by the message that pops up in the CA Portal (California often seems to be doing things differently than other states...).

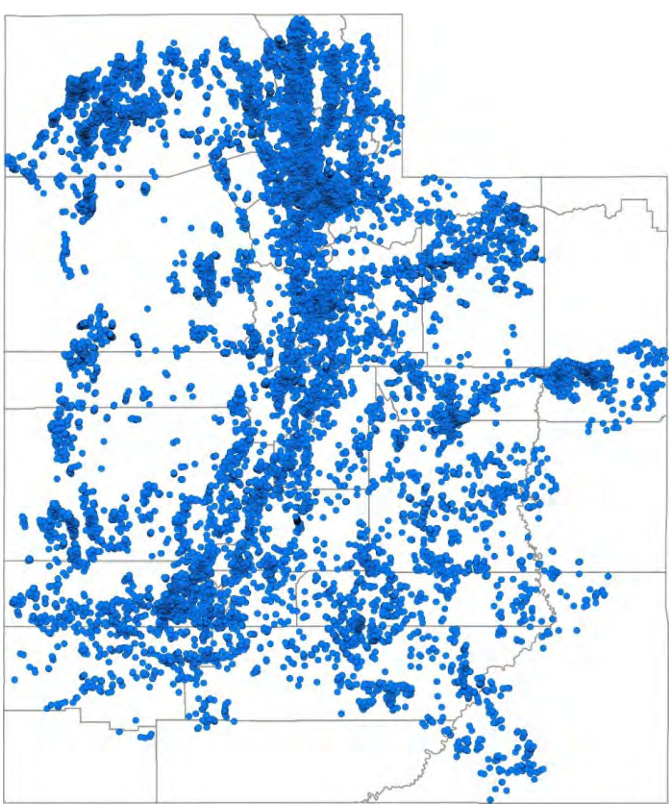
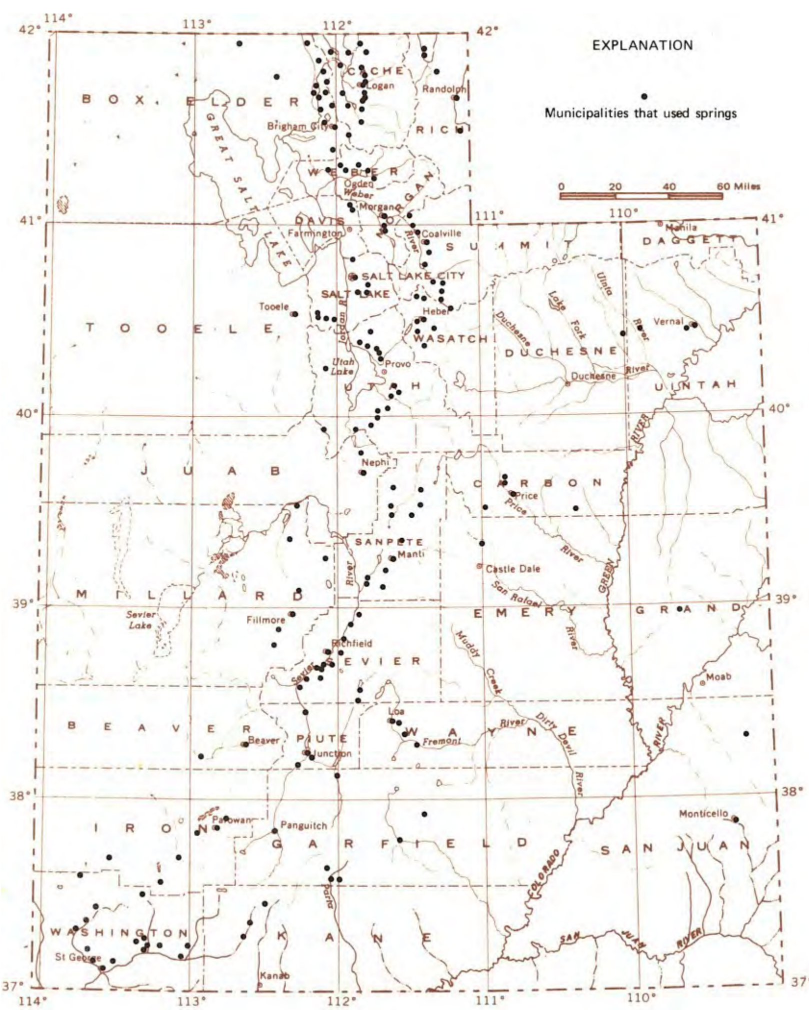


Figure 7.69 Locations of 16,719 springs in the Utah Geospatial Center database. https://gis.utah.gov/products/sgid/water/nhd-springs/

In 1971, J.C. Mundorff of the USGS, in cooperation with the Utah Geological and Mineralogical Survey (now Utah Geological Survey; https://geology.utah.gov/), published a comprehensive report on the State's nonthermal springs. For this report a nonthermal spring is defined as one having a temperature that does not exceed the mean annual temperature of the surrounding area by more than about 10° F (5° C). The report includes information on the location, chemical characteristics, water discharge, and geologic setting of selected major springs and presents a compilation showing the locations of thousands of known springs in Utah with a caveat that "many more" springs were not inventoried.

Most major springs which have a discharge of several cubic feet per second (cfs) or more are in or near mountain ranges or plateaus where precipitation is much greater than in other parts of the State. The largest instantaneous discharge observed at any spring was at Mammoth Spring in southwestern Utah (314 cfs; Wilson and Thomas, 1964, p. 24). Discharges exceeding 100 cfs have been observed at Swan Creek Spring in northern Utah, and Big Brush Creek Spring in northeastern Utah. Maximum discharges of several other springs range from 25 to 90 cfs. Maximum discharges generally are during or within a few weeks after the main period of snowmelt, which is usually from late April to the middle of June.

The largest springs generally discharge from or very near carbonate rocks in which solution channels and fractures are numerous or from areas of porous and fractured volcanic rocks. Most nonthermal springs in Utah probably are variable springs-that is, their variability of discharge exceeds 100 percent (Mundorff, 1971).



Water from springs in Utah is used for domestic, irrigation, municipal, livestock, mining, and industrial purposes. At the time of the Mundorff's report, data from the office of the Utah State Engineer indicated that about 1,910 claim applications were filed for use of spring water for domestic purposes, about 3,470 applications for use of the water for irrigation, and about 2,670 applications for use for stock water. As noted, additional use was made of water from many springs for which legal application has never been made.

The locations of municipalities that used springs as the source of all or part of their water supplies in 1970-1971 are shown in Figure 7.70.

Figure 7.70 Map showing locations of more than 220 municipalities in Utah that used springs in 1963 for all or part of their source of municipal water supply. From Mundorff, 1971.

Many springs in Utah have been described or mentioned by other investigators including Meinzer (1927) who describes Swan Creek Spring in Wasatch Range near Garden City in northeastern Utah as one of the large springs of the United States. Wilson and Thomas (1964), Cordova (1964), and Bjorklund and Robinson (1968) present detailed information about a few large springs in Utah.

The lack of continuous records of discharge for nearly all springs in Utah prevents any statewide classification of springs by magnitude. Mammoth Spring near town of Mammoth Creek, and Swan Creek Spring near Garden City are recognized as the largest springs in Utah. If average discharge is the basis for classification of spring magnitude, there are no first magnitude springs in Utah. The number of second magnitude springs in Utah is not known but is probably less than a hundred; most of these springs are near the minimum average discharge required for designation as second magnitude (Mundorff, 1971).

The importance of a spring is not directly related to the magnitude of its discharge. A small spring having a discharge of only a few gallons per minute in a desert area may be of much greater importance than a large spring in an area of abundant water supplies. More than a hundred years ago, Simpson Spring, which is near the western base of the Simpson Mountains and at the east side of the deserts of western Utah, was of critical importance on the Pony Express and Overland Stage routes; this spring usually has a discharge of less than 10 gpm (Mundorff, 1971).

The Utah Geological Survey recognizes the importance of springs and maintains a state-wide groundwater monitoring network consisting of approximately 65 wells and 35 springs which are distributed in the principal aquifers of Utah (Basin and Range Basin-Fill Aquifers, Basin and Range Carbonate-Rock Aquifers, and Colorado Plateau Aquifers) and other aquifers that support withdrawals of regionally significant quantities of water (see Figure 7.71).

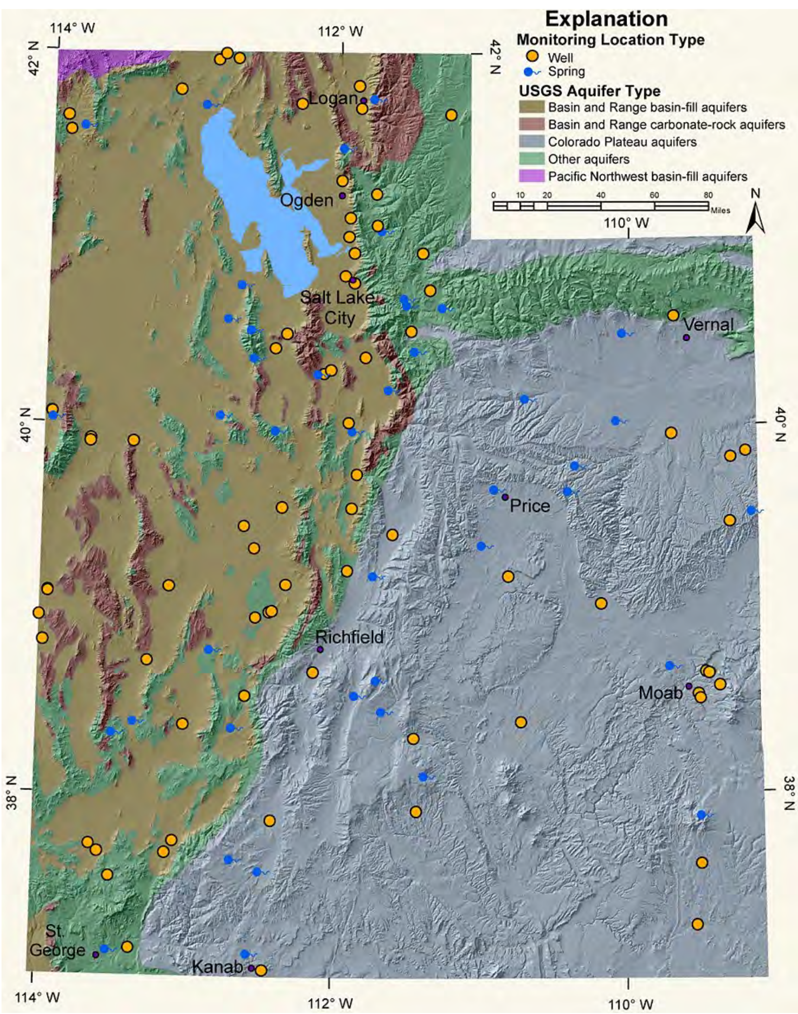


Figure 7.71. Groundwater monitoring network in Utah.
https://geology.utah.gov/map-pub/survey-notes/ugs-role-groundwater-network/

The sampled springs throughout the state range from smaller springs in mountain blocks or mountain fronts to large regional springs. Selected springs are (1) accessible sampling points that represent major aquifer chemistry where no nearby well is available, (2) large springs that represent the integrated aquifer chemistry for an entire drainage basin, or (3) springs in mountain areas that represent the chemistry of water recharging the adjacent aquifers.

The Utah Geological Survey has also been a vanguard for other states by adding a new category to the data portal to include water-quality information for springs. Because springs are an important water resource for some of the state's public water suppliers, the USGS is currently adding a "spring" option to amend the data portal to include and recognize springs as significant water resources for other states.

7.5.5 Mammoth Spring, Utah

Numerous springs discharge from the volcanic rocks and underlying limestone on the Markagunt Plateau in southwestern Utah (see Figure 7.72) including Mammoth Spring, the largest and one of the most variable springs in Utah, with discharge that ranges from less than 5 to more than 300 ft^3/s. The Plateau lies at an altitude of about 9,500 feet, largely within Dixie National Forest. It is capped primarily by Tertiary- and Quaternary-age volcanic rocks that overlie Paleocene- to Eocene-age limestones of the Wasatch (Claron) Formations, which form escarpments on the west and south sides of the plateau.

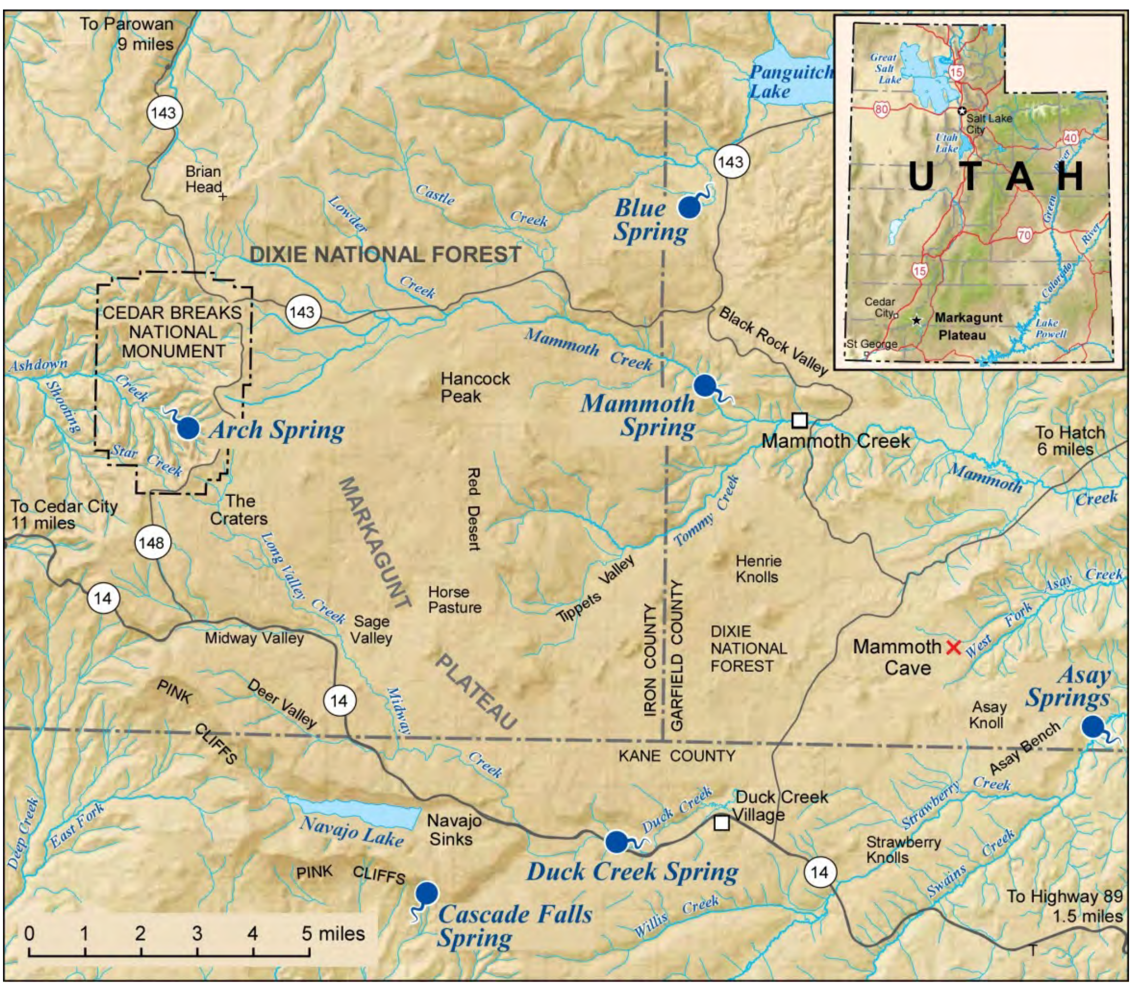


Figure 7.72 Locations of Mammoth Spring, the largest spring in Utah, and other large springs on the Markagunt Plateau in southwestern Utah. Modified from Spangler, 2012.

As noted by Bowers (1972), certain confusion exists when naming the sedimentary formations in Utah such as those on the Markagunt Plateau and exposed in the Cedar Breaks National Monument (Figure 7.73). The rocks of latest Cretaceous to early Tertiary age in the southern High Plateaus of Utah have commonly been referred to as the Wasatch Formation, whereas in the eastern Basin and Range province the name Claron Formation has been used for similar strata of Eocene (?) age. Use of the name Wasatch for lower Tertiary rocks in southern Utah has been questioned by some workers because of differences in age and lithology from the type Wasatch Formation (Eocene) in northeastern Utah. Some prefer the name Claron Formation, which has been used for similar strata west of Cedar Breaks National Monument, and other names have been proposed as well.

The amazing display of plateaus, terraces, cliffs, and canyons in southwestern Utah is the consequence of structural adjustments, simple in process; vast areas of originally flat-lying sediments and lava, uplifted and broken into tabular masses by faults, have provided favorable conditions for rapid and profound erosion (Gregory, 1950, p. 105). Within the drainage basins of Asay and Mammoth Creeks there are 20 volcanic cones, and many of these retain their summit craters. The highest and western-most of these cones reaches an altitude of 10,670 feet and projects about 500 feet above the lava plain that surrounds it. Other cones are generally 150-500 feet high (Wilson and Thomas, 1964).

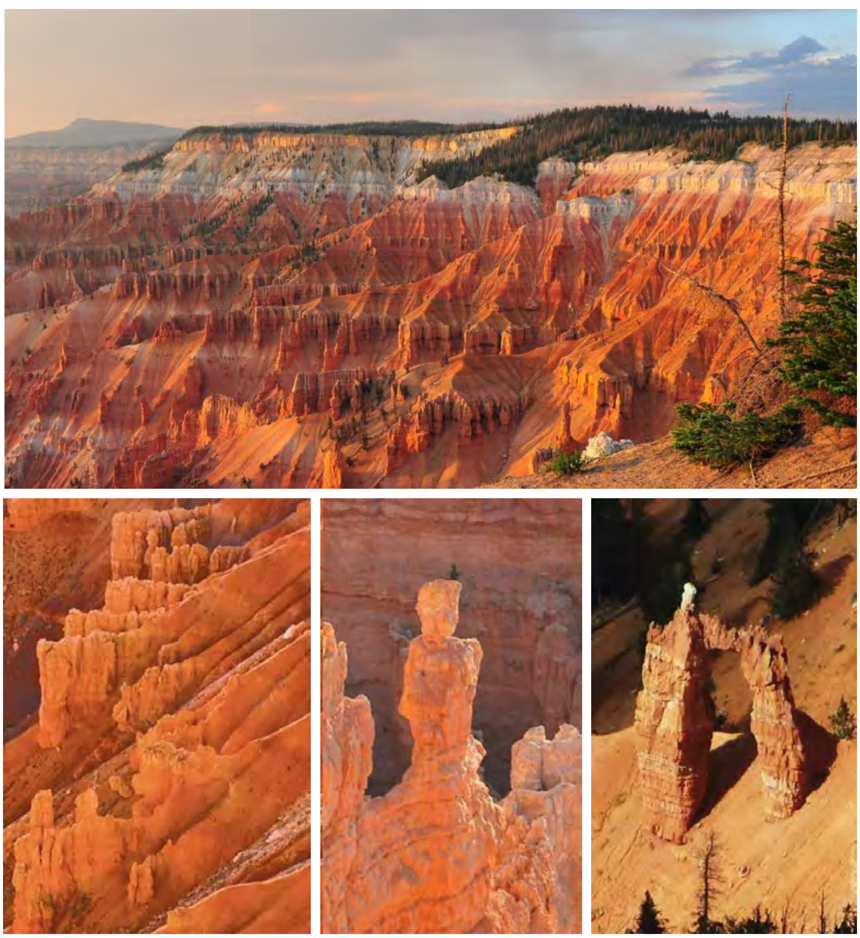


Figure 7.73 *Top*: Claron Formation in Cedar Breaks Amphitheater in Cedar Breaks National Monument, Utah. The formation contains alternating layers of limestone, marl, calcareous sandstone, and minor conglomerate; the layers are vividly colored orange, red, pink, and white by a combination of sediment composition, weathering (oxidation) of iron-bearing minerals, and soil-forming processes. *Bottom*: Erosional features found in the Amphitheater include, from left to right: Fins, Hoodo and Arch. Photographs courtesy of NPS. https://www.nps.gov/cebr/index.htm.

Results of dye-tracer tests performed by USGS indicate that recharge to Mammoth Spring largely originates from southwest of the spring and outside of the watershed for Mammoth Creek, particularly in areas where large sinkholes and losing streams are present. This includes Midway, Sage, and Long Valleys, and the Horse Pasture, Hancock Peak, and Red Desert areas.

Figure 7.74 Mammoth Spring at average high flow during the snowmelt runoff period on the Markagunt Plateau, southwestern Utah. Spring flow diminishes to less than 10 cubic feet per second during periods of baseflow (Figure 7.75). From Spangler, 2012.

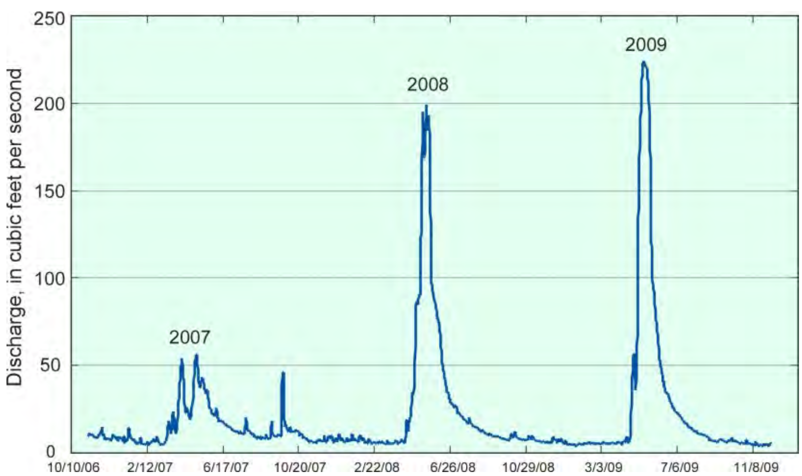


Figure 7.75 Daily mean discharge for Mammoth Spring, Markagunt Plateau, southwestern Utah, November 2006 to December 2009. From Spangler, 2012.

A significant component of recharge to the spring takes place by both focused and diffuse infiltration through the basalt and into the underlying Claron Formation. Losing reaches along Mammoth Creek are also a source of rapid recharge to the spring.

Maximum groundwater travel time during the snowmelt runoff period from focused points of recharge as far as 9 mi away and 1,900 ft higher than the spring, was about 7 days, indicating a velocity of more than a mile per day. Samples collected from Mammoth Spring during baseflow conditions and analyzed for tritium and sulfur-35 showed that groundwater in storage is relatively young, with apparent ages ranging from less than 1 year to possibly a few tens of years. Ratios of oxygen-18 and deuterium also showed that water from the spring represents a mixture of waters from different sources and altitudes. Based on evaluation of dye-tracer tests results and relations to adjacent basins, the recharge area for Mammoth Spring probably includes about 40 square miles within the Mammoth Creek watershed as well as at least 25 square miles outside and to the south of the watershed (Spangler, 2012).

The land surface in some areas of the Markagunt Plateau can be characterized as a *pseudokarst* terrain (see Chapter 4 for detailed explanation). In these terrains, karst-like features such as sinkholes and caves, are produced by non-solutional processes, such as surface collapses into lava tubes, which previously served as conduits for molten lava (Figure 7.76-*Left*). In the southwestern part of the plateau, particularly between the Red Desert and an area known as The Craters (see Figure 7.72), a unique terrain is present that is characterized by large sinkholes or dolines as much as 1,000 ft across and 100 ft deep (Figure 7.76-*Right*). Most of these sinkholes are related to dissolution of limestone in the underlying Claron Formation and subsequent collapse and (or) subsidence of the basalt, rather than collapse into lava tubes. Sinkholes also are developed in the Claron Formation where it is not covered by basalt, particularly in the areas north and southeast of Navajo Lake (Spangler, 2012).

Figure 7.76 Typical pseudokarst features on the Markagunt Plateau, southwestern Utah. *Left*: Entrance passage in Mammoth Cave, formed by collapse of the roof of the lava tube allowing access to more than 2,000 feet of passage. *Right*: Sinkhole in the Red Desert area of the Markagunt Plateau. Dissolution of the underlying Claron Formation has resulted in subsidence and (or) collapse of the basalt to depths up to 100 feet. Photographs and text from Spangler, 2012.

Many of the outcrops of basalt, particularly the flows that have broken into jagged blocks, are permeable enough that they can absorb the water of maximum storms or maximum snowmelt without runoff, and the water percolates downward rapidly from the bare outcrops. In other places, vegetation has obtained a foothold, even developed a forest cover, but the soil is capable of absorbing precipitation at high rates with negligible runoff (Wilson and Thomas, 1964).

7.5.6 Cascade Falls Spring, Utah

Cascade Falls Spring discharges from the limestone of the Claron Formation which forms Pink Cliffs, the southern escarpment of the Markagunt Plateau (see Figures 7.72 and 7.77). In the 1950s and 1960s, USGS performed detailed hydrologic and hydrogeologic investigations of the area because several proposals for additional development and use of the water of Navajo Lake led to controversies and raised questions regarding the total water supply in arid regions downstream where competition for municipal, industrial, and irrigation water supplies was very intense.

The entire outflow of Navajo Lake, located in a closed basin on the plateau less than two miles northwest of the Cascade Falls Spring, disappears underground. During parts of low-water years, this outflow was great enough to completely drain the lake until it was artificially impeded by a north-south dike about 17 feet high constructed across the lake; the dike separates the western three-fourths from the sink area and creates a permanent lake on the west side for fish propagation and human recreation (Wilson and Thomas, 1964).

The lake receives subterranean inflow from an area appreciably larger than that of the topographic basin in which it lies. It is unique in that large quantities of surface water escape from its eastern end through a sink area called Navajo Sinks. Hydraulic tests and dye tracing showed that the sinks are connected by underground channels developed in the limestone of Claron Formation with springs in two adjoining river basins—Duck Spring in Duck Creek in the east, a tributary of the Sevier River in the Great Basin, and Cascade Falls Spring in the south which flows to Provo Deer Creek, headwaters of the Virgin River in the Colorado River basin (Wilson and Thomas, 1964).

The discharge of Cascade Falls Spring increased 1 hour after water was released to the sink area and the discharge of Duck Creek Spring increased 12 hours later. Fluorescein dye placed in the sinks appeared at Cascade Falls Spring within 8.5 hours and at Duck Creek Spring in 53 hours. All the water entering Navajo Sinks eventually discharged from Cascade Falls and Duck Creek Springs when sufficient time was allowed to drain the added storage from the groundwater reservoir. The apportionment was 60 percent to Duck Creek Spring and 40 percent to Cascade Falls Spring.

Water issuing from Duck Creek Spring flows about 2.5 miles eastward and enters Duck Creek Sinks. During August 1954, water released to Duck Creek Sinks caused an increased flow from Lower Asay Spring in 9 hours, and fluorescein dye showed a travel time of 68 hours. Lower Asay Spring is a major contributor to the base flow of the Sevier River. The observed rates of travel of fluorescein dye from Navajo Sinks to Cascade Spring ranged from 5.6 to 12.5 fpm (feet per minute); the velocity to Duck Creek Spring was 5.8 fpm.

Figure 7.77 Discharge of Cascade Falls Spring from the Claron Formation along the Pink Cliffs, Markagunt Plateau. The cave from which the spring discharges is developed along north, east, and northwest-trending joints and extends for more than 1,000 feet into the plateau. Photographs courtesy of Utah Geological Survey. Available at https://geology.utah.gov/map-pub/survey-notes/geosights/cascade-falls/

Renewed volcanic activity during the Pleistocene Epoch produced numerous cones and flows of basalt in the Navajo Lake region. Some of the lava flowed down the preexisting valleys, and some flowed across and formed barricades in former drainage channels. The broad valley whose lower part is now occupied by Asay Creek has been barricaded in two places by basalt flows. Duck Creek occupies the part of the valley between the two barricades, and Navajo Lake occupies the part above the upper basalt barricade. The original eastward drainage is maintained solely by underground channels between Navajo Sinks and Duck Creek Spring, and between Duck Creek Sinks and Lower Asay Spring (Wilson and Thomas, 1964).

Studies in the vicinity of Navajo Lake show that subsurface movement of water is primarily in solution channels rather than in a continuous body of saturated sediments. The numerous sinks and springs in the Navajo Lake region also indicate the existence of various compartments or channels that may be isolated or very indirectly connected with each other. One example of such isolation is provided by the two Asay Springs: dye tracing tests show that one is connected with Duck Creek Sinks, the other completely independent (Wilson and Thomas, 1964).

Cascade Falls Spring is located just south of State Highway 14. Highway 14 can be accessed from I-15 in Cedar City on the west or from U.S. Highway 89 at Long Valley Junction on the east. To get there from I-15 and Cedar City, head 27 miles east on Highway 14. After passing the Navajo Lake scenic pull-out with its descriptive signs, turn right (south) on the road to the lake. After 0.4 mile, the road splits. The right fork goes on to the Navajo Lake boat docks and lodges, and the left fork goes approximately three miles to the Cascade Falls overlook and trail parking lot. The trail to the falls is approximately 1/2-mile one way.

Cascade Falls Spring is one of three springs featured in an outstanding series of GeoSights articles produced by the Utah Geological Survey. The articles. which highlight lesser-known geologic wonders in Utah and are accompanied by photographs, are available at https://geology.utah.gov/apps/geosights/?page=GeoSights.

7.5.7 Bear River Range Springs, Utah

The alpine Bear River Range, which stretches north-south between the City of Logan in the west and Bear Lake in the east, consists in large part of a thick sequence of carbonate rocks (more than 3,000 feet of limestone and dolomite) that range in age from Cambrian to Mississippian (Dover, 1987). The sequence is composed of eight principal geologic units, all of which are capable of transmitting water along dissolution-enhanced fractures, faults, and bedding planes. The formations make up the upper part of the Logan Peak syncline in the Logan Canyon area (see Figure 7.78), a large regional structure that influences the movement of groundwater in much of the western portion of the range (USGS, 2004).

Annual average precipitation in the area is 61 inches as reported by the Tony Grove Lake SNOTEL station (Natural Resources Conservation Service (NRCS), 2024) with an average of 71% falling as snow.

In all of the Bear River Range, karst development is extensive and includes large springs that discharge along major streams, losing streams in tributary drainages, caves (Figure 7.78) and pits, blind valleys, sinkholes, dolomite pavement, and surficial karst forms such as karren (Neilson et al., 2018; Spangler, 2001, 2019). Glaciation occurred above 8,000 ft during the Pleistocene, resulting in destruction of karst landforms that developed during interglacial periods (Wilson, 1979).

Speleothem age-dating, fluvioglacial deposits in caves, and deranged topography indicate that existing karst features, particularly caves, are largely remnants of former karst landscapes. Karst systems in alpine terrains are substantially different from those in relatively flat-lying strata in more temperate regions. Characteristics of alpine karst systems include a large component of vertical solution development and a thick unsaturated (vadose) zone, steep hydraulic gradients, spring discharge that responds primarily to snowmelt runoff, pit development in high-altitude meadows, and cold-temperature dissolution of carbonate rocks (USGS, 2024).

Discharge from the carbonate karst aquifer in the western portion of the Bear River Range is primarily from large springs along the Logan River which is the principal base level stream for groundwater discharge (Figure 7.79). Three second magnitude (average discharge between 10 and 100 cubic feet per second (ft^3/s)) and two third magnitude (average discharge between 1 and 10 ft^3/s) springs, along with several smaller springs, discharge along the north and west sides of the river. These include Dewitt, Wood Camp Hollow, Logan Cave, and Ricks Springs. Only one large (second magnitude) spring, Spring Hollow Spring, is known to discharge along the south side of the river (Figure 7.79). Collective discharge of the springs provides a substantial component of streamflow in the Logan River.

Spring discharge responds primarily to snowmelt runoff, with peak flow from late spring to early summer and base flow during the winter months (Figure 7.80). Recharge to the carbonate aquifer occurs through point sources (sinkholes and sinks), as seepage losses through fluvioglacial deposits, and as diffuse infiltration. Based on dye tracing, recharge areas for Dewitt, Wood Camp Hollow, and Ricks Springs are estimated to be between 7.5 and 15 square miles and as much as 3,200 feet higher than the altitude of the springs. Results of dye tracing indicate maximum groundwater travel times of 8 to 31 days from losing streams as far as 7.2 miles. Dye tracing also indicates that surface water drainage basins generally do not coincide with groundwater basins (Spangler, 2001).

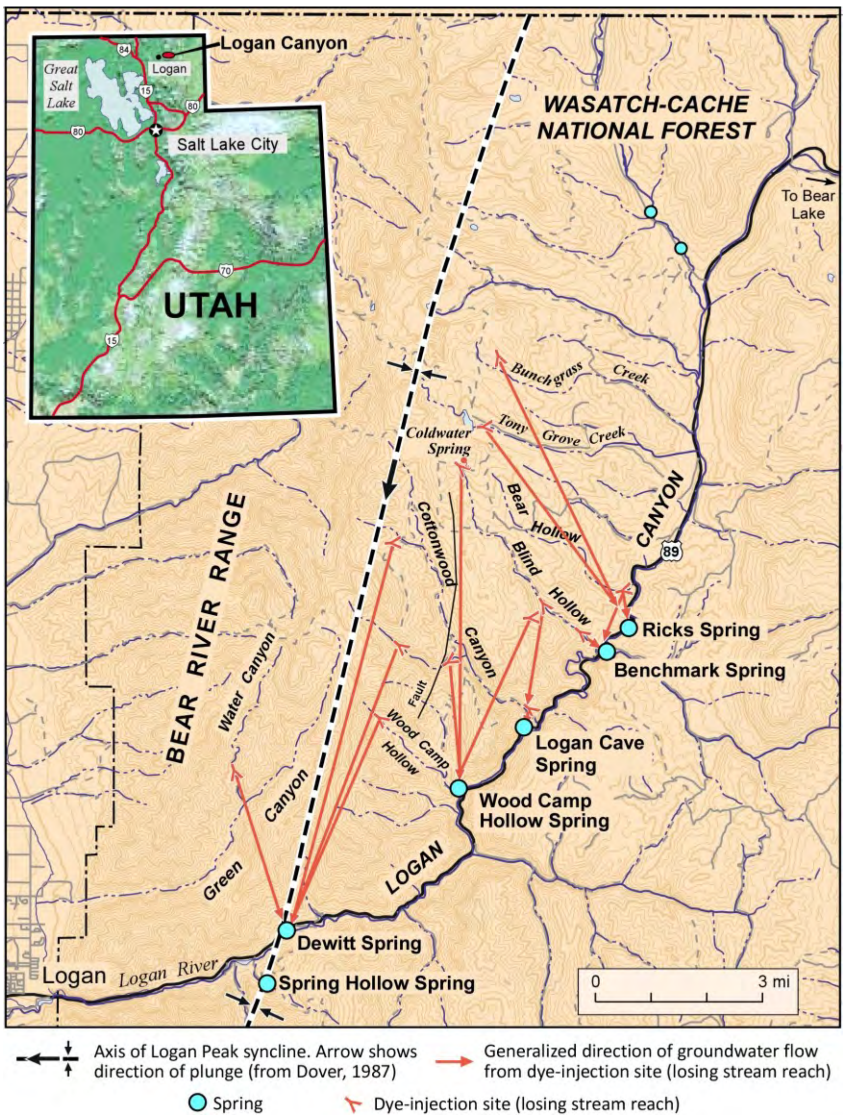


Figure 7.79 Generalized groundwater flow paths to selected springs, based on dye tracing results, Logan Canyon, Utah. Modified from Spangler, 2001.

According to Kolesar et al. (2006), chemical and flow data suggest that aquifer characteristics are different north and south of the Logan River. Spangler's (2001) data show that the northern part of the aquifer is a very well-developed karst drainage system, with estimated flow velocities on the order of a thousand feet per day or greater. Mineral saturation indices (log(IAP/Ksp)) are indicators of the degree to which a water is saturated with respect to particular minerals. A saturation index of 0 indicates saturation or equilibrium, a negative number indicates undersaturation, and a positive number indicates supersaturation. The mean calcite saturation index in water from DeWitt Spring is 0.2 and for quartz 0.1, slightly supersaturated, consistent with a relatively short period of water-rock interaction. However, the mean calcite saturation index in water from the spring at Spring Hollow, south of the Logan River, is 1.2 and for quartz 2.0, an order of magnitude greater. Such a difference suggests a much lower flow velocity, more time for water-rock interaction, and thus implies a less-well-developed karst system.

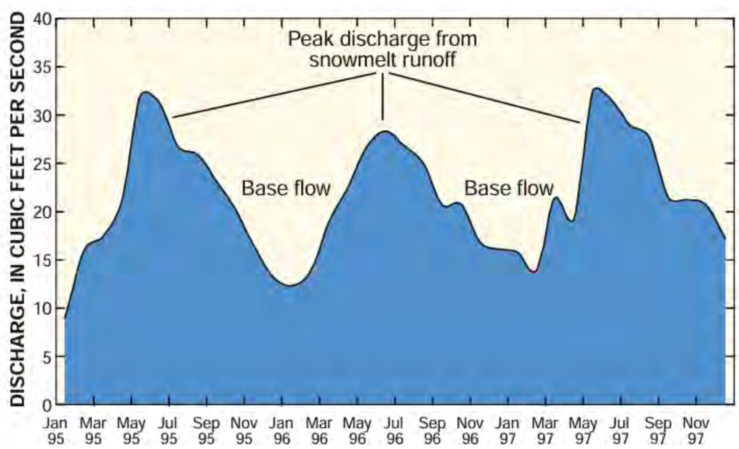


Figure 7.80 Hydrograph showing typical seasonal response of an alpine karst spring to snowmelt runoff, Dewitt Spring, Logan Canyon, January 1995 to January 1998 (Data from City of Logan Water Department, written communication., 1998). From Spangler, 2001.

7.5.7.1 Dewitt Spring

Dewitt Spring discharges from the Water Canyon Formation along the flood plain of the Logan River (Figures 7.78 and 7.81). Water discharges from an unknown number of capped outlets and is diverted into a collection system. Water from the spring serves as a public supply for the city of Logan, about 7 miles (mi) to the west. Discharge of the spring is metered and generally ranges from about 10 to 35 ft^3/s (Dennis Corbridge, City of Logan, written communication, 1998).

Figure 7.81 Dewitt Spring. Photo courtesy of City of Logan.

As discussed by Spangler (2001), four dye traces to Dewitt Spring indicate a recharge area northwest to northeast of the spring that largely coincides with the extent of the Logan Peak syncline. Groundwater movement is probably downdip along the west and east limbs of the syncline toward the axis, and subsequently southwest to the spring, which is located along the axis of the syncline where the Logan River breaches the structure (Figure 7.79).

Results of dye tracing during moderate flow indicate a maximum groundwater travel time of 22 days for losing streams in drainages 7.2 mi from, and 2,900 ft higher than Dewitt Spring. The substantial base flow of this spring relative to peak flow may indicate a large storage component that is recharged primarily from infiltration. Groundwater travel times from this diffuse component of flow are likely to be considerably longer than those from losing streams. Based on dye tracing, geology, and discharge, the groundwater basin for Dewitt Spring is estimated to be about 15 square miles (Spangler, 2001).

The spring and a secluded, riverside picnic area next to it got their name from Aaron Dewitt, one of Logan's first pioneers. The city of Logan acquired the water rights, built a reservoir, and started providing drinking water to the city's residents.

7.5.7.2 Ricks Spring

Ricks Spring is located along U.S. Highway 89 in Logan Canyon about 17 miles northeast of (up-canyon from) the city of Logan, at mile marker 477. It lies within Uinta-Wasatch-Cache National Forest (Figure 7.82) at an elevation of 5880 feet. Situated at the base of a hillside, the spring is one of the largest and most scenic along the Logan River (Figures 7.83 through 7.85). Water from the spring flows out of a large alcove, under Highway 89, and into the Logan River, about 150 feet from the spring. Pullouts on both sides of the highway provide parking for visitors to the spring, and a boardwalk crosses the spring run, which allows access to the rise pool in the alcove. Several signs at the spring provide information about its history and hydrology. Ricks Spring typically flows during the spring, summer, and fall months, but can have periods of no flow during the winter months, particularly during extended periods of cold weather (see Figure 7.85; Spangler, 2019; Tennant and Neilson, 2024).

Figure 7.82 The Uinta-Wasatch-Cache National Forest encompasses 2.2 million acres in Northern Utah and southwestern Wyoming. The Forest receives 9 million visitors annually and is one of the most heavily visited forests in the nation. The Forest is where civilization meets the "wild." Metropolitan areas and communities bordering the forest make up some of the fastest growing areas in the Intermountain West. Uinta-Wasatch-Cache National Forest - Home (usda.gov)

Since 2007 when it was first accessed, the submerged conduit feeding Ricks Spring has been explored by cave divers for about 2300 feet into the mountainside. The initial discovery and exploration of Ricks Spring Cave are summarized in an article published in the National Speleological Society (NSS) Cave Diving Section's Underwater Speleology newsletter in May/June 2008.

As described by Stephanie Carney in the January 2024 Survey Notes of the Utah Geological Survey featuring Ricks Spring GeoSight (available at GeoSights: Ricks Spring, Cache County - Utah Geological Survey), Ricks Spring has been a roadside attraction for more than 100 years since it was discovered by and named after a well-known Utah pioneer Thomas E. Ricks, who lived in the Cache Valley area in the mid- to late 1800s. At the recommendation of Mormon leader Brigham Young, he and several others began constructing a road eastward along the Logan River with the goal to connect Cache and Bear Lake Valleys. The first "leg" of the road ended at Ricks Spring. While in Cache Valley, Ricks served as sheriff and county assessor and devoted much effort to building railroads.

Figure 7.83 *Left*: Ricks Spring rises along a nearly vertical normal fault (dashed red line) in the Ordovician Garden City Formation. Bedding dips to the southeast at about 36° near the fault. The small cave on left side of photo could have been a former spring outlet. Photograph by Larry Spangler, August 2011. *Right*: Ricks Spring at high flow during the spring runoff of 2017. Estimated discharge is about 100 ft3/s. Photograph by Larry Spangler, June 2017. From Spangler, 2019. Available at https://giw.utahgeology.org/giw/index.php/geosites/article/view/64/82

Figure 7.84 *Left*: Dry Ricks Spring channel and cave entrance in February of 2022. *Right*: Ricks Spring rise pool and cave entrance August 2024. Photographs by Hyrum Tennant. From Tennant and Neilson, 2024, Civil and Environmental Engineering, Utah Water Research Laboratory.

During the winter of 1972, severe cold weather froze the river, resulting in ice jams in some locations, which caused the water to back upstream. Subsequently, Ricks Spring began to flow and then subsided when the river level dropped again, suggesting a link between the river and the spring. Later that summer, dye was added to the Logan River and was subsequently observed in Ricks Spring, confirming the connection between the river and the spring (U.S. Forest Service, Logan District Ranger, verbal communication, 2010, From Spangler, 2019).

Beginning in 1991, the USGS (Spangler, 2001) started further investigations into the source of water for Ricks Spring. Results of these investigations, based on dye-tracer tests, showed that in addition to the river, water also originated from Bear Hollow, northeast of the spring, Tony Grove Creek near Tony Grove Lake, and from Bunchgrass Creek, north of the spring (Figure 7.79). Results of the dye tracing indicated that the source area or groundwater basin for Ricks Spring extends more than 5 miles to the northwest in the Tony Grove Lake area and 2600 feet higher than the spring. Maximum groundwater travel time from the dye-injection points to the spring was about 4 weeks during low-flow conditions.

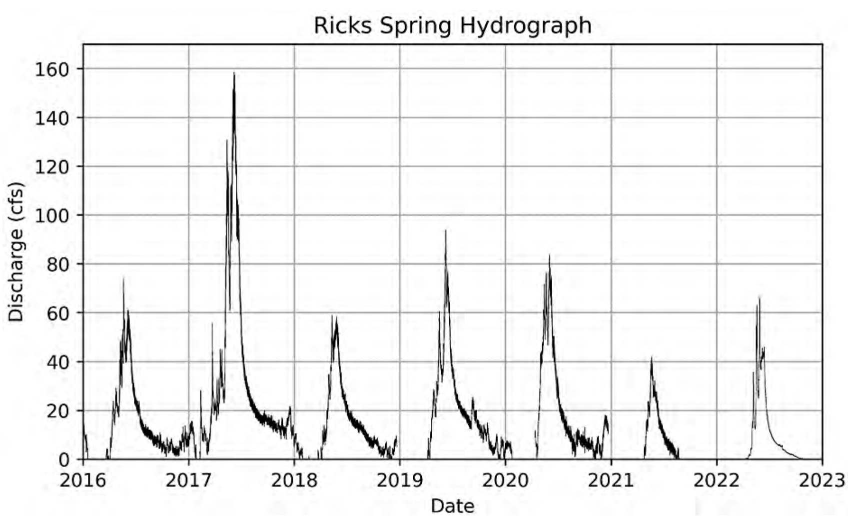
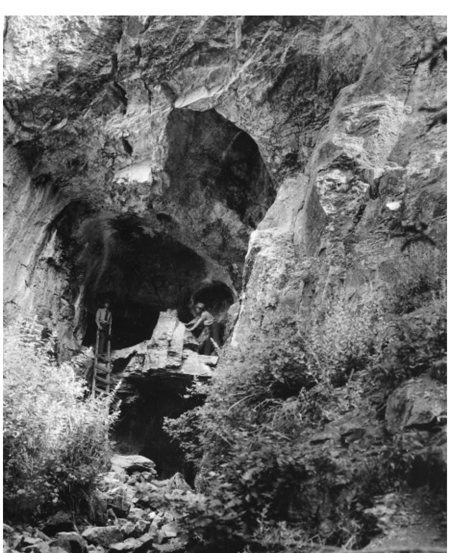


Figure 7.85 Ricks Spring hydrograph from 2016 through 2023 (*Logan River Observatory: Ricks Spring above Confluence with Logan River Aquatic Site (RS_CONF_A) Raw Data | CUAHSI HydroShare*, 2024). Winter gaps represent no-flow conditions. From Tennant and Neilson, 2024, Civil and Environmental Engineering, Utah Water Research Laboratory.

7.5.7.3 Logan Cave Spring



Logan Cave Spring discharges from the base of the Garden City Formation. Water from the spring normally discharges from talus below the entrance to Logan Cave, but during spring runoff, also discharges directly from the cave entrance (Figure 7.86). Discharge of the spring normally ranges between 1 and 10 ft^3/s; Wilson (1976) estimated flows of as much as 25 ft^3/s in June 1975. Peak flow of Logan Cave Spring generally occurs earlier than that of the other springs. Most of Logan Cave is developed along a master joint that trends due north, with dissolution along secondary northwest trending joints in some areas (Spangler, 2001).

Figure 7.86 Logan Cave, Cache National Forest. Photo taken by W.H. Shaffer in July 1937. Courtesy Utah State Historical Society.

Two dye traces to Logan Cave Spring indicate a recharge area generally north of the spring and at a lower altitude than that of the recharge areas for the other springs (Figure 7.79). Substantial contributions to discharge of this spring originate from the lower part of Cottonwood Canyon and the Blind Hollow drainage. Movement of groundwater to this spring is probably largely within the Garden City Formation. Dye tracing, discharge, and relations to adjacent groundwater basins indicate that the recharge area for Logan Cave Spring is probably less than 5 square miles (Spangler, 2001).

7.5.7.4 Swan Creek Spring, and Big Spring

Springs emanating from carbonate karst terrain in the eastern Bear River Range are numerous (Figure 7.87) and their discharges differ by an order of magnitude. Swan Creek Spring, one of the two largest in Utah, has an average discharge of about 60 cfs (Mundorff, 1971) and a maximum discharge of about 321 cfs (based on periodic measurements between 1979 and 2004 conducted by U.S. Environmental Protection Agency; Bright, 2009).

According to Kaliser (1972), the only available daily record of Swan Creek's flow was for 1944 and 1945 when Swan Creek was gaged. Estimates for instantaneous discharge of about 300 cfs have been made, however, for the spring. Rain and snowfall readily recharge the aquifer as far as 6.25 miles away and 1,500 ft above the spring outlet including through large sinkholes on the Bear River Range (Tennant and Neilson, 2024). Recharge west of the divide also contributes to the flow of Swan Creek Spring as indicated by dyes tracing results. Dye injections have appeared at the spring outlet within 3 days of injection (Spangler, verbal comm., 2024).

Swan Creek Spring provides by far the greatest part of Swan Creek's total discharge. Another spring of significant magnitude also is tributary to Swan Creek. Figure 7.88 shows the Swan Creek hydrograph for part of 1945 in relation to the daily precipitation at Lifton Pump Station. Although the precipitation regime at Lifton is not exactly that of the Bear River Range, it was the closest station at which daily precipitation rates were recorded. The discharge measurements reflect the rapid response of the carbonate springs feeding Swan Creek to snowmelt during April and May and to large rainfall later.

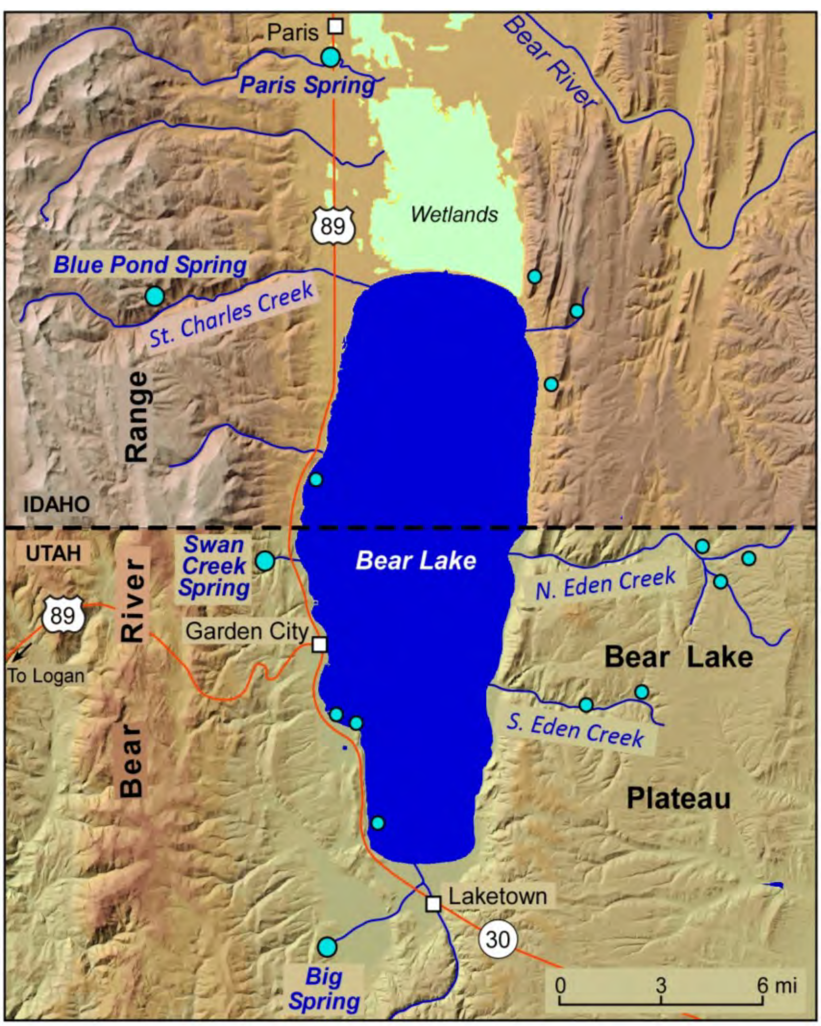


Figure 7.87 Large (labeled) and other springs (blue circles) in the Bear Lake area. Shaded relief map courtesy of USGS. Spring locations from Bright, 2009.

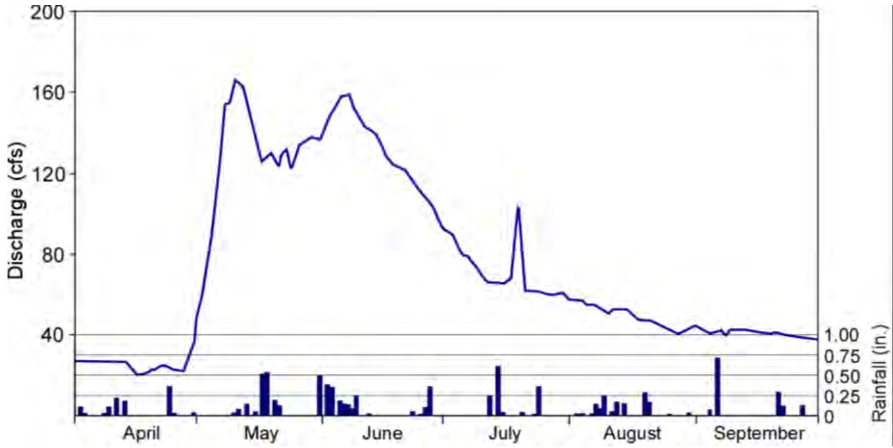


Figure 7.88 Relation of Swan Creek discharge to daily precipitation in 1945 recorded at Lifton Pump Station. From Kaliser, 1972.

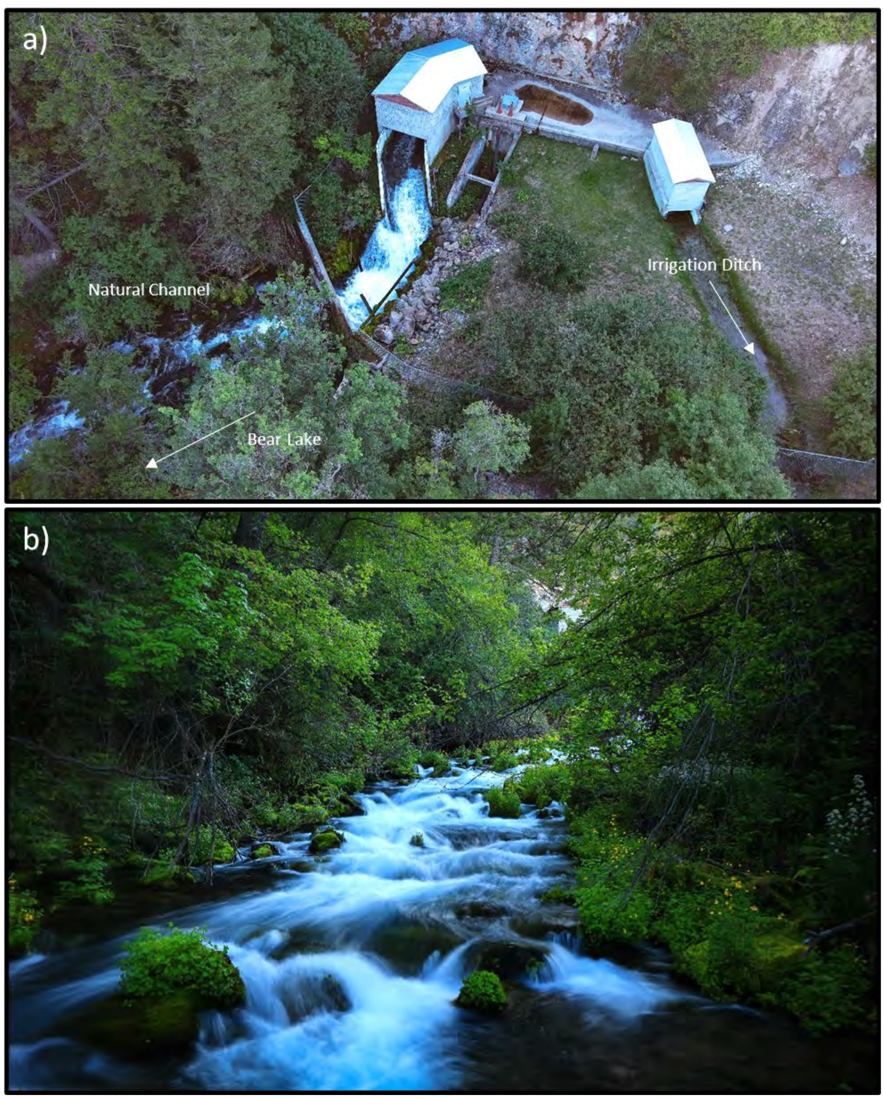


Figure 7.89 Swan Creek control structure (a) where approximately 50 cfs is allowed to naturally flow from the discharge point in the cliff band to Bear Lake while approximately 10 cfs is being diverted for agricultural irrigation. Swan Creek natural channel (b). Photographs by Hyrum Tennant, August 2024. From Tennant and Neilson, 2024, Civil and Environmental Engineering, Utah Water Research Laboratory.

The impressive discharge of Swan Creek Spring is indicative of a large and well-developed karst conduit system within the Bear River Range. The sensitivity of Swan Creek Spring to rainfall events (Kaliser, 1972) indicates a strong linkage to the surface. Infiltration into the Swan Creek Spring aquifer is likely fast, and given the spring's cold temperature (42 to 50 ºF), passes quickly through the mountain range along shallow, and possibly short, flow paths (Bright, 2009). The spring is fed by a large solution channel (Kaliser, 1972) and is located along one of a series of north-south–trending faults in the Bear River Range, west of Bear Lake (Dover, 1995).

The solute chemistry of Swan Creek Spring varies in response to its discharge. Solutes derived primarily from dolomite dissolution dominate baseflow and solutes derived from increased limestone dissolution dominate peak discharge (Bright, 2009).

The large volume of water issuing from Big Spring (average is 26 cfs, max is 67 cfs, based on periodic measurements by U.S. EPA from 1979 to 2004; Bright, 2009) also suggests a strong connection to the Paleozoic carbonate aquifer, but the calcium and magnesium concentrations at Big Spring during assumed peak discharge (April) and base flow (September) conditions are not discharge dependent. The groundwater basin and conduit-fracture network that feeds Big Spring may be significantly different from the system that feeds Swan Creek Spring. Additional data are needed to test this hypothesis, however (Bright, 2009).

The groundwater divide between Big Spring and Swan Creek Spring may lie relatively close to Big Spring such that a large portion of the infiltration from the southern portion of the valley flows northward and discharges at Swan Creek Spring. Additionally, the paucity of large springs and streams south of Garden City might be explained by the presence of the Wasatch Formation in this area: with its relatively low permeability it acts as a confining bed where it overlies the local Paleozoic carbonates so groundwater cannot reach the surface. Big Spring, the only major groundwater discharge point within the Wasatch Formation, emanates from a fault that may penetrate to the Paleozoic carbonate aquifer (Bright, 2009).

Bear Lake is a large (>108 mi^2), deep (>200 ft), turquoise blue lake straddling the border of north-central Utah and southeastern Idaho (Figure 7.89). It is situated in the rain shadow of the Bear River Range and had a small local watershed prior to the diversion of the Bear River. Between 1911 and 1917, a canal system and a pump station were constructed to divert the Bear River into Bear Lake which is now utilized to store spring runoff to use for late season irrigation and for power generation.

Figure 7.89 Bear Lake contains abundant suspended microscopic particles of white-colored calcium carbonate (lime) that reflect the water's natural blue color back to the surface, giving the lake its intense turquoise-blue color. This color is why Bear Lake is known as the "Caribbean of the Rockies." These particles of calcium carbonate are mainly derived from the abundant limestone of the Bear River Range and are brought in by spring-fed streams, submerged springs, and diffused discharge of groundwater. Numerous faults and fractures in the Bear River Range further enhance and direct the underground flow of water (Davis and Milligan, 2011). Photo courtesy of Bear Lake Valley Convention & Visitors Bureau. https://bearlake.org/

The canal system was finished by Utah Power and Light (now PacifiCorp). The diversion of the river starts at Stewart Dam, where the river is channeled southward into the Rainbow Canal, through Dingle Swamp and Mud Lake, and then into northern Bear Lake. Bear Lake water, when needed, can then be pumped out through the Lifton pumping station where it is returned to the Bear River through the Bear Lake Outlet Canal. The outlet canal roughly follows natural, ancient stream courses that flowed occasionally when Bear Lake topped the north shore sand bar and spilled out into Bear Lake Valley and to the Bear River. A small dam on the outlet canal keeps the water level of Mud Lake high to enhance waterfowl habitat at the 19,000-acre Bear Lake National Wildlife Refuge, especially for Canada geese, redhead and canvasback ducks, and trumpeter swans (Davis and Milligan, 2011).

Only a handful of small streams drain the surrounding highlands, yet the hydrologic budget of the lake is balanced, or nearly so (Lamarra et al., 1986; Bright et al., 2006). Long sediment cores (328 and 394 ft) from the lake extend back over 250,000 years (Bright et al., 2006; Kaufman et al., 2009) and seismic evidence reveals that the valley, and likely the lake, has been in existence much longer (Colman, 2006). There are no evaporite minerals (gypsum or halite) in the long cores, indicating that the lake has survived major changes in climate without becoming saline, like the Great Salt Lake, or drying out (Bright, 2009).

Without the engineered input of water from the river, the lake is sustained primarily by spring-fed streams and groundwater entering the lake directly. Groundwater provides a more consistent flow of water than local rain and snow-fed streams, enabling Bear Lake to persist through major climatic and hydrologic changes through long periods of time.

Another line of evidence for the age of Bear Lake can be found around Bear Lake Valley as ancient shorelines, marking former lake levels. Shorelines above Bear Lake have been recorded as high as 230 feet above the current lake level. The large offset between ancient shoreline and modern lake level is mostly caused by Bear Lake Valley moving downward relative to the mountains at each major earthquake. Based on rates of fault movement, and the uppermost relict shoreline, the lake is thought to be around 2.5 to 3 million years old (Davis and Milligan, 2011).

7.6 Other Springs in the West

7.6.1 Periodic Spring, Wyoming

Periodic Spring discharges from a solution cave in the Madison Limestone along the axis of the Periodic anticline in the Absaroka thrust sheet of the Salt River Range of western Wyoming (Figures 7.89 through 7.91). The spring turns on and off with variable cyclicity during low discharge stages. The intermittent yield is caused by the mechanical operation of a siphon in the cave behind the spring (Figure 7.92). The cold, good quality water discharged from the spring serves as the Town of Afton municipal water supply. The major component of recharge to the spring originates on elevated outcrops of the Madison Limestone four miles east of the spring on the eastern side of the topographic divide of the Salt River Range. Smaller amounts of water are derived from infiltration through fractures along the axis of the Periodic anticline between Swift and Cry Creek canyons. The Spring varies from low flows of 5 cubic feet per second (cfs) to high flows of up to 100 cfs (Huntoon and Coogan, 1987).

Periodic Spring Trail can be reached from Highway 89 in Afton, Wyoming heading west on County Road 138 that continues as Forest Service Road 10211 at the Bridger-Teton National Forest boundary. This gravel road winds through the Swift Creek canyon for about four miles where it ends. The Trail follows the creek side for a little over 1/2 mile to the Periodic Spring.

The U.S. Forest Service provides the following description of the Periodic Spring Trail: “A wide, stony trail continues upstream from the parking area, climbing gently and staying close to the creek for nearly a mile until arriving at the base of the short side ravine that contains the spring. The path splits, with one branch starting to ascend the steep hillside on the north side, and the other crossing the creek on a footbridge then going up the ravine to the spring; the last section is over boulders kept moist by spray from the exit stream, and so is liable to be slippery. The cliffs above are sheer, angular, dark and crumbling, enclosing the spring on three sides to create a cool, sheltered alcove. The actual source is less exciting to look at, since it has been modified to prevent rocks falling into the vent, and now has a concrete roof, metal baffles and assorted pipework, resulting in a rather unnatural appearance. The water typically flows normally for 15 to 20 minutes, decreases in intensity during the next few minutes and stops completely for several minutes more. The current resumes quickly, preceded by muffled subterranean noises, though without the sudden surge that characterizes a geyser. The cycle is best observed during mid to late summer, as at other times the periodicity is less evident.

Afton's spring was (re)discovered early in the 20th century by a local sawmill owner who observed the regular fluctuations of Swift Creek, and tracked up the canyon to find the cause, though long before this the location was known to the native Shoshone Indians.”

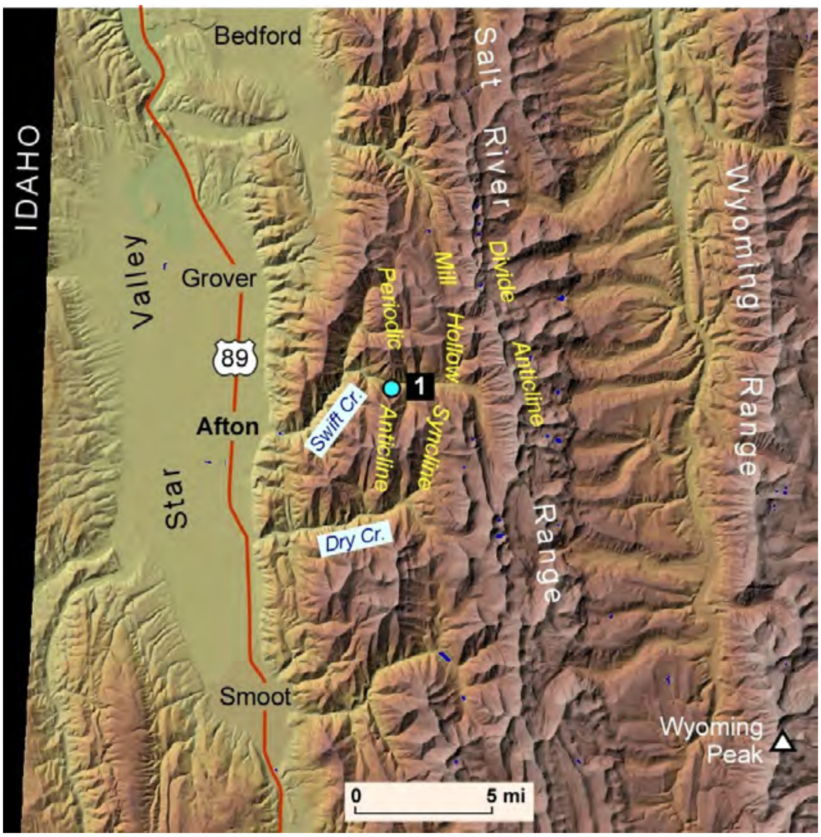


Figure 7.89 Periodic Spring (#1) can be reached from Highway 89 in Afton, Wyoming heading west on County Road 138 which continues as Forest Service Road 10211 at the Bridger-Teton National Forest boundary. This gravel road winds through the Swift Creek canyon for about four miles where it ends. The Periodic Spring Trail follows the creek side for a little over 1/2 mile to the Periodic Spring. Shaded relief map courtesy of USGS.

Several descriptions of Periodic Spring including mechanism(s) that are thought to cause its intermittent (“ebb-and-flow”) nature, as well as photographs and videos taken before the recent rockslide (shown in Figure 7.92) can be found at World’s Largest Rhythmic Spring, world record near Afton, Wyoming (worldrecordacademy.org)

> Nature is full of many things that the human mind can’t decode. One such thing is a natural spring at the foot of a rocky mountain in the United States of America. ‘The Spring That Breathes’ is situated on a mountain in Wyoming. The magical thing about this water body is that it intermittently stops and restarts flowing after an approximate gap of 15 minutes. As expected such springs are very rare in the world and the one in Wyoming’s Swift Creek canyon is the largest.
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> News18

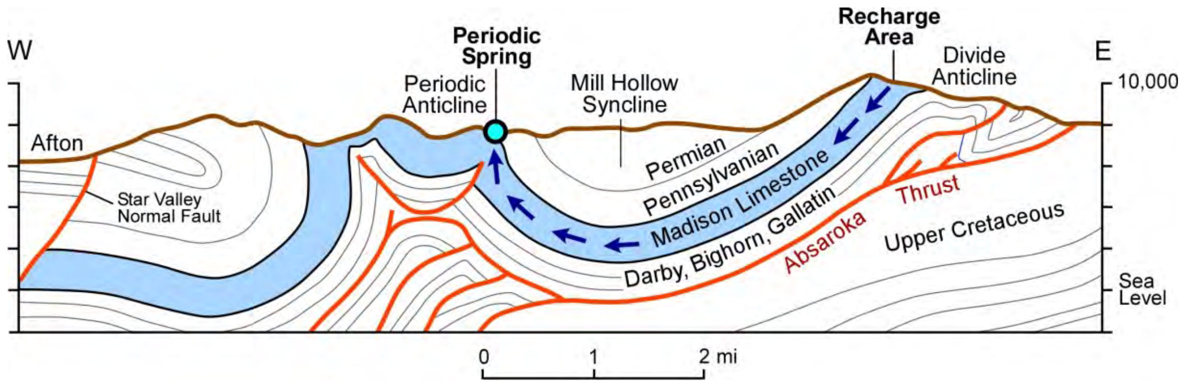


Figure 7.90 Portion of an East-West cross section through the overthrust belt developed by Huntoon and Coogan (1987). Arrows denote the probable flow of groundwater in Madison aquifer (colored blue) from the recharge area on the eastern topographic high of the Salt River Range (Divide Anticline) through Mill Hollow Syncline to Periodic Spring (see also Figure 7.89). Faults and Absaroka Thrust are shown in red. Modified from Blanchard et al., 1990.

Figure 7.91 Left: Photograph of Swift Creek as it tumbles out of the Periodic Spring, near Afton, Wyoming, as seen from the bottom (taken in September 2009). Author: Ninjatacoshell. The file is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license. Available at https://en.wikipedia.org/wiki/File:Periodic_Spring_(from_the_bottom).JPG. Right: A rock slide that occurred in late May 2024 has partially covered the Periodic Spring in Swift Creek Canyon east of Afton. The slide prompted the Bridger-Teton National Forest to implement a closure of the path from the picnic table area leading up to the mouth of the spring. The rockslide has obstructed Periodic Spring causing abnormal pressure on the water supply system for the town of Afton. Photo by Eric Buehler taken on June 1, 2024. More photographs of the slide can be found at the Afton's Star Valley Independent News website: (Photos) Intermittent Spring Rock Slide – SVI-NEWS (svinews.com)

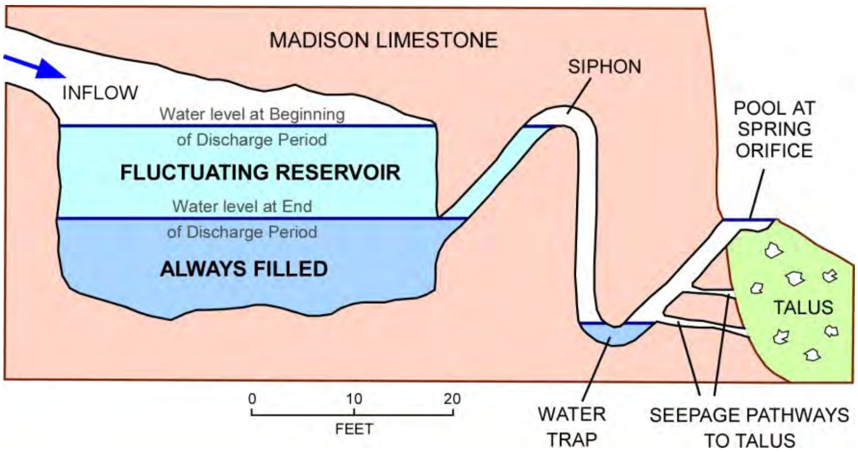
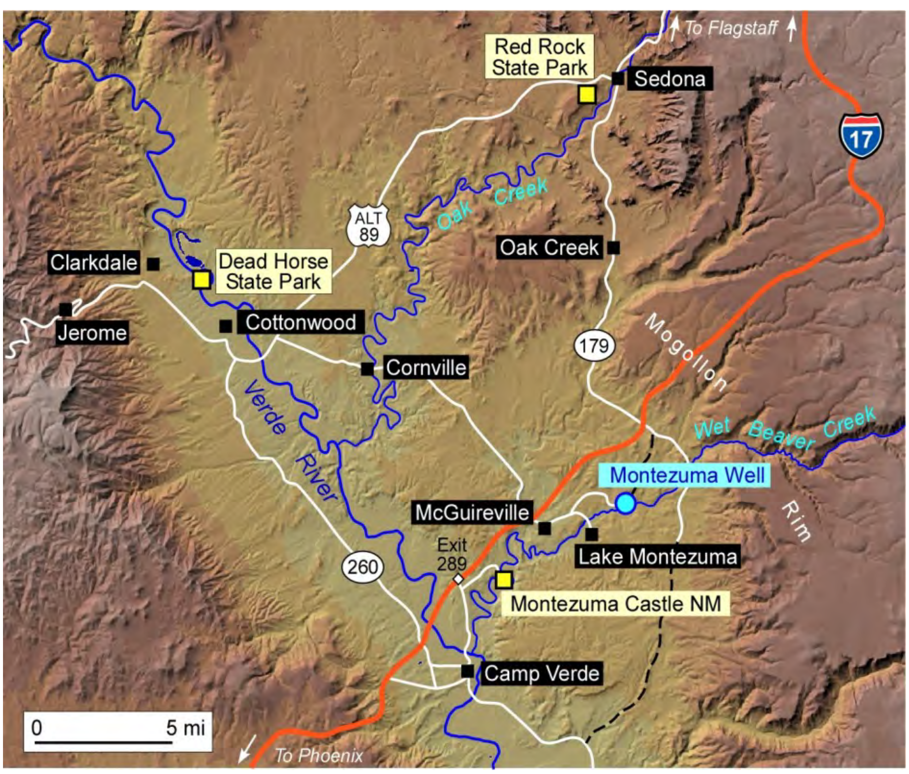


Figure 7.92 Siphon model *of* Periodic Spring reservoir. When the reservoir water level reaches the siphon level flow commences. Flow continues until the reservoir level drops *to* base level. From Blanchard et al., 1990; modified from Huntoon and Coogan, 1987.

7.6.2 Montezuma Well, Arizona



Montezuma Well is a spring-fed sinkhole on the north bank of Wet Beaver Creek, about 8 miles northeast of the town of Camp Verde in the Verde Valley of Arizona. Montezuma Well is part of the Montezuma Castle National Monument, managed by the National Park Service (NPS; see Figures 7.93 through 7.100).

Figure 7.93 Location map for Montezuma Well, which is part of Montezuma Castle National Monument (NM). The monument lies in central Arizona, off interstate highway 17 (Exit 289). It is composed of two units: the Well Unit, which contains Montezuma Well, and the Castle Unit, which contains the Montezuma Castle cliff dwellings. Shaded relief map courtesy of USGS.

As described by NPS, Montezuma Well sinkhole is 368 feet wide, with cliffs that tower 70 feet above the water's surface. Every day over 1.5 million gallons of warm (74°F) water flows into the Well, which is a near constant aquatic environment. The Well formed when the limestone collapsed sometime between 12 and 15 thousand years ago. Water is fed into the Well through four large underwater vents, and exits the Well through a swallet and a cave 300 feet long, with the outlet draining into a prehistoric irrigation canal. The canal was originally constructed almost 1,000 years ago by the people of the Sinagua (see-NAH-wah) culture who lived and farmed here for centuries (https://www.nps.gov/moca/planyourvisit/exploring-montezuma-well.htm; virtual tour of the

Well is provided by NPS at [Montezuma Well Virtual Tour - Montezuma Castle National Monument (U.S. National Park Service) (nps.gov)](https://www.nps.gov).

Both the water level and temperature are nearly constant throughout the year, with the first fluctuating by only 6 inches and the latter averaging 70 degrees Fahrenheit (Blinn 2008). The water also has a stable pH because of high alkalinity and a high amount of dissolved carbon dioxide, which enters the well from the bottom vents in concentrations more than 500 mg per liter, more than 100 times higher than normal (Blinn 2008). In addition, the concentration of dissolved arsenic of 114 micrograms per liter is an order of magnitude higher than any other groundwater tested in the area (Johnson et al., 2011). These extreme chemical conditions mean that no fish can survive in the Well, and that organisms living in the water have had to adapt to survive. This unique and isolated ecosystem enabled amphipods (small, shrimp-like animals), and the leeches which feed on them, to evolve into endemic species found nowhere else in the world.

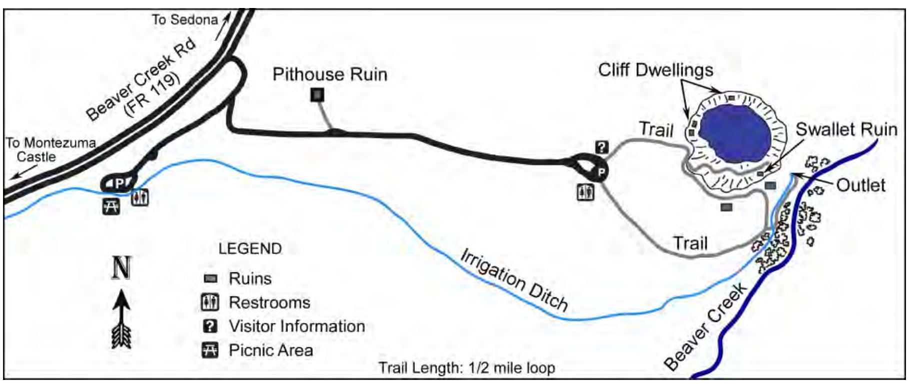


Figure 7.94 Montezuma Well is a 368 feet wide natural sinkhole, with cliffs that tower 70 feet above the water's surface. Every day over 1.5 million gallons of water flows into the Well, fed by large underwater vents. The water exits the well through a cave 300 feet long, emerging on the southeast corner of the mound into an irrigation ditch originally constructed almost 1,000 years ago by the people of the Sinagua. Text and trail map courtesy of NPS.

The land around Montezuma Castle and Well has been home to many prehistoric groups of people since as early as 11,000 BC. The fascinating geologic and cultural history of Montezuma Well, Castle and this part of the American southwest are described in an excellent 1958 handbook by NPS that can be found at http://www.npshistory.com/handbooks/historical/27/hh27b.htm

> MONTEZUMA CASTLE, *a pueblo ruin in the Verde River valley of central Arizona, has no connection with the Aztec emperor whose name it bears. The name was given by early settlers in the Verde Valley in the belief that the striking 5-story ruin with its 20 rooms had been built by Aztec refugees, fleeing from central Mexico at the time of the Spanish conquest. It follows naturally that the small lake inside a hill 7 miles away should be named Montezuma Well. While the story of the flight is known to be false, the names remain.*
>
> Shroeder and Hastings, 1958

"How could water be the most important player in a story about the desert? In an entire year, Montezuma Well receives less than 13 inches (33 cm) of rainfall—barely ⅓ of the national average for the United States. Yet the Well contains over 15 million gallons (56.8 million liters) of water! Where does it come from? How did it get there? Until 2011 the answers to these questions were a mystery. Though water may be easily turned aside, it is patient, persistent, and unrelenting. More than 10,000 years ago, the Well's water fell as rain and snow atop the Mogollon Rim, visible to the north. Over millennia, it has percolated slowly through hundreds of yards of rock, draining drop by drop through the path of least resistance. But here the water encounters an obstacle much harder than the others through which it has flowed. Beneath the Well, a vertical wall of volcanic basalt acts like a dam, forcing water back toward the surface. In its long trip toward daylight, it eroded an underground cavern until its roof collapsed and created the sinkhole you see today. The water still flows. Every day, the Well is replenished with 1.5 million gallons (5.7 million liters) of new water. Like a bowl with a crack in its side, the water overflows through a long, narrow cave in the southeast rim to reappear on the other side at the outlet." (https://www.nps.gov/moca/planyourvisit/exploring-montezuma-well.htm).

Figure 7.95 *Left*: Montezuma Well on a clear day. NPS Photo by Ed Goodwin. *Right*: Aerial view showing Montezuma Well and Beaver Creek. From Schroeder and Hastings, 1958: Montezuma Castle National Monument, Arizona. National Park Service Historical Handbook Series No.27 (Reprint 1961).

Figure 7.96 *Left*: People have been using the constant supply of warm, fresh water flowing from Montezuma Well to irrigate their crops for over 1,000 years. This section of a "fossilized" 800-year-old irrigation ditch can be seen near the picnic area at Montezuma Well. The walls of this ditch were formed from deposits of lime that built up over hundreds of years of use. *Right*: An irrigation ditch built by the Sinagua Indians near Montezuma Well about 800 years ago. The water it carries is still used today. Photographs courtesy of NPS. USGS reports that monthly mean discharge of the Montezuma Well outlet ranged between about 1 and 3 cfs for the 1977-1992 period of record (Konieczki and Leake, 1997, p.4).

Unfortunately, the above upbeat excerpt from the NPS narrative is based on various assumptions, sometimes contradictory to each other, and the Well remains an unsolved mystery. Figure 7.97 shows a cross section featured on various NPS webpages dedicated to Montezuma Well and reproduced widely on the Web by many. It shows that the Well is formed in thick continuous deposits of travertine, and water leaves it via a long "cave" in travertine.

The main source of water to the Well, shown in Figure 7.97, is deeply seated Redwall limestone. The upward groundwater flow to the Well basin is forced by an assumed, thin, vertical basalt dike located directly below the Well basin. The assumed dike cuts the entire thickness of all the sediments shown, including young travertine deposits directly below the Well basin. Its existence was inferred from a geophysical survey. Notably, no dikes were mapped at the land surface near or farther away from the general area of the Well.

The cross section in Figure 7.97 contradicts other reports such as Johnson et al. (2011), Konieczki and Leake (1997), Vance (2014), and NPS' own narratives including in a pamphlet *Montezuma Castle National Monument, Montezuma Well* available at https://www.nps.gov/moca/planyourvisit/exploring-montezuma-well.htm:

"Over millions of years, underground streams dissolved away the soft limestone formed by sedimentation from Lake Verde, producing caverns below the surface of the Verde Valley. 11,000 years ago one of these caverns collapsed into a sunken pool, creating what we now call Montezuma Well."

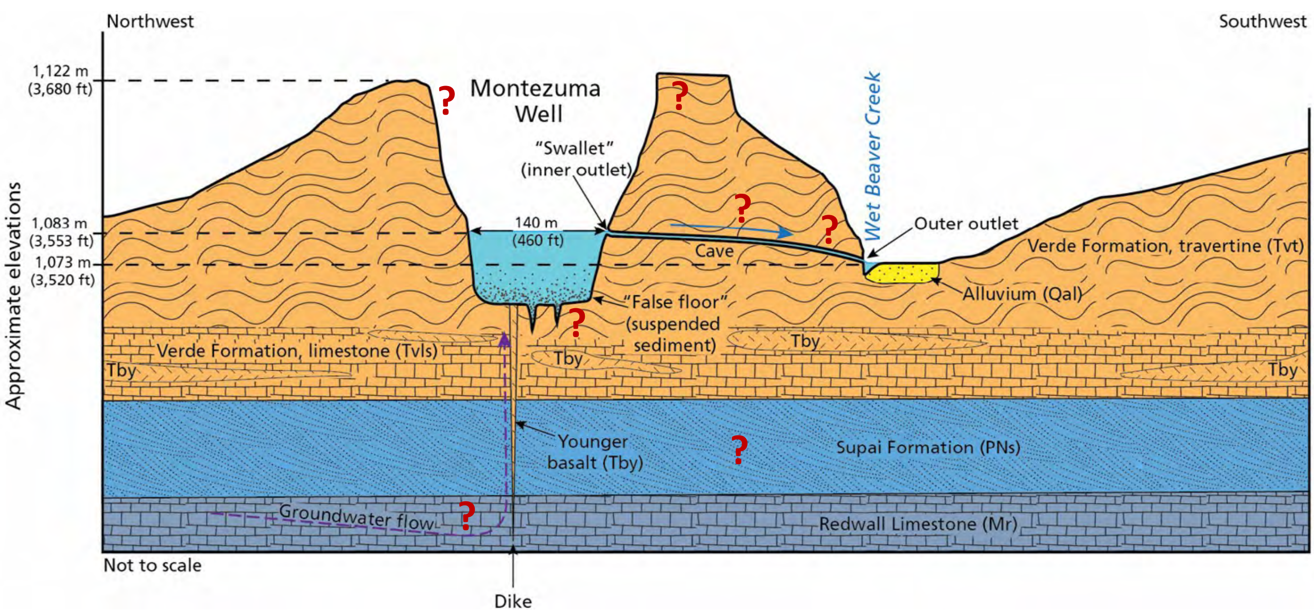


Figure 7.97 Figure and caption from KellerLynn, 2019 (question marks are added by the author of this book): Generalized cross section through Montezuma Well. Montezuma Well occurs in the Verde Formation, travertine (Tvt). Groundwater (represented by the purple arrow on the graphic) follows flow paths (shown in fig. 13) reaching permeable fractures along and above a basalt dike below the well. These fractures serve as conduits that carry groundwater and deep sourced carbon dioxide (CO2) to the surface, which dissolves carbonate minerals along the transport path in response to the added CO2; this mechanism likely formed the cavity of Montezuma Well. At the surface, CO2 degasses, depositing travertine. As evidence, travertine coats the current irrigation ditch that transports water away from Montezuma Well. Groundwater enters Montezuma Well with such force to keep sand particles in suspension, creating the "false floor." At the surface, water flows through the swallet, cave, and outer outlet into an irrigation ditch. Under natural conditions, Wet Beaver Creek would transport this water away from the well. Graphic by Trista Thornberry-Ehrlich (Colorado State University) after Konieczki and Leake (1997, figure 15) and Johnson et al. (2012a, figure 9) with information from Lange (1957) and Lenihan (2011).

Johnson et al. (2011) state that "The source of water to Montezuma Well, a flowing sinkhole in a desert setting is poorly understood. Water emerges from the middle limestone (emphasis added) facies of the lacustrine Verde Formation (Twenter and Metzger, 1963), but the precise origin of the water and its travel path are largely unknown (McKee and others, 1947; Lange, 1957). Some have proposed artesian flow to Montezuma Well through the Supai

Formation, which is exposed along the eastern margin of the Verde Valley and underlies the Verde Formation (Konieczki and Leake, 1997). The groundwater recharge zone likely lies above the floor of the Verde Valley somewhere to the north or east of Montezuma Well, where precipitation is more abundant."

According to Konieczki and Leake (1997), "The Supai Formation, consisting primarily of sandstone and siltstone underlies (emphasis added) the Verde Formation beneath the Montezuma Well pond and is exposed east of the pond. Near Montezuma Well, drillers' logs indicate that the Supai Formation is overlain by the Verde Formation and stream alluvium to a depth of about 52 feet. Near Montezuma Well, the Verde Formation is thin and has been removed by erosion to the east. Drillers' logs show a difference in composition of the Verde Formation between the area around Montezuma Well and the area near Camp Verde. The lithology near Montezuma Well mainly is limestone with some basalt flows, and the formation has extensive fractures and solution features. (emphasis added; see also Figures 7.98 and 7.99).

Most of the water supply wells in the area were drilled into the Verde Formation, and a few wells in the Beaver Creek drainage basin penetrate the Supai Formation. Water levels in wells completed in the Verde Formation range from flowing at the land surface to about 61.0 m (200 ft) below land surface. Well owners report that some wells drilled into the Verde Formation flow during the winter and not in the summer."

To make their groundwater flow model work, Konieczki and Leake (1997), assumed a hypothetical horizontal flow barrier and a vertical conduit to force groundwater flow upwards and discharge at Montezuma Well. A basalt dike was never mentioned in the entire report, nor were "extensive, thick travertine deposits".

Figure 7.98 Outlet of Montezuma Well in what appears to be Verde Formation limestone. Photo by Meghann M. Vance, 2010. From Vance, 2014.

"The possibility remains, however, that the flow system in the Verde Formation could include solution channels that transmit water to Montezuma Well from other areas within the Verde Formation. Although the mechanism for inflow from the Verde Formation is not understood, the Verde Formation and the underlying Supai Formation probably are the sources of water to Montezuma Well." (Konieczki and Leake, 1997.)

Vance (2014) states that "The Well is fed by two powerful underwater vents and maintains a constant temperature year round. Water exits the Well at the southern edge, traveling through a swallet (a dissolved channel in the stone that drains the surface water) some 300 feet through the limestone (emphasis added) surrounding the Well and exiting into a prehistoric irrigation canal on the other side, near Beaver Creek. Roughly 1.5 million of gallons, 74 degrees in temperature regardless of the time of year, flow out of the Well every day."

On the cross-section AA' by Johnson et al. (2011; Fig. 3, p.16), there is not Supai formation directly below travertine and limestone; instead, it is Tertiary Verde Formation limestone which overlies several hundred feet thick basalt (including an assumed thin and vertical basalt dike, not mapped anywhere in the vicinity of the Well). Only below this thick basalt there is sandstone of Supai Formation, and below all that are Mississippian Naco and Redwall limestones.

Importantly, in Johnson et al., (2011; Fig. 50, p.60), the groundwater flow direction is from the east-northeast (from the Transition Highlands of the Mogollon Rim– see Figure 7.93) to the west-southwest and the Verde Valley, and not from northwest to southwest as shown on the cross-section in Figure 7.97.

Travertine is a young sediment deposited from groundwater flowing to the land surface and supersaturated with calcium carbonate. It is virtually impermeable as evident by numerous travertine dams around the world which impound flowing surface water and create pretty waterfalls. Recently deposited travertine is not readily or quickly dissolved by water, and one cannot expect hundreds of feet long, dissolutional, tubular caves in it.

Highly transmissive vertical fractures in travertine, shown in Figure 7.97 to extend below the Well pond and presumably facilitate an exceptionally strong inflow of groundwater through the "vents" are also highly unlikely in travertine but could arguably be formed in areas of strong seismic and tectonic activity.

Figure 7.99 The people who lived at Montezuma Well over 700 years ago spent their winters living in these southeast-facing cliff dwellings. They built their homes here to take advantage of passive solar heating during the coldest months of the year. Note horizontal, fractured and cavernous rock layers at the top of the cliff. Photo courtesy of NPS.

Before a sinkhole collapse occurs, the material that has been eroded and/or dissolved must be transported away by groundwater, via karst conduits and their network, so that the cavity can be formed. When a sinkhole collapse occurs, the material that collapsed remains at the bottom of the cavity and can also be transported away via a conduit network. None of these mechanisms is likely to exist within the travertine deposits shown in Figure 7.97.

Below are several excerpts from a fascinating story about various Well diving expeditions told by Steve Ayers, courtesy of Verde Valley Newspapers (https://www.nps.gov/moca/learn/photosmultimedia/dive-to-the-bottom-of-the-well.htm). Especially telling is the encounter with the force of groundwater coming up to the Well at its bottom, effectively preventing any downward removal of the geologic material by groundwater, before or after a "collapse" in the mischaracterized travertine deposits.

- *The report of diver H.J. Charbonneau seemed to verify a conclusion drawn by the famous newspaper reporter and adventurer, Charles Lummis, some 60 years earlier, that the well was a "creepy place."*
- *In 1962, diver G.J. Murray became the first to report that the mysterious bottom was perhaps not the bottom.*
- *In an article in Skin Diver magazine, Murray reported of the eeriness of swimming "in a 'bottomless pit' with thousands free swimming leeches."*

- *Murray labeled it a bottomless pit after observing that the bottom of the well appeared as "an irregular boiling surface, like that of thin mush cooking."*
- *Numerous other divers have since reported the strange layer of sandy sediments, describing the "false bottom" as "a white lava flow moving on top of a suspended bottom with a silica gel consistency," or "quick sand" or even "boiling oatmeal."*
- *A probe dropped into the west vent went down 69 feet through the fluidized sand. Added to the 55 feet from the water's surface to where the sand layer starts, makes the west vent 124 feet deep overall. The east vent measured 19 feet, or 74 feet overall.*
- *Of all the discoveries made during their 2006 dive, perhaps the most interesting for the dive team was the correlation of their scientific research with the traditional stories of the Yavapai and Apache people.*
- *One day while Conlin and Lenihan were studying the well, they met a group of tribal elders, who told of stories from their past that said there was a place at the bottom from which once something emerged, it could never return.*
- *"It was a very interesting view for us, in all our scientific splendor, and it kept coming back to us," Lenihan said. "Everything we tried putting down those holes -- cameras, rovers, sensors -- kept being pushed back out. It was an interesting convergence of how they viewed the well and how science looks at it."*

Whatever the case may be regarding various geologic and hydrogeologic inconsistencies mentioned earlier, Montezuma Well remains a great mystery. Before this mystery is solved by experienced karst hydrogeologists, one can only with awe read the following excerpt from a Native American oral tradition:

> *The Hopi have been an agricultural people for a long time. However, even though we have always grown our own food, life was still difficult. When our ancestors (who people now call Sinagua) found the Well, they realized life could be easier. So they stayed and made it their home. However, life became too easy and the people became complacent. It was as though they had forgotten who they were and how they should live. The village was in a state of shameless corruption. One day, the village began to shake and the houses caved in. Water gushed in and filled the hole where the village once stood. Suddenly, a great serpent rose up out of the water in anger at what the people had become. Upon seeing the serpent, everyone became very scared and ran away to the north and east, never to return.*
>
> Summary of "The Legend of Montezuma Well", as told
> by Fred Lomayesva of the Hopi Snow Clan

7.6.3 Santa Rosa Blue Hole, New Mexico

Santa Rosa Blue Hole is one of this author's ten favorite springs in the country. If the reader ever finds herself/himself anywhere near the spring, say within several hours' worth of driving, a strong recommendation is to try and visit the spring. The Spring is located right off Interstate Highway 40, 117 miles east of Albuquerque. Below are several excerpts from the Santa Rosa Blue Hole webpage describing the Spring.

Blue Hole appears in the midst of the desert like a great blue gem. (Agua Negra Chiquita) Once known as Blue Lake, it is one of seven sister lakes connected underground by a vast system of water.

Nomadic tribes, cowboys driving their dogies across the Pecos, and Americans going west on the Mother Road, Route 66, all sought respite here.

In 1932, Blue Hole became a National fish hatchery, morphed into the Blue Hole Recreation Area in the seventies, and more recently expanded to become the Blue Hole Dive and Conference Center.

Now it's a destination meeting site for everyone from brides to board chairs. Halfway between Albuquerque and Amarillo, it's within two hours drive of 80 percent of all New Mexicans.

Not just for drivers wanting to get out of the fast lane or divers eager to get on down, it's more than just a watering hole.

Figure 7.101 Santa Rosa Blue Hole spring in Santa Rosa, New Mexico. Ball-shaped buoys are anchored to the *cenote* bottom and provide orientation for divers. Courtesy of https://www.santarosabluehole.com/

Still, we never forget that the real sapphire is the incredible beauty of the Blue Hole itself.

The lake is unsurpassed for its clear, pure water. That's why we work so hard to protect it, ensuring, for example, that surface runoff won't impair its purity. Like scuba divers who drive ten hours to get here, we know it's the crystalline water that draws them in.

Visibility is an astonishing 100' due to the fact that the water completely renews itself every six hours—it's truly never the same lake twice.

What doesn't change is the temperature—a constant 62 degrees, ideal for storing a fine Cabernet or tossing in the kids on a hot summer's day. Within a few minutes of exiting the interchange, they'll literally be climbing the walls—the lovely rock surrounds of Blue Hole, that is—and jumping in.

About The Blue Hole Santa Rosa New Mexico (santarosabluehole.com)

The 90 foot deep Blue Hole is an example of a sinkhole or *cenote* (a water-filled sinkhole in Spanish) that is formed in limestone karst. Collapse sinkholes, like this one, typically form when the land surface collapses into a dissolution void formed in soluble limestone bedrock. Inflow and outflow of groundwater from Blue Hole is a constant 3,000 gpm.

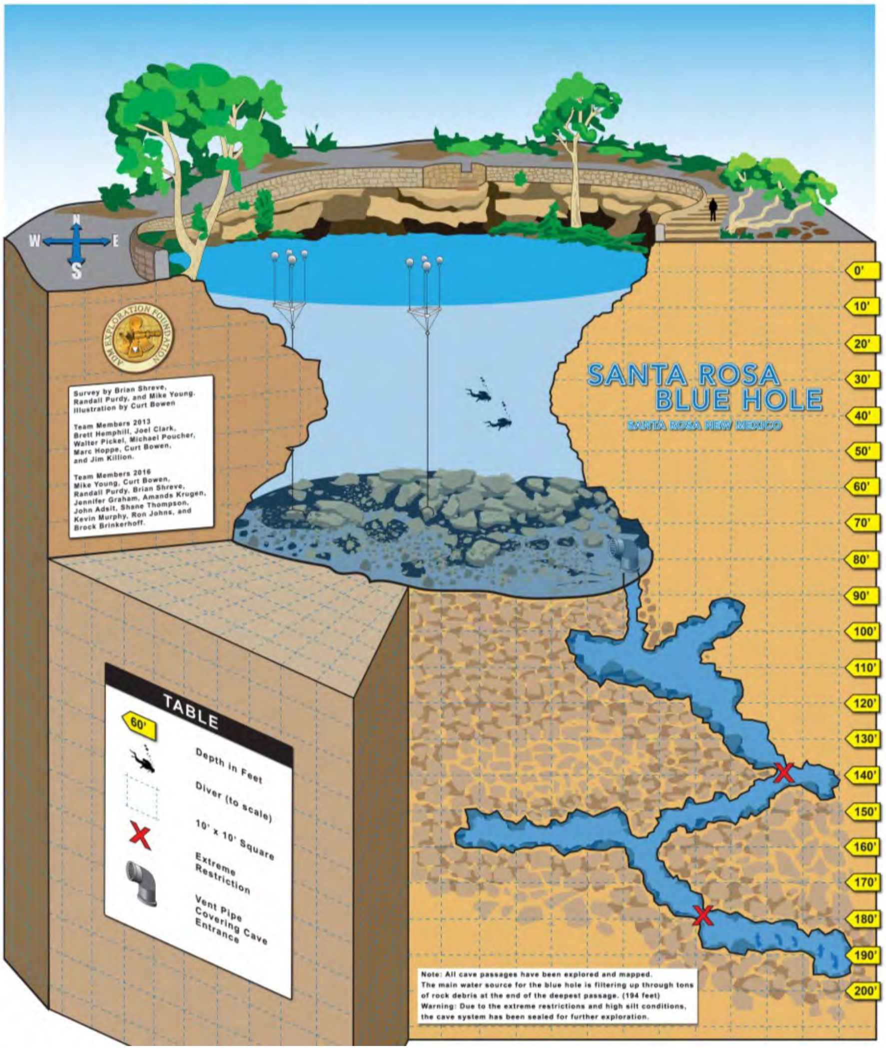


Figure 7.102 Divers assembled by ADM Exploration Foundation surveyed cave passages below the sinkhole on several occasions. The expeditions are documented on an excellent web site which features diving videos as well. Note at the bottom of the map reads: All cave passages have been explored and mapped. The main water source for the blue hole is filtering up through tons of rock debris at the end of the deepest passage. (194 feet) Warning: Due to the extreme restrictions and high silt conditions, the cave system has been sealed for further exploration. Available at *http://www.admfoundation.org/projects/santarosa/santarosaexpedition.html*

Bottomless Lakes State Park 14 mi southeast of Roswell, on the east edge of the Pecos River valley, has seven lakes which also are solution and collapse sinkholes created by upward artesian flow of groundwater through gypsum bedrock (see Figure 7.103). The Park's website includes nice photographs of the lakes and a thorough explanation of how they were formed (Geologic Tour: Bottomless Lakes State Park (nmt.edu)).

Figure 7.103 Mirror Lake, one of several sinkholes filled with water at Bottomless Lakes State Park east of Roswell. Courtesy of Bottomless Lakes State Park.

7.6.3 Cascade Springs, South Dakota

As described by Rahn and Gries (1973), Cascade Spring is the largest single spring in the Black Hills of South Dakota. It issues forth dramatically at the contact of the Minnekahta and Spearfish Formations. It has a steady discharge and constant temperature of 67°F. One mile north of Cascade Spring itself is a smaller spring called "Cold Spring," which has a discharge of about 1.1 cfs and a temperature of 64°F. The discharge of Cascade Spring and Cold Spring together averages 23.65 cfs. Because of the large discharge rate of the spring, and because of the small surface drainage basin above the spring, it is obvious that Cascade Spring is recharged by water entering the limestone underlying other surface drainage basins; namely, the expanse of limestone to the northwest towards Jewel Cave.

"Based on water quality data and piezometric levels of wells in the Edgemont area, Keene (in preparation) suggests that Cascade Spring is derived from groundwater in the Minnelusa Formation. Because of the high dissolved solids in this spring water (table 3), the vegetation and stream bed become coated with limestone. The waterfalls 3 miles downstream from the spring are caused by these deposits called calc-tufa (i.e., travertine – author's note). The clear, briskly-flowing waters make Cascade Creek one of the most scenic locales in the Black Hills." (Rahn and Gries, 1973.)

A description provided by Darton of USGS in 1901, reads "*Cascade Creek.*-This vigorous stream is the product of the springs at Cascade, where a large volume of water issues from the Minnekahta limestone. In Pl. CIII (Figure 7.104 in this book) are shown the two largest springs at this place. The water is slightly warm, and contains a large amount of mineral matter. The volume of the creek at its mouth was 25 second-feet on May 18, 1900."

Figure 7.104 Two largest springs at Cascade Springs emerging from crevices in Minnekahta Limestone. Plate CIII from Darton, 1901.

The Black Hills is an extensive, elliptically domed area in northwestern South Dakota and northeastern Wyoming, about 125 miles long and 65 miles wide (Figure 7.105). Rapid City, South Dakota, is on the Missouri Plateau at the east edge of the Black Hills. Uplift caused erosion to remove the overlying cover of marine sedimentary rocks and expose the granite and metamorphic rocks that form the core of the dome. The peaks of the central part of the Black Hills are 3,000 to 4,000 feet above the surrounding plains. Harney Peak, with an altitude of 7,242 feet, is the highest point in South Dakota. These central spires and peaks all are carved from granite and other igneous and metamorphic rocks that form the core of the uplift. The heads of four U.S. Presidents are sculpted from this granite at Mount Rushmore National Memorial. Joints in the rocks have controlled weathering processes that influenced the final shaping of many of these landforms. (See also [Park Geology - Wind Cave National Park (U.S. National Park Service) (nps.gov)](https://www.nps.gov).

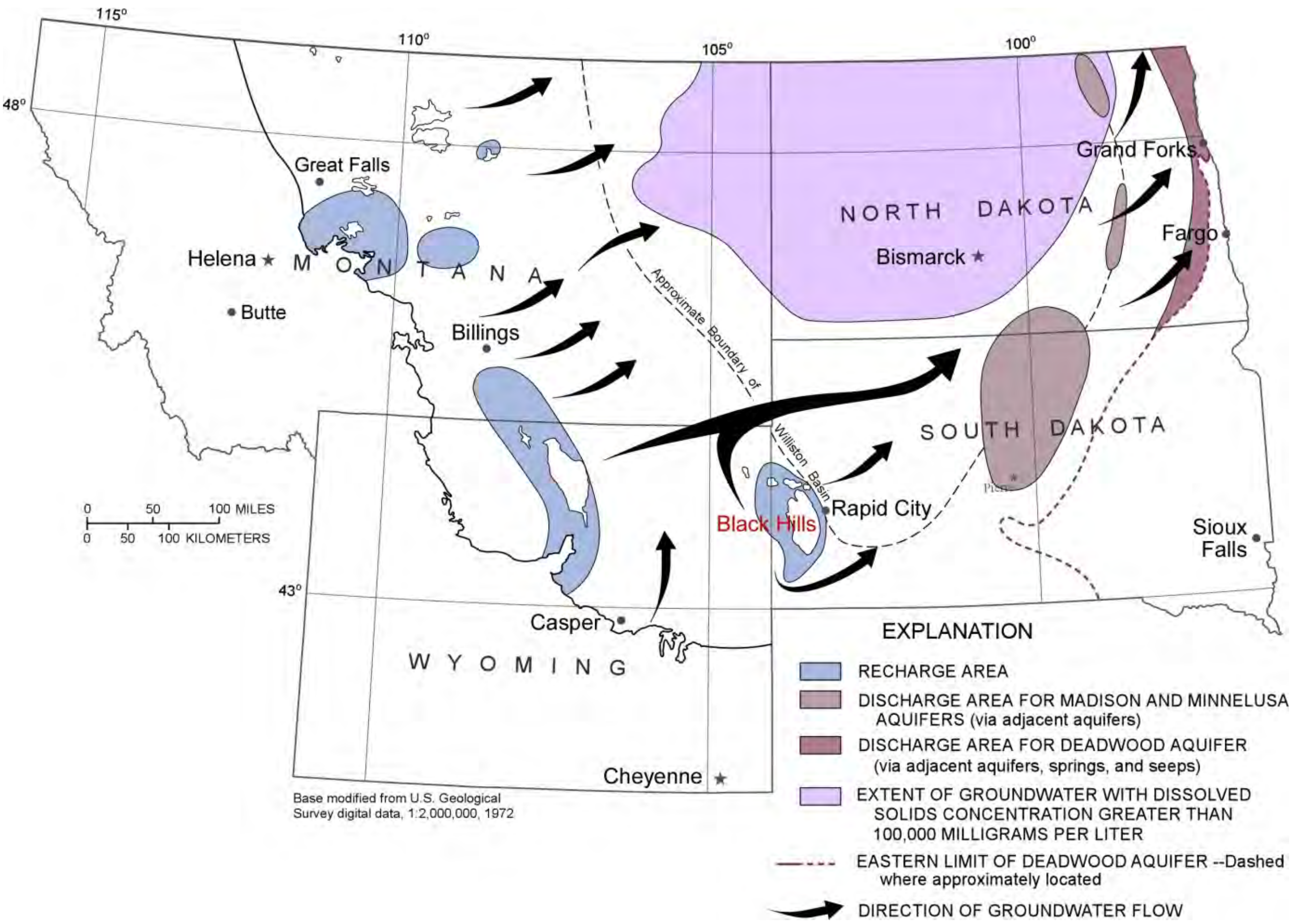


Figure 7.105 Position of Black Hills in the regional aquifer system within Paleozoic aquifer units of Montana, Wyoming and the Dakotas (from Driscoll et al., 2002; modified from Downey and Dinwiddie, 1988; Whitehead, 1996).

The scientists of the USGS have produced numerous reports on the geology, hydrology, and mineral deposits of the Black Hills uplift starting in the early 1900s (e.g., Darton, 1901; Bowles and Braddock, 1963; Naus et al., 2001; Driscoll et al., 2002—see Figures 7.106 and 7.107); however, springs that drain the prolific limestone aquifers of the Black Hills, including the largest, Cascade Springs, and the famous Hot Springs (just a few miles to the north of Cascade Springs; see Chapter 9.4) were not the main focus of any of these reports and were usually mentioned only in passing.

An informative overview of the hydrogeology of Cascade Springs is provided by Rick Clawges of the Nature Conservancy (available at Cascade Springs Hydrogeology (nature.org)) and includes references to relevant sections in various reports by the USGS and South Dakota Geological Survey, and theses of students at western universities.

The Nature Conservancy project area lies within the southern Black Hills and is part of a hydrogeologic setting characterized by streamflow losses that occur as streams cross outcrops of the karstified Madison (Pahasapa) Limestone of Mississippian age, and Minnelusa Formation of Pennsylvanian to Permian age (Driscoll et al., 2002). Within this setting, large artesian springs, originating primarily from the karstic Madison and Minnelusa aquifers, occur in many locations downgradient from the loss zone, most commonly within or near the outcrop of the

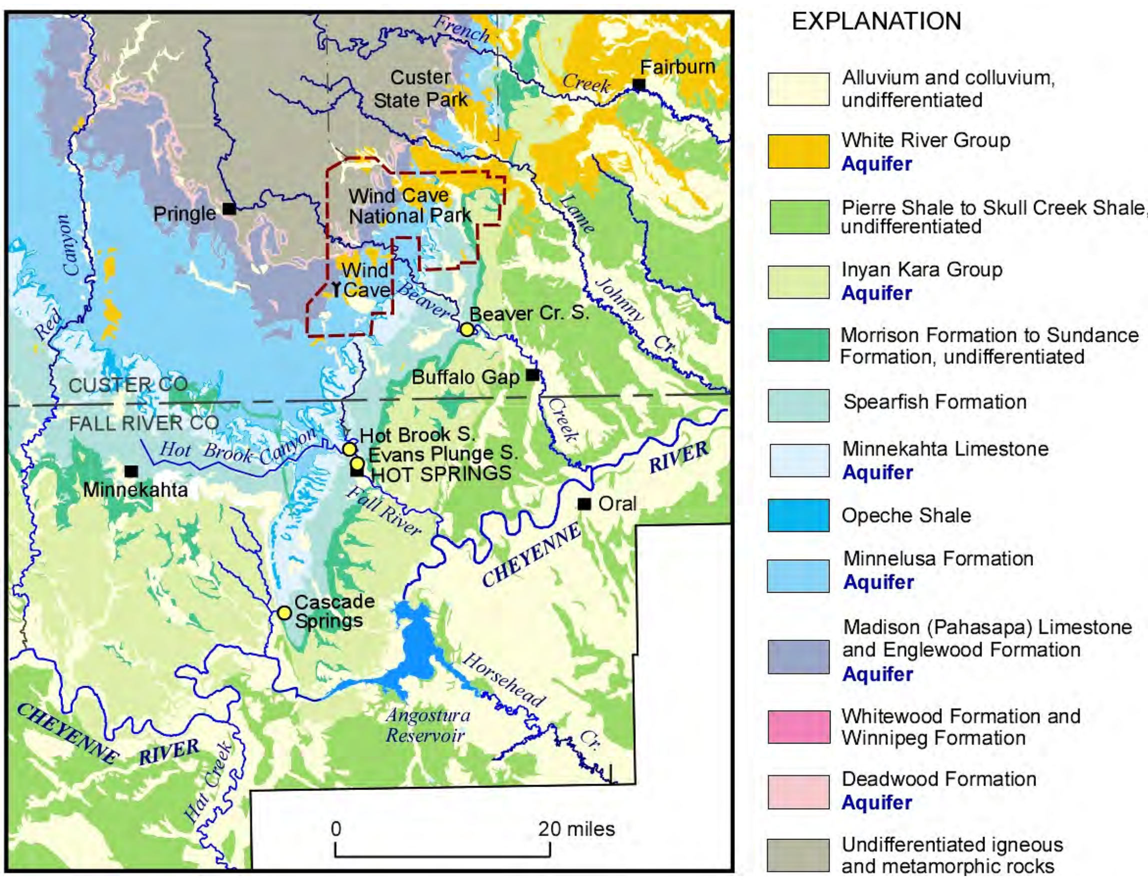


Figure 7.106 Distribution of hydrogeologic units in the southern portion of Black Hills area. Part of map in Figure 14 from Driscoll et al., 2002. Springs are shown with yellow dots. Modified and simplified for clarity.

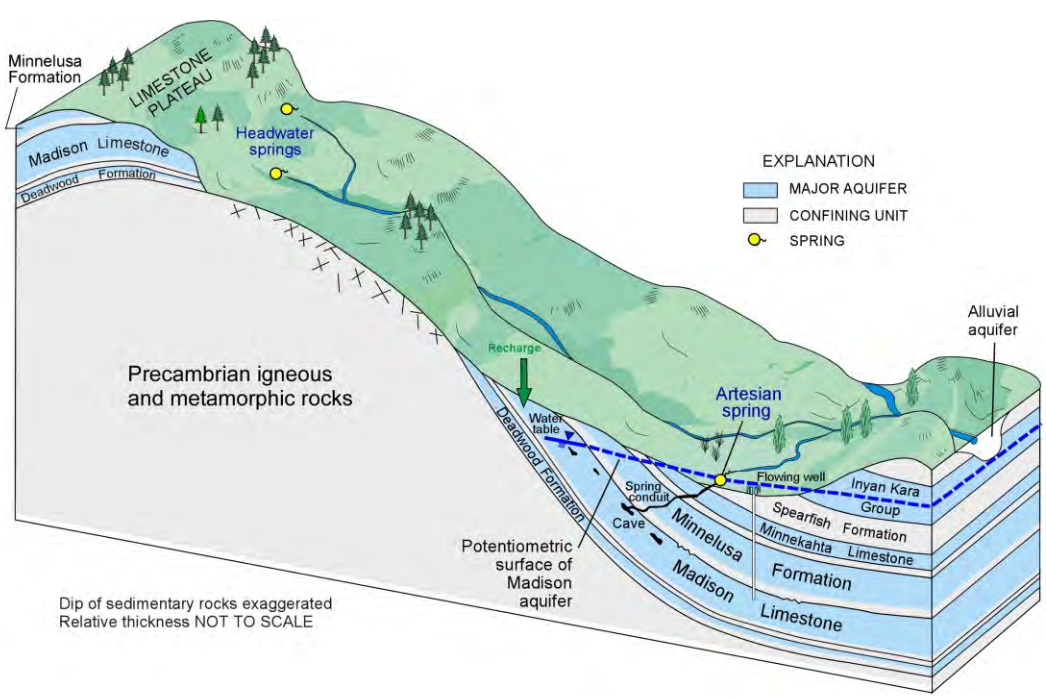


Figure 7.107 -Schematic showing hydrogeologic setting of Black Hills area. Modified from Driscoll et al., 2002.

confining Spearfish Formation of late Permian to Triassic age (see Figure 7.107). These springs provide an important source of baseflow in many streams beyond the periphery of the Black Hills (Rahn and Gries, 1973; Miller and Driscoll, 1998). Cascade Springs is a group of artesian springs within the Nature Conservancy's Cheyenne River Canyons Project area on the Nathaniel and Mary Whitney Preserve. Year-round discharge from Cascade Springs contributes most of the flow to Cascade Creek, a tributary to the Cheyenne River.

Figure 7.108 Southern Black Hills. Photo courtesy of NPS.

As discussed by Rahn and Gries (1973), large amounts of water are recharged to the inner edge of the karstified carbonate aquifer encircling the impermeable Precambrian core of the Black Hills. When the streams originating at the impermeable core and flowing radially away from it cross the karstified surface, they lose significant quantities of water to the underlying carbonate aquifers. Even larger quantities of water discharge from the outer edge of the carbonate aquifers via numerous springs at topographic lows in the "groundwater dam" caused by the thick sequence of shales of Triassic and Jurassic age. As postulated by Rahn and Gries, the difference between the total streamflow loss (44 cfs) and the average spring discharge (190 cfs) must be due to precipitation falling directly on the carbonate aquifers.

Leakage between the Madison and Minnelusa aquifers is common, but highly variable (Peter, 1985; Greene, 1993). The general direction of groundwater flow in the southern Black Hills in both the Minnelusa and Madison aquifers is from north to south, but also may be from the northwest to southeast, or west to east (Whalen, 1994).

Contributions from the Madison and Minnelusa aquifers to individual artesian springs cannot necessarily be quantified precisely (Naus et al., 2001) because of geochemical similarities between the aquifers. For some springs, high sulfate concentrations could indicate Minnelusa influence but may also result from dissolution of Minnelusa minerals by water from the Madison aquifer. Previous investigators (Whalen, 1994; Klemp, 1995; and Hayes, 1999) used geochemical modeling to estimate contributions of the Madison and Minnelusa aquifers to selected springs. The Madison aquifer generally was identified as the primary source, with variable contributions from the Minnelusa aquifer, or chemical influences resulting from residence time within the Minnelusa Formation (Driscoll et al., 2002).

Hayes (1999) hypothesized that upward leakage from the Madison aquifer was contributing to ongoing development of breccia pipes at Cascade Springs. He noted that breccia pipes commonly occur in the upper Minnelusa Formation, but very few have been observed in the lower part of the formation. Development of breccia pipes probably contributes to enhanced vertical hydraulic conductivity in the Minnelusa aquifer. Breccia pipes are a likely pathway for upward movement of large quantities of water through the Minnelusa aquifer at artesian spring locations.

Hayes (1999) further hypothesized that many exposed breccia pipes of the upper Minnelusa Formation probably are the throats of abandoned artesian springs. An outward (downgradient) shifting of locations of artesian springs probably has occurred as upgradient spring-discharge points are abandoned and new ones are occupied, keeping pace with regional erosion over geologic time (Hayes, 1999). In response, hydraulic heads in the Madison and Minnelusa aquifers have declined over geologic time, as indicated by exposed breccia pipes located upgradient from Cascade Springs (Hayes, 1999). Further supporting evidence is provided by Ford and others (1993), who concluded that water-level declines of more than 300 ft have occurred in the Madison aquifer during the last 350,000 years, based on geochemical data for Wind Cave.

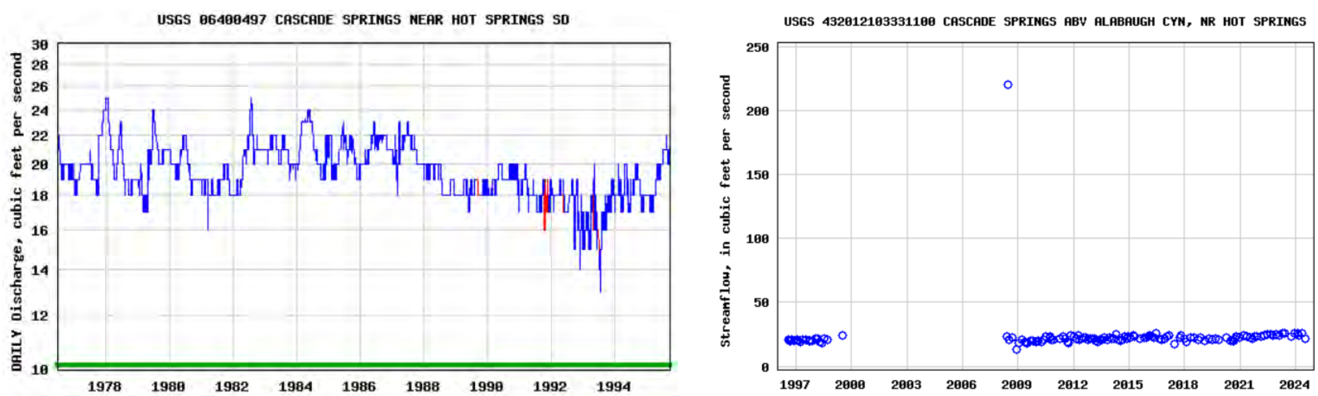


Figure 7.109 Daily (left) and field measurement (right) of discharge rate at Cascade Springs available from USGS.

Water discharging from Cascade Springs contains some tritium, but in relatively low concentrations, indicating that most of the water was recharged prior to nuclear testing, but that a smaller proportion of post-nuclear-testing water is also present. The major proportion of Cascade Springs water has probably been out of contact with the atmosphere for more than 40 years, indicating long travel times from precipitation recharge to discharge at the springs (Naus et al., 2001; Driscoll at al., 2002).

Cascade Springs differs from many other artesian springs occurring around the periphery of the Black Hills because of the relatively high temperature of its water (mostly cited to be about 20° C, or 67-68°F; interestingly, Post (1967) states that the water temperature of Cascade Springs is 72°F). Other springs discharging around the City of Hot Springs, including those at Evans Plunge, have similarly high and higher relative temperatures (see Chapter 9.4). The cause of anomalously warm water in springs and wells of the southern Black Hills remains an enigma. Theories for the cause include heat generation by radioactive decay of basement rocks, geochemical reactions between groundwater and soluble rocks, a partially cooled magma lying at shallow depth in the southern Black Hills, and areas of high geothermal gradients caused by proximity of heat-conducting Precambrian rock (Rahn and Gries, 1973; Schoon and MacGregor; 1974; Knircsh, 1980; Whalen, 1994).

The area of Cascade Springs and Hot Springs in southern Black Hills has a fascinating history and has attracted both Native Americans and white settlers because of the thermal waters and natural beauty, but also other reasons as illustrated by the following excerpts.

Dakota Life: The life and death of Cascade by Lee Zion (Lee.zion@capjournal.com), Jun 9, 2016; updated Sep 24, 2019 (Dakota Life: The life and death of Cascade | News | capjournal.com).

Of all the "ghost towns" in South Dakota, the grandest one may have been Cascade, sometimes referred to as Cascade Springs because of the nearby hot springs. Back in 1892, its heyday, the town had about 400 people and 50 businesses, including a hotel, a sanatorium and a bowling alley.

But that time was brief. By 1900 the town was down to 25 residents. Most of them left shortly after.

A real estate brochure dated June 25, 1891, touted the new 90-acre town, sometimes with inflated language that bordered on near hilarity — and sometimes in language that would be unacceptable today.

"In Fall River County, Black Hills, South Dakota, is situated the town of Cascade Springs, which is nine miles south-west of the celebrated Hot Springs, that are attracting the attention of the health seekers on account of the marvelous cures that have resulted in the mineral waters that abound in the region," the brochure says.

Figure 9.111 The W. Allen Bank, the Fargo grocery store, and the Cascade Club at Cascade ghost town. Photo courtesy of South Dakota Historical Society

"Particularly did they (Native Americans) *mourn after the pine-clad hills and the gushing springs that exist at Cascade as a health and pleasure resort," the brochure stated. "Twenty years ago, the buffalo were very plentiful in South Dakota, and after a hard chase, the Indians used to seek the country that surrounds Hot Springs and Cascade Springs, particularly the warlike Sioux and Cheyenne Indians. They also sent their sick and aged here for the purpose of regaining health and strength. ... The Indians regarded it as the special manifestation of the Great Spirit, who had sent them this spot as a haven of rest and cure for all their afflictions."*

"We give special inducements to parties who are looking for business locations. All branches of business will prosper, and the man who buys property this year, 1891, at Cascade Springs, will do well," the brochure stated. "The time to buy lots is recognized on all sides as now — before the grand rush of the next summer, 1892, carries everything, and especially business lots, on the top crest of a Big Boom."

As readers that visit the Capital Journal's website to read the whole story will find out, the anticipated railroad from the north, which triggered all the frenzy, bypassed the town-to-be, and the dream of grandeur never materialized.

Figure 9.110 Located just 8 miles south of Hot Springs, the consistent 67°F waters of Cascade Falls are a hidden gem in the southern Black Hills. Located a mile and a half below Cascade Springs, water of the Cascade Creek flows over prominent travertine terraces. Locals love to visit in the heat of the summer. There are designated parking lots with paved pathways that lead right to the falls, where swimming is allowed. Swimming at Cascade Springs is not allowed. The Black Hills National Forest manages land adjacent to Cascade Creek in two areas: J.H. Keith Park Cascade Springs Picnic Ground and Cascade Falls Picnic Ground, located approximately 6 and 8 miles, respectively, south of Hot Springs, South Dakota on SD Highway 71. Photo Courtesy of Hot Springs Chamber of Commerce.

The fascinating karst of the Black Hills hosts the second and third longest cave in the United States: Jewel Cave near Custer (219.66 miles long as of January 8, 2024; see Cave Exploration - Jewel Cave National Monument (U.S. National Park Service) (nps.gov)), and Wind Cave, located 14 miles north of Hot Springs via US-385N (167 mi long as of July 1, 2024; see South Dakota's Wind Cave is now the world's sixth longest • South Dakota Searchlight). At 426 miles long (as of September 2022), Mammoth Cave in Kentucky is the longest cave in the United States and the world.

Wind Cave National Park and Jewel Cave National Monument are two spectacular features in the Black Hills. Jewel Cave is beautifully decorated with stalagmites and stalactites, flowstones, and large calcite crystals. Wind Cave (Figures 7.111 and 7.112) too has beautiful speleothems and acts as a 'natural barometer,' with wind blowing out of the cave when outside pressure is low, and into the cave when the outside pressure is high.

Figure 7.111 *Top Left*: Tiny natural entrance to Wind Cave; NPS photo. *Top Right*: The boxwork on the ceiling of the Elk's Room is a popular photography subject and has been featured on many postcards and other souvenirs. NPS photo by Kim Acker. *Bottom Left*: Cave Frostwork, NPS photo. *Bottom Right*: Skyway Lake, NPS photo.

Figure 7.112 *Left*: Helictite bushes NPS Photo by Dave Bunnell. *Right*: Dogtooth spar. Vugs are common along tour routes and other places where chunks of rock have been broken or fallen off the wall. Vugs are very similar to geodes and are usually lined with calcite crystals. Because of the crystal's tooth-like shape, this form is called dogtooth spar. NPS Photo by Jason Walz.

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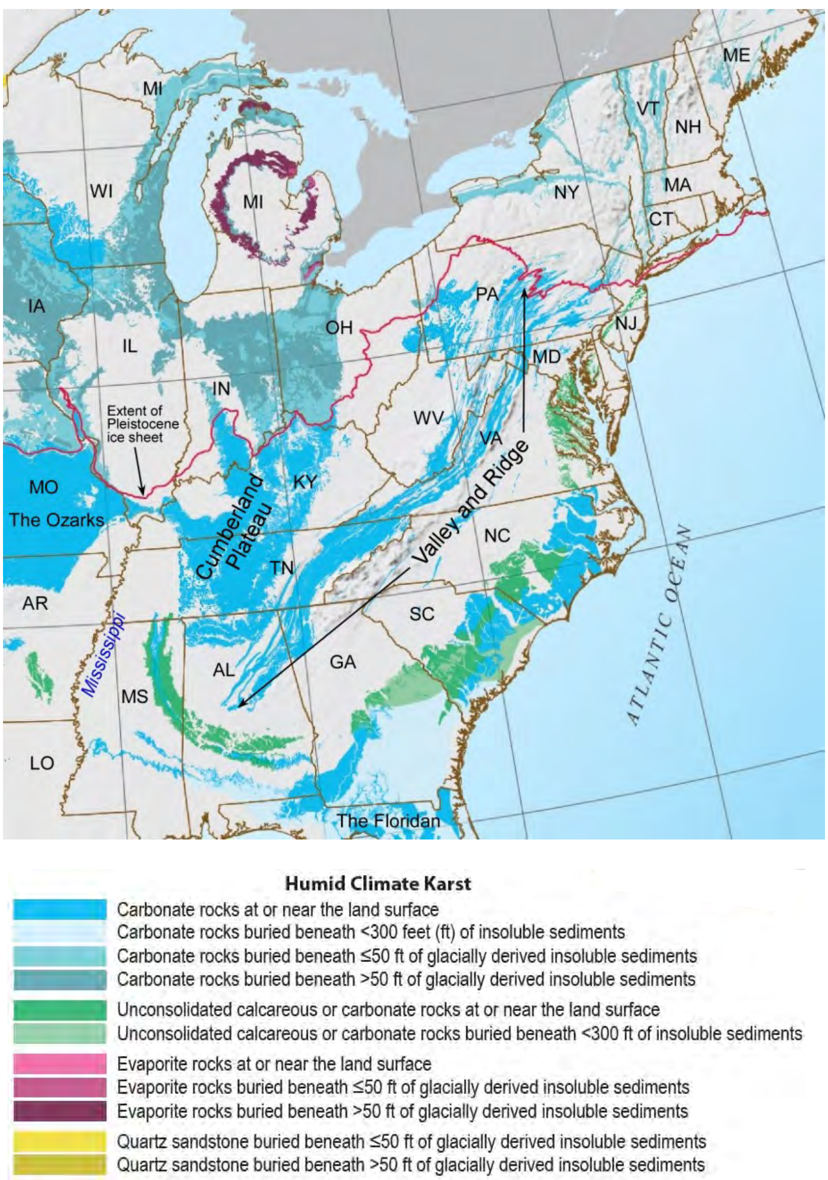
Chapter 8 The East

8.1 Introduction

Although the physiographic provinces in the eastern United States contain extensive karst terrains that stretch through multiple states (Figure 8.1), and sometimes occupy a better part of a state as in the case of Kentucky, there are no reliably confirmed first-magnitude springs outside Florida. A possible exception is Davis Spring in West Virginia. Tuscumbia Spring, a second-magnitude spring in Alabama, is the second largest in the East. Figure 8.2-*Left* shows the hydrograph of discharge rates for Davis Spring, recorded by USGS daily between October 1971 and October 1973 (there are no daily measurements by USGS before or after that period); Figure 8.2-*Right* shows the available field measurements for Tuscumbia Spring conducted over the years by the Alabama Geological Survey (Smith and Guthrie, 2022).



Primary reasons for the lack of first-magnitude springs in the East are the geology and geomorphology of the areas underlain by soluble carbonate rocks. In addition, there are no basaltic and other volcanic rock aquifers in the East which give rise to many spectacular, large, first-magnitude springs in Oregon, Idaho, and California.

Individual karst aquifers in the East are of limited extent, both in area covered as well as depth. The carbonate rock layers are interrupted by numerous folds, faults, successions of less permeable or impermeable layers of sandstone and fine-grained sedimentary rocks, and well-developed surface drainage (Figure 8.3). This results in the compartmentalization of the karst aquifers and the small discharge of springs that drain them.

Figure 8.1 Distribution of karst and potential karst areas in soluble rocks in the eastern contiguous United States. From Weary and Doctor, 2014; USGS; annotation added. Most larger springs are in the Valley and Ridge province of the Appalachians and the Cumberland Plateau in Kentucky and Alabama.

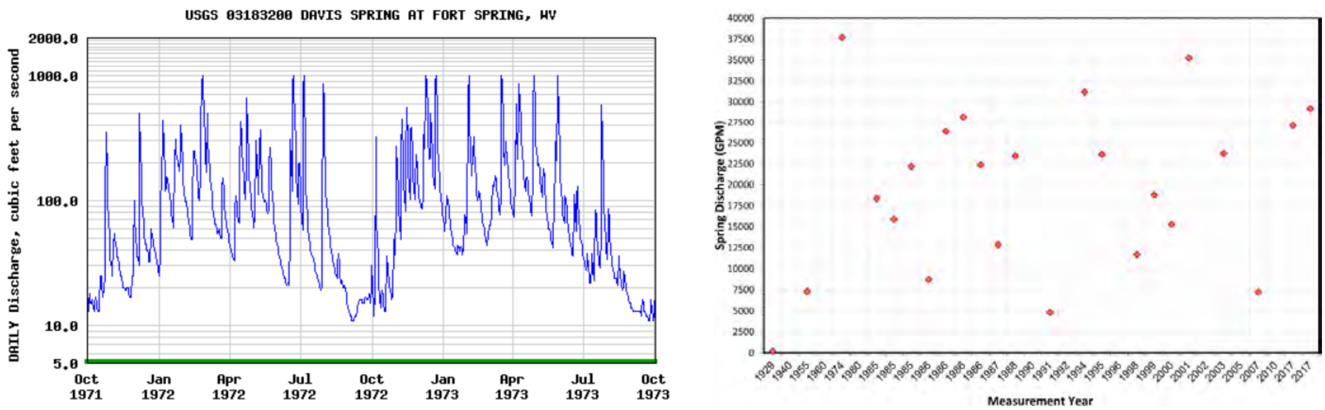


Figure 8.2 *Left*: Daily discharge rate of Davis Spring, West Virginia for the period of record. The average is 124.6 cfs, with a minimum of 11 cfs and maximum >1,000 cfs (the graph is truncated at 1,000 cfs for reasons that are not clear; see Section 8.2.2.1). *Right*: Discharge hydrograph for Tuscumbia Spring in Colbert County, Alabama. It is a second-magnitude spring with an average discharge rate of 20,769 gpm (56 cfs). The highest recorded discharge rate was measured at 46,791 gpm (125 cfs) on April 12, 2018, and the lowest recorded discharge rate of the spring was 200 gpm (0.5 cfs) on August 6, 1929. From Smith and Guthrie, 2022.

Figure 8.3 *Left*: "Nate reviews the meaning of torture"; tight small folds in a Bath County, Virginia cave. Photo courtesy of Phil Lukas. *Right*: Devil's Bone Anticline in Tuscarora sandstone, Pocahontas County, West Virginia.

Karst is fully developed in the carbonate terrains of the East as attested by the photographs in Figures 8.4 to 8.9. Throughout the region there are classic karst landforms such as sinkholes, sinking streams, caves, and numerous springs that discharge from often spectacular cave entrances.

Figure 8.4 *Left*: Sinkholes in Monroe County, West Virginia. Photo courtesy of William Jones.

Figure 8.5 Natural Bridge. The 37th Virginia state park (Natural Bridge State Park (virginia.gov)) was dedicated on September 24, 2016, and was listed on the National Register of Historic Places as a National Historic Landmark in 1988. At the center of the park, the 200-foot tall Natural Bridge sits in a limestone gorge carved out by Cedar Creek. The park is 30 minutes' drive from Roanoke via I-81 and US-11. Photo courtesy of https://gohikevirginia.com/

Figure 8.6 Hydrogeologist Jim Quinlan showing a collapse sinkhole in a road cut, Mammoth Cave National Park, Kentucky. For many years, Jim was a powerful force behind the hydrogeological characterization of the Park, including mapping and numerous tracing tests.

Figure 8.7 *Left*: Sinks of Pots Creek, Alleghany County, Virginia. Photo courtesy of Phil Lukas. *Right*: Large collapse sinkhole in central Alabama (often called Goly Hole) appeared in a matter of hours in December 1972, just south of the intersection of Shelby County Road 84 and Overhill Road in northern Calera. It is 425 feet long, 350 feet wide, and 150 feet deep. Photo by George Sowers, printed with kind permission of Francis Sowers.

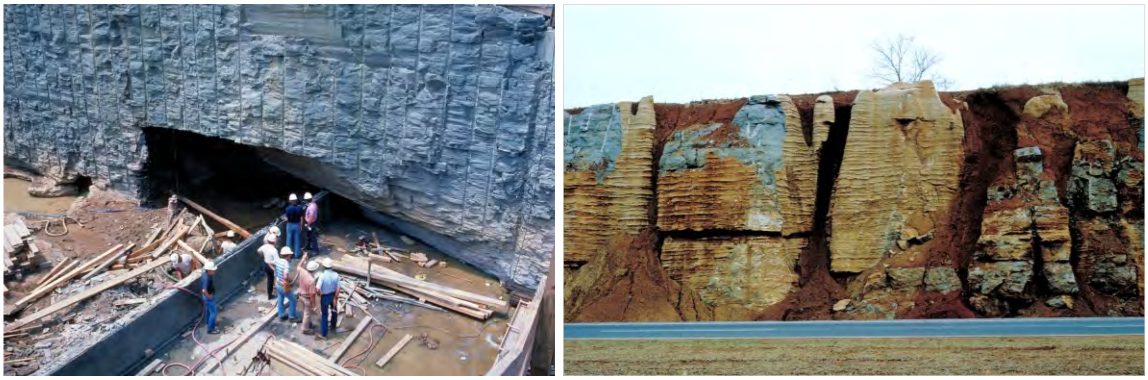


Figure 8.8 *Left*: Large cavern uncovered during construction dewatering at a deep facility in Tennessee. *Right*: Highly weathered top portion of limestone ("epikarst") exposed in a road cut in Kentucky. Photographs by George Sowers, printed with kind permission of Francis Sowers.

Figure 8.9 *Left*: Grand Canyon in Crystal Cave, Mammoth Cave National Park, Kentucky. Note caver for scale. Photograph by Art Palmer (SUNY Oneonta), courtesy of Rick Olson (Mammoth Cave NP). *Right*: Delicate drapery (speleothem) in Shenandoah Caverns in Virginia.

One of the key consequences of the well-developed karst and the excessive three-dimensional compartmentalization of the karst aquifers is that springs in the East have very large fluctuations of discharge rates (Figure 8.10), often accompanied by very high turbidity (they are "muddy") after rainfall events, sometimes for long periods of time (see Figures 8.11 through 8.13). As a result, few springs in the East can compare with many of the magnificent springs described in the previous chapters, discharging crystal-clear water all the time.

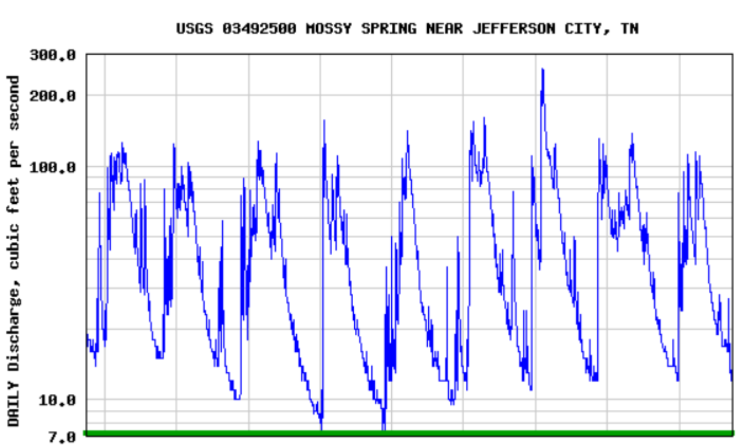


Figure 8.10 Daily discharge rate of Mossy Spring near Jefferson City, Tennessee for the period of record.

Figure 8.11 Aqua Spring has the largest flow rate and the largest variation of flow of all springs in the Bullpasture Gorge, Virginia. *Left*: Average flow conditions. *Right*: High flow rate after heavy rainfall carrying a heavy sediment load. The boils or mounds of water above the spring are more than ten feet high. Photographs courtesy of Phil Lukas.

Figure 8.12 *Left*: Cave passage in a Highland County, Virginia cave filled with fine sediments which often cause high turbidity at spring outlets after rainfall events. Intensive recharge episodes can sometimes very forcefully transport the sediments ("mud") throughout the cave channel systems. *Right*: Low stream passage in the Culverson Creek Cave system, West Virginia. Photographs courtesy of Phil Lukas.

Figure 8.13 It is not unusual to see Blue Hole Spring in Bowling Green, Kentucky look like this. The spring is the head of a short stream that disappears into Lost River Cave. Photo courtesy of Chris Groves.

There are few state parks established in the East solely because of a large, beautiful spring. In Florida, Texas, The Ozarks, or the West, citizens from all around the country and the world come to enjoy parks established because of a beautiful spring. These visitors may swim, snorkel, camp, or otherwise enjoy the sight of water flowing powerfully from the ground, sometimes creating an entire river (which often acts as a magnet for those that enjoy fly-fishing and a good trout meal). There are simply no such springs in the East.

In the cases where karst springs do have a significant and less fluctuating discharge, and do not exhibit frequent turbidity or are always or mostly clear, they already have been "snatched" by the utilities for public water supply a long time ago (Figure 8.14).

Figure 8.14 Coldwater Spring in Calhoun County, the second largest spring in Alabama, is used for the public water supply of the City of Anniston. Photo courtesy of Gheorghe Ponta, Alabama Geological Survey.

This includes several exclusive resorts that were established because of the springs many decades ago, as described further and in Chapter 9.12, Warm and Hot Springs, Virginia. Otherwise, the vast majority of springs in the East are privately owned and remain inaccessible and largely unknown. There of course are many springs and spring-fed streams in the East that are beautiful, if not for the flow rate but for the overall, sometimes a fairy-tale-like, experience (Figure 8.15).

Figure 8.15 Hydrogeology Category Winner of the 2022 Karst Waters Institute Photo Contest (Photographer: Chuck Sutherland, Location: Ranger Falls, Grundy County, Tennessee, USA). Dye tracing is useful for scientists to determine where fluids are moving. In this image, rhodamine dye has been injected at Ranger Falls in Grundy County, Tennessee. The water sinks below the falls into a largely inaccessible cave system whose resurgence was unknown before this study. Courtesy of Karst Water Institute (https://karstwaters.org/kwi-photo-contest/kwi-photo-contest-2022/).

Sadly, for the public agencies responsible for the well-being of groundwater in the East, springs seem to be an afterthought at best. This is even though the quantity and quality of groundwater discharged by the springs are the ultimate judge of the well-being and the health of the groundwater in the aquifers that feed them. Notable exceptions are the Geologic Survey of Alabama, which in 2022 published an excellent report entitled *Springs of Alabama* (Smith and Guthrie, 2022), and the Virginia Department of Environmental Quality which in 2023 published *Springs of Virginia* (Maynard, 2023). Both reports are textbook examples, full of details on the springs' geology, hydrogeology, water quality, and use, accompanied by various graphs and color photographs of the springs. In 1986, the West Virginia Geological and Economic Survey published a revised, 50th anniversary, 493-page edition of *Springs of West Virginia* (McColloch, 1986) which also is an admirable work although obviously outdated.

Reports on springs prepared by other state agencies in the East, or by the USGS, are decades old, and not much more than a simple inventory of larger springs, with their discharge rates estimated by very few field measurements. For the most part they lack details about springs' use, hydrogeological, and other characteristics (e.g., *Large Springs of East Tennessee* by Sun, et al., 1963; *Characteristics of Large Springs in Kentucky* by Couvering, 1962; *Large Springs in the Valley and Ridge Physiographic Province of Pennsylvania* by Saad and Hippe, 1990).

It is understandable why the reports published decades ago may have been limited in scope. The nation's groundwaters were not yet seriously impacted by various anthropogenic influences and contaminants as they are today. Still, it is mystifying that the citizens are kept in the dark about the current state of their springs. The reasons and excuses may be numerous: lack of mandate, funding, political support, initiative, technical expertise, and such. This includes a possibility of unwillingness to make the results of any spring water sampling for contaminants publicly available, if such sampling is indeed happening. After all, as shown in Chapter 4, the Idaho Conservation League had to file a public records request to obtain, from Idaho Fish and Game (IDFG), the alarming data on increasing phosphorus concentrations at several large springs.

Whatever the case may be, the citizens of the "karst state" of Kentucky, for example, cannot easily find out if there is any publication, by their own or other agencies, which shows how many of the 2,899 springs included in the Kentucky Geological Survey's database currently are, or may (statistically) be impacted by, say, elevated concentrations of nitrate, various pesticides, and other harmful anthropogenic chemicals. Anyone can search various web pages, including those of Kentucky agencies, and easily find many popular publications, pamphlets, and online narratives explaining that the longest cave in the world, Mammoth Cave, is in Kentucky, together with many other caves and countless karst features. However, addressing the importance and water quality of the 2,899 Kentucky springs is a completely different story.

For example, the following excerpts from a report prepared by the USGS in 2014, entitled *Water Quality in the Principal Aquifers of the Piedmont, Blue Ridge, and Valley and Ridge Regions, Eastern United States, 1993–2009* (Lindsey et al., 2014) will serve as an example of a missed opportunity. Although the state of Kentucky was excluded from the USGS program of assessing the groundwater quality of the Nation's principal aquifers (see DeSimone et al., 2014), the karst development and other characteristics of Kentucky aquifers are comparable to the carbonate aquifers evaluated in this USGS study of smaller parts of Pennsylvania, Virginia, and Tennessee.

In the Piedmont and Blue Ridge and the Valley and Ridge carbonate-rock aquifers, concentrations of nitrate in more than 25 percent of samples from drinking-water wells exceeded the MCL of 10 mg/L as N. (Note by the author: MCL refers to Maximum Contaminant Level allowed.)

Concentrations of nitrate in the carbonate-rock aquifers were among the highest in the Nation.

One of the reasons that the carbonate-rock aquifers are susceptible to nitrate contamination is that they have high-permeability karst features, such as sinkholes and conduits, which allow contaminants from the surface to easily enter the aquifer and to rapidly move through them. As a consequence, much of the water that reaches a well is very young. In addition, the presence of sinkholes favors oxic conditions, making denitrification unlikely. The combination of direct infiltration of contaminants into the aquifer, rapid movement through the aquifer, and oxic conditions within the aquifer, coupled with large nitrogen inputs, explains the high nitrate concentrations in samples from the carbonate-rock aquifers.

Figure 8.16 *Weathered rocks that make up the carbonate-rock aquifer are exposed at the surface and provide direct pathways for water and contaminants to enter the aquifer without the filtering effects of soils. Voids, or enlarged holes in carbonate rocks, such as the ones shown here, are common in the aquifer. Water moves rapidly through these voids and remains oxygenated. Photograph by William Kochanov, Pennsylvania Geological Survey*. From Lindsey et al., 2014.

In the Piedmont, Blue Ridge, and Valley and Ridge regions, total coliform bacteria were detected in all samples from springs and nearly 60 percent of samples from wells. E. coli, an indicator of fecal contamination, was detected in 91 percent of samples from springs and 17 percent of samples from wells. Although detections were frequent in all aquifers and settings, the carbonate-rock aquifers had a higher frequency of detection for E. coli and total coliform, as did areas overlain by agricultural land use.

Sinkholes, fractures, and rapid flow of water are typical of carbonate aquifers and make these aquifers vulnerable to bacterial contamination.

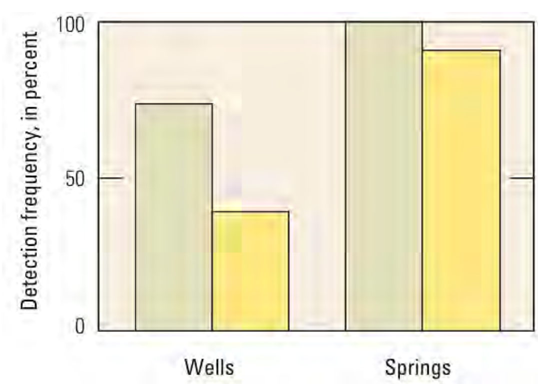


Figure 8.17 *Total coliform bacteria (*green bars*) were detected in all, and Escherichia coli (E. coli;* yellow bars*) was detected in nearly all, of the 23 springs sampled, which are used for drinking-water supply. Drinking water that contains E. coli, a common indicator of fecal contamination, could be a risk to human health*. From Lindsey et al., 2014.

At least one pesticide was detected in 55 percent of samples, and multiple pesticide compounds were commonly detected in a single sample. Median atrazine concentrations in domestic wells in the Piedmont and Blue Ridge carbonate-rock aquifers and the Valley and Ridge carbonate-rock aquifers were higher than those measured in domestic wells nationally (Note: springs were not sampled for pesticides in this USGS study).

Thirty-five of the 47 pesticide compounds measured were detected in at least one sample, and at least one pesticide was detected in 55 percent of samples. The most frequently detected pesticides were atrazine, deethylatrazine, metolachlor, simazine, prometon, tebuthiuron, and dieldrin.

Mixtures of pesticides (two or more pesticides detected in the same sample) also were detected more frequently in the carbonate-rock aquifers than in crystalline- and siliciclastic rock aquifers. In fact, mixtures of pesticides in the Piedmont and Blue Ridge and Valley and Ridge carbonate-rock aquifers were much more prevalent than in aquifers nationwide with five or more pesticides detected in more than 40 percent of wells in agricultural areas and more than 80 percent of the wells in urban areas.

Pesticides with highest use—atrazine and metolachlor—were among the most frequently detected pesticides in domestic and public-supply wells.

All seven of the most frequently detected pesticides were detected most often in samples of groundwater from domestic wells in the carbonate-rock aquifers. Many of these domestic wells are also in agricultural areas.

Human-health benchmarks are not available for most mixtures of pesticides, but the detection of multiple pesticide compounds in drinking-water wells is a potential health concern, even at concentrations below human-health benchmarks. The reason is that the health effects of mixed compounds may be different from the health effects of each compound in isolation, and these interactions are not well understood.

A large percentage of individual households outside urban centers in the East, including almost all farms, rely on domestic (private) wells and many utilize springs for their water supply. Sampling for all the constituents on the U.S. EPA list of primary drinking water contaminants (those that have established MCLs, i.e., Maximum Contaminant Levels) is prohibitively expensive for many if not all users that do not rely on public water supply systems.

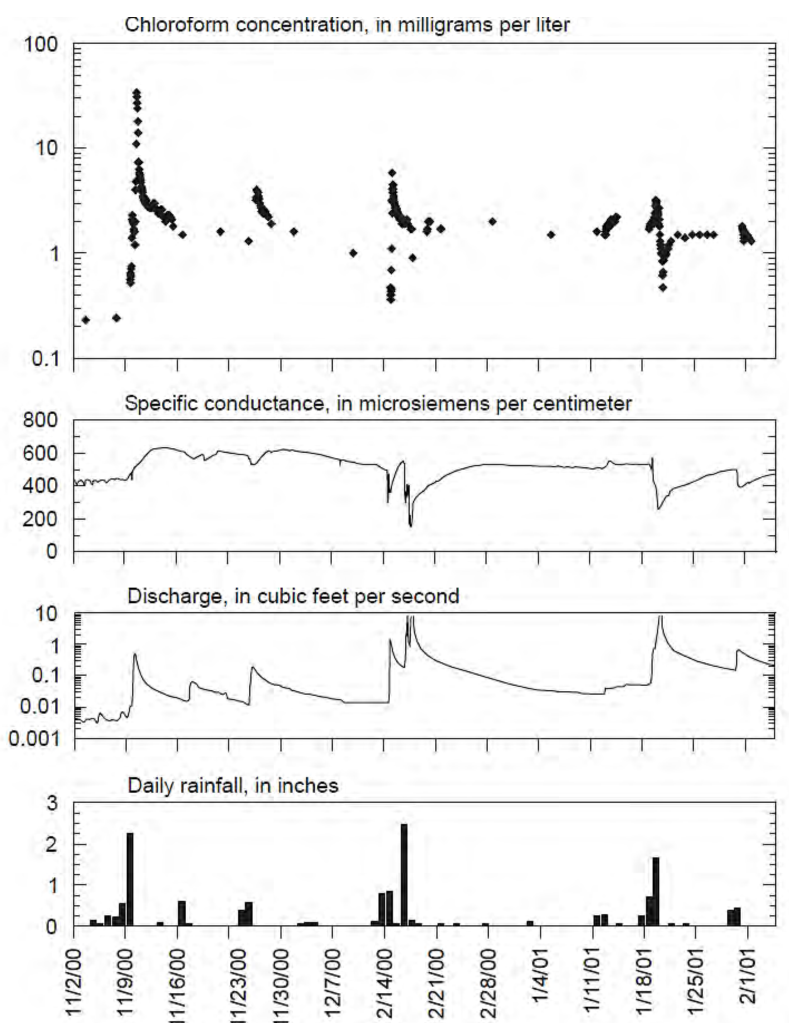


Figure 8.18 Results of high-frequency measurements at Wilson Spring in the Central Basin karst region of Tennessee. Modified from Williams and Farmer, 2003. Discharge, rainfall, temperature, pH, specific conductance, and dissolved oxygen were measured at 10- or 15-minute intervals at the Wilson Spring in Central Basin karst region of Tennessee. Non-isokinetic dip-sampling methods were used to periodically collect samples of volatile organic compounds (VOCs) from the spring. During selected storms, automatic samplers were used to collect samples which were analyzed using a portable gas chromatograph (GC). Significant changes in water quality and discharge were detected with rapid changes observed during storms. The greatest change was observed during the first storm in the fall of 2000, when chloroform concentrations increased from about 0.5 to about 34 mg/L. From these results, it is apparent that a sampling interval of one week or one month would not provide any meaningful information as to a possible contaminant.

To make things worse, the nature of karst and karst aquifers requires that any meaningful sampling protocol must take into consideration both the periods of no-recharge, and the periods of rapid aquifer recharge after rainfall events as illustrated with Figures 8.18 and 8.19.

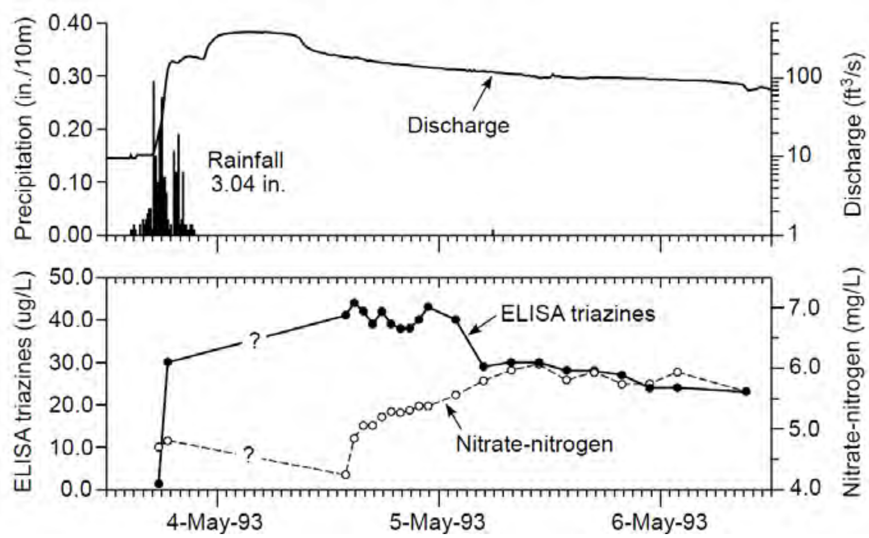


Figure 8.19 Chemographs and discharge hydrograph for a high-flow event at Pleasant Grove Springs in Logan County, Kentucky is an example of non-point source contamination from agricultural activities (Currens, 1999). Concentrations of triazines (including atrazine) and alachlor have exceeded drinking water MCLs during peak spring flows. Flow-weighted average concentrations for 1992–93 were 4.91 μg/L for atrazine-equivalent triazines and 5.0 mg/L for nitrate-nitrogen. In comparison, the maximum allowed concentration of any individual pesticide in drinking water in the European Union is 0.1 μg/L, and of all pesticides combined it is 0.5 μg/L.

Without any help from public agencies, and without knowing what the groundwater quality of "their" aquifer and spring really is, individual households and farms are left to their own devices. This situation is perhaps best illustrated with the following excerpt from Kresic and Mikszewski (2013):

"One example of a thought-provoking topic similar to others included in this book is the current regulatory policy related to arsenic (As) in private drinking water supplies in eastern New England. Arsenic occurs naturally in metasedimentary bedrock units in the regions that are extensively tapped by private water supply wells. In 2003, it was estimated that over 100,000 people across eastern New England were using private water supplies with arsenic concentrations above the Federal Maximum Contaminant Level (MCL) of 10 μg/L (Ayotte et al, 2003). This represents a widespread exposure to a chemical universally acknowledged as poisonous.

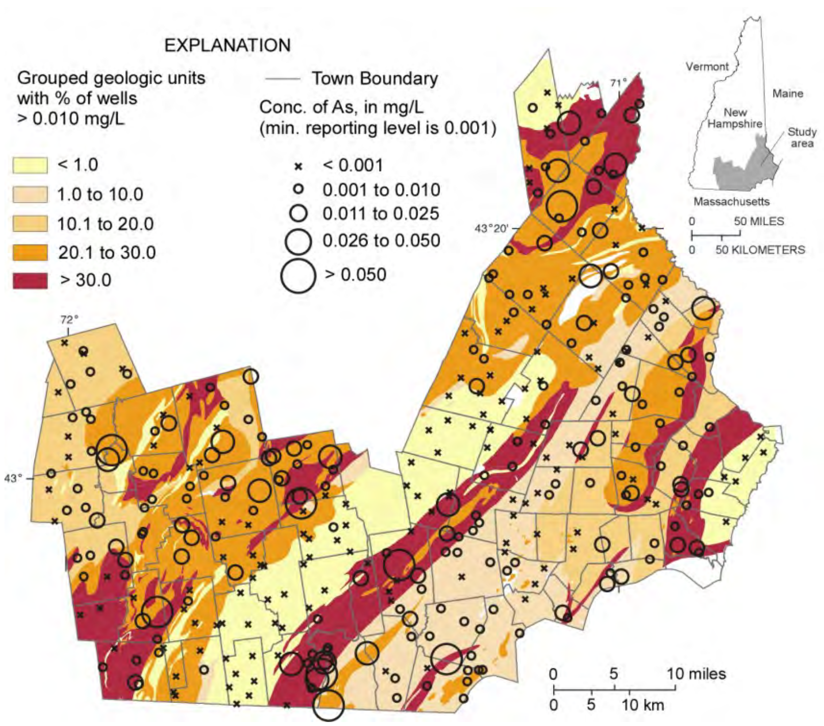


Figure 8.20 Arsenic concentrations in private bedrock wells in southeastern New Hampshire, and grouped geologic units showing percent of wells with concentrations of arsenic greater than the current MCL of 0.010 milligrams per liter. From Kresic and Mikszewski, 2013. (Modified from USGS, 2003.)

Figure 8.20 is a map of arsenic concentrations measured at private bedrock wells in southeastern New Hampshire during a 2003 study performed by the United States Geological Survey (USGS).

Despite these alarming data, arsenic is not regulated by the state of New Hampshire in private drinking water wells, and there are no current requirements to even test existing wells for the contaminant. Regulations passed in 2010 have made it a requirement to test new wells and wells involved in home sales (Susca and Klevens, 2011); however, the removal of arsenic from these private supplies prior to consumption remains optional, and is a decision left to individual property owners.

In contrast to this policy of allowing arsenic exposure, environmental regulations require the expenditure of millions and millions of dollars to remediate Superfund and state-led contaminated sites where the exposure often constitutes a very low risk (e.g. one in a million excess lifetime cancer risk), or is hypothetical in nature (e.g. potential future consumption of groundwater). For example, at the Visalia Pole Yard Superfund site in California well over $20 million was spent to remediate groundwater contamination that was not posing an actual risk. This is a classic example of policy that permits "self-inflicted" risk while disproportionately targeting "externally-inflicted" risk, ignoring the relative costs and benefits of the overall outcome. One potential declaration of this ideology is presented below:

"When protecting human health and the environment, it is not our place to address risk related to naturally occurring contamination or individual lifestyle choices, but we will act aggressively to remedy any minimal level of risk caused by a third-party agent." (Kresic and Mikszewski, 2013).

While the high concentrations of nitrates and the wide presence of pesticides in the carbonate aquifers in the East are not caused naturally, the analogy is clear. In either case, the entire society acts as an "enabler", a "*third-party agent*".

Before the reader turns to notable springs in the East next, here is one more disturbing fact, for the benefit of the springs because the springs cannot speak for themselves.

In 2003, and again in 2020, the U. S. Environmental Protection Agency (U.S.EPA) allowed continuing use of atrazine. This herbicide has been banned for use in the European Union since 2004. In the U.S., it is one of the most commonly reported contaminants in groundwater and public drinking water. While atrazine is applied to a wide range of crops, it is primarily used on sugarcane, soy, sorghum, and corn; the U.S. Department of Agriculture notes that more than 65 percent of all corn crops in the U.S. have been treated with the herbicide. It is also a weed killer for golf courses, fields, and residential and commercial lawn spaces across the United States (https://usrtk.org/pesticides/atrazine/).

A significant body of scientific research suggests that atrazine is an endocrine disruptor and linked to various cancers, premature birth and birth defects (Atrazine, an endocrine disruptor, is a common herbicide in the US (usrtk.org)).

The endocrine system, made up of all the body's different hormones, regulates all biological processes in the body from conception through adulthood and into old age, including the development of the brain and nervous system, the growth and function of the reproductive system, as well as the metabolism and blood sugar levels. The female ovaries, male testes, and pituitary, thyroid, and adrenal glands are major constituents of the endocrine system.

Overview of the Endocrine System | US EPA

The U.S. EPA has concluded that the risks from atrazine for approximately 10,000 community drinking water systems using surface water were low. Incidentally, as stated by the Agency, 40,000 community drinking water systems using groundwater were not included in the related study, and private wells or springs used for water supply were not even mentioned in the Agency's decision to allow continuing use of atrazine (January 31, 2003: Interim Reregistration Eligibility Decision (IRED) for the herbicide atrazine; October 31, 2003: Revised IRED for atrazine; https://www.epa.gov/ingredients-used-pesticide-products/atrazine).

8.2 Virginia and West Virginia

8.2.1 Glorious Days of The Past

For almost 150 years, between the early 1760s and early 1900s, Virginia was the center of an extraordinary group of exclusive resorts and modest establishments alike, all developed to use springs and their waters. More specifically, a long, narrow area of the *Piedmont and Blue Ridge and the Valley and Ridge aquifers* shared by Virginia and what is now West Virginia (which split from the big sister during the Civil War) was the place to come and try to heal many different ailments, and along the way to be seen, socialize, think, and (for those who were powerful), strategize about the future of the State and the Country. Never before or since, anywhere else in the world, did springs achieve this status of being glorified and cared for, as in this narrow stretch of land in Virginia and West Virginia.

Readers wanting to learn more about this fascinating, mostly forgotten piece of the Nation's history, are pointed to two equally fascinating sources of information: Stan Cohen's book, *Historic Springs of The Virginias, A Pictorial History* published in 1981 (revised edition – Figure 8.21) and the collection *Medicinal Springs of Virginia in the 19th Century* at Historical Collections, The Claude Moore Health Sciences Library, University of Virginia. This collection is also available online at https://exhibits.hsl.virginia.edu/springs/. An interesting perspective on the golden age of mineral springs resorts in the Virginias is provided by Lauren E. LaFauci in her paper, *Taking the (southern) waters: science, slavery, and nationalism at the Virginia springs* (*Anthropology & Medicine*, Vol. 18, No. 1, April 2011, 7–22).

Quotes from Cohen's book are provided further to spark interest.

Figure 8.21 Stan Cohen's book describes 75 springs that were developed into resorts, with reproductions of historic drawings, paintings, photographs and documents, along with contemporary photographs by the author. "*All of the resorts, both large and small, could be divided into three loose historical periods: Ante-bellum, from the late 1700s to 1861; post Civil War to World War I; and 1918 to the present. If one were to chart their development and popularity on a graph, the peak would occur in the middle 1800s, and the low point would be seen during and after the Civil War. The line would rise again in the late 1800s, but there would be a steady decline shown after World War I.*"

After reading about the activities and amusements available to guests, I wonder what kind of luck the resident physician had who prescribed this exacting schedule: "If the weather and other circumstances admit, rise about 6, throw your cloak on your shoulders, visit the Spring, take a small-sized tumbler of water, move about in a brisk walk; drink again at 7, and once more at half past 7; breakfast at 8. After breakfast, if you can command a carriage, take a drive, otherwise a slow ride on horse-back until 10. From 10 to 12, enjoy yourself in conversation or other mode most agreeable to you-eat no luncheon-at 12 take a glass of water, at 1 take another. From 12 to 1, take exercise at ten pins, quiots, billiards; dine at 2; amuse yourself in social intercourse until 5. Take a drive, ride, or walk, until 6-drink a glass of water; exercise until 7-take a cracker and a cup of black tea. If you are a dancer, you may enjoy it, but in moderation, until 9-quaff a glass of water from the Spring, and retire to your room." And, I wonder, how many patients followed the advice of the doctor who counseled against "deep potations of mint julap (sic) and other spiritous mixtures, after coming from the bath"?

The major resorts were founded on the premise that their waters, no matter what type, could cure common diseases at a time when medical science really could not do much for patients. Lured by the advertising, patients came and drank the water, bathed in it, or rubbed it on themselves, and the resorts prospered.

Two diseases prevalent in the United States then, yellow fever and cholera, probably were instrumental in the rapid growth of the health spas.

These two diseases did not exist in the mountains—cholera, because water, which carried the cholera vibrio, flowed away from the mountains, and yellow fever, because the mosquito carrier preferred the warmth of the seacoast and rivers to the coolness of the mountains.

Other diseases, too afflicted mankind at this time including: bronchial or throat diseases, hemorrhages of the lungs, tubercular consumption, pulmonary afflictions, dyspepsia, pheumonia, dysentery, skin diseases, diseases peculiar to females, gout rheumatism, neuralgia, paralysis, diseases of the blood, disorders of the urinary organs and the list goes on and on ....

This makes it easy to see why these sites became so popular, especially as there was little hope of being cured by other means.

If a person did not need a cure, there was always the attraction of social events and the chance to see and be seen. Those who could afford the time and money, travelled the circuit, going from one spa to another, in the summer months, and it was a delightful way to spend the summer.

The great prosperity of the Southern planter in the middle 1800s contributed to the development of the Virginia springs.

A number of factors contributed to the demise of the spas through the years. Three main reasons for the closure of most of them were: destruction during the Civil War and the changing social systems in the South after the war; better treatment and newly-discovered cures for diseases, especially after 1900; and, last, the start of the automobile age in the early 1900s which changed the fabric of American life. Cars gave people the mobility to travel from mountains to beaches or wherever else they wanted to go, and summering at the spas was no longer fashionable. A variety of other factors such as mismanagement, competition and transportation problems spelled the end for certain other spas.

Today, out of all 75 spas described by Cohen, only four survive, still featuring and offering waters of their springs: Warm and Hot Springs in Virginia (see Chapter 9.12), and The Greenbrier (home of White Sulphur Springs), Capon Springs, and Berkeley Springs in West Virginia.

Many of the once magnificent buildings and gardens of the spas disappeared over the years. Some were burned to the ground by fires, and many changed owners, multiples times, none of whom cared to risk getting into the spa business. A few establishments and properties still carry their famous names from days past, and keep the memorabilia for members and guests (Figure 8.22). For the most part, springs at almost all of these historic resorts are now abandoned, overgrown, or have fallen into obscurity.

Figure 8.22 19th century painting of the Fauquier White Sulphur Springs resort located 7 miles south of Warrenton, Virginia. Courtesy of Fauquier Springs Country Club (https://www.fauquiersprings.com/)

As described on the web page of Virginia's Fauquier Springs Country Club, "Before the War Between the States, Fauquier White Sulphur Springs was the most celebrated mineral water resort in the country. In the late 1700's, Captain Hancock Lee built a lodge near the sulphur water spring on the Rappahannock River. The location of the Springs was fortunate, as it was just a one-day stage coach ride from Washington, D.C., making it accessible to the entire Atlantic seaboard which was already served by railroads. Southern plantation owners would spend a month or two each summer with their families at "The Springs." The fame of the sulphur waters and their miraculous healing properties spread and people began to flock to the Springs.

In the 1830's, Lee's son and a business partner purchased additional land totaling 3,000 acres and built a grand hotel, a semicircle of 16 cottages, a spring house and a variety of other buildings, walks and fountains to accommodate the growing number of visitors. The grand hotel, known as the Pavilion, stood four stories high with majestic columns, a large dining room that would seat 400 guests and a 4,000 square foot ballroom that would host the finest orchestras in the country. Horse racing, medieval-style jousting tournaments, fox hunting, bowling, billiards, cards, and fancy dress balls were all provided for the entertainment of guests, including many celebrities of the time including Chief Justice John Marshall and Presidents James Monroe, James Madison and Martin Van Buren. To escape a cholera outbreak in Richmond in 1849, the Virginia Legislature moved their entire operations to the Springs. Chief Justice Roger B. Taney spent the summer of 1856 at the Springs—the same year he authored the famous Dred Scott Decision which became a catalyst for the Civil War."

Figure 8.23 The only remaining cottage out of 16 original ones that were part of the Fauquier White Sulphur Springs Resort shown in Figure 8.22.

Figure 8.24 Blue Sulphur Spring in Greenbrier County, West Virginia. “The Temple” over the spring is an example of Greek Revival architecture. It was built in 1834 along with the resort and was added to the National Register of Historic Places on October 29, 1992. The Temple is all that is left from once famous Blue Sulphur Springs Resort pictured in Figure 8.25. In April of 2013, Ms. Rebecca Fleshman Lineberry, the owner of the pavilion and the surrounding acreage, donated the title to the pavilion and 2 acres to the Greenbrier Historical Society. That same year The Friends of the Blue formed to spearhead the restoration of the structure. The renovated pavilion was dedicated in 2023 (left photo; courtesy of Bill Jones). Historic photograph of the spring courtesy of Greenbrier Historical Society.

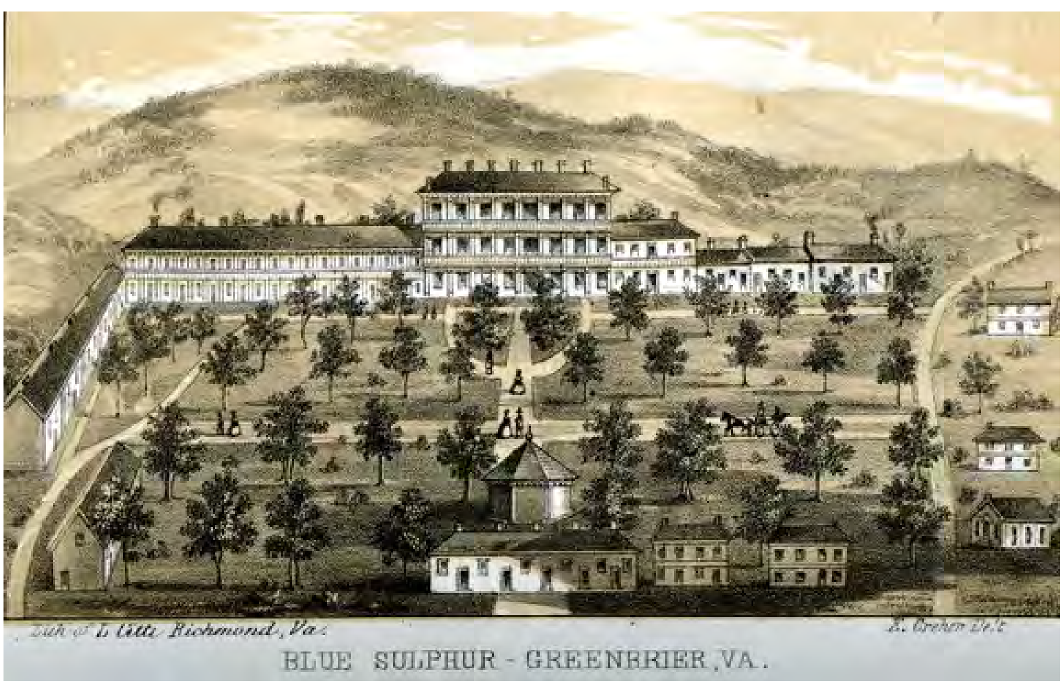


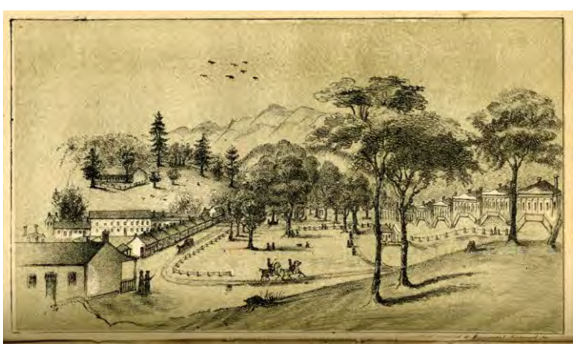
Figure 8.25 Dr. William Burke described the style of living at Blue Sulphur as more elegant with nicer furniture and better service than that at any of the other springs except possibly Warm Springs and Salt Sulphur. He described the spring as being in the center of the valley, with a “well-designed but badly executed Temple” over it. (https://exhibits.hsl.virginia.edu/springs/).

8.2.2 The White Sulphur Springs, The Greenbrier

The White Sulphur Springs, now The Greenbrier resort (www.greenbrier.com), is in Greenbrier County, West Virginia, 43 miles from Warm Springs, Virginia, via US-220S, VA-687, VA-641, and I-64. Along the way, one should not miss to stop and see Falling Spring from an overlook on VA-641.

> *If the estimation in which the White Sulphur water is held, in the United States, be any evidence of its merit, it needs no other eulogy; for it is well known that its fame has spread to every portion of the nation. It is indeed a noble fountain, destined, we hope and trust, to be a blessing to countless generations.*
>
> William Burke, 1846

Dr. William Burke, author of *The Mineral Springs of Western Virginia* (1846), devoted a remarkable 80 percent of his chapter on the White Sulphur Springs and more than 10 percent of his entire book to his disagreement with the resident doctor, John Moorman, concerning the effectiveness of White Sulphur Springs water that no longer contained "sulphuretted hydrogen gas." Dr. Moorman and his supporters testified in lengthy quotes that water transported for the use of the general public and lacking the gas was as beneficial to the user as the water with the gas that was consumed at the springs. With increasing fervor and the creative use of a satirical drama, Dr. Burke rebuked Dr. Moorman's theory which Burke believed stemmed from a desire for pecuniary gain and resulted in the sale of "putrid" and "stale" water.



https://exhibits.hsl.virginia.edu/springs/

Figure 8.26 This is the image of White Sulphur Springs chosen for the book written by John J. Moorman, the resident physician (*The Virginia Springs*. J.W. Randolph, Richmond, Virginia, 1857).

Figure 8.27 The Greenbrier resort, West Virginia. White Sulphur Springs is in the photo on right. Courtesy of The Greenbrier.

Dr. Burke eventually wrote, “We shall make no further quotations from Dr. M[oorman]. His facts are without foundation in truth; his arguments puerile and shallow; his theories untenable; his absurdities ridiculous; his motives palpable and culpable; and his efforts to bolster up a selfish practice, a gross imposition.” (Burke, p. 172; from https://exhibits.hsl.virginia.edu/springs/).

“The historic trajectory of The Greenbrier takes a momentous turn as the Chesapeake and Ohio Railway acquires the property in 1910, embarking on an ambitious expansion endeavor. A new chapter of opulence unfolds in 1913 as the railroad introduces The Greenbrier Hotel, now the heart of our grand resort. Alongside it emerges the iconic Mineral Bath Department and an 18-hole golf course, famously known today as The Old White.

A year of pivotal transformations ensued in 1914 as the resort’s name shifts to The Greenbrier, and it extends its welcome year-round. This landmark year also witnessed the visit of President and Mrs. Woodrow Wilson during Easter, while Joseph and Rose Kennedy journeyed from Boston to celebrate their October honeymoon.

Amidst the Roaring Twenties, The Greenbrier finds its place among the esteemed circuit of high society destinations that span from the sun-soaked coastlines of Palm Beach, Florida, to the historic charm of Newport, Rhode Island. A substantial reconstruction of The Greenbrier Hotel took place in 1930 as guest rooms doubled to five hundred to accommodate its newfound popularity.

In 1941, during the Second World War, the U.S. State Department leased The Greenbrier Hotel for seven months, providing refuge for diplomats. The following year, in 1942, the U.S. Army acquired the hotel, transforming it into a 2,000-bed hospital named Ashford General Hospital, caring for over 24,000 soldiers during its four years of operation.

During the Cold War era of the 1950s, The Greenbrier’s pivotal role in crisis continued as the U.S. government enlisted the resort’s help to construct an Emergency Relocation Center — an underground bunker codenamed Project Greek Island — designed to house the U.S. Congress during times of conflict. This project includes the addition of the West Virginia Wing to the hotel’s above-ground facilities, maintaining the bunker in a constant state of readiness for thirty years.” (https://www.greenbrier.com/discover-more/about-us/history/)

The Greenbrier remains one of the most prestigious and exclusive resorts in the United States, with numerous offerings including those utilizing its famous springs.

Figure 8.28 Swimming pool at The New Greenbrier, White Sulphur Springs (circa 1913). Courtesy of Library of Congress.

8.2.3 Capon Springs

"Imagine the year is 1855 and you arrive to Capon Springs, a fashionable watering place during this time, by way of a four-horse stagecoach from Winchester, Virginia. The 25-mile trip, which required crossing the creek numerous times, would have taken you four hours! You step out of the stagecoach and look up to admire the four story, grand Mountain House building which graced the property during the resort's "Golden Age." An advertisement during this time cited the Mountain House as, "one of the most magnificent structures in the country" with its large dining room (which could seat 600 guests), ballroom and portico with a 35 feet high ceiling supported on ten massive pillars.

You and your fellow guests have traveled here because you read in the *National Intelligencer* that, "the baths have no parallel in this country nor Europe." Doctors and diplomats testified to their luxury and health benefits. Daniel Webster once wrote, "The Baths … are far superior to anything I have witnessed elsewhere in the country."

Figure 8.29 Engraving of the Mountain House from a 1890-91 brochure. Courtesy of Capon Springs and Farm.

"Fast forward 167 years, and folks are still traveling here for healing relief from pain and stress. Today, Capon's Hygeia Bath House & Spa remains a "spa" in the true sense of the word – a place where mildly alkaline spring water is used in Roman style soaking baths. Although we no longer employ a resident physician, the experience of "taking the waters" is much the same as it was for bathers in the 1800s. The soaking baths at the Hygeia were modeled after the original brick-style baths in the Bathing Establishment. Descend down four steps into a tiled bath filled with 500 gallons of pure Capon Springs Water heated to a relaxing 102 degrees. Because the baths are filled, emptied and cleaned for each person, we do not have to treat the water with the chemicals most hot tubs require. The result: a hot, relaxing, pure Capon Springs Water bath without the chemical smell or feel. Take a soak at the Hygeia Bath House & Spa and take a step back in time… you will quickly understand why folks have been drawn to this special spot for over a hundred years! To learn more about the spa and to book your relaxation time, please visit our website: www.caponsprings.net/spa."

Figure 8.30 Main resort building at Capon Springs and Spa today.

8.2.4 Berkeley Springs

Berkeley Springs are in the town of Berkeley Springs, Morgan County, West Virginia. Originally, the site of the springs was called Warm Springs until October 1776, when the General Assembly of Virginia passed an act establishing the town as Bath (after Bath in England, famous for the Roman baths) in what was then Berkeley County. The name Berkeley Springs was adopted around 1863.

As written by Cohen (1981), the town can trace its history back probably thousands of years to when Native Americans used the warm waters for medicinal purposes. Tribes from the Great Lakes to the Carolinas, including Six Nations, the Delawares, the Tuscaroras and the Catawbas came to the springs, and although they were eternally at war with one another, they established a truce regarding the area around the springs so that all might benefit.

Perhaps the most notable and influential advocate of the curative powers of the Berkeley springs was George Washington, who, at 16, visited them as a member of a survey party. As the party, which was surveying the western limits of Thomas Lord Fairfax's lands, camped there for the night, young Washington noted in his diary, "March 18th, 1748, We this day called to see Ye Fam'd Warm Springs." For many years afterwards, George Washington visited the springs regularly, and it was largely through his efforts that its fame as a health spa grew throughout the colonies. At the urging of the Colony of Virginia and in the public interest, Lord Fairfax conveyed his land holdings at the springs and fifty adjacent acres to the Colony of Virginia in 1776. Shortly thereafter, the land was offered for public sale.

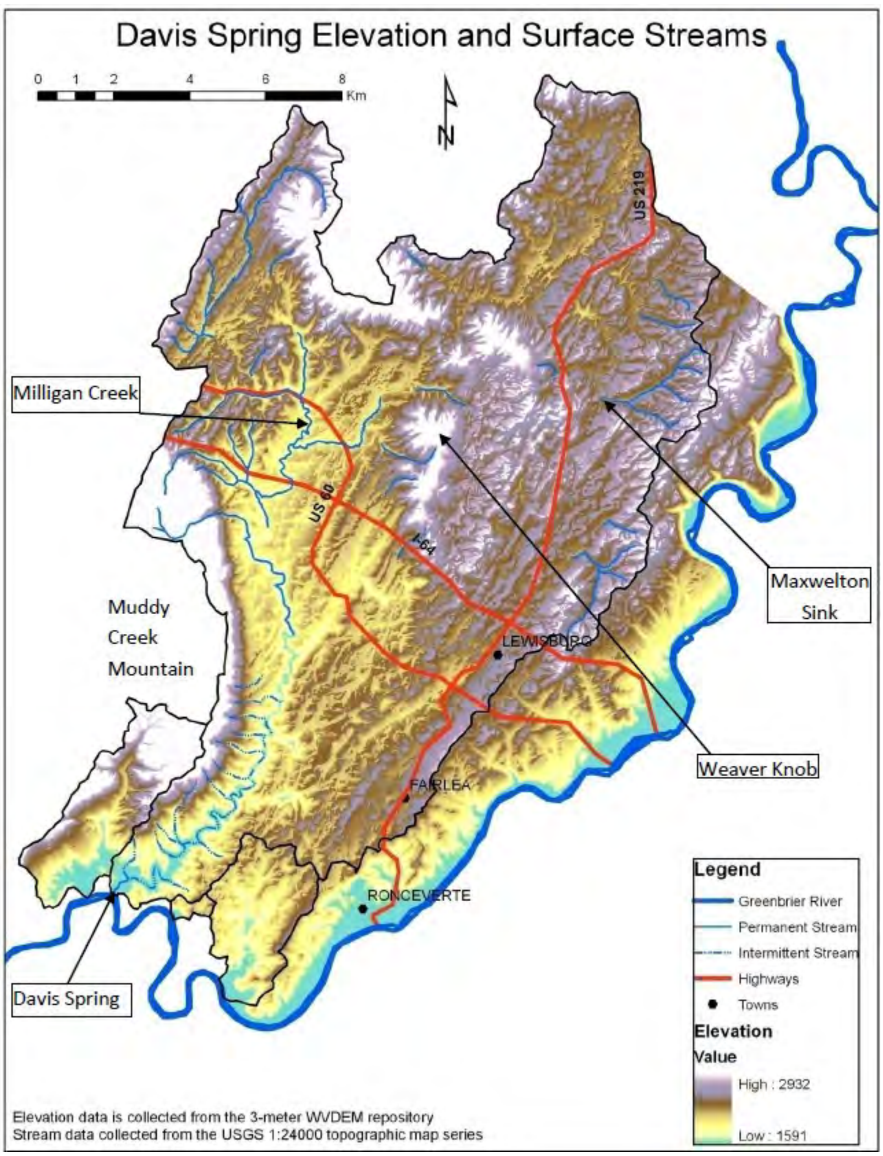
George Washington, three signers of the Declaration of Independence, four signers of the Constitution, seven members of the Continental Congress and five Revolutionary generals were among the prominent colonists who made initial purchases there. Hence, the springs' reputation as a health resort became firmly established. (https://wvstateparks.com/park/berkeley-springs-state-park/)

Figure 8.31 *Left*: View, from Old Roman Bath House, of the main area where Berkeley Springs issue from the base of a steep ridge rising about 450 feet above the valley. There are five principal sources and numerous smaller ones all within 100 yards of each other. The combined flow is approximately 2,000 gallons per minute, with a uniform temperature of 74.3°F (Cohen, 1983). *Right*: View towards Old Roman Bath House, now a museum (building on the right), and gentlemen's spring ("Pagoda"). Urban legend, promoted by the park as seen on the sign above the small "bath tub" in the wall, is that George Washington liked to use this bathtub when in town. Photo courtesy of West Virginia Tourism.
https://wvtourism.com/company/berkeley-springs-state-park/

The original warm mineral springs are the centerpiece of various treatments offered to the public in two facilities operated by the state of West Virginia. The newly renovated main bathhouse provides massage, facials, body treatments, sauna sessions, and Roman or whirlpool baths filled with mineral water accessed directly from the springs located in the park. The historic Roman Bath House on the north end of the park has 9 individual, 750-gallon walk-in tubs in private chambers available for 30 or 60-minute sessions. The park is in the heart of town and has an outdoor pool open in summer, a public tap for free spring water, and open pools of springs run-off. Budget-conscious spa-goers love the park's modest prices.

There also are three privately owned spas in the town using Berkeley Springs mineral water ([Full Service Spas - America's First Spa - Berkeley Springs, West Virginia]())

8.2.5 Davis Spring, West Virginia.



The privately owned Davis Spring is the largest spring in the Eastern United States outside Florida. The spring drainage area of approximately 73 square miles is entirely in Greenbrier County, West Virginia (Figure 8.32) and contains one of the most developed karst terrains in the country. The only surface water perennial stream in the drainage area is Milligan Creek which originates in the Richland area, flows for 6.8 miles and sinks into the karst, only to surface again at the Davis Spring. Water from the spring flows along an unnamed surface channel for about 1200 feet before emptying into the Greenbrier River (Figure 8.33).

Figure 8.32 Elevation and surface streams of the Davis Spring and some surrounding basins. Milligan Creek is the drainage in the upper left. The paleo-Milligan Creek drainage is indicated by dashed lines in the lower left. Drainage feeding the contact caves is in the upper right, with Maxwelton Sink identified. Weaver Knob is the high peak in the center. From Tudek, 2010.

As explained by Tudek (2010) in an excellent master's thesis which remains the definitive work on the hydrogeology of Davis Spring, Milligan Creek parallels the eastern slope of the mountain, receiving discharge from the mountain as it progresses towards Davis Spring. At any given point in location or time Milligan Creek can either flow on the surface, completely underground or a combination of both. This gives Milligan Creek a disjointed appearance. At approximately 6 mi north of Davis Spring, Milligan Creek sinks in its bed a final time, leaving only a paleo-channel on the surface. This paleo-channel is clearly traceable until it joins with the Davis Spring channel less than 50 meters downstream of the spring. Under flood conditions, the sinking point is unable to accommodate all the water from Milligan Creek and the channel backs up into a long lake lasting hours or days.

Other surface drainage in the basin comes from allogenic water to the east flowing off clastic deposits and into integrated, explorable cave systems. The largest of these feeds a cave called Maxwelton Sink Cave. Maxwelton Sink Cave is found at the downstream end of a very large blind valley at the base of 100+ feet high cliff. Dozens of miles of cave passages have been mapped in the eastern portion of the drainage basin. However, none of these passages has led to a primary or "master" conduit through which the entire eastern half of the drainage basin flows.

Some of the more telling points in Tudek's thesis include references to previous investigations performed by other researchers and the USGS. For example, William Jones , in conjunction with others, traced several routes of groundwater flow in the 1960s and 1970s, providing rough estimates for tracer travel time from different locations to Davis Spring (Jones, 1997). These investigations also established the basic shape and size of the drainage basin. In the early 1960s, a USGS staff gauge was placed a few hundred feet downstream from the spring. Jones measured stage at the spring in 1972 and 1973 at regular intervals. Discharge measurements by Jones and others placed the average flow of the spring at 3.2 m^3/sec (110 cfs) (Jones, 1997). Peaks of over 28 m^3/sec (1000 cfs) were estimated based on stage–discharge relationships and occurred most frequently during the winter – spring months. However, the actual peaks were lost as the USGS arbitrarily cropped the peak flow at 28 m^3/sec (1000 cfs; see graph in Figure 8.2) (Jones, 2009). Jones estimates that the highest flow may have approached 57 m^3/sec (2000 cfs) during that year (Jones, 2009).

Figure 8.33 Davis Spring, West Virginia. *Left*: Aireal photograph; the spring is in the center, Greenbrier River is in lower left; photo courtesy of William Jones. *Right*: Spring during high flow; photo courtesy of John Tudek.

As explained by Tudek (2010), datalogger evidence and tracer tests both suggest that most of the Davis Spring conduit system must be open flow throughout most of the year. The Davis Spring basin is a particularly flashy system. During fieldwork, discharge at Davis Spring was as high as 30 m^3/sec (January 2009) and as low as 0.4

m^3/sec (August 2008).Throughout the entire study hydrograph peaks at Davis Spring were sharp and tall. Consistent with an open flow system, tracer travel times from Milligan Creek to Davis Spring decreased substantially from the dry season (246 hours in August 2008) to the wet season (96 hours in March 2009).

The Davis Spring basin is underlain by Mississippian age carbonates and clastics, most notably the Greenbrier Group. These strata generally dip gently to the northwest between 5 and 10 degrees, except at faults or near folds. Where these structures are present, the local dip can be steeper, frequently more than 45 degrees. The Greenbrier Group in the basin are a thick accumulation of limestone of the middle Mississippian age. It corresponds in age to the massive limestones in the Mammoth Cave region as well as the limestones in Indiana (Bennison, 1989).

8.2.6 Rouss Spring, Virginia

In 1890, philanthropist Charles Broadway Rouss gave the city of Winchester $30,000 to buy a large spring outside town. The city bought the spring and the neighboring Hollingsworth Mill in 1890. The mill became a pumping station, and the spring was used as the city's main water supply until 1956, when Winchester began drawing water from the North Fork of the Shenandoah River.

Throughout history, the spring has had several names. To honor Mr. Rouss, the name was changed from Hollingsworth Spring to Rouss Spring. The spring now feeds into Wilkins Lake in Jim Barnett Park which is owned by the City and provides recreational activities for citizens and visitors alike, including fishermen who frequent the lake because of the excellent catch thanks to always clear water of the spring.

Figure 8.34 *Left*: Historic Frank Turgeon Jr. aerial photograph of the Rouss Spring area, 1933. Courtesy of Winchester-Frederick County Historical Society. The City Water Works Filtration Plant (dismantled after 1956) is in lower left. At center is historic Hollingsworth Mill, and to the right is Abrams Delight historic house. Rouss Spring holding ponds are in center right. *Right*: Rouss Spring and the first, smaller holding pond built around it; large holding pond is in the background.

The history of Winchester, including the accounts on how first settlers chose land near natural "fountains" in the Abrahams Creek watershed, is told by Wilbur S. Johnston in a book entitled *On The Town! Celebrating James Wood and The Founding of Winchester in The Shenandoah Valley of Virginia* published by Winchester-Frederick County Historical Society in 2016. Here is a "hydrogeology" excerpt from this outstanding book:

Trending northeast-southwest with the Valley, remnants of anticlines expose sedimentary beds of shale, limestone, and sandstone leveled by streams revealing a narrow band of 95% pure calcium carbonate. The *limestone belt enters Frederick County above Clear Brook, crosses the county through Winchester, and passes between Middletown and aptly named Marlboro. The artesian flow of water under this carbonate belt tilts eastward. The power of the Shawnee/Rouss Spring became evident from a well drilled in 1926 by the former Arthur Jones Woolen Mill on Abrams Creek at Millwood Avenue through limestone all the way. "The deepest well in the area ... was drilled to a depth of 1,432 feet through dolomite and limestone. Water bearing openings in the rock were passed through at about 100, 300, and 700 feet and between 1,100 and 1,200 feet. The driller reported that the water was flowing through the deepest channels with sufficient force to wash out the drill cuttings. Cady cites an artesian pressure as the cause of strong flows in the well's deep cavities. These springs discharge at the rate of several cubic feet per second. Ground water flows eastward through the limestone, passing cavernous zones at 400 feet or more below the surface.*

Figure 8.35 Rouss Spring in Winchester, Virginia. *Left*: The large holding pond of the former City Water Works at the spring. Visible is old plumbing from when the spring was used as the main source of water supply for the City. *Right*: normal overflow from the large holding pond shown in the left photo.

Figure 8.36 *Left*: Rouss spring was powerful enough to move these huge millstones of the Historic Hollingsworth Mill visible in the background. The stone mill was built in 1833 by David Hollingsworth, the great-grandson of Abraham Hollingsworth, Frederick County's first settler. Abraham, who died in 1748, operated one of the county's first gristmills and passed the business on to his son, Isaac. *Right*: Wilkins Lake in Jim Barnett Park, fed by Rouss Spring.

In 1808, just 32 years after the signing of the Declaration of Independence, Winchester was the first town in the United States to lay pipelines for its public water system. The fascinating story of the first pipeline, as well as the development of the Winchester Water Works through time, is told by R.H. Lemon (*Pipe Salesman*) in an article entitled *A Modern Water Supply for Historic Winchester* published in magazine *The Iron Worker* in 1955 (Vol. XIX, No. 3). Here are several excerpts:

To supply the necessary pipe, since none was being manufactured in this country at that time, a Dr. Brown introduced a horse-driven device for boring logs. The logs used were approximately ten inches in diameter. A two-inch hole was bored through those used for the main line, while a one-inch hole was bored through those used for service connections. The ends of these wooden pipes were joined by short iron sleeves on the inside and iron bands around the outside.

This initial water system operated by gravity flow and extended from Town Spring on Amherst Street down to Loudoun Street. The citizens along this line opened ditches in front of their property and the corporation furnished the log pipe and laid them.

In 1826 the first cast iron pipe was used. This was a six-inch line from Town Spring to Cameron Street.

In 1891 a second source of supply, Rouss Spring, was brought into service by the installation of a steam-driven pump and a ten-inch cast iron force main through the south end of town. This main led to a 300,000 gallon reservoir which acted as a stand pipe and water was distributed to different sections of town by branches from the ten-inch main.

Figure 8.37 A section of the original wooden pipe laid in Winchester in 1808. Mr. S. L. Grant, Winchester City Manager, shows how the log pipe was fastened together. The iron sleeve (to which he is pointing) was on the inside while the iron ring (which he holds in his left hand) was on the outside. From Lemon, 1955.

8.2.7 Other Springs

Falling Spring. This thermal spring is about 5 miles north of Covington in Alleghany County, Virginia. The water emerging at the spring first flows through Warm River Cave where the downstream sump in the cave is about 500 feet from the spring. The cave is still being explored and now has 3.92 miles of surveyed passages. There are several cold water and warm water tributaries within the cave. The hottest tributary near the upstream end of the cave was measured at 100°F. The discharge and water temperature at the spring varies with storm events. Reported flow ranges from 3.7 to 90 cfs and the average is around 4 – 5 cfs. Water temperature at the spring is highest during low-flow conditions and is about 81°F. At one time the water was used for a watercress farm operation and a hydroelectric plant was just downstream from the falls (William Jones, personal communication).

The falls, the most scenic in Virginia, and the spring area are owned by the Virginia Department of Conservation and Recreation as part of Douthat State Park. Access to the waterfalls is prohibited to protect the travertine deposits and biological communities flourishing in thermal water.

Figure 8.38 **Falling Spring** (in the past also referred to as the Warm River Cave Spring) is where water from Warm River Cave emerges. Warm River Cave is one of the longest known caves with thermal water. The spring is shown during a dye tracing test (green color is from the dye released in the cave). After about 0.8 miles, the stream from the spring falls over 80 feet high travertine waterfall called Falling Spring Falls, shown in Figure 8.39. Photo courtesy of William Jones.

Figure 8.39 80 feet high travertine deposits at **Falling Spring Falls**, as seen from a scenic overlook off VA-641. Photo courtesy of Ryan Mauer.

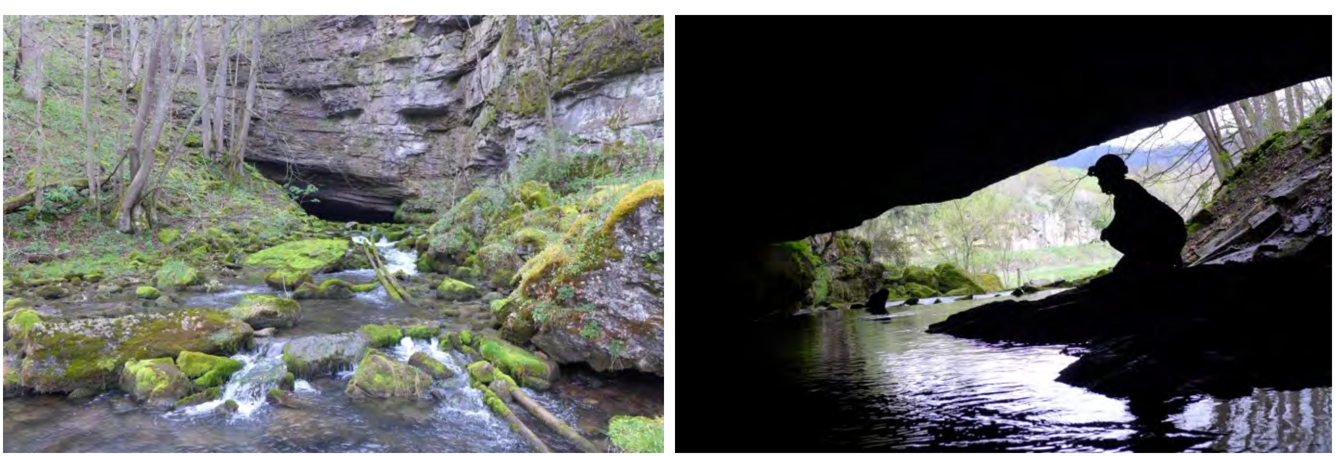


Figure 8.40 **Maiden Spring** in Tazwell County Virginia. This spring, visible from the road, is privately owned. It drains a large cave and provides important habitat for aquatic amphipods and isopods. It discharges from Cambrian-Ordovician Carbonates Hydrogeologic Unit and has at least one discharge measurement greater than 1,000 gpm (2.22 cfs). Photographs courtesy of Mike Ficco.

Surgener Cave Spring is in The Cedars Natural Area Preserve which covers approximately 40 square miles in Lee County, Virginia near the Powell River. The preserve is owned and managed by the Virginia Department of Conservation and Recreation, Natural Heritage (The Cedars Natural Area Preserve (virginia.gov)). It lies within a significant karst region and supports an exceptional natural community of rocky, dry, limestone glades and woodlands located in southwest Virginia. In the preserve, thin soils develop over easily-dissolved limestone bedrock, creating terrain that tends to be rolling, rocky, rugged, and full of sinkholes, caves, and sinking streams. The preserve is a haven for rare plants which are adapted to the mostly thin, nutrient-poor soils of the area.

Figure 8.41 **Surgener Cave Spring**. The impressive size of the cave reveals how much water can flow through the system during high water levels. It is also home to more cave-adapted species than any other cave in Virginia. The stream flows into Powell River, home to several rare freshwater mussels. Text and photographs courtesy of Katarina Kosič Ficco

Figure 8.42 **Blue Sapphire Spring** is in western Augusta County, Virginia. The beautiful deep blue karst water emanates from a conduit near the bottom of its 50 feet deep pool. Blue Sapphire Spring is one of 23 springs that issue from Cambrian-Ordovician Carbonates Hydrogeologic Unit and have at least one discharge measurement greater than 1,000 gpm (2.22 cfs). This unit is the most aerially extensive grouping of carbonate rocks in the Valley and Ridge Province of Virginia (approximately 1,351 square miles) and as such has the greatest number of springs represented in the Virginia springs database (n = 262). From Maynard, 2023.

8.3 Alabama

Alabama's springs are a spectacular natural resource and should be protected and preserved. These springs serve as an important water supply source for municipal, agricultural, domestic, and recreational use, as well as for contributions to the State's scenic beauty.

Improving and expanding the consistency of monitoring efforts is greatly needed to develop long-term hydrological and geochemical characteristics and allow for improved understanding of the effects of climate, land use, and groundwater withdrawal on the overall health of Alabama's springs and shallow groundwater reserves.

Smith and Guthrie, 2022
Alabama Geological Survey

8.3.1 Tuscumbia Spring, Colbert County

Tuscumbia Spring, referred to as Colbert County Spring 033M09001 by Alabama Geological Survey, is in the Tennessee Valley physiographic district and is currently used for public recreation serving as the central attraction at Spring Park, a municipal park in Tuscumbia, Alabama. Tuscumbia Spring issues from below the water surface of the receiving pool from solution openings in the Tuscumbia Limestone. The receiving pool is an engineered pond (Figure 8.43-*Left*) constructed for the municipal park. This water cascades over an artificial waterfall in the park (Figure 8.43-*Right*) and eventually enters Spring Creek, a tributary of the Tennessee River.

The period of discharge rate record for Tuscumbia Spring, the largest spring in Alabama, is from 1929 to 2018, during which time 24 measurements were collected. The average discharge rate is 20,769 gpm or 56 cfs (Smith and Guthrie, 2022; see also graph in Figure 8.2).

Figure 8.43 *Left*: **Tuscumbia Spring** receiving pond. From Smith and Guthrie, 2022. *Right*: Spring Park, located in the heart of Tuscumbia, Alabama offers a variety of amenities, including walking trails, picnic areas, and playgrounds, making it a perfect spot for family outings and community events. Visitors can enjoy captivating water features, including the iconic Coldwater Falls (https://cityoftuscumbiaparksandrecreation.sportngin.com/locations).

8.3.2 Big Spring, Huntsville

Big Spring in Huntsville (also known as Huntsville Spring) issues from a bluff face formed by an outcrop of the Tuscumbia Limestone and discharges to the engineered receiving pool and stream channel within the surrounding Big Spring International Park (Figure 8.44). The water eventually discharges to the historic, hand built, stone lined, channel of the Indian Creek Canal which flows to Huntsville Spring Branch, a tributary of the Tennessee River.

Big Spring is a third-magnitude spring with an average discharge rate of 4,169 gpm. The highest recorded discharge rate is 13,800 gpm measured on August 11, 1958, and the lowest recorded discharge rate is 0 gpm measured on October 4, 2000 (Smith and Guthrie, 2022).

Historically, Big Spring was used for municipal supply for the City of Huntsville and was also the main source of water for the northern terminus of the Indian Creek Canal. The Indian Creek Canal was constructed to connect this area with the Tennessee River, allowing cotton and other goods to be transported to market. Construction of the canal began in the early 1820s and was completed in 1831 (according to Alabama Historical Association, 1965 Historical Marker).

Figure 8.44 Big Spring in Huntsville, Alabama. *Left*: Spring orifice. Photo courtesy of the City of Huntsville. *Right*: The Indian Creek Canal. Photo courtesy of Gheorghe Ponta, Alabama Geological Survey.

On the web page of the City of Huntsville (The History of Huntsville, Al Big Spring International Park), one can read that "More than 200 years ago, future U.S. Senator John Williams Walker remarked that "Huntsville is situated around the finest spring in the world," and two centuries later, it's still true. Huntsville's Big Spring Park is located at the heart of the city, just off the courthouse square, and will always be near and dear to the hearts of Huntsvillians."

In 1805, Revolutionary War veteran John Hunt chose Big Spring as the location for a new community – the 7 to 20 million gallons of fresh water the spring produces every day were an invaluable resource for the new town. Before it was Huntsville, the community was called "Hunt's Spring," in honor of the two ingredients on which it was started. Hunt built the first cabin in what would become Huntsville atop the bluff by the spring. It would be the better part of a century before Big Spring became part of Big Spring Park; the U.S. Army Corps of Engineers renovated the site of the spring beginning in 1898, under the leadership of Hiram Chittenden, who had just been involved in the early development of Yellowstone National Park. Text and image Courtesy of the City of Huntsville.

Figure 8.45 In 1805, Revolutionary War veteran John Hunt chose Big Spring as the location for a new community. Courtesy of the City of Huntsville.

8.3.3 Blue Springs, Barbour County

Blue Springs is in Blue Springs State Park in Clio, Barbour County, in the Wiregrass Region of Alabama. The park's main attractions, the swimming pools with sandy bottom, are fed by a crystal-clear spring that remains a comfortable 68 degrees Fahrenheit year-round (https://www.alapark.com/parks/blue-springs-state-park).

Blue Springs has a long history of recreational use dating back to at least the latter part of the 19th century. In 1890, the Harrison Family built the first hotel to accommodate travelers visiting the popular summer resort. The Whigham Family constructed the second hotel in 1900 and enclosed the spring with concrete walls in 1913 in order to stabilize the spring pool. In 1963, Blue Springs was designated as an Alabama state park.

Blue Springs discharges from the Clayton Formation and is considered both a "pool spring" and a "boiling spring." The spring pools (Figure 8.46) are lined with concrete containment walls and have spillways which discharge to a natural stream channel that eventually discharges to the West Fork of the Choctawhatchee River.

The period of record for Blue Springs is from 1967 to 2017, during which time 21 discharge measurements were collected. It is a third-magnitude spring with an average discharge rate of 2,862 gpm. The highest recorded discharge rate is 4,093 gpm measured June 6, 2017, and the lowest is 310 gpm measured May 22, 1986 (Smith and Guthrie, 2022).

Figure 8.46 Swimming pools fed by Blue Springs in the Blue Springs State Park. Courtesy of Alabama Department of Archives and History.

Below are several excerpts about this famous Alabama spring from an article by Donna R. Causey published in *Alabama Pioneers* on April 26, 2021 (A famous spring in Alabama moved twice before finally settling down – Alabama Pioneers)

The spring at Blue Springs State Park actually moved by itself to two other locations before finally settling in at the current location. Some oldtimers remembered that the spring first appeared north of the highway approximately 300 yards from its present site.

But suddenly the spring dried up and reappeared just south of the highway at the west end of the Choctawhatchee river bridge. The spring was then improved and made into a swimming pool.

Around Blue Springs, resided some of the most prominent politicians of the County. During campaigns, it was a popular place to hold the speakings and candidates were always sure of getting together more listeners at Blue Springs than most any other place in the County.

For many years, Confederate soldiers from all parts of the South, held reunions at Blue Springs in the month of July. "The people of the community furnished lunch to those who attended. Also during July the horse traders in the area annually held three-day meetings to trade horses and enjoy the Blue Springs hospitality. Often the crowd at Blue Springs for a single day was estimated at one thousand."

8.3.4 Other Springs

Figure 8.47 **McCrary Spring** in Jackson County is a domestic spring that is privately owned and currently not in use. It issues from openings and solution channels formed along fractures and bedding planes in the Tuscumbia Limestone outcropping at the base of a ridge (Figure 8.45). The spring discharges directly to the receiving channel, Big Coon Creek, a tributary of the Tennessee River. The period of record for McCrary Spring is from 1971 to 2017, during which time six discharge measurements were collected, with an average of 6,895 gpm. The highest recorded discharge rate is 16,000 GPM measured April 12, 1971, and the lowest discharge rate recorded is 5 GPM measured on November 10, 1971 (Smith and Guthrie, 2022).

Figure 8.48 **Robinson Spring** in Jackson County, is a domestic, privately owned spring that is currently not in use. It issues from a cave developed in the Monteagle Limestone outcropping at the base of a hill and discharges directly to the receiving channel, Robinson Creek, a tributary of Mud Creek and the Tennessee River. The period of record for Robinson Spring is from 1971 to 2017, during which time six discharge measurements were collected Robinson Spring is a second-magnitude spring with an average discharge rate of 9,414 gpm. The highest recorded discharge rate is 20,000 gpm measured April 8, 1971, and the lowest discharge rate recorded is 750 gpm measured November 10, 1971 (Smith and Guthrie, 2022).

8.4 Tennessee

Figure 8.49 **Big Spring at Caney Fork** is located in Scott's Gulf Wilderness Area, a recently designated Kentucky state park in White County that spans over 9,500 acres of state property with public access. The spring can be accessed on foot. It discharges from the Mississippian Monteagle Limestone and feeds the Caney Fork River. This is one of the larger springs in Kentucky (see person on right side for scale). Text and photo courtesy of Amy M. Hourigan.

The Caney Fork River is a major tributary of the Cumberland River. The downstream section below Center Hill Dam is annually stocked by Tennessee Wildlife Resources Agency with Rainbow, Brown and most recently Brook Trout. The Caney Fork is one of the best trout rivers in Tennessee due to the cool water and abundant food source.

Figure 8.50 **Jasper Blue Spring** is in Jasper, Marion County. It is on private property and used for community water supply. This large spring is formed in Mississippian Monteagle Limestone, on the Eastern Escarpment of the Cumberland Plateau. Jasper Blue Spring is currently the second longest underwater cave in Tennessee. Text and photo courtesy of Amy M. Hourigan.

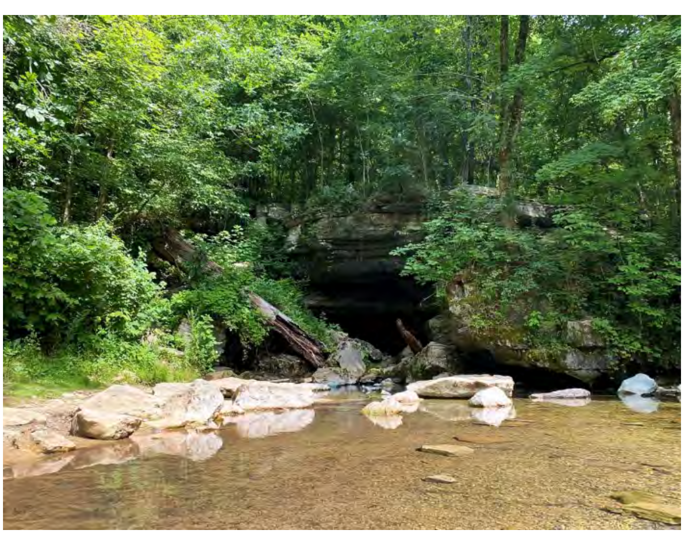


Figure 8.51 **Owen Spring** in Marion County is located in a 133-acre natural area in Marion County owned by the state. The spring discharges from the Late Mississippian Bangor Limestone, on the Eastern Escarpment of the Cumberland Plateau. This cave and spring site is managed to protect three federally and state listed species, three additional species of concern, as well as many other aquatic and cave species. It is the type locality for the Sequatchie Caddisfly (Glyphopsyche sequatchie) and one of two sites where the federally endangered Royal Snail (Marstonia ogmorhaphe) is known to exist in the world. Text and photo courtesy of Amy M. Hourigan.

Figure 8.52 **Virgin Falls Cave Spring** is located in Virgin Falls State Natural Area, in White County. The spring emerges from the Late Mississippian Bangor Limestone of Virgin Falls Cave before dropping over a 110-foot waterfall, where it immediately sinks back into the subsurface. The area is on the Western Escarpment of the Cumberland Plateau. Due to the sequence of soluble and confining geology on the Cumberland Plateau, springs often emerge and immediately sink several times before reaching the valley floor. Significant other waterfalls in the Natural Area include Big Laurel Falls and Sheep Cave Falls, which are formed by the springs emerging from the caves with same respective names. Text and photo courtesy of Amy M. Hourigan.

Figure 8.53 **Lost Creek Spring** is in Lost Creek State Natural Area situated on the western flank of the Cumberland Plateau. Lost Creek Falls pictured here is geologically similar to its nearby cousin, Virgin Falls, in that the creek emerges from large spring, or collapsed cave on top, drops over the 40-foot high falls, and disappears underground again. On the opposite side of this large sink is the spectacular entrance to Lost Creek Cave. Because the Falls and Cave open into this large sink, or bowl, with no surface drainage, cold air is trapped in the hottest and most humid times of summer, essentially wicking the water from the humid air and coating the rocks and vegetation in the bottom of the bowl with moisture. This increased moisture helps to stimulate rich ferns, flowers, and liverworts in the bottom of the sink in the late Spring and Summer. The beauty of this area attracted the Walt Disney Corporation in 1994 to film several scenes from the "Jungle Book" at the area, utilizing both the beautiful Falls and the Cave entrance. Text and photo courtesy of Lost Creek Natural Area Lost Creek (tn.gov)

8.5 Kentucky

8.5.1 Gorin Mill Spring

Gorin Mill Spring in Hart County is reputedly the largest spring in Kentucky and is located in the Rush Island Bottoms portion of the Green River State Natural Area which protects over a mile of frontage on the Green River. This section of the Green River is habitat for several rare mussel species such as fanshell, clubshell, rough pigtoe, northern riffleshell, catspaw, pink mucket, ring pink, and sheepnose. Both Indiana and gray bats are also found here; both are federally listed and threatened by White Nose Syndrome, a fungal infection that is decimating bat populations in the Eastern US. By protecting the land from development and agricultural use, it is also expected that water quality in the greater Mammoth Cave Nation Park will benefit and therefore improve habitat for the rare Kentucky cave shrimp (Green River State Natural Areas - Kentucky Energy and Environment Cabinet).

Due to limited access, Rush Island, which is on the south bank of Green River 2.8 miles below Munfordville, is not currently open to the public except by boat. Paddling access is available at Thelma Stovall Park in Munfordville.

As described by Norman Warnell on the Heart County Tourism Facebook page (Another great photo and story from... - Hart County Tourism | Facebook), who also cites investigations performed by hydrogeologist James Quinlan, Gorin Mill Spring issues from beneath a shear rock bluff on the east side and flows 70 feet into Green River. The water depth at the spring basin is 20 feet at the bluff face. Several passages lead down to a depth of 30 feet. Dye tracing indicates the spring is connected with the Hidden River complex.

A water mill was constructed at the Gorin Spring by Major James H. Gorin. It was a two-story weather-boarded mill sitting on the top of the cliff and operated by a steel line and turbine water wheel located at the foot of a cliff. By the 1960's the old mill was reportedly torn down and used for firewood.

Just above the spring an old road once ran from Munfordville, crossing the river, and into 'Epes' Bend. This was a strategic location for a water mill which furnished most of the residents of Munfordville with corn meal for many years.

In 2021, ten new national recreation trails were designated in eight states, including Kentucky's Green and Nolin Rivers Blueway. On its path through Hart County, the Green River includes stretches of springs, blue holes and the dramatic 300 Springs Waterfall, which is only accessible by boat. Kentucky's first national water trail also flows through Mammoth Cave National Park and parts of Edmonson County.

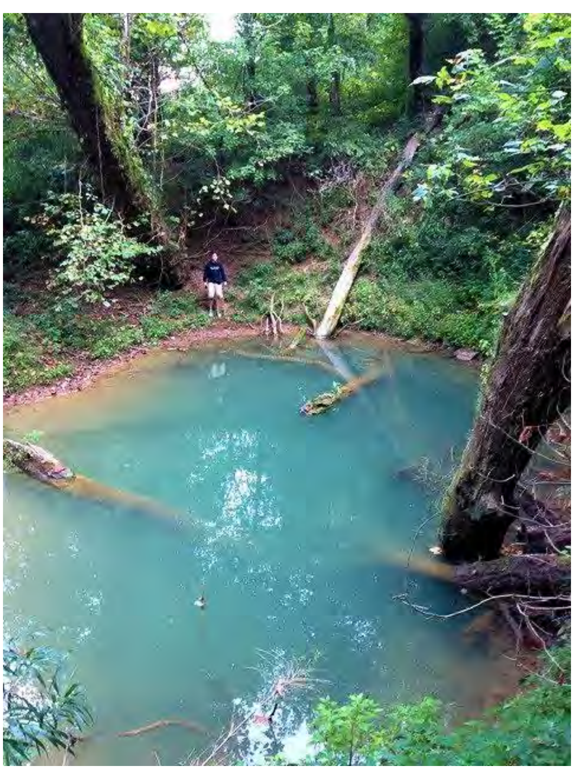


Figure 8.54 Gorin Mill Spring, the largest spring in Kentucky, has an average discharge rate of 28 cfs as listed in the Kentucky springs database. Photo by Norman Warnell, available at Another great photo and story from... - Hart County Tourism | Facebook

8.5.2 Mill Springs

Mill Springs, located 7 miles from the town of Cadiz in Trigg County, issues from St. Louis Limestone at the head of narrow, deep gorge. There is a chain of prominent ellipsoidal sinkholes oriented east-southeast upgradient of the spring, and a deep sink to the east named Boatwright Hole. Average discharge rate of Mill Springs is about 10,000 gpm (Couvering, 1962).

The spring powers the historic grits mill, Mill Springs Mill, on the shores of Lake Cumberland. Mill Springs Mill and Park are located 19 miles from downtown Somerset and 8 miles from downtown Monticello.

The Mill is a three-story frame structure built in 1877 with a still operational 40-foot overshot water wheel, the largest of its kind in the world. The Mill Springs Mill is owned by the U. S. Army Corps of Engineers and is open for tours seasonally, on weekends and holidays.

Figure 8.55 Historic Mill Springs Mill on the shore of Lake Cumberland, powered by Mill Springs. Photo By Tyler Warner, courtesy of The Kentucky Wildlands Mill Springs Falls - Wayne County (explorekywildlands.com)

8.5.3 Mammoth Cave National Park Springs

As described on the Mammoth Cave National Park webpage, the park and surrounding area is dotted with sinkholes, which is typical for karst topography. As the sinkholes south of the park drain, the surface water flows underground through caves within the Mammoth Cave plateau eventually emerging through springs along the Green River which flows from east to west through the center of the park.

Echo River Spring and **River Styx Spring** (Figures 8.56 through 8.58) are two springs accessible to park visitors via marked trails. The two springs are often just a trickle of water and may even act as sinks for the Green River rises sufficiently (the flow is reversed). The locations of many springs along Green River, and particularly for River Styx Spring, are then unrecognizable unless pointed out by a park ranger or a knowledgeable visitor (Figure 8.58).

The Mammoth Cave area is one of the most researched karst systems in the United States and boasts the largest number of dye tracing tests carried out in the country, in order to reveal the many secrets of the underlying karst aquifer (Figure 8.59). This is not surprising because of the simple fact that Mammoth Cave is the longest cave in the world, with 426 miles of mapped passages as of September 2022. A national park was established in 1941 because of the cave. Although the park was authorized in 1926 , it was another15 years before becoming official.
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Figure 8.56 Echo River Spring in Mammoth Cave National Park. Photo courtesy of Nenad Maric.

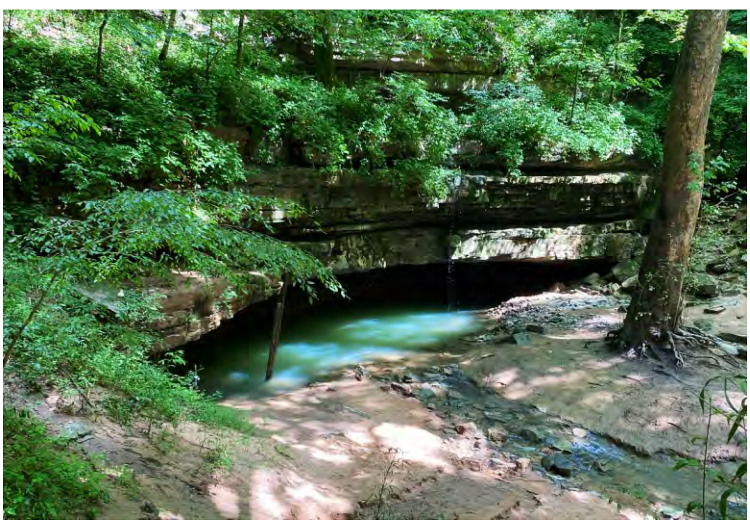

Figure 8.57 River Styx Spring in Mammoth Cave National Park. Photo courtesy of Nenad Maric.

Figure 8.58 River Styx Spring when backed up by muddy water from Green River. Water falls from the rock ledges above the cave orifice of the spring. Spring drains parts of the hydrologically active passages of the Mammoth Cave system and saturated portion of the karst aquifer. Photo courtesy of NPS.

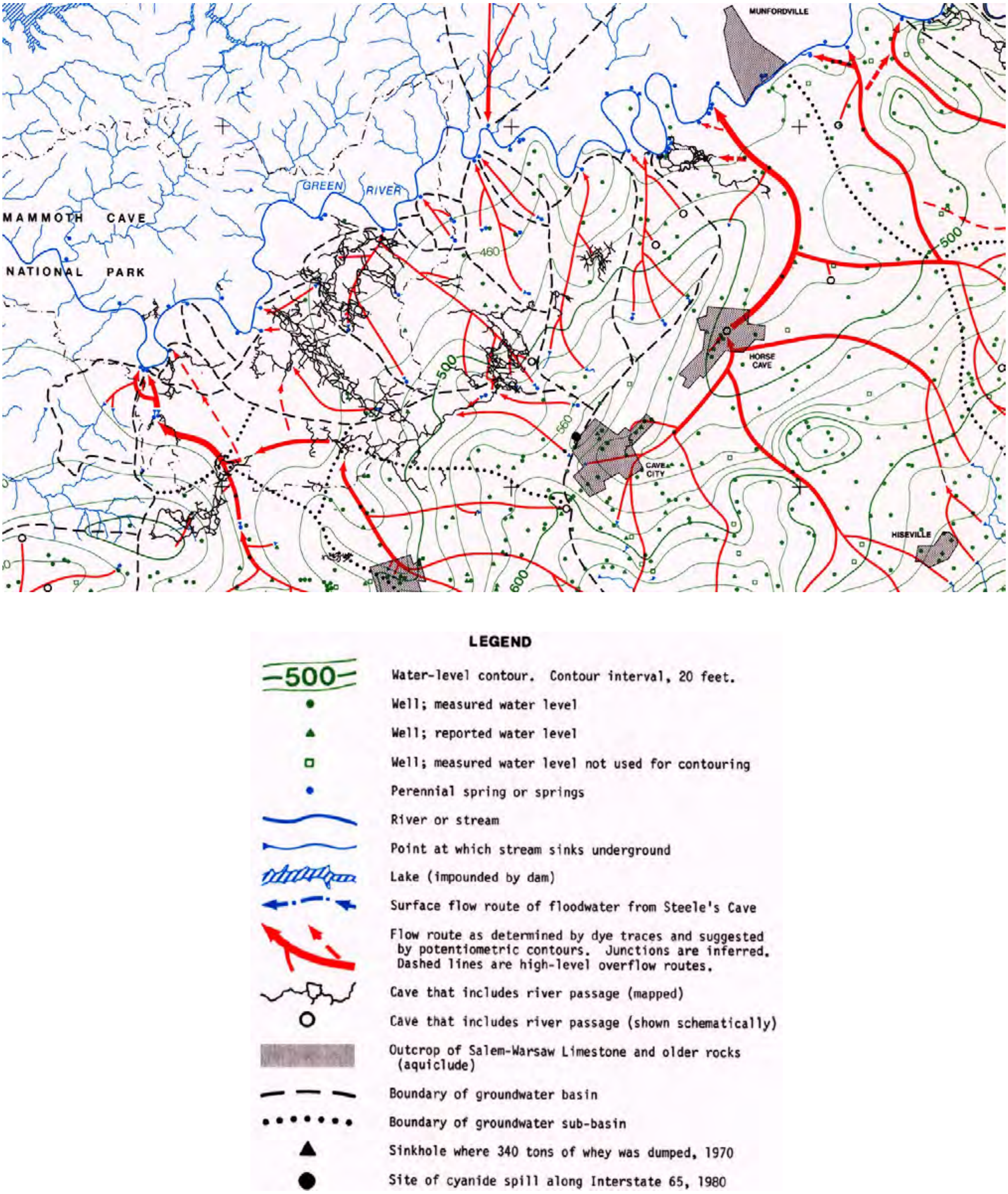

Figure 8.59 Part of map of "*Groundwater Basins in Mammoth Cave Region, Kentucky Showing Major Caves, Flow Routes, and Potentiometric Surface*" by hydrogeologists James F. Quinlan and Joseph A. Ray of National Park Service, published in 1981 (revised in 1989) as Occasional Publication No. 2, Friends of Karst, Mammoth Cave, Kentucky. This map remains the gold standard for hydrogeologic mapping in karst terrains.

8.5.4 Blue Hole Spring, and Lost River Rise

Blue Hole Spring and Lost River Rise (aka Spring) in Bowling Green, together with Lost River Cave, are prominently featured on many websites which promote them as part of Kentucky's natural wonders. This is the reason for their inclusion in this book.

According to some websites (e.g., The Wonders of the Lost River Cave of Kentucky - Ocean Info) "The Blue Hole at Lost River Cave is 16 feet deep at the visible surface, but it connects to a deeper underground river system that has been measured at over 437 feet deep. This unique geological feature has earned the Lost River the title of "shortest, deepest river in the world" by Ripley's Believe It or Not."

It is interesting that similar "marketing" information exists for the Poe River formed by Giant Springs in Montana (see Chapter 7.4.1): "The springs are a source of the Roe River (only 201 feet long, before it empties into the Missouri River), once listed as the shortest river in the World by the Guinness Book of World Records before Guinness eliminated the category." Perhaps, the secret of this slight "discrepancy" is that Lost River is allegedly also the deepest short river in the world? At the same time, one can also find on the web that "The actual hole is 10 feet deep but links to another underground river."

In any case, the old truth is that "non-professional" or "popular" websites cannot always be trusted entirely, especially if credible sources of the information are not listed. Additionally, it seems that the information in question is often miraculously multiplied on similar sites. It attains a life of its own. This aside, it is true that the Blue Hole Spring – Lost River Cave – Lost River Rise karst system is a nice example of a fully developed karst landscape that fascinates professionals and "the general public" alike. In more scientific terms, the Lost River Groundwater Drainage Basin in Warren County, Kentucky, is a karst drainage system encompassing 55 square miles developed within the Mississippian St. Louis and Ste. Genevieve Limestones (Groves, 1987).

Unfortunately, the actual relationship between the three main features of the system is usually misinterpreted on various websites, and it may end up being entirely mystifying to those that are not intimately versed with which feature flows into which feature, for example. One confusing thing is that many refer to the Lost River Rise as the Lost River Spring. Visiting the Lost River Cave website (https://www.lostrivercave.org/) will not help much in figuring all this out.

Fortunately, Lost River Cave is worth visiting no matter what, and the friendly hosts will explain this "complicated" karst hydrogeology situation very patiently while one enjoys a cave boat tour. Those that want to learn a bit more can try to get hold of the master thesis of Chistopher Groves (1987), paper by Glennon and Groves (2002), or read several chapters in the book edited by White and White (1989) that may help.

Figure 8.60 Blue Hole spring in Bowling Green, head of a small stream that disappears into Lost River Cave after flowing several hundred feet. Photo courtesy of Nenad Maric. See also Figure 8.13.

Figure 8.61 *Left*: After flowing several hundred feet, the unnamed stream shown here dissapears into Lost River Cave visible in the background. Photo courtesy of Chris Groves. *Right*: Lost River Cave is one of only a few caves in the country that offer boat tours. It is managed by the Friends of the Lost River, Inc., a non-profit 501(c)3 organization. This group of committed individuals works to provide fiscal sustainability for the conservation and protection of Lost River Cave's natural and cultural resources while providing outdoor experiences and education. Photo courtesy of https://www.lostrivercave.org/.

As illustrated with Figures 8.60 through 8.62, it is not as complicated as it might seem. Blue Hole is a spring that drains part of the regional karst aquifer; this spring creates a short, unnamed surface stream that flows into Lost River Cave and then "disappears" underground after flowing in the cave. Lost River Rise (aka "Spring") is at the end of this chain where part of the water that disappeared in Lost River Cave emerges again and flows briefly as a surface stream until joining Jennings Creek. Jennings Creek is a surface stream, mostly fed by karst springs, and is a tributary to the Barren River, the base level stream for the area. Figure 14 in the thesis by Groves (1987) illustrates this system with a nice hydrogeologic cross section.

Figure 8.62 *Left*: Lost River Rise which is connected with Lost River Cave as determined with dye tracing inside the cave. *Right*: View downstream from the Rise. Photographs courtesy of Nenad Maric.

8.5.5. Royal Spring

Royal Spring in Scott County is the largest spring in Inner Bluegrass and drains an area of over 25 square miles. The city of Georgetown and Scott County residents use Royal Spring as source of public water supply. The groundwater basin for the spring extends into northern Fayette County, and is susceptible to contamination from development, agriculture, and transportation on I-75.

The city lost its water supply from the spring during the winter of 1988-89 when gasoline was detected.. The gasoline leaked into the ground from a storage tank somewhere in the watershed of the spring. Georgetown water customers had to be issued bottled water for several weeks until a new water-treatment system could be installed (Currens, 2002).

Urban legend has it that Royal Spring is the birthplace of bourbon, a liquid with a transparent color, and taste agreeable to an unknown number of citizens in the United States and the world (the author of this book is not an exception). This legend is reinforced by a historic landmark near the spring. However, there are also differing opinions including a very convincing one by Tom Wilmes available at Kentucky Bourbon Myths | Elijah Craig, Limestone & More – Garden & Gun (gardenandgun.com)

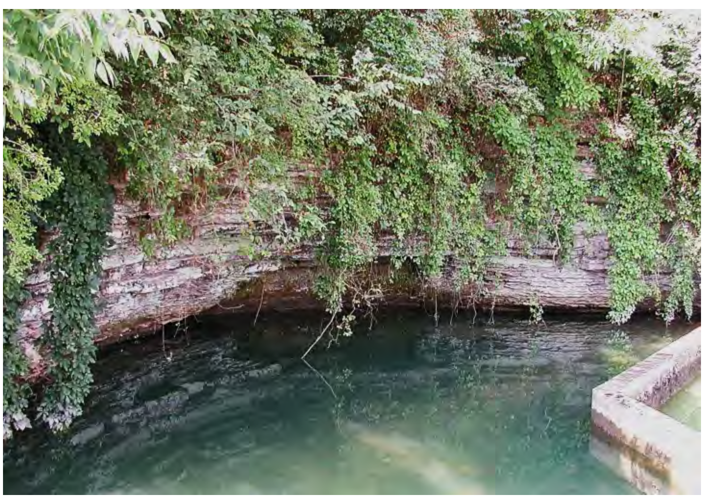

Figure 8.63 Royal Spring in Georgetown, Scott County. Photo by Bart Davidson, Kentucky Geological Survey.

"The main source of water for our area has been the Big Spring since John McClelland and his party of frontiersmen and women built a fortified settlement in 1775. In 1889, Georgetown Water Works Company was incorporated as the first authority to regulate, treat and distribute this spring water for the community. In 1945, The City of Georgetown purchased that company and established the 'Municipal Water Works Plant'. In 1962, the water and sewer systems were consolidated, and Georgetown Municipal Water and Sewer Service was formed. The Big Spring is now known as Royal Spring." (https://www.gmwss.com/about.htm).

8.5.6. McConell Springs

As explained on the webpage of McConnell Springs Park in Lexington, sponsored by the Friends of McConell Springs (https://mcconnellsprings.org/), McConell Springs are the visible portion of an underground drainage system that underlies part of central and south Lexington. The sinks and rises of McConnell Springs form windows along the flow path of underground streams, where the subterranean conduits are briefly exposed before vanishing again into the rock.

The second spring of the McConnell Springs system is called the Boils (Figure 8.64) because of the action of the water emerging from the underground conduit. During heavy rains a column of water rises from the spring to a height of up to 24 inches. This spring and the first spring (Blue Hole) visible upgradient, at the beginning of the park, are both considered artesian springs.

In June 1775, a pioneer from Pennsylvania named William McConnell, his brother Francis McConnell, and their fellow frontiersmen were exploring the wilderness of the Virginia territory known as Kentucky. Like many other Scots-Irish settlers of the time, they were interested in acquiring land and improving their family circumstances. As they surveyed and mapped the land around the forks of the Elkhorn Creek, they build crude improvements that allowed them to stake claims to the land under the laws of Virginia at that time. William McConnell's claim included the land around a "sinking spring" where the party had set up camp. It was at this encampment that the explorers received word from nearby Fort Boonesborough that the first battles of the American Revolution had been fought April 19, 1775 in Lexington & Concord, Massachusetts. In honor of this event, the group named their future settlement "Lexington". The ensuing years were marked by raids and invasions by the British & Indians, but the influx of settlers from the East continued. In 1779 a permanent blockhouse was built, and in 1780 Lexington was named seat of Fayette County, Virginia, and in 1782 the town was chartered. Kentucky then became the 15th state to join the union in 1792.

Figure 8.64 "The Boils", second spring of the McConnell Springs system. Photo courtesy of Alan Fryar.

Reading an outstanding 2020 publication by Nancy O'Malley entitled *McConnell Springs in Historical Perspective* is a must for anyone interested in the fascinating archaeology of the Paleo-Indian Period through Later Prehistoric Period, followed by the history from the Historic Contact Period (A.D. 1540-1795) to present. The publication is packed with meticulously researched materials, archeological evidence, drawings, photographs, and facsimiles of historic documents, with McConell Springs in the middle of it all (available at McConnell Springs in Historical Perspective).

> *The many people who support the effort to save McConnell Springs from industrial development consider the place to be important. But why should this place be preserved? Part of the value of McConnell Springs is derived from the natural environment: the springs, the karst features, and the remnant native vegetation. The rest of the significance of this place is derived from the human activities that left discernible traces on the landscape (in the form of culturally altered soil deposits, structural foundations, stone fences, dam abutments, vegetational patterns and the like). Without detailed documentation, understanding the exact nature, date, and meaning of these human activities can be difficult, and insufficient or ambiguous information may lead to their misinterpretation. While there is still more to be learned about McConnell Springs, the following represents the current state of our knowledge about what has happened at the springs over the last few millennia. It is not nor should it be a static story. Rather, the past of McConnell Springs is seamlessly connected to its present and its future.*
>
> Nancy O'Malley

8.5.7 Big Springs, Princeton

Downtown Princeton is home to a small park with a cave and Big Springs which issue from limestone of the Western Pennyroyal Karst System. Adjacent to the city park is a Trail of Tears Commemorative Park featuring a large, engraved granite stone monument that reads "A Mother's Burden" both in English and in Cherokee. The stones for the monument were sourced from a quarry location along the original trail route, and dedicated to the park. The monument is shaped like a tear drop to depict forced removal of the Cherokee Nation from their ancestral lands.

Figure 8.65 A close look at the Big Springs Cave in downtown Princeton. Photo courtesy of Four Rivers Explorer. Detailed description of the spring and Princeton's history, accompanied by more photographs is available at [Big Springs Cave in Princeton - Four Rivers Explorer]

"During the forced removal of 1838-1839, 11 of the 13 detachments of Cherokee followed the northern route of the Trail of Tears. More than 10,000 men, women, and children endured the long trek and difficult conditions traveling on foot or in horse-drawn carts. Each detachment would stretch for miles along the route. Big Springs, a natural spring that emerges from the limestone, served as a water source and stopping point for the weary travelers.

Today, people visit Big Springs for day trips or weekend getaways. The serene and peaceful environment, combined with the natural setting, provides an enjoyable escape from the city. It is a picturesque destination where visitors can connect with nature, learn about local history, and recreate. The site around Big Springs features picnic spots, walking paths, and seating areas where people can relax and enjoy the beautiful surroundings. Please note that the cave is not accessible, and visitors are cautioned not to drink from the spring." https://home.nps.gov/places/big-spring-kentucky.htm

> *Several ancient buffalo trails converged at Big Springs Cave and were used by Native Americans for centuries prior to the arrival of European settlers. No doubt these men explored and used these old but well-traveled pathways. Finding three intersecting at one location with a great source of fresh water proved to be an ideal location for a community.*
>
> Four Rivers Explorer

8.6 Pennsylvania

8.6.1 The Big Spring, Bellefonte

The Big Spring is the defining element of the City of Bellefonte in Pennsylvania. A story in John Blair Linn's *History of Centre and Clinton Counties* published in 1883 relates that the French statesman Charles Maurice de Talleyrand visited the Big Spring with Mrs. Ann Dunlop Harris (1765-1844). There he exclaimed "La belle font," leading her to suggest the name Bellefonte to her father Col. James Dunlop and her husband James Harris, who together laid out the town in 1795.

Talleyrand was in exile in America from the French Revolution, from March 1794 to June 1796. His principal residence during that time was a rented house in Philadelphia. On a visit to nearby Centre Furnace, he may have come to Bellefonte to visit James Harris, and may have seen the spring. The story was relayed to Linn by Mary Orbison of Huntington County, who was the great-granddaughter of Ann Harris. A file at the Centre County Historical Library contains, however, letters from other descendants who did not believe the story to be true. In any case, until the city's Water Street was carved out of a steep bank, the spring did bubble out of the side of the bank and cascade down in a fountain-like manner (Bellefonte Historical and Cultural Association; http://www.bellefontearts.org/Virtual_walk/Bellefonte_name.htm).

The spring has continually been the source of drinking water for the town's residents since 1807, with a daily flow of 11.5 million gallons (1.5 cfs). Major William F Reynolds gave The Big Spring to the town on October 1, 1879, for the price of $1.00. The present pumphouse was built in 1926 and was restored in 2006. The spring is now covered with a synthetic fabric because of environmental regulations (see Figure 8.X-*Left*). Many historic images of the spring are available online, featuring the Fred D. Smith collection of postcards and photographs (see Figure 8.66; http://www.bellefontearts.org/Smith_pages/Smith_spring.htm).

Figure 8.66 Current (*left*) and historic (*right*) look of The Big Spring in Belefonte.
From http://www.bellefontearts.org/Smith_pages/Smith_spring.htm

Big Spring also provides water to several other communities, and various industrial facilities including Coca-Cola which bottles more that 33 million cases of water a year. In 2014, the Big Spring's water was named "Best Tasting Water" in Pennsylvania by the Pennsylvania Rural Water Association.

Below are two excerpts about The Big Spring from an article by Emma Gosalvez, published in The Express on Sep 10, 2016, *Beneath the cover: Shining a light on the significance of Bellefonte's Big Spring*.

(Big Spring) is typically covered in front of the pump house that is located at the edge of Talleyrand Park, but on Monday, Aug. 15, the cover to Big Spring was lifted, and for 24 hours, it could be seen in all its glory, which will not happen again for about another 20 years. This is due to environmental elements that determine the life expectancy of the cover, which is approximately 20 years, according to Frank "Buddy" Halderman, vice chairman of Bellefonte Area Industrial Development Authority and former Bellefonte Borough Council president.

The cover to the spring is a requirement as a result of the Federal Safe Drinking Water Act, which states that if a drinking water source is groundwater, it has to be protected from surface contaminants, according to Halderman. The spring, which is classified as groundwater, was first covered around 1999, when Bellefonte Borough signed an agreement with the AquaPenn, the first owner of the Coca-Cola bottling plant. AquaPenn required that Bellefonte cover the Big Spring in order to be the supplier of its products.

8.6.2 Bedford Springs

Located in Bedford, a small town in the Allegheny Mountains of southern Pennsylvania, Omni Bedford Springs Resort has long, famed history which started with the Native Americans using the mineral springs for their curative properties, and in the late 1700s, sharing the powers of the springs with a doctor named John Anderson. In 1796, Dr. Anderson purchased the 2,200-acre property on which the resort now stands. He built a home on the property and as word spread of these unique waters, visitors arrived from around the country to experience them. He housed the guests in tents and offered custom prescriptions for guests based upon their needs.

As more and more guests came from the east to "take the waters," Dr. Anderson decided to build a hotel. The Stone Inn was built in 1806 from stone quarried atop the mountain located adjacent to the springs and carried down the mountain by oxen.

Guests making the trek to the hotel encountered a rugged journey. They often arrived by train to Cumberland, and then made the 21-mile trip through the Cumberland Valley to Bedford Springs.

In 1984, the resort was designated a National Historic Landmark, and it closed its doors two years later. Omni Hotels purchased the property and in 2004 started $120 million restoration and expansion. A completely restored Omni Bedford Springs Resort was opened in 2007.

Figure 8.67 Omni Bedford Springs Resort in Bedford. Courtesy of Upscale Resorts Pennsylvania | Omni Bedford Springs Resort (omnihotels.com)

As explained on the resort's webpage, The Bedford Springs Hotel was originally built because of Magnesia Spring (also called Mineral Spring), located at the base of the ridge east of the hotel buildings. The Iron Spring, which also has been called Fletcher's Spring or the Upper Spring issues forth copiously from a fissure in limestone outcroppings on the upper part of Shober's Run. This highly mineralized water is similar to the popular Magnesia Spring but has less magnesia content and a slightly higher amount of iron salts. The two mineral waters were similar in composition and the Iron Spring water proved to be as popular as that of the Magnesia Spring, and it flowed as abundantly. The Iron Spring water, once thought to have laxative and stimulant effects, was recommended for ailments associated with digestive tract, and for run-down conditions.

Crystal Spring and Black Spring also emerge from the Silurian-Devonian Limestones at 0.3 miles and 1.0 miles south of Magnesia Spring along the same ridge. On the top of the ridge sinkholes indicate the general karstic character of the area, and there is a small stream which flows into a cave entrance, but quickly disappears into a debris-choked crevice.

A cave on the Bedford Springs Hotel property named Bedford Springs Cave (called Davey (or Davy) Lewis Cave in the past) has been known to the caving community since the 1950s. It is located near an old stone mill.

Figure 8.68 Left: Perspective view from south of the 1903 pool building at Bedford Springs Hotel. Note Greek revival lobby/dining room building on right. Author Nocholas Traub, courtesy of Library of Congress Prints and Photographs Division. Right: Fig 6.X Restored pool at Omni Bedford Springs Resort. Photo courtesy of Bedford, PA Wellness | Omni Bedford Springs Resort (omnihotels.com)

Below are some interesting tidbits from the fascinating history of the original Bedford Springs Hotel.

1943 – 1945 Japanese diplomats captured in Germany during WWII are housed at the resort.

1941 – 1943 The U.S. Navy occupies the resort, using it as a training facility for radio operators.

1923 Renowned golf course architect Donald Ross remodels Bedford Springs' 18-hole golf course.

1905 One of the first indoor pools in the nation is constructed at Bedford Springs, complete with a mineral water-fed swimming pool, solarium and hydrotherapy rooms.

1895 One of the first golf courses in America is laid out by Spencer Oldham at Bedford Springs.

1858 First transatlantic cable is received by President Buchanan in the lobby of the Bedford Springs Resort. He spent 40 summers in Bedford Springs.

1848 James K. Polk is the first sitting president to visit Bedford Springs. A total of 10 U.S. presidents will eventually be hosted by the resort, including visits by seven presidents during their time in office. These include Presidents Andrew Jackson, John Tyler, James K. Polk, Zachary Taylor, James Buchanan, James Garfield and William H. Taft.

1821 Future U.S. President James Buchanan makes the first of many visits to Bedford Springs, which will become his "summer White House" during his time in office.

1819 Thomas Jefferson, 3rd President of the United States, visits the resort for several weeks.

8.7 Saratoga Springs, New York

Experience the Natural Mineral Springs in Saratoga, NY, by MacKenzie Zarzycki, Aug. 06, 2024

Saratoga's natural mineral springs have been a longstanding tourism draw, boasting magical healing powers that aid skin ailments, digestion issues, strengthen blood, and more! Our mineral springs are vast and easily accessible. We've highlighted each mineral spring below so you can plan a trip to Saratoga and taste the waters for yourself. Don't forget to bring your own cup or water bottle to sample each one.
Experience the Natural Mineral Springs in Saratoga, NY (discoversaratoga.org)

And indeed, when it comes to taking good loving care of their springs and promoting them around the world, the City of Saratoga Springs is in a league of its own, unrivaled by any other place on earth. In addition to the "miraculous springs that cure many diseases", it did not (and still does not) hurt that the New Yorkers sought summer refuge in the cooler parts of the state up north, bringing along their money and famed entrepreneurial spirit.

Dozens of pretty spring houses (e.g., see Figures 8.69 and 8.70), hotels, and entertainment establishments sprouted in the nineteenth century throughout the city. As demand grew, wells were drilled and they were quickly touted as *Wonderful Mineral Fountains* (Figure 8.71). The springs were immortalized in various publications, on postcards, and with novel stereophotographs that lured many visitors. Those seeking a cure and those that just wanted to escape the hot big city in the south to socialize, to be entertained, to be seen, and to attend horse races in one of the most famous racetracks in the country, all found what they were seeking at Saratoga.


Figure 8.69 *Left*: Hathorn Spring, also known as the "hangover cure" water. Located on the corner of Putnam and Spring Street, this spring is considered one of most effective digestive waters. The elaborate pavilion, benches and landscaping add to its allure. Photo taken in 1904 by Detroit Publishing Company, courtesy of Library of Congress *Right*: High Rock Spring is located across Maple Avenue from The Olde Bryan Inn. At its base, High Rock Spring is distinguished by a cone of hardened mineral deposits. It is considered an excellent source of natural spring water. Address: High Rock Park, 112 High Rock Avenue. Photo taken between 1900 and 1906 by Detroit Publishing Company, courtesy of Library of Congress.

In 2023, Arthur Palmer and Margaret Palmer from Oneonta, New York, nominated Saratoga Springs for inclusion in the list of Nationally Important Karst Aquifer Springs (NIKAS) assembled by Karst Commission (KC) of the International Association of Hydrogeologists (Palmer and Palmer, 2023). The following description of the hydrogeologic characteristics of the springs is from this nomination, courtesy of KC, and Arthur & Margaret Palmer.

Figure 8.70 Stereophotograph of Congress Spring. Discovered in 1792 by a congressman from New Hampshire, Congress Spring became the centerpiece of Congress Park and the village that grew up around it. Bottled and sold around the world, Congress water was the most famous of the Saratoga mineral waters. Address: Congress Park, 268 Broadway. Photo published by George Stacy in 1865, courtesy of Library of Congress.

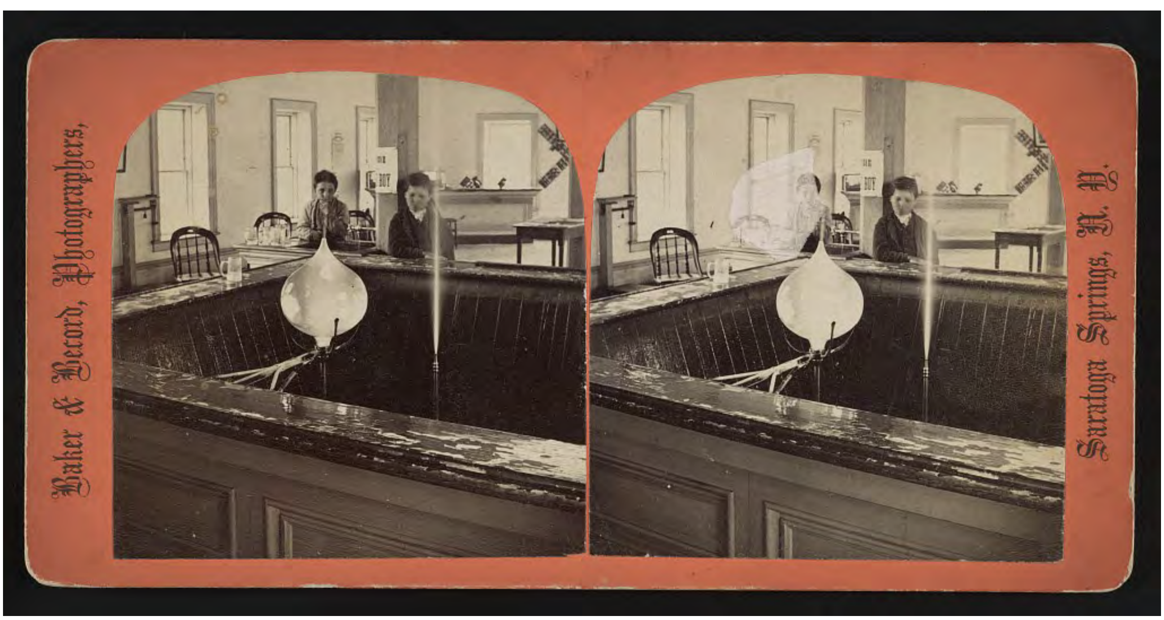

Figure 8.71 Geyser Spring, Saratoga Springs, N. Y.; Baker & Record, photographers; published between 1870 and 1880. Courtesy of Library of Congress. Text on the back of this stereo photograph card reads: *This Wonderful Mineral Fountain was discovered in February, 1870. It was developed by experimental drilling in the solid rock. It is located in the "Coeesa Valley," near Cady Hill, on the Ballston road, one and a half miles south of the principal hotels at Saratoga Springs. The water vein was struck by the drill in the birds-eye limestone, one hundred and fifty feet beneath the surface rock. The water immediately commenced spouting at the surface, being forced up from the depths of the earth by the pressure of its own carbonic acid gas, spouting through an inch nozzle to the height of thirty feet. During the season of 1870 over fifty thousand persons visited the Geyser Spring, and the universal testimony of all is that the waters are the best and the spring the most wonderful in the world.*

Figure 8.72 Saratoga Spa State Park trail map. Available at [Saratoga Spa State Park (ny.gov)]

The principal aquifer feeding the Springs is the Cambrian-Ordovician dolomite and limestone of the Beekmantown Group, which is overlain by a shale cap-rock. The original springs are located where the Saratoga normal fault cuts across the units. During the 20th century, wells drilled through the shale have encountered the CO_2-rich water, releasing additional groundwater as springs under pressure.

Besides high content of carbon dioxide (CO_2), the water has a high saline content and thousands of milligrams per litre total dissolved solid concentrations. The springs lie along the north-south trace of the Saratoga normal Fault. Inorganic carbon and helium isotope ratios indicate a mantle or magmatic origin for the CO_2. The stable isotopic content of the spring water and strontium (Sr) isotopic composition (dissolved Sr) define mixing lines between modern local meteoric waters and a probable Canadian Shield-type brine under the Adirondack Mountains (Siegel, 2005). The springs are saturated with respect to calcite and spring mounds and precipitates have formed indicating solution of carbonate rocks at depth; therefore, the springs represent the surface expression of suspected hypogenic karst (Palmer et al., 2017).

Native Mohawk and Iroquois Tribes knew about the springs and believed in their medicinal properties. In the 19th century it became popular as a spa. Bottled water was sold; however, pumping depleted the wells. Laws were passed to limit use and in 1962 the springs were named a state park and declared a National Historic landmark. In 1971 the state ended the economic operations. Today there are 17 springs in the Park and a network of scenic paths that lead to the spring mounds and fountains. The water now is coming from wells, as the natural springs are plugged with carbonate precipitation (Palmer and Palmer, 2023). Additional references are Hollocher et al. (2002), and Young (1978).

Figure 8.73 “Island Spouter” – mound of travertine formed around a drill-hole which releases pressure and has highly variable flow (max./ min. peaks varying over minutes or even seconds). Location #4 on map in Figure 8.72. Photo courtesy of Arthur Palmer.

8.8 Kitch-iti-kipi (The Big Spring), Michigan

Palms Book State Park, located at the north end of Indian Lake in Michigan's Upper Peninsula, is home to Kitch-iti-kipi or "The Big Spring." The state of Michigan received the spring with accompanying land as a gift from the federal government in 1926, under the stipulation that it be turned into an official public park. It is now one of the most visited state parks in Michigan.

The park is 11 miles from Manistique, small town on the shores of Indian Lake, via County Roads 442 and 455, and State Highway M149 (which changes name to Sawmill Drive). Wayfinding signage refers to the park as Palms Book; however, locals also refer to the park as The Big Spring and Kitch-iti-kipi.

Figure 8.74. Kitch-iti-kipi or "The Big Spring". Photos courtesy of Michigan Department of Natural Resources.

This famous natural attraction is Michigan's largest freshwater spring with more than 10,000 gallons of water per minute gushing through fissures in the underlying limestone at a constant 45 degrees Fahrenheit. Concessions and souvenirs are available at a store open seasonally and a boating access site provides access to Indian Lake (the Upper Peninsula's fourth-largest inland lake). More information is available at Palms Book State Park Detail and Palms Book State Park | Michigan

Perhaps the following excerpts from an article about the spring by Jil Halping, available on the webpage of My Michigan Beach & Travel, will do it justice and draw readers to learn more about this out-of-this-world spring (https://mymichiganbeach.com/kitch-iti-kipi/)

The word is out about Kitch-iti-Kipi, Michigan's "Big Spring," located in the Upper Peninsula, near Manistique MI.

This brilliant, emerald green freshwater spring is pure Michigan beauty at it's most stunning. More than 40 feet deep and 200 feet across, the water is so crystal clear that you can actually see all the way to bottom!

The best part? You can take a clear-bottom, hand-operated raft across the pond to peer into the water below. Imagine catching a glimpse of big lake trout as they congregate at spring's limestone bottom to search for food. It's so much fun!

Whether you call it Kitch iti Kipi, the Big Spring or even the "Mirror of Heaven," (the name given to it by native Ojibwe), you'll agree that it's a true wonder of nature.

In 2020, Carole Lynn Hare published a book titled, "The Legend of Kitch-iti-kipi," which tells her tribe's version of the story of the spring:

Many folk tales exist about this natural wonder found deep in the woods of the Upper Peninsula. Many of those stories were admittedly made up by John I. Bellair, a local businessman in the 1920s, in an effort to attract more visitors to the area. But what is the authentic Native American legend of Kitch-iti-kipi? The story in this book has been passed down orally in the author's Native American family for more than one hundred years. Although Natives seldom write down their folklore, the author's great-great-aunt actually did write this legend in a published booklet which was found when she passed away in 1969. That booklet was the author's inspiration for this book. The Legend of Kitch-iti-kipi reads like a Native version of Romeo and Juliet. In it, the deep love between a handsome brave and a young maiden drives a powerful chief to act out his jealousy. The results are tragic for all three!

Figure 8.75 Kitch-iti-kipi or "The Big Spring". Photo courtesy of Travel Michigan.
https://www.travel-mi.com/Big-Spring.html

HOW KITCHITIKIPI CAME TO BE (GIMDL-GGKITCH.PDF (michigan.gov)

"....But Nature, never satisfied with what she builds, was busily at work destroying the limestone she had made, to fashion something else. Pure limestone is readily soluble and some of the Silurian limestones are pure lime. Water entered the cracks, dissolved the stone, made funnel-shaped depressions as it went dissolving down the joints, and made caves and caverns as it dissolved its way along the bedding planes. It made one cave above another with a thin cracked layer of stone between and the tops or roofs of the upper caves fell in, making funnel-shaped surface pits and hour-glass fashion carrying down the sands of the glacial drift through the cracks into the cave below. Two such caves united below the surface, and their unsupported roofs collapsed making one oval depression loading to a crack in the floor. Waters from the lower cave bubbled up through the crack bringing a fountain of sands--lime, sand, shell fragments, and exquisitely formed microscopic shells of ostracods. The water-filled depression became a pool and vegetation gave its emerald color in reflection to the clear waters. Big Spring was born. Dying and dead trees fell into the pool. Nature draped them with verdant mosses--making them eerie things of beauty in their watery graves. The Indians built their village Osawanimiki on the southeastern shore of Indian Lake and dreamed the legends of the wonder spring.

In the region west of Indian Lake where the limestone is near the surface with little or no covering of glacial drift, the area is pitted with many depressions or sink holes which range in size from small depressions 15 to 20 feet in diameter and six to eight feet deep to large conical sinks 100 to 150 feet across and 40 to 60 feet deep. All the depressions appear to have been caused by infalling cave roofs. The Big Spring depression is the largest- 300 feet along and 175 feet wide with sides that drop abruptly 40 feet to the crack in the floor. Water under strong pressure constantly boils up through the crack bringing sand which may be derived in part from the layers of quicksand found in the glacial drift 47.5 feet below the surface in the park well, or from a fine sand and gravel 55 feet below the surface. Since the sands contain fragments of modern as well as fossil shells, it is possible that the sands have been carried from the surface through underground drainageways to the Big Spring sandy fountain."

Figure 8.75 Kitch-iti-kipi or "The Big Spring". Photo courtesy of My Michigan Beach & Travel. https://mymichiganbeach.com/kitch-iti-kipi/

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Chapter 9 Thermal Springs

9.1 Introduction

Thermal springs can be divided into *warm springs* and *hot springs*, depending on their temperature relative to the human body temperature of 98° Fahrenheit or 37° Celsius: hot springs have a higher and warm springs a lower temperature. It is also understood that a warm spring has a temperature higher than the average annual air temperature at the location of the discharge. The water temperature of both groups of thermal springs can fluctuate over time, reflecting various degrees of surficial influence. One such example is Granite Hot Springs near Jackson, Wyoming (Figure 9.1). The schematic in Figure 9.2 illustrates a common situation where springs of different temperatures can occur close to each other.

Figure 9.1 In the mid-1930's the Civilian Conservation Corps (CCC) constructed a cement pool to capture the thermal heated water of Granite Hot Springs. Temperatures vary from 93 degrees F in the summer to 112 degrees in the winter. The 45 by 75-foot hot pool is bordered by large granite boulders and beautiful scenic views. Granite Campground is located about a mile away from the site. The spring flows from the contact of the Cambrian period Death Canyon Limestone and Flathead Formation. Fluctuating flow indicates influence by surface waters and snowmelt. Regionally, the thermal spring is in the Bridger-Teton National Forest, in the Gros Ventre Mountains that were thrust upward along the Cache Creek Fault millions of years ago. The peaks are mainly Paleozoic and Mesozoic age sedimentary rocks jaggedly carved through glacial activity (Blackstone, 1988). To get to the spring, in Hoback Junction, 13 miles south of Jackson, WY, head east on Highway 189/191 and follow the Hoback River south up the canyon. Take Granite Creek Road 10 miles east to Granite Hot Springs. Road is clearly marked. Courtesy of the U.S. Forest Service.

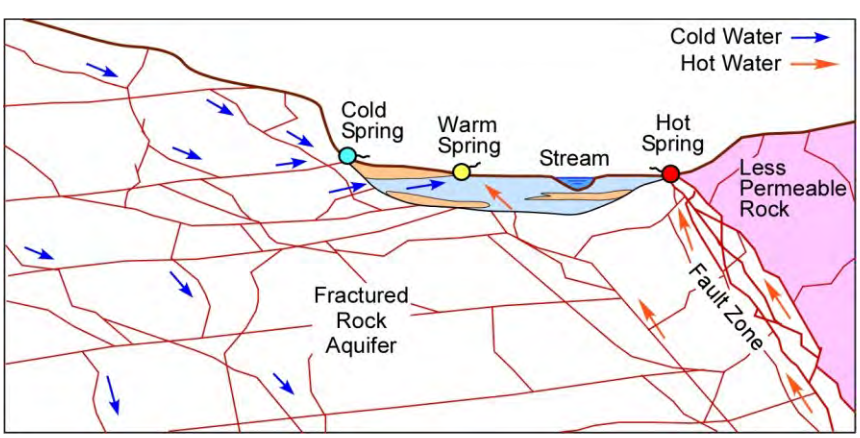

Figure 9.2 Three springs of different temperature in a barrier fault zone overlain by alluvium. Modified from Kresic, 2023.

Meinzer (1940) gives the following illustrative discussion regarding the occurrence and nature of thermal springs in the United States: *An exact statement of the number of thermal springs in the United States is, of course, arbitrary, depending upon the classification of springs that are only slightly warmer than the normal for their localities and upon the groupings of those recognized as thermal springs. Nearly two-thirds of the recognized thermal springs issue from igneous rocks—chiefly from the large intrusive masses, such as the great Idaho batholith, which still retain some of their original heat. Few, if any, derive their heat from the extrusive lavas, which were widely spread out in relatively thin sheets that cooled quickly. Many of the thermal springs issue along faults, and some of these may be artesian in character, but most of them probably derive their heat from hot gases or liquids that rise from underlying bodies of intrusive rock. The available data indicate that the thermal springs of the Western Mountain region derive their water chiefly from surface sources, but their heat largely from magmatic sources.*

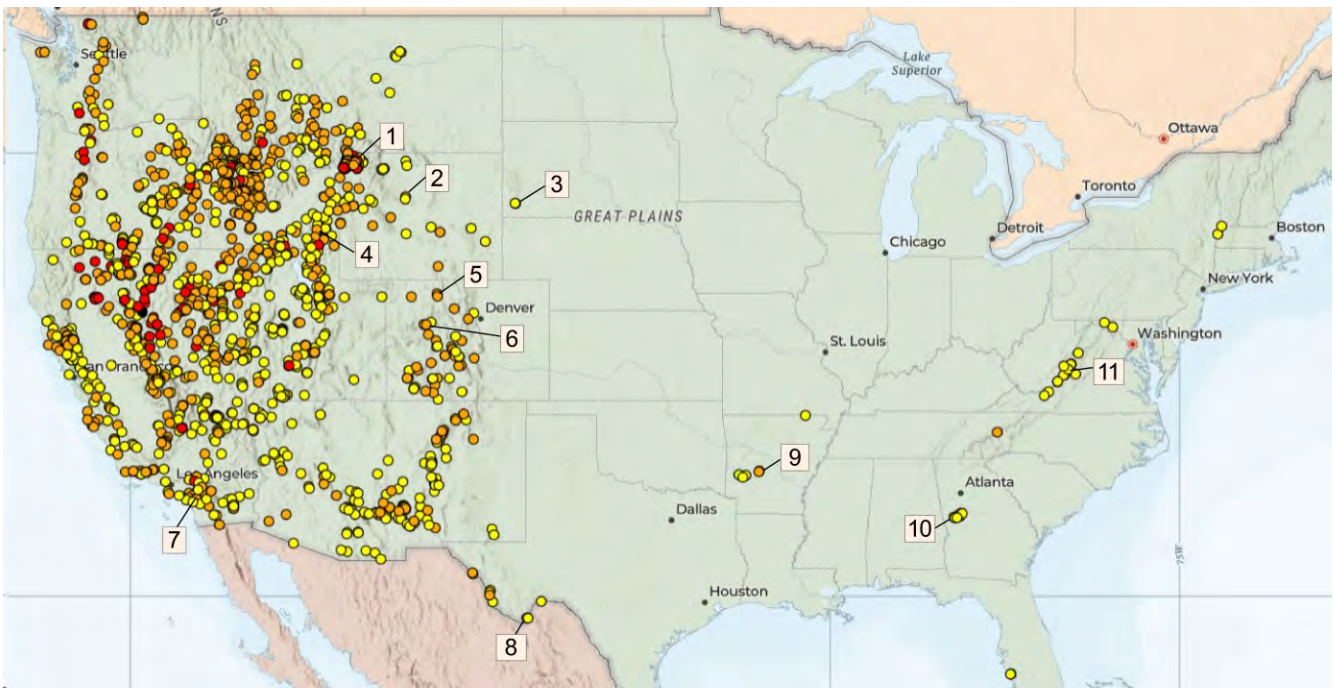

Figure 9.3 GIS database of thermal springs in the United States by the National Center for Environmental Information of NOAA includes 1,702 thermal springs in 23 of the 50 States. Earthstar Geographics | NOAA National Centers for Environmental Information (NCEI) | Esri, TomTom, Garmin, FAO, NOAA, USGS, EPA, USFWS. Powered by Esri. Available at https://experience.arcgis.com/experience/b4e8785f0f75464b9e08547ccf0b18d7). Locations of the thermal springs were originally published in Berry et al., 1980 (available at http://www.ngdc.noaa.gov/hazard/data/publications/Kgrd-12.pdf). Numbers show select springs described in this book: (1) Yellowstone springs; (2) Hot Springs in Thermopolis, Wyoming; (3) Hot Springs, South Dakota; (4) Lava Hot Springs, Idaho; (5) Steamboat Springs, Colorado; (6) Glenwood Hot Springs, Colorado; (7) Murrieta Hot Springs, California; (8) Langford Hot Spring, Texas; (9) Hot Springs, Arkansas; (10) Warm Springs, Georgia; (11) Hot and Warm Springs, Virginia.

Figure 9.3 is a screenshot from the GIS database of 1,702 thermal springs in the United States compiled by NOAA (National Oceanic and Atmospheric Administration). The database, available online, can be searched by springs' names and includes their geographic coordinates, water temperature and other information where available. It is based on a report by Berry et al. (1980) which contains bibliographic references to more than 100 publications on thermal springs in various states prepared by the United States Geological Survey (USGS) as well as other agencies and authors.

In 1937, Stearns et al. of the USGS authored an excellent publication entitled Thermal Springs in The United States which remains the definitive work on the subject. It features 1,060 springs with their locations shown on various maps (see Figure 9.4 for an example). All these springs are included in the NOAA' GIS database. Below are the summary and some key points from Stearns et al. (1937).

The present paper is chiefly a compilation and summary of the available information on the thermal springs of the United States, but it also contains a large amount of original data obtained in the field by several geologists of the Geological Survey and by the United States Forest Service and the United States Indian Service. It summarizes the work that has previously been done, presents maps showing the location of the springs, tabulates the principal data, and includes a selected bibliography.

An attempt has been made to present in very concise form as much information as possible regarding the geologic relations of the springs. Chemical analyses of the water are not included, but in the annotated bibliography publications that contain analyses of the water of the springs described are indicated.

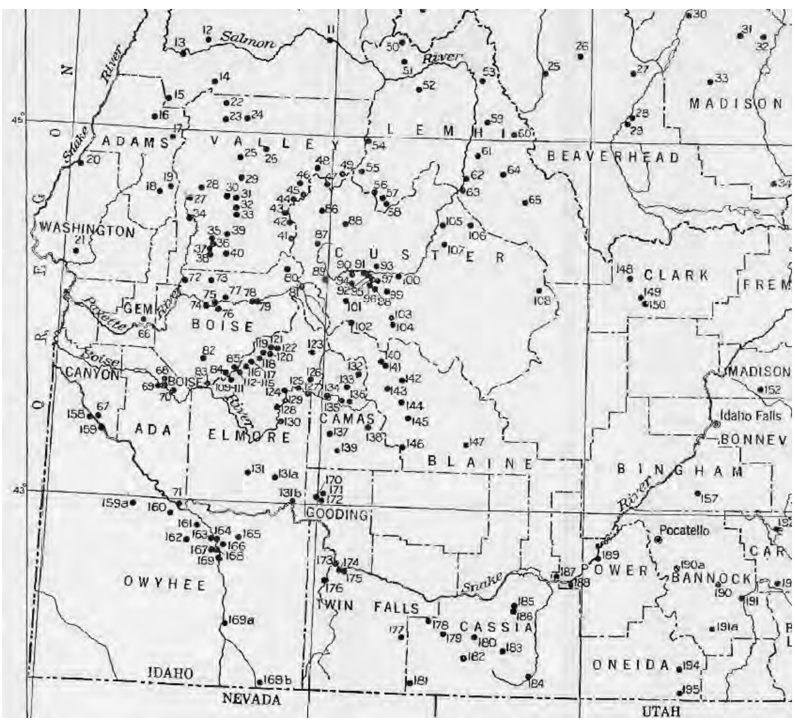

Figure 9.4 Part of Plate 11 from Stearns et al., (1937) showing area with the highest concentrations of thermal springs in Idaho, and the country. Note that Banbury Hot Springs (#175) is just a few miles downgradient of the beautiful Blue Heart Springs on Snake River described in Chapter 4.5 and accessible only by boat/kayak which can be rented from Banbury Adventures at the Banbury Hot Springs resort (Kayak Blue Heart | Banbury Adventures | Buhl, ID).

The earliest extensive studies of thermal springs in the United States were made by physicians. In 1831 Dr. John Bell published a book entitled "Baths and Mineral Waters" in which he listed 21 spring localities. In the edition of his work published in 1855 the number was increased to 181. The earliest report on a geologic study of thermal springs was that of W.B. Rogers in 1840 on the thermal springs of Virginia. In 1875 G.K. Gilbert published a map and table showing thermal springs in the United States and pointed out that they are present chiefly in the mountainous areas of folded and faulted rocks.

All the notable thermal springs in the eastern United States are in the Appalachian Highlands, principally in the region of folded rocks. The Atlantic Coastal Plain contains no appreciably warm springs. In Florida there are large springs whose water rises from a depth of a few hundred feet and is about 5° above the mean annual temperature, but they are not usually classed as thermal.

The only warm springs in the great Interior Plains region are at and near Hot Springs, South Dakota, in the vicinity of the Black Hills uplift of crystalline rocks.

In the Interior Highlands thermal springs occur only in the Ozark region, the largest group being at Hot Springs, Arkansas.

The Rocky Mountain System includes Yellowstone National Park, with its world-famous hot springs and geysers, and there are many other hot springs within this great mountainous region. In the Intermontane areas of great lava plains and faulted lava mountains in Utah, Nevada, southern Idaho, and eastern Oregon there are many hot springs, closely associated with the larger faults. In the Pacific Mountain System, including the Cascade Range and Sierra Nevada, there are many warm and hot springs, some of which issue in areas of granite, and others in areas of lava. In the Coast Ranges of California many thermal springs issue from different geologic formations.

Of the total of more than 1,000 thermal-spring localities listed in this paper more than half are situated in the three States of Idaho, California, and Nevada, each of which contains more than 150 thermal-spring localities. Wyoming, including the Yellowstone National Park, contains more than 100 hot-spring localities.

Oregon, Utah, Colorado, Montana, and New Mexico contain several dozen thermal springs each, of which the principal ones are developed as resorts.

The other thermal springs are scattered through 12 States, of which Massachusetts, New York, Pennsylvania, and North Carolina contain one spring or group each. More than half of the total number are developed as resorts or used for irrigation or water supply, but many have remained undeveloped because they are not easily accessible.

Thermal springs in regions without recent magmatic activity are heated by the naturally occurring thermal energy within the Earth (geothermal energy). Measurements in boreholes indicate that temperature increases downward within the Earth’s crust at an average rate of about 1.5°F per 100 feet; commonly cited rates also are 25 to 30°C/km (72 to 87°F/mi). From this average geothermal gradient, it has been calculated that about 4×10^{26} J of thermal energy, assuming a surface temperature of 15°C (59°F), is stored within the outer 10 km of the crust (White, 1965). Although most of the energy is stored in rocks, water and steam contained in fractures and pore spaces of the rocks are the only naturally occurring media available for transferring this energy to the Earth’s surface.

Certain “hot spots” of the Earth, generally near areas of recent or Pleistocene volcanism, discharge heat at rates of 10 to more than 1000 times that of areas of “normal” heat flow of comparable size. These hot spring areas are characterized by the physical transport of most of the total heat flow in water or steam. Some of the largest and hottest spring areas have been utilized for geothermal energy. These areas are characterized by high permeability, at least locally on faults, fractures, and sedimentary layers; this high permeability permits fluid circulation, where most of the total heat flow is being transported upward in water or steam. The circulation has produced reservoirs of stored heat closer to the Earth’s surface than is normally possible by rock conduction alone. Local near-surface thermal gradients are typically very high, but the gradient decreases greatly, and even reverses, at greater depths in any single geothermal drill hole (White, 1965).

Hot-water systems are dominated by circulating liquid, which transfers most of the heat and largely controls subsurface pressures (in contrast to vapor-dominated systems). However, some vapor may be present, generally as bubbles dispersed in the water of the shallow low-pressure parts of these systems. Most known hot-water systems are characterized by hot springs that discharge at the surface. These springs, through their chemical composition, areal distribution, and associated hydrothermal alteration, provide very useful evidence on probable subsurface temperatures, volumes, and heat contents (Renner et al., 1975).

Direct temperature measurements of geothermal systems are made in either surface springs or wells. The temperatures of springs generally do not exceed the boiling temperature at existing air pressure (100°C or 212°F at sea level to 93°C or 199 °F for pure water at an altitude of 2200 m or 7,220 ft), although some springs in Yellowstone Park and elsewhere are superheated by 1–2°C (Renner et al., 1975).

In the past, the use of hot springs and geothermal water in general in the United States was primarily for hot-water baths and pools (balneology). After 1920, however, the abundance of inexpensive natural gas for heating baths and pools caused a rapid decline in the use of natural hot water. Some use of geothermal water for space heating dates from before 1890 in such areas as Boise, Idaho, but interest in this application was rather slight until the 1970s and the first global oil crisis.

Low-temperature geothermal resources occur in two types of geothermal systems: hydrothermal convection and conduction dominated. In hydrothermal-convection systems, the upward circulation of water transports thermal energy to reservoirs at shallow depths or to the surface via thermal springs. These systems commonly occur in regions of active tectonism and above-normal heat flow, such as much of the western United States. In conduction-dominated systems, the upward circulation of fluid is less important than the existence of high vertical temperature gradients in rocks that include aquifers of significant lateral extent. These conditions occur beneath many deep sedimentary basins throughout the United States (Sorey et al., 1983a).

Most of the identified low-temperature geothermal resources associated with hydrothermal-convection systems fall into areas of isolated thermal springs and wells. In such areas, the only evidence that a geothermal reservoir exists at depth is a single thermal spring or group of closely spaced springs or a well that produces thermal water. In the western United States, thermal springs commonly occur along normal faults, whereas in the eastern United States, thermal springs occur in regions of folded and thrust-faulted rocks. Figure 9.5 shows three possible models of fluid circulation in such areas according to Sorey et al. (1983a); other models are presented by Breckenridge and Hinckley (1978) and Hobba et al. (1979).

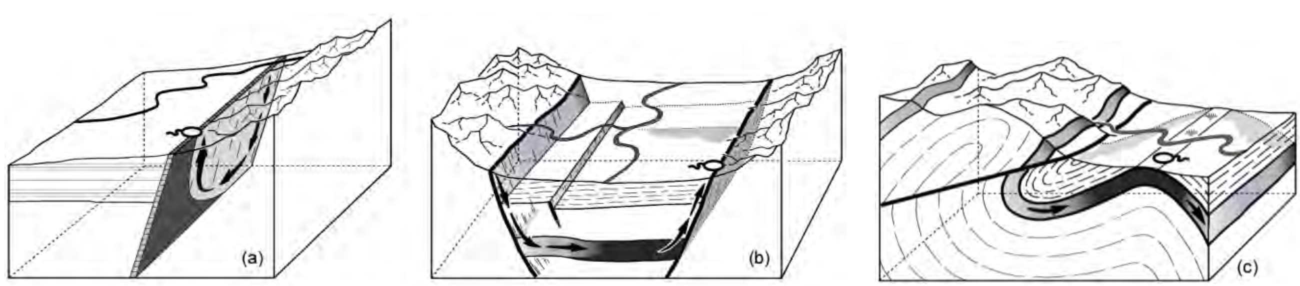

Figure 9.5 Conceptual models for types of hydrothermal-convection systems in which low-temperature geothermal-resource areas in category of isolated thermal springs and wells occur. (a) Fault plane; (b) Deep reservoir; (c) Margin of anticline. Arrows indicate direction of fluid circulation; dark shading shows location of reservoir containing low-temperature geothermal resources. From Sorey et al., 1983a.

Much of the western United States lies within the Basin and Range geologic province, which has a heat flow generally higher than normal and is characterized by extensional tectonism. The combination of range-front faults and sediment-filled basins is favorable for the occurrence of geothermal systems. Young silicic volcanic centers along the east and west margins of the province provide localized heat sources for hydrothermal-convection systems. Most thermal waters in the province result from deep circulation. Normal faults provide near-surface conduits for the circulating waters and thus control the positions of most of the identified hydrothermal-convection systems (Figure 9.5). Basin-fill sediment may act as a thermal blanket that traps heat in relatively shallow aquifers beneath large areas of some of the basins. Leakage away from fault conduits is probably the source of the thermal waters in these aquifers (Mariner et al., 1983).

In western Arkansas, identified low-temperature geothermal resources occur in areas of thermal springs in the Ouachita province, including those at Hot Springs National Park and Caddo Gap. These springs are associated with tightly folded and thrust-faulted rocks. Studies by Bedinger et al. (1979) and Steele and Wagner (1981) indicate that the chemical compositions are similar in all the springs in this province and suggest that circulation systems feeding the springs occur largely in silica-rich sandstone and chert formations. Little is known, however, about the configuration of associated low-temperature geothermal reservoirs in these areas (Sorey et al., 1983b).

Thermal springs in the eastern United States are associated with fault and fracture zones in several provinces of the Appalachian Mountains. Early descriptions of these springs dealt with their therapeutic and recreational values (Moorman, 1867; Crook, 1899; Fitch, 1927). The locations of thermal springs are controlled mostly by the structural setting and, to a lesser extent, lithology. The springs occur in areas of steeply dipping folded rocks that are transected by nearly vertical east-west-trending fracture zones. Correlation of springs with topographic lows, or gaps, apparently results from the fact that easily eroded areas correspond to zones containing many fractures, which, in turn, provide the increased vertical permeability needed to establish a hydrothermal-convection system.

The warm springs in the Appalachians issue from sandstone or carbonate rocks exposed in the steeply dipping limbs of anticlinal folds (Hobba et al., 1979). Chemical analyses of the warm-spring waters issuing from carbonate rocks exhibit consistently low concentrations of dissolved silica and high concentrations of magnesium and calcium, which indicate that the flow of warm water is restricted to the carbonate rocks. Analyses of waters from springs issuing from fractured sandstone show higher concentrations of dissolved silica and lower concentrations of magnesium and calcium, which indicates that flow is restricted to the sandstone beds (Sorey et al., 1983b).

Geochemical considerations suggest that reservoir temperatures are not substantially higher than the measured surface temperatures at most eastern thermal springs; observed temperatures range from 18 to 41ºC (64 to 106 ºF). The occurrence of these springs in areas of average heat flow and relatively low-temperature gradients (Costain et al., 1976; Perry et al., 1979) indicates that the depths of hydrothermal circulation are generally 1 to 3 km.

As discussed by Duffield and Sass (2003), hot springs that are indicators of moderate- to high-temperature geothermal resources are concentrated in places where hot or even molten rock (magma) exists at relatively shallow depths in the Earth’s outermost layer (the crust).

Figure 9.6 Hot springs in Hot Creek which flows through the Long Valley Caldera in a volcanically active region of east-central California. USGS photo by Chris Farrar.

Such "hot" zones generally are near the boundaries of the dozen or so slabs of rigid rock (called *plates*) that form the Earth's lithosphere, which is composed of the Earth's crust and the uppermost, solid part of the underlying denser, hotter layer (the mantle). High heat flow also is associated with the Earth's "hot spots" (also called *melting anomalies* or *thermal plumes*), whose origins are related to the narrowly focused upward flow of extremely hot mantle material from very deep within the Earth. Hot spots can occur at plate boundaries (for example, beneath Iceland) or in plate interiors away from the nearest boundary, for example, the Hawaiian hot spot in the middle of the Pacific Plate, hotspot track in the Columbia Plateau of Oregon and Washington, the Snake River Plain of Idaho, and the current position of the Yellowstone Hotspot beneath Yellowstone National Park. Regions of stretched and fault-broken rocks (rift valleys) within plates, like those along the Rio Grande River in Colorado, New Mexico, and Texas also are favorable target areas for high concentrations of the Earth's heat at relatively shallow depths.

Zones of high heat flow near plate boundaries along the Pacific Coast and in Cascade Range of the western United States are where most volcanic eruptions and earthquakes occur. The magma that feeds volcanoes originates in the mantle, and considerable heat accompanies the rising magma as it intrudes into volcanoes. Much of this intruding magma remains in the crust, beneath volcanoes, and constitutes an intense, high-temperature geothermal heat source for periods of thousands to millions of years, depending on the depth, volume, and frequency of intrusion. In addition, frequent earthquakes—produced as the tectonic plates grind against each other—fracture rocks, thus allowing water to circulate at depth and transport heat toward the Earth's surface. Together, the rise of magma from depth and the circulation of hot water (hydrothermal convection) maintain the high heat flow prevalent along plate boundaries (Duffield and Sass, 2003).

Figure 9.6 shows a stretch of Hot Creek in east-central California. The creek flows through the Long Valley Caldera in a volcanically active region. This stretch of the creek, looking upstream to the southwest, has long been a popular recreation area because of the warm waters from its thermal springs. The thermal springs in Long Valley Caldera have long been known to Native Americans. Many of the hot springs have special status with Native American tribes and have been used for spiritual and medicinal purposes.

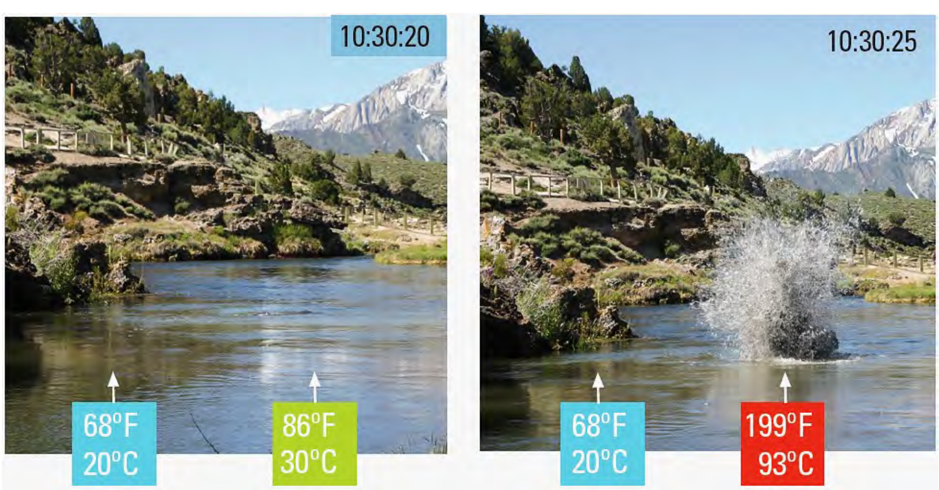

Figure 9.7 The temperature in Hot Creek can change in seconds. These photos were taken 5 seconds before and then during a violent geysering event, in which boiling water (at 199°F or 93°C, the boiling point at this elevation) erupted above the surface. Any swimmer caught in this part of the creek would have been severely scalded. From Farrar et al., 2007; photographs courtesy of Alix Ginter.

Since the 2000s, springs in and near the formerly most popular swimming areas have been "geysering" or intermittently spurting very hot, sediment-laden water as high as 6 ft (2 m) above the stream surface. Earthquakes also can cause sudden geyser eruptions and overnight appearances of new hot springs at Hot Creek. Water temperatures can change rapidly, and so entering the water is now strictly prohibited.

All the springs in Hot Creek emerge along a stream section between two faults and discharge a total of about 8.5 ft^3/s (about 3,800 gpm) of hot water. A detailed explanation of the possible reasons for development of the geysering activity in the creek is given by Farrar et al. (2007).

Hot Creek Geologic Site is accessible by a 3.4-mile dirt road off of U.S. 395 near the Mammoth Lakes airport. The path down to the creek is steep and, according to USGS, "Many adults find themselves needing to catch their breath on the way back up." For more information, including nice color photographs, visit Long Valley Caldera Field Guide - Hot Creek Geologic Site | U.S. Geological Survey (usgs.gov), and Inyo National Forest - Hot Creek Geologic Site (usda.gov).

Most thermal springs in the NOAA database are undeveloped because they are not easily accessible or are privately owned. Many springs on public lands that are accessible are left undisturbed or are only provisionally marked and without any facilities (Figure 9.9). Unfortunately, with the proliferation of social media some of these springs have developed followings of sorts which has led to the unintended consequences of overuse and vandalism. A very sad example is the fascinating Umpqua Hot Springs located across the North Umpqua River in Oregon's Umpqua National Forest. Because of drug use, serious waste issues, and the alarming behavior of some visitors, the U.S. Forest Service had to ban overnight Umpqua Hot Springs camping and close access to the springs altogether (it is still closed as of August 2024). For all these reasons, there are no undeveloped ("wild") thermal springs featured in this book.

Many large thermal springs near population centers have been developed, and quite a few of them are nationally and internationally recognized as prime tourist destinations, and some are quite exclusive in addition. The selection of thermal springs presented in this book, which all are well-managed and safe spa resorts (except for the Yellowstone National Park hot springs and Langford Hot Spring in Big Bend National Park), is limited by the scope of the book and it is certainly subjective: it would be more than challenging to cram into one book all of the nice thermal springs-spas in the United States.

Although such a book is long overdue, there are numerous substitutes in the form of web pages, blogs, and social media that are filling this gap with varying degrees of success. In any case, those interested in experiencing bathing in thermal springs are certain to find what they are looking for, provided they have enough patience browsing the web.

Figure 9.9 *Left*: A hot spring in Stanley, Idaho, the coldest town in conterminous United States, right next to Salmon River. *Right*: One of many hot springs along Salmon River in Custer County, Idaho.

9.1.1 Risks and Benefits of Bathing in Thermal Springs

Those that are preparing to experience thermal springs for the first time, as well as those that consider themselves "seasoned" thermal-springs visitors, are strongly encouraged to (perhaps finally) familiarize themselves with the various risks and benefits of bathing in thermal springs in general, and in a spring under consideration in particular. Good starting points are papers by Gianfaldoni et al. (*History of the Baths and Thermal Medicine*, 2017), Zajac (*Inhalations with thermal water in respiratory diseases*, 2021), and Protano et al. (*Balneotherapy using thermal mineral water baths and dermatological diseases: a systematic review*, 2024) respectively available at
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5535692/
https://pubmed.ncbi.nlm.nih.gov/34371115/
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC11108950/

Warm Springs in Bath County, Virginia (described in Chapter 9.15) is the first and still active thermal spa in the United States, established in 1761. Fascinating materials about this and other thermal springs in Virginia are presented by the University of Virginia in its historical collection *Taking the Waters. 19th Century Medicinal Springs of Virginia* housed at the Claude Moore Health Sciences Library. The collection is also available online at https://exhibits.hsl.virginia.edu/springs/introessay/index.html).

Particularly interesting are various reflections, analyses, and polemics about the healing effects of "Medicinal Springs" at the time. For example, Dr. William Burke, author of "The Mineral Springs of Western Virginia" published in 1842 (second edition was published in 1846), included in his book a discussion on a lengthy article about Warm Springs which appeared in the *Southern Literary Messenger* in 1838. The article indicated that the analysis of the water by Professor William Rogers from the University of Virginia showed that the gas bubbling up was mainly nitrogen with small amounts of sulphuretted hydrogen (hydrogen sulfide) and carbonic acid. These same gases were found within the water as well as salts including magnesium sulfate or Epsom Salts. These salts and gases worked as gentle diuretics and laxatives. The *Messenger* paper indicated that the waters were not a panacea in all cases and that the baths were best avoided by those "*who are afflicted with hemorrhages, pain in the chest, cough, quick pulse and other indications of pulmonary disease*" but had been effective in dyspepsia of long standing, chronic rheumatism, and paralytic afflictions especially if the patient bathed in the water and drank the water for a period of time.

Calling the Warm Spring bath "one of the greatest subjects of curiosity in Western Virginia", Burke also cautioned the prospective visitors:

Thus far we have looked on the sunny side of the picture; we regret that a regard to truth requires us to introduce more of the sombre than is agreeable. Tempting, then, as is this pellucid fountain, it is necessary that the traveller should know there is danger in the indulgence. Experience, fatal in some cases, has taught this fact.

Dr. Huntt makes the following statement: "On the third evening I arrived at the Warm Springs, a distance of two hundred and thirty miles from Washington; and immediately after getting out of the stage, I plunged into the delightful bath at that place, an imprudence against which I would earnestly caution all invalids, who arrive after a long journey with the whole system exhausted by fatigue. The consequence in my own case warrants me in pronouncing it fraught with great danger. While in the bath, its effects were very grateful and pleasant; but shortly after leaving it I became chilly, and this feeling was followed by hot skin, intense headache, and pain in the chest."

In any case, Dr. Burke did praise the general positive effects of bathing in Warm Springs on various diseases by referring to the work of Dr. Bell entitled *Baths and Mineral Waters* who *"...enumerates the following diseases, in which the Warm Bath, from 95° to 98°, will exert a curative agency, viz.: "Acute pain, with irregular and* *convulsive action of the muscles; convulsions of children and hysterical affections of females; mania and mental derangement generally; bilious cholic; infantile cholera and cholera morbus; chronic diarrhœa; croup; catarrh; bronchitis, in chronic form; asthma; organic affections of the heart; chronic affections of the liver; nephritic disorders; amenorrhœa; affections of the skin in various forms; violent cases of gout; chronic rheumatism; suppression of perspiration and pains in the muscles and joints; pains in the limbs, following a mercurial course; paralytic affections," &c. In all these cases the Warm Bath acts as a powerful auxiliary to the appropriate remedies prescribed by the physician.*

Thomas Jefferson was at Warm Springs in August 1817 and saw the need for a resident physician to attend to those seeking healing at the various springs. Anticipating men like Dr. Burke at Red Sulphur Springs, Dr. Moorman at White Sulphur Springs, and Dr. Goode at Hot Springs, he wrote, "*it would be money well bestowed could the public employ a well educated and experienced physician to attend at each of the medicinal springs, to observe, record, and publish the cases which recieve benefit, those recieving none, and those rendered worse by the use of their respective waters*." His words seem almost prophetic considering what he wrote during and after spending time at the spring the following year, hoping it will help cure his rheumatism.

Thomas Jefferson's visit to Warm Springs in August 1818 covers a wide range of experiences. He describes the bath as "delicious" and within a week calls the spring with the Hot and Warm "of the first merit." He also presumes that the "seeds of his rheumatism" are "eradicated." But the passing of another week brings an alarming occurrence. He tells his daughter, "I do not know what may be the effect of this course of bathing on my constitution; but I am under great threats that it will work it's effect thro' a system of boils." Indeed, he claims that he suffers "prostrated health from the use of the waters" with abscesses, fever, sweats, and extreme debility. In December his summer visit still finds its way into a letter, "my trial of the Warm springs was certainly ill advised. for I went to them in perfect health, and ought to have reflected that remedies of their potency must have effect some way or other. if they find disease they remove it; if none, they make it."
(https://exhibits.hsl.virginia.edu/springs/warm/index.html)

Balneotherapy includes practices and methods using medically and legally recognized mineral-medicinal waters, muds and natural gases from natural springs for therapeutic purposes. One of the most widely used method in balneotherapy is bathing with thermal mineral water. In the course of the years, the scientific community has produced an increasing number of evidences that this practice is an effective method for treating signs and symptoms of several pathologies such as rheumatic, cardiovascular and dermatological diseases.

Protano et al., 2024

The infection occurs when the amoeba known as Naegleria fowleri gets into your brain through your nasal cavity. It can enter your body if you inhale any infected water. Usually, the amoeba lives in freshwater bodies of water that are warm, including hot springs (geothermal water).

People who become infected by this amoeba develop a condition called primary amoebic meningoencephalitis (PAM). PAM is a very serious infection of the central nervous system that's almost always fatal.

https://my.clevelandclinic.org/health/diseases/24485-brain-eating-amoeba

9.1 Yellowstone

9.1.1 Introduction

Yellowstone National Park (https://www.nps.gov/yell/index.htm) is the oldest national park in the world, established on March 1, 1872, primarily because of its more than 10,000 spectacular hydrothermal features including hot springs, geysers, fumaroles (steam vents), and mud pots which all are the current manifestation of the activity caused by a deep-mantle hotspot (Figure 9.10). Yellowstone is one of the most geologically dynamic areas on Earth due to its shallow source of magma and resulting volcanic activity. It is one of the largest volcanic eruptions known to have occurred in the world, creating one of the largest known calderas. And it has approximately 500 geysers which is the largest concentration of active geysers in the world, more than half of the world's total.

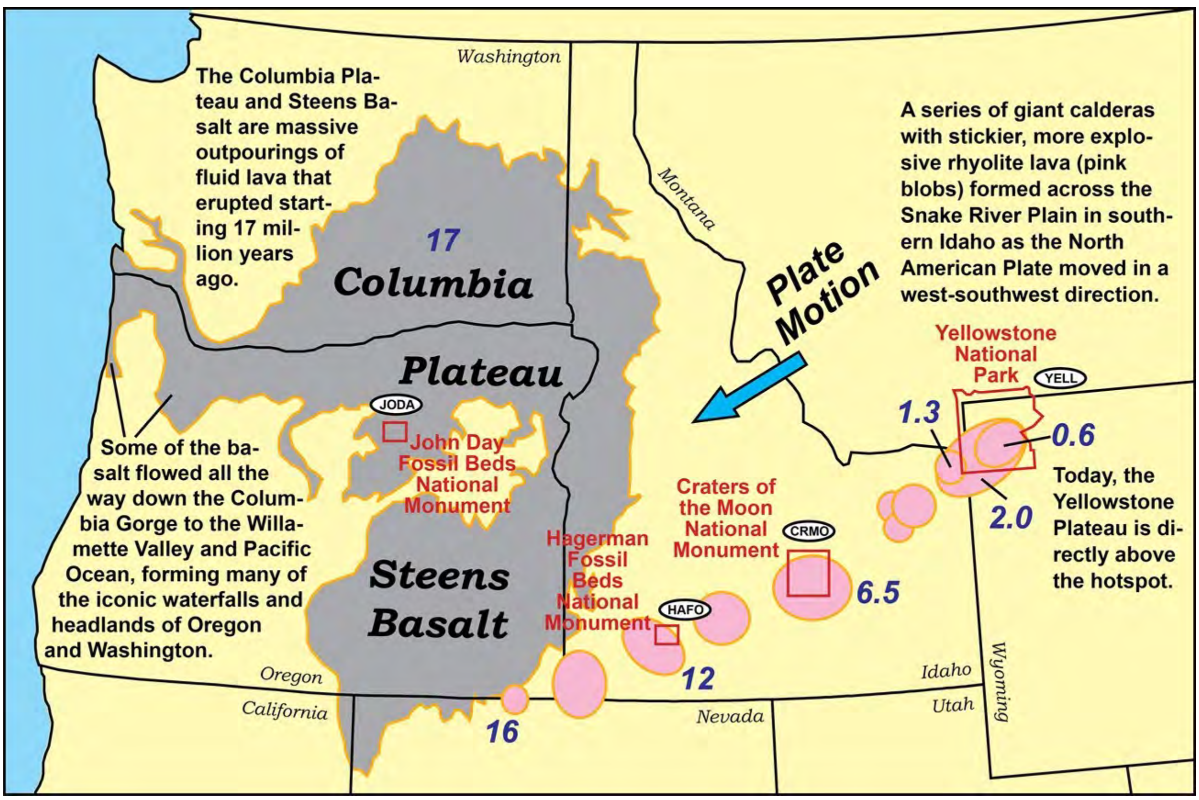

Figure 9.10 Columbia Plateau—Yellowstone Hotspot Track. Volcanic rocks in the Pacific Northwest show the effects of a tectonic plate riding over a deep-mantle hotspot. A rising mantle plume has a massive head as much as 500 miles (800 kilometers) in diameter. The volume of basaltic magma that rises initially through the overriding plate can be so enormous that it matters little what kind of crust is capping the plate – huge volumes of basaltic lava pour out on the surface. The numerous lava flows that poured out in the Columbia Plateau and the Steens Basalt region of southeastern Oregon are thought to represent the original surfacing of the Yellowstone Hotspot that began 17 million years ago. Since then, the North American Plate has continued to move in a west-southwestward direction over the Yellowstone Hotspot. Starting near the Oregon/Nevada/Idaho juncture 16 million years ago, a line of rhyolite magma centers—supervolcanoes—formed across what is now the Snake River Plain of southern Idaho. Yellowstone National Park today lies directly over the hotspot. Numbers are the age of initial volcanism (millions of years ago). Letters are abbreviations for National Park Service sites: CRMO— Craters of the Moon National Monument, Idaho; HAFE— Hagerman Fossil Beds National Monument, Idaho; JODA— John Day Fossil Beds National Monument, Oregon; YELL— Yellowstone National Park, Wyoming, Idaho & Montana. Text and map courtesy of National Park Service; available at https://www.nps.gov/subjects/geology/plate-tectonics-continental-hotspots.htm.

In 1978, Yellowstone was added by UNESCO to the World Heritage list – the United States' first World Heritage Site. It encompasses over 2 million acres in the northwestern corner of Wyoming and includes portions of Idaho and Montana. Along with geysers and hot springs, Lodge Pole pine forests dominate the landscapes of the park. There are seven species of coniferous trees and some 1,100 species of vascular plants growing in the park. The park is one of the few remaining intact large ecosystems in the northern temperate zone of the earth. The park's bison are the only wild, continuously free-ranging bison remaining from herds that once roamed the Great Plains. The park is also home to grizzly bears, grey wolves, and large herds of elk, among others.

Simply put, Yellowstone is a natural wonderland. As such, it is featured in dozens of public domain publications by various government agencies, and on many websites that include photographs and videos of the Park's spectacular natural features. Geologic History of the Yellowstone National Park by Arnold Hague of USGS is available at https://www.nps.gov/parkhistory/online_books/yell/hague/sec1.htm) while many dozens of color photographs and multimedia resources are on the Park's web page at https://www.nps.gov/yell/learn/index.htm.

USGS' Yellowstone Caldera Chronicles is a weekly column written by scientists and collaborators of the Yellowstone Volcano Observatory at https://www.usgs.gov/observatories/yvo. This web page includes links to numerous downloadable publications at https://www.usgs.gov/volcanoes/yellowstone/publications.

Yellowstone National Park is also a place with great historic and cultural value. Native American archeological sites date back 10,000 years. Perhaps of equal importance is the fact that the park's establishment spawned the "national park" idea that has spread throughout the world (https://home.nps.gov/articles/000/yellowstone-national-park-world-heritage-site.htm). Photographs in Figures 9.11 through 9.25 illustrate just a tiny fraction of what Yellowstone has to offer.

Figure 9.11 *Left*: The Grand Canyon of the Yellowstone River is carved through rhyolite lava flows from the explosive Yellowstone Supervolcano, forming as the North American Plate, and capped by thick continental crust, it rides over the Yellowstone Hotspot. At 308 feet, the Lower Falls on Yellowstone River is the tallest waterfall in the park. In terms of height alone, it is more than twice the size of Niagara Falls. The amount of water flowing over the falls varies greatly depending on the season. At peak runoff times in the spring, 63,500 gal/sec flow over the falls, whereas at lower runoff times in the fall, the flow diminishes to 5,000 gal/sec. *Right*: Mineral stains mark the sites of hot springs and steam vents in the canyon walls. For thousands of years, upwardly percolating fluids have altered the chemistry of the rocks, turning them yellow, red, white, and pink. From the rim, the bright patches of color are the most visible evidence of hot spots. Puffs of steam, visible on all but the warmest days of summer, mark areas of ongoing thermal activity in the canyon. Text by NPS.

Figure 9.12 *Top*: Basaltic lava flow in the canyon wall of the Yellowstone River as viewed from Calcite Springs Overlook near Tower Junction in Yellowstone National Park. The lava flow is overlain and underlain by glacial gravels. *Bottom*: The basalt in Yellowstone National Park occurs as thin sheets overlying the rhyolite and, in some instances, as dikes cutting the more acidic rocks. As the lava slowly cooled and contracted, it formed contraction cracks, producing hexagonal columns of basalt.

As explained by the USGS (Yellowstone's Active Hydrothermal System | U.S. Geological Survey (usgs.gov), and National Park Service (https://www.nps.gov/yell/learn/nature/hydrothermal-systems.htm), the park's hydrothermal system is the visible expression of the immense Yellowstone volcano; it would not exist without the underlying partially molten magma body that releases tremendous heat. The system also requires water, such as groundwater which originates from the mountains surrounding the Yellowstone Plateau where rain and snowfall slowly percolate through layers of permeable rock.

Within Yellowstone Caldera, deeper groundwater fluids are heated as they circulate through rocks that overlay the magma storage region. It is here where the chemical composition of both the fluid and rock become altered by geochemical reactions, resulting in heated "hydrothermal fluids" that absorb gases and chemical compounds from the magma and crust (CO_2, H_2S, H_2, CH_4, Ar, and He).

Some of the cold groundwater meets hot brine directly heated by the shallow magma body. The water's temperature rises well above the boiling point, but the water remains in a liquid state due to the great pressure and weight of the overlying water. The result is superheated water with temperatures exceeding 400°F.

The superheated water is less dense than the colder, heavier water sinking around it. This creates convection currents that allow the lighter, more buoyant, superheated water to begin its journey back to the surface following the cracks and weak areas through rhyolitic lava flows. This upward path is the natural "plumbing" system of the park's hydrothermal features.

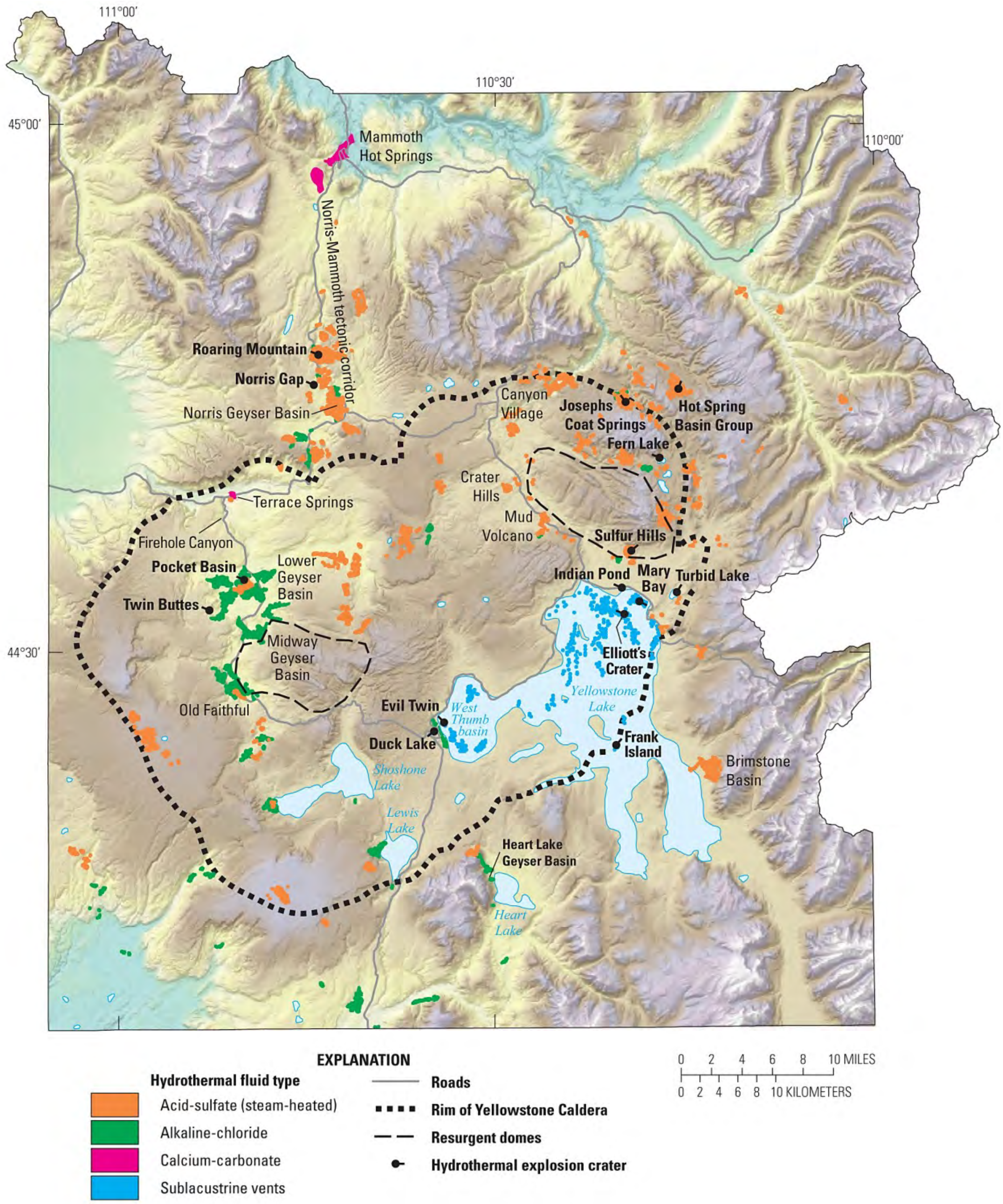

Figure 9.13 Map showing the location of active thermal areas categorized by hydrothermal fluid type and the location of large hydrothermal explosion craters (location shown with black dot and leader) with associated breccia deposits in Yellowstone National Park (from Morgan et al., 2017).

As hot water travels through the rocks, it dissolves some silica in the rhyolite, as well as calcium carbonate in limestone where present, such as in the Mammoth Springs area in the far north of the park (see Figure 9.13). When they near the surface, hydrothermal fluids mix with the cold groundwaters and deposit siliceous (SiO_2) sinter deposits (known as geyserite) or calcareous ($CaCO_3$) travertine deposits that form the impressive cones, mounds, and terraces in Yellowstone's thermal basins.

Hot Springs are the most common hydrothermal features in Yellowstone. An open plumbing system allows the hot water to rise back to the surface unimpeded. Convection currents constantly circulate the water, preventing it from getting hot enough to trigger an eruption. In Yellowstone, hot springs typically collect in depressions to form thermal pools (Figure 9.14). They can come from 1) silica-bearing alkaline chloride waters, 2) travertine-forming calcium carbonate waters, or 3) steam condensation originating from fumaroles.

Figure 9.14. In 1935, Chief Park Naturalist C.M. Bauer named Abyss Pool, a hot spring of the West Thumb Geyser Basin by Yellowstone Lake (visible in the background), for its impressive deepness. Bauer may have taken the name from Lieutenant G.C. Doane's 1870 description of a spring in this area: "the distance to which objects are visible down in [its] deep abysses is truly wonderful". Abyss Pool may also be the spring that visitors referred to during the 1880s as "Tapering Spring" because of its sloping walls. Nineteenth century observers were impressed with the pool's beauty. In 1871, F.V. Hayden reported that this spring's "ultramarine hue of the transparent depth in the bright sunlight was the most dazzlingly beautiful sight I have ever beheld" and W.W. Wylie observed in 1882 that the spring's walls, "coral-like in formation and singular in shape, tinted by the water's color, are surely good representations of fairy palaces". (Text courtesy of NPS; https://www.nps.gov/yell/learn/nature/west-thumb-geyser-basin.htm).

Hot Springs Colors. Many of the bright colors found in Yellowstone's hydrothermal basins come from thermophiles – "heat-loving microorganisms" that thrive in hot temperatures that would cause 2nd to 3rd degree burns in humans with exposure of only a few seconds. An abundance of individual microorganisms grouped together appear as masses of color.

Different types of thermophiles live at different specific temperatures within a hot spring and cannot tolerate much cooler or warmer conditions. Yellowstone's hot water systems often show distinct gradations of living, vibrant colors where the temperature limit of one group of microbes is reached, only to be replaced by another group.

The intense blue color of some springs results when sunlight passes into their deep, clear waters. Blue, a color in visible light, is scattered the most and, therefore, the color we see.

Figure 9.15 Excelsior Geyser Crater (left; photo credit: NPS/Jim Peaco) and Grand Prismatic Spring (right; photo credit NPS/Jim Peaco; June 22, 2006) are located next to each other in Midway Geyser Basin. Their colors offer clues as to which thermophiles (heat-loving microorganisms) are present: Blue and green colors indicates temperature range of 95–185°F (35–85°C) and green non-sulfur bacteria (*Chloroflexus*) or Archaea; yellow to orange to brown colors indicate progressively lower temperatures of 122–166°F (50–72°C); 95–122°F (35–50°C); and 86–113°F (30–45°C); and different types of Cyanobacteria: *Synechococcus*, *Phormidium*, and *Calothrix* respectively (https://www.nps.gov/yell/learn/kidsyouth/hydrothermal.htm).

Geysers (Figures 9.16 and 9.17) provide most spectacular displays of Yellowstone's active hydrothermal systems, but their mechanisms are not completely understood. All geysers require two fundamental features: (1) a subsurface reservoir where hot waters can accumulate and reach boiling temperatures, and (2) a constriction in the geyser conduit that provides throttling and focusing of erupting fluids. For a geyser to erupt, the subsurface reservoir boils, builds pressure, then ejects small amounts of water. When enough water is ejected the pressure drops, causing the remaining water to become a steam-water mixture that is forcibly ejected through the constricted conduit. Water is expelled faster than it can enter back into the geyser's plumbing system, and the heat and pressure gradually decrease. The eruption stops when the water reservoir is depleted or when the system cools. This cycle can be repeated with remarkable regularity, as for example, at Old Faithful Geyser which erupts on an average of about once every 65 minutes.

Figure 9.16 Old Faithful Geyser is the most iconic hydrothermal feature in Yellowstone National Park.. In the 1990s, researchers lowered a video camera into Old Faithful's vent: At 22 feet (6 m) underground, Old Faithful's plumbing system shrinks to a few inches wide; At 24 feet (7 m), a small waterfall of relatively cool groundwater flows into the conduit; At 35–45 feet (10–13 m), a large cavern, about the size of a small car, lies inside Old Faithful; A "liquid tornado" of wildly boiling, churning water at the lower end of the cavern stopped the camera from seeing any further. NPS photo by Jim Peaco, June 22, 2006.


Figure 9.17 *Left*: Midway Geyser Basin at sunset; NPS photo by Neal Herbert. *Right*: Pink Cone Geyser eruption, Lower Geyser Basin; NPS photo by Jacob W. Frank.

Fumaroles (or Steam Vents) exist when a hydrothermal feature has so little water in its system that the water boils away before reaching the surface. Steam and other gases emerge from the feature's vent, sometimes hissing or whistling. Steam vents are often superheated, with temperatures as high as 280°F (138°C).

Located in Norris Geyser Basin, Black Growler is one of Yellowstone's most famous steam vents (Figure 9.18). This feature has a history of shifting its location several times. It has been active since 1878 at least, often roaring in a noisy stream of hot vapor. Another place to enjoy the marvels of fumaroles is at Roaring Mountain, where fumaroles dot an entire mountainside. It is especially dramatic on cool days when the steam is more visible.

Figure 9.18 The hottest of Yellowstone's geothermal features are steam vents (fumaroles). Black Growler Steam Vent shown in the photo has measured 199 to 280 degrees F (93 to 138 degrees C). A plentiful water supply would help cool these features; however, steam vents are usually found on hillsides or higher ground, above the basin's water supply. They rapidly boil away what little water they contain, releasing steam and other gases forcefully from underground. Text and photo courtesy of NPS.

Figure 9.19 A **mudpot** is a natural double boiler. Surface water collects in a shallow, impermeable depression (usually due to a lining of clay) that has no direct connection to an underground water flow. Thermal water beneath the depression causes steam to rise through the ground, heating the collected surface water. Hydrogen sulfide gas is usually present, giving mudpots their characteristic odor of rotten eggs. Some microorganisms use hydrogen sulfide for energy. The microbes help convert the gas to sulfuric acid, which breaks down rock into clay. The result is a gooey mix through which gases gurgle and bubble. Minerals tint the mudpots with such a large palette of colors that the mudpots are sometimes called "paint pots." Iron oxides cause the pinks, beiges, and grays of the Fountain Paint Pot. NPS photo by Jim Peaco; text by NPS.

New Study Unveils the Secrets of Yellowstone's Hydrothermal Plumbing | U.S. Geological Survey (usgs.gov)

Communications and Publishing, March 23, 2022; United States Geological Survey

For the first time, scientists have mapped the network of underground geological pathways that feed Yellowstone National Park's legendary geysers and hot springs.

Scientists from the U.S. Geological Survey, Virginia Technical University, and Aarhus University in Denmark used a combined electrical and magnetic mapping technique deployed on a helicopter to reveal this system across the entire park and to depths of 1-2 miles. The detail provided by this approach reveals the paths of fluids through each part of the system.

"This is the first time we've been able to create images of the subsurface plumbing system that feeds so many of the amazing features of Yellowstone," said Carol Finn, USGS research geophysicist and first author. "It's also one of the largest and highest-resolution airborne geophysical surveys over a hydrothermal area in the world."

"We generated more than 100,000 models spanning the entire park - but it's the overarching view from pouring over them all that gives us insight into what controls the nature and distribution of the Park's thermal features," said Paul Bedrosian, a co-author who led the modeling effort. "It boils down to three factors - where the underlying magma resides, the location of fractures and faults, and the elevation of the surface relative to groundwater."

The models show most thermal features are located above buried faults and fractures that act as fluid conduits. Shallow horizontal pathways contribute colder groundwater into the system, which mixes with hot fluids from the conduits. As fluids ascend toward the surface, local constrictions help induce boiling, degassing or conductive cooling that produce the diversity of thermal features at Yellowstone National Park.

9.1.2 Grand Prismatic Spring

Grand Prismatic Spring is the largest hot spring in the United States, and one of the largest in the world (Figures 9.21 and 9.22). Its massive expanse stretches approximately 300 feet across (at its widest point it is 370 feet) and more than 120 feet deep. The high temperature of its water, 160F° (70C°), ensures that the spring is often cloaked in steam. It discharges almost 500 gallons of hot water each minute into the Firehole River. Minerals dissolved in the hot water are deposited and gradually build its gracefully terraced shoulders.

Prismatic means brilliantly colored. The center of the pool is near boiling temperature and sterile. It has a deep blue color which is the color in sunlight being scattered the most by fine particles suspended in the water. The yellow, orange, and brown colors encircling the hot spring and lining the runoff channels are caused by microscopic organisms called thermophiles: "thermo" for heat and "phile" for lover. These microbes contain colorful pigments that allow them to make energy from sunlight and thrive in the harsh conditions of hot springs (see also Figure 9.15).

As explained by Michael Poland of USGS (2023), the first accounts of Grand Prismatic Spring are probably from 1839, when a group of trappers noted a "boiling lake" 300 feet across. The description left by trapper Osborne Russell is the earliest written account of a Yellowstone thermal feature that can be accurately identified. Russell's account is worth reproducing in its entirety:

"At length we came to a boiling Lake about 300 ft in diameter forming nearly a complete circle as we approached on the South side The stream which arose from it was of three distinct Colors from the west side for one third of the diameter it was white, in the middle it was pale red, and the remaining third on the east light sky blue Whether it was something peculiar in the state of the atmosphere the day being cloudy or whether it was some Chemical properties contained in the water which produced this phenomenon I am unable to say and shall leave the explanation to some scientific tourist who may have the Curiosity to visit this place at some future period - The water was of deep indigo blue boiling like an immense cauldron running over the white rock which had formed [round] the edges to the height of 4 or 5 feet from the surface of the earth sloping gradually for 60 or 70 feet. What a field of speculation this presents for chemist and geologist."

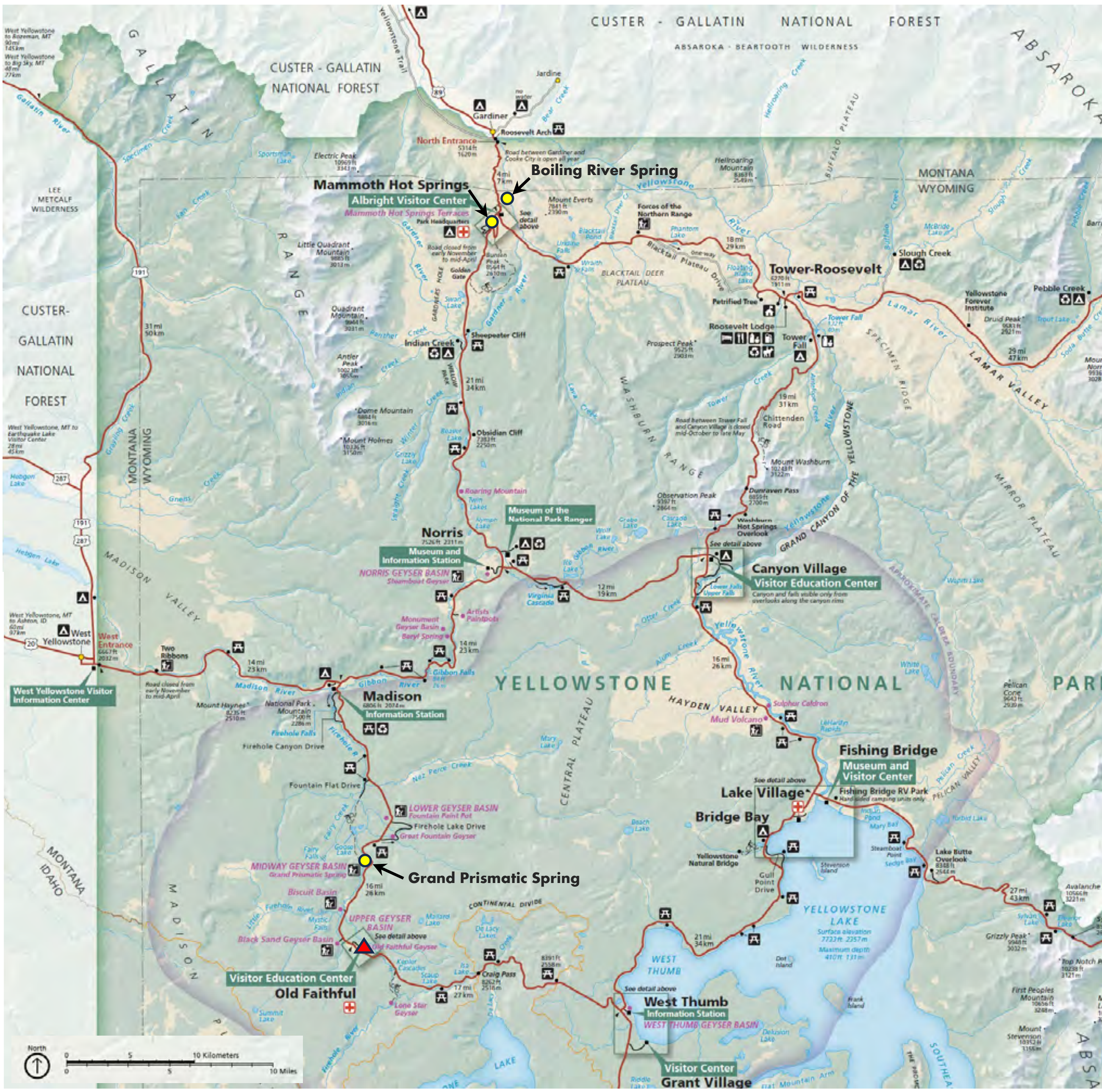

Figure 9.20 Part of the NPS' Yellowstone National Park map with locations of three springs described in this book: Grand Prismatic Spring, Mammoth Springs, and Boiling River Spring.

The most detailed early description of the feature came from the Hayden Geological Survey expedition of 1871—the first federally funded exploration of Yellowstone (The Hayden Survey was a predecessor to the USGS).

In his report, geologist Ferdinand Vandeveer Hayden recorded: “This is perhaps the handsomest spring in the whole Park, and it is certainly one of the largest, if not the largest. … I have named it Prismatic on account of the brilliant coloring displayed in it.”

Hayden’s explorations were especially thorough, and the descriptions, paintings, and photographs that resulted led directly to the founding of Yellowstone National Park in 1872.

Figure 9.21 Aerial view of Excelsior Geyser (in the foreground) and Grand Prismatic Spring in Yellowstone’s Midway Geyser Basin. The colors around the thermal features are locations of different thermophile communities. These thermophiles fix carbon both from the atmosphere and from the hot water. NPS photo by Jim Peaco; June 22, 2006.

Figure 9.22 Grand Prismatic Spring in Yellowstone National Park, Wyoming, Photo credit: Stephen P. Shivers, United States Geological Survey.

9.1.3 Mammoth Hot Springs

As explained by the scientists of USGS (Bargar, 1978; White et al., 1975; Sorey et al., 1991; Morgan et al., 2017; and Shanks, 2021), Mammoth Hot Springs is the only major thermal area in Yellowstone National Park dominated by deposition of hydrothermal $CaCO_3$ (travertine) rather than siliceous sinter. Samples of hot spring fluids at Mammoth Hot Springs, including from USGS drill hole Y-10, show that measured near-surface temperatures never exceed 73℃ (163.4°F), and the chemistry of the water suggests that subsurface fluid temperatures have not exceeded 100℃ (212°F). Compared with alkaline-chloride waters, like those from Old Faithful, thermal waters at Mammoth Hot Springs are rich in calcium, magnesium, bicarbonate, and sulfate.

Alinement of young volcanic rocks along a fault zone between Norris Geyser Basin and Mammoth Hot Springs zone suggests that the thermal water that eventually reaches Mammoth may be heated by partly molten magma within the fault zone. During transport along the fault, the water is enriched in calcium and bicarbonate, the two ingredients necessary for the formation of travertine. The trend of White Elephant Back Terrace and the tension fractures to the southwest of this fissure ridge suggest that the thermal water moves up through the old terrace deposits along preexisting vertical linear planes of weakness. As the water reaches the surface, pressure is released, carbon dioxide escapes as a gas, and bicarbonate in the water is partitioned into more carbon dioxide and carbonate; the carbonate then combines with calcium to precipitate pure white calcium carbonate, forming travertine of famous terraces of Mammoth Hot Springs (Figures 9.23 through 9.25).

Figure 9.23 Travertine terraces of Mammoth Hot Springs. NPS photo by Jim Peaco

Sulfide-oxidizing Aquificales bacteria contribute to the bright yellow, orange, and red coloration of the pools and channels (Figures 9.23 and 9.24). When discharge of a hot spring ceases, the microorganisms die, and the travertine deposits become white again and then dingy gray. For hundreds of years, Shoshone and Bannock people collected minerals from Mammoth Hot Springs for white paint.

Most travertine has precipitated rapidly from solution and is lightweight and porous; however, a few fissure ridges contain denser, vertically banded travertine layers that line the fissure. These vertical bands were apparently deposited over a long period of time. Dense travertine also forms beneath the surface of the terraces by deposition in the pore spaces of older deposits.

With the passage of time, the surface travertine deposits develop a loose soil capable of supporting the growth of small plants and eventually large trees, such as occur on Pinyon Terrace.

The active Mammoth Hot Springs area is an elongate northeast-southwest depositional mound that hosts approximately 100 active hot springs. The total thickness of travertine deposits can be approximated using results from drill hole Y–10, which was drilled near Bath Lake in 1967 to 1968, to a total depth of 113 m (371 f). Travertine comprises the upper 77 m (253 ft) of the section, with Mississippian Madison Formation dolomitic limestones below the travertine.

Some hot springs are pools with little or no deposition of travertine, whereas others form magnificent arrays of terracettes, cone-shaped deposits, or linear mounds called fissure ridges. Fissure ridges occur in numerous sizes and shapes. In some places water from new hot-spring activity becomes ponded behind fissure-ridge barriers or darns, with the result that travertine deposits eventually form large Rat terraces.

Most of the thermal water from Mammoth Hot Springs re-enters the subsurface through karst terrain and re-issues along the Gardiner River in a series of springs the largest of which is known as Boiling River Spring.

Figure 9.24 Travertine terraces and deposits at Mammoth Hot Springs. Bottom photos courtesy of Miles Kresic.

9.1.4 Boiling River Spring

In the general area of Mammoth Springs, the portion between Hotel Terrace and the Gardner River has few small thermal springs and one spring with a very large rate of discharge which is the source of Boiling River (historically also referred to as Hot River). The spring emerges from a small cave beneath an old, partially collapsed travertine ledge near the level of the Gardner River (Figure 9.25-*Left*). The discharge channel is about 9 feet wide and 2 feet deep, and the stream flows for about 400 feet before emptying into the river over a series of cascades (Figure 9.25-*Right*).

Figure 9.25 *Left*: Orifice of the Boiling River Spring. *Right*: Boiling River, seen in the center left, flows for about 400 feet before it empties into Gardiner River over a series of cascades. Boiling River water is too hot (~160°F) for direct bathing, so the visitors are soaking in the mixing zone with cold water of Gardiner River. This is only one of two places in Yellowstone National Park where bathing and swimming are allowed. As of fall 2024, the access to and the area of Boiling River are closed because of the extensive damage caused by the flooding of Gardiner River in summer of 2022.

The underground stream conduit can be followed upstream for an additional 420 feet through a series of collapse depressions features in travertine (Figure 9.26), one of which (MHS-1) contains visible flowing water.

According to Bargar (1978), the spring which feeds Hot River has the greatest discharge of any hot springs in Yellowstone National Park. Several discharge measurements reported by Allen and Day (1935) show that the flow of Hot River ranges from about 33 to 40 m^3/min (19.4 to 23.5 cfs), with the average flow being slightly greater than 38 m^3/min (22.4 cfs). A measurement by USGS in 1967 yielded about 41 m^3/min. Allen and Day also suggest that the variation in temperature of Hot River from an average of about 71°C (160°F) at different time of the year may be caused by dilution with cold meteoric water.

As discussed by the USGS authors in a publication edited by Sorey (1991), hot-spring discharge from the Mammoth hydrothermal system totals 590 L/s (20.8 cfs), approximately 10 percent of which flows from springs in the Mammoth Terraces. Most of the remaining 90 percent flows into the Gardner River from the Boiling (Hot) River Spring. Mammoth thermal water is derived from some combination of lateral flow moving northward in the Norris-Mammoth corridor and deep circulation originating from more local sources (for example, the Gallatin Range to the west). The main feature of hydrothermal system at Mammoth Hot Springs is flow through pre-Cretaceous sedimentary rocks in the Gardiner syncline where reservoirs for thermal fluids and sources of dissolved chemicals are most likely provided by Paleozoic carbonate rocks, such as the Mississippian Mission Canyon Limestone. Stratigraphic and hydrologic relations favor an overall south-to-north direction for groundwater flow

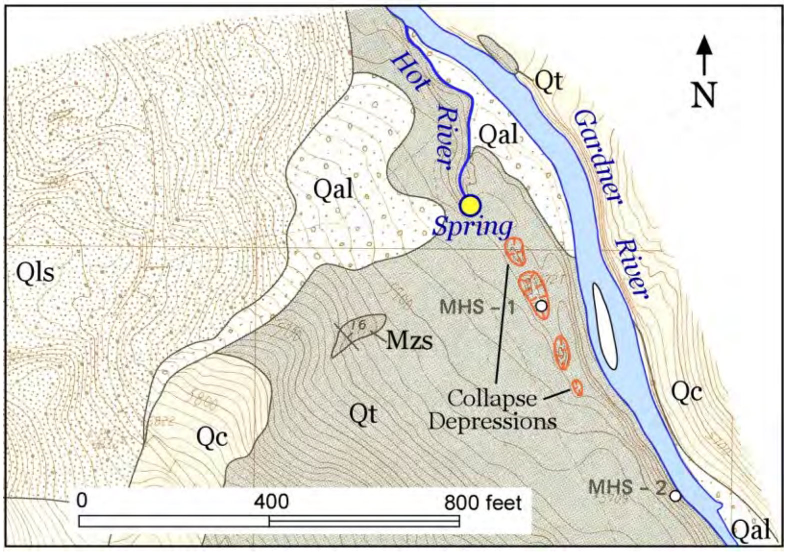

Figure 9.26 Geologic map of the Hot River Spring area. From Bargar, 1978 (part of Plate 1; modified for clarity). Qal–Alluvium; Qc–Colluvium; Qt–Travertine; Qls–Landslide deposits; Mzs–Sedimentary rocks; MHS–New unnamed spring.

in the syncline from Mammoth toward the Gardiner fault. Reservoir temperature estimates of 100°C (212°F) based on chemical geothermometers are consistent with such a flow system. Minimum depths of fluid circulation required to reach these temperatures range from 2-3 km (approximately 1-2 mi). The Paleozoic carbonate rocks occur at such depths under the Sepulcher structural low west of Mammoth and beneath the Yellowstone River valley between Bear Creek and La Duke (Figure 9.27).

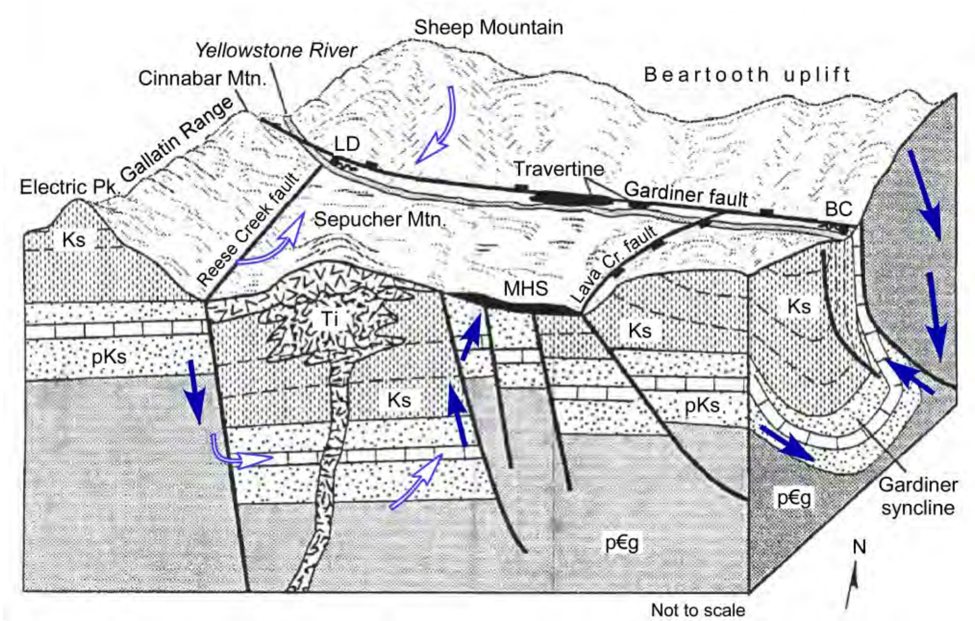

Figure 9.27 Conceptual model of possible flow systems associated with thermal areas at Mammoth Hot Springs (MHS), Hot River (HR), Bear Creek Springs (BC), and La Duke Hot Spring (LD). Arrows indicate general directions of fluid flow (solid in exposed planes of the diagram and open along zones unseen in exposed planes of the diagram). Faults shown as heavy solid lines, with block teeth on overriding plate of reverse faults. Simplified stratigraphic units are labeled Ks (Cretaceous sedimentary rocks), pKs (pre-Cretaceous sedimentary rocks), Ti (Tertiary intrusives), and p€g (Precambrian gneiss and schist). Approximate position of the Mississippian Mission Canyon Limestone, a regionally continuous aquifer, is shown by the blocky pattern. From Sorey, 1991; modified for clarity.

9.3 Thermopolis Hot Springs, Wyoming

Hot springs in Hot Springs State Park in Thermopolis (Greek for "hot city"), Wyoming is the largest group of thermal springs in the country outside Yellowstone. Thermopolis is 214 miles west of Jackson, Wyoming via US-26E, WY-133N to US-26E, and US-20N.

The Hot Springs State Park (Hot Springs State Park, a Wyoming State Park) is renowned for its spectacular *Rainbow Terraces* of travertine (Figure 9.28) where more than 1.8 million gallons flow over the terrace every 24 hours at a temperature of 128 degrees Fahrenheit. A winding, concrete walkway atop the terraces provides a view of algae and mineral formations on the bluffs overlooking the Big Horn River.

The park's free State Bath House (Figure 9.29) has both indoor and outdoor pools open to the public year-round where the water is maintained at 104°F for therapeutic bathing (Hot Springs State Park Bath House - Hot Springs Wyoming Tourism (thermopolis.com). In addition to the State Bath House, Hot Springs State Park also has two commercial hot springs pool areas: Hellie's Tepee (https://tepeepools.com/) and Star Plunge (https://starplunge.com/). Both facilities have indoor and outdoor pools and hot tubs, baby pools, waterslides, and steam rooms. The Plaza Hotel, constructed in 1914, and the Holiday Inn accommodate park visitors, and each establishment owns its own hot mineral water swimming pools which are open to the public.

Figure 9.28 Photo courtesy of Hot Springs Travel & Tourism;
available at Hot Springs State Park - Hot Springs Wyoming Tourism (thermopolis.com)

As explained on the Park's website, the terraces were known and used for many years by Native Americans, who believed that the waters were beneficial to health and that they could make a warrior invincible in battle. Chief Washakie of the Shoshone tribe, who built a personal bath house there, and Chief Sharp Nose of the Arapaho tribe sold the hot springs to the United States in 1896 with the provision that a portion should be forever reserved for the use and benefit of the public. Today nothing is left of Washakie's bath house, although a small marker may be found at the site. At Thermopolis each year in early August the presentation of the springs to the white man is re-enacted in the "Gift of the Waters Pageant." When the United States released a one-square mile tract of land to the state in 1897 to establish Big Horn Hot Springs State Reserve, the Reserve became the first of Wyoming state parks.

Figure 9.29 Hot Springs State Park has free *State Bath House* with both indoor and outdoor pools open to the public year-round where the water is maintained at 104°F for therapeutic bathing. Courtesy of State Bath House.

Breckenridge and Hinckley (1978) provide a description of the hydrogeologic setting of the Thermopolis spring system and the characteristics of six main springs including the largest and most impressive, Big Spring (Figure 9.30), which at the time had flow rate between 2,280 and 3,173 gpm over a period of 8 years, with an average of 2,648 gpm. The water temperature remained constant throughout the 20th century, in the 133-135°F range.

"Big Spring forms a 25-foot diameter pool through vents in the pool bottom. Inflow is accompanied by constant gas bubbling which produces a churning, boiling effect. Two manmade ditches and a buried pipeline accommodate outflow. One ditch flows into a swimming pool 170 yards south while the other, larger channel feeds water across 200 yards of extensive and spectacular terrace formations (Rainbow Terraces), then into the State Bathhouse and a second swimming pool. In addition, the underground pipe system serves the pools and bathhouse. Outflow from all these springs finally enters the nearby Bighorn River. Spring waters piped to commercial establishments at the south end of the park have a vapor vent in the form of a standpipe. Around this pipe mineral deposition has created a 20 feet high cone known as Teepee Fountain (Figure 9.31)" (Breckenridge and Hinckley, 1978).

Figure 9.30 Big Spring in Hot Springs State Park, Thermopolis, Wyoming. Photo by Julie Henning; available at https://www.roadtripsforfamilies.com/hot-springs-state-park-thermopolis-wyoming/

Figure 9.31 Teepee Fountain, a cone of travertine formed by mineral deposition around a standpipe. Photo courtesy of Hot Springs State Park.

Breckenridge and Hinckley (1978) describe the hydrogeology of the Thermopolis springs system as a nearly ideal natural artesian system where recharge occurs at exposed portions of Paleozoic formations in the Owl Creek uplift, and discharge at the crest of the Thermopolis Anticline cut by Bighorn River. The distribution of travertine deposits in the area indicates that the springs have not always issued from their present locations and have slowly migrated from approximately three miles northwest of Thermopolis (still at the crest of the anticline) towards their present site.

All the springs now flow from outcrops of the red Chugwater Formation at the crest of the anticline. However, based on the formation's low permeability and water chemistry (the Chugwater characteristically has Total Dissolved Solids >30,000 ppm), the authors conclude that the source of water is deeper: "Because strata are bent so sharply at the anticlinal crest, many have fractured and shifted, providing a ready water pathway from much lower formations."

Breckenridge and Hinckley find that the most reasonable hypothesis is that the water comes in large part from the deeply seated Madison limestone, probably modified in chemistry as it cools and rises through rock units above it. They emphasize the main problem in explaining the Thermopolis spring system: the source of heat. A variety of possibilities have been proposed, including chemical or frictional heating which may contribute some energy, but to what extent this might supplement thermal gradient heating is unknown. If the waters are assumed to circulate into the Madison and deeper, a locally high geothermal gradient may account for the observed temperatures. Such an explanation is, however, based on a poorly understood geothermal gradient and the supposition that waters have a fairly rapid access to the surface to prevent cooling enroute. Until all these factors are more clearly defined, no explanation can be completely accepted (Breckenridge and Hinckley, 1978).

Figure 9.32 Travertine deposits above White Sulphur Springs, Hot Springs State Park, Thermopolis, Wyoming. © 2024 Hot Springer Ken. White Sulphur Spring (Thermopolis) - Hot Springs in Wyoming - HOT SPRINGERS

9.4 Hot Springs, South Dakota

The town of Hot Springs is in Fall River County at the southern edge of South Dakota's Black Hills, 57 miles south of Rapid City via US-79 (SD-79S) and US-385. There are several spring groups in the town, the largest of which is Evans Plunge with a constant temperature of 87°F. The total average discharge of all the springs forming Hot River which flows through downtown Hot Springs, exclusive of Hot Brook, is 22.92 cfs, and does not vary significantly throughout the year. These gaging values are about 2.2 cfs higher than the U.S. Geological Survey gage located in downtown Hot Springs during the period of October 1968 to January 1969, probably because they include sewage effluent discharge (Rahn and Gries, 1973).

In 1901, Darton provided the following description: "*Fall River*. This vigorous stream is the product of springs of warm water in the gorge a short distance above Hot Springs. The principal flow is from orifices in the western part of the town, which have in all an average, nearly uniform flow of 25 second-feet. Above these springs there is a stream of small volume known as Hot Brook, fed from springs rising in the axis of the anticline 3 miles west of Hot Springs. Fall River as it flows through Hot Springs is good-sized stream of beautifully clear, tepid water, which continues down the gorge to Cheyenne River."

In the "Story of Hot Springs" published in July 2018 in *Black Hills Visitor* (The Story of Hot Springs – Black Hills Visitor) one can read that Native American tribes in the Minnekahta Valley of the southern Black Hills referred to the area as *mni kȟáta* ("hot water") thanks to an abundance of natural warm mineral springs. The Sioux and Cheyenne people considered the springs sacred and long congregated there to take advantage of the water's therapeutic properties. When European settlers arrived in the latter half of the 19th century, they originally called the town by its Lakota name, Minnekahta, but changed it to the easier-to-pronounce Hot Springs in 1882.

Figure 9.33 Evans Plunge pool with thermal water, owned by the City of Hot Springs. Historic (left) and current (right) photographs courtesy of Evans Plunge Mineral Springs, available at https://www.evansplunge.com/.

These early settlers were drawn to the mineral-rich thermal springs (six of which surface from the ground within the city's limits) for their perceived healing properties. Unlike other communities in the Black Hills that popped up to take advantage of the gold rush, Hot Springs staked its fortunes on its water.

A South Dakota Historic Marker in the town reads "Tribal tradition states that as long ago as the 16th century the Fall River Valley and canyon area were seldom without groups of tipis belonging to the North American Plains Tribes. They knew the curative value of the warm springs located there and used them for bathing their sick and lame. Exploration of the area by white men in 1874-75 led to settlement and discovery of 75 geothermal springs.

The crystal clear water issues from clefts in rocks or bubbles out of the ground. Bathhouses, swimming plunges, hotels, hospitals and sanitariums were built turning the City of Hot Springs into an early national health resort. Some of these structures still exist, including a sanitarium now used as the VA Center, and the South Dakota Soldiers Home. Cowboys and others crippled by rheumatism and other afflictions would arrive in wagons or trains and leave on horseback after three weeks in the springs. From this point the rushing Fall River can be seen and heard."

The fascinating history of the development of Hot Springs into a premier tourist destination is described on the town's webpage at Welcome to City Of Hot Springs, SD (hs-sd.org). Here are couple of excerpts:

By 1887, the health resort business was developing steadily, with several bathhouses. Plunge and vapor baths were given from 10 AM to 6 PM during the season at a cost of twenty-five cents.

The biggest development in baths was the Plunge, built by Fred Evans in 1891. The building was constructed of wood, iron, and glass, and covered a pool approximately seventy by two hundred feet. Various slides, diving boards, rafts, and other accessories were provided for the enjoyment of the guests. Evans Plunge is still operating at the same site.

Evans Plunge is now owned by the City of Hot Springs. On the dedicated webpage (https://www.evansplunge.com/), one can learn about its offerings and history, together with historic and current photographs (e.g., see Figure 9.33 in this book).

"The largest spring, at the north end of the pool in the interior of the Plunge, is known as the "Original Indian Spring." Here Native Americans drank and bathed in the spring's warm healing water. Today, numerous areas of warm sparkling springs may be felt as one moves through the crystal clear water towards the original Indian Spring.

A lot has changed in Hot Springs since 1890. No longer promoted as a cure for ills, the water still invites visitors for rejuvenation, refreshment, relaxation and recreation. Purchased by the City of Hot Springs in 2013, Evans Plunge is forging a new name for itself by looking to its past. With each day the City of Hot Springs is working diligently to restore Evans Plunge to the iconic tourist destination it has been for over a century."

The Black Hills Spa was the first bathhouse in Hot Springs, established in 1881 and owned and managed by Dr. Jennings. "Stories have been passed down for more than a century of Indigenous people soaking in the warm, mineral waters of the red rock, moccasin-shaped pool. The waters were compared to that of Carlsbad, Germany, known for their quality of mineral content. The property officially closed in 1963 and remained closed until purchased in 2014 by Kara Hagen. It underwent a process of revitalization and re-opened in 2019. The name was returned to its original name, given by the native people, who honored the water as medicine." (Moccasin Springs Natural Mineral Spa | Hot Springs SD)

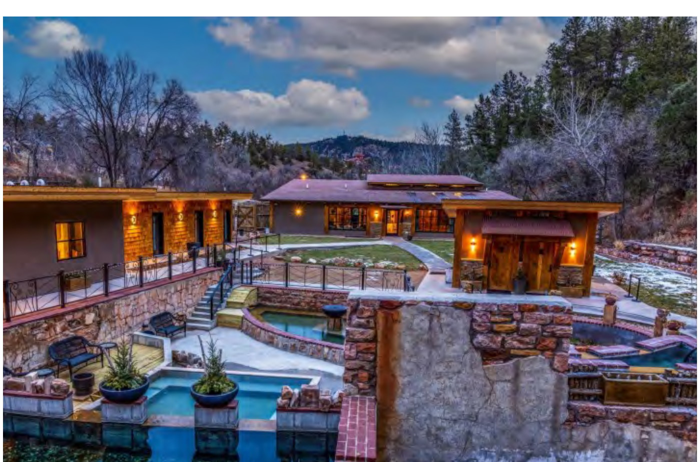

Figure 9.34 The Moccasin Springs Natural Mineral Spa has been rebuilt around the original structures, preserving as much history as possible. It features four outdoor naturally thermal pools, ranging in temperatures from 88-102ºF (31°C to 39°C). The spa prides itself on using no chemicals in its waters. Photo courtesy of Moccasin Springs Natural Mineral Spa.

More details about the hydrogeologic settings of the Hot Springs area are provided in Chapter 7.6.3 on the nearby Cascade Springs. The cause of anomalously warm water in springs and wells of the southern Black Hills remains an enigma. Theories for the cause include heat generation by radioactive decay of basement rocks, geochemical reactions between groundwater and soluble rocks, a partially cooled magma lying at shallow depth in the southern Black Hills, and areas of high geothermal gradients caused by proximity of heat-conducting Precambrian rock (Rahn and Gries, 1973; Schoon and MacGregor, 1974; Knircsh, 1980; Whalen, 1994).

9.5 Lava Hot Springs, Idaho

The City of Lava Hot Springs in Idaho is centrally located between Salt Lake City, Utah in the south (150 miles) and Yellowstone National Park in the north (192 miles). It is 36 miles southeast of Pocatello via I-15 (US-30&91), and 11 miles off I-15 via US-30E.

"Bubbling up from an ancient volcano, 2 ½ million gallons of natural hot spring water flow directly from the source through our pools daily. Our odor-free, naturally filtered waters are ever-changing, with no chlorine or sulfur. Our Hot Springs feature five outdoor pools at five different temperatures—some with soothing pebbles underfoot or jets for extra relaxation. Find the pool that suits you perfectly. There are family, women's and men's dressing rooms with lockers and heated floors that extend to the sidewalks outside. Bottled water, ice cream, snacks, drinks and souvenirs are available in the gift shop. Renew, Refresh and Relax any time of year at Idaho's most wonderful and unique recreational oasis.

Our Olympic Swimming Complex is the only one of its kind in the Intermountain West. With heated indoor and outdoor pools, diving boards and platforms, waterslides, speedslides, a natural hot water spa, and the Portneuf Kiddie Cove, it's the best fun for kids of all ages." Lava Hot Springs Hot Pools, Swimming Pool & Water Park - Idaho Hot Springs

Figure 9.35 Lava Hot Springs features indor and outdor pools including an olympic size outdoor pool complex, all heated by thermal waters of the springs. Photographs courtesy of https://lavahotsprings.com/

A geothermal source located between the soaking pools and the Olympic pool complex supplies geothermal water to heat exchangers that are used to heat the Olympic and lap pools. The water is discharged into the Portneuf River after it is used. According to the IDWR water rights, the soaking pools utilize 3 cubic feet per second (cfs), which is equivalent to 1,346 gpm (St Marie, 2002). The temperatures of spring water in the pools range from approximately 102ºF to 112 ºF.

Local businesses, primarily hotels and motels, divert geothermal water from hot springs, and from one deep and several shallow (less than 100 feet) wells for space heating and for soaking tubs and pools for their guests. Most of these sites are located within approximately 200 feet of the Portneuf River.

Once part of the original Fort Hall reservation, the springs and land were subject of a treaty agreement between the Indians and the US Government in the late 1800's. The federal government purchased the springs and land, approximately 178 acres including the springs. A 1902 act granted the lands to the State of Idaho to be held by the State for public use. Later all rights to the operation, management, control, maintenance and improvement of the lands and property were vested in the Lava Hot Springs Foundation, an agency within the Idaho Department of Parks & Recreation.

Figure 9.36 Historic photographs of the Lava Hot Springs outdoor soaking pool. Available at [Lava Hot Springs Area History and Photo Slide Show]

According to St. Marie (2002), at one time, the City of Lava Hot Springs piped geothermal water from the Chicken Soup Spring (the name used by local residents) just east of town. A well was drilled at the Chicken Soup spring to provide water for the city. This well was washed out by a Portneuf River flood years ago. The spring discharges from the riverbank with an estimated flow of 1.5 cfs (673 gpm). The temperature of the water was 47°C (117°F) in August, 2002. Schwarze (1960) describes a series of north-south trending normal faults in the area. These faults are likely candidates for the geothermal fluid conduits. However, the hydrogeology of the geothermal system in the Lava Hot Springs area has not been studied in detail and, therefore, is poorly understood (St. Marie, 2002).

A geologic map by Crain et al. (2001) suggests that the thermal springs are fed by groundwater from the deeply seated Ordovician carbonate rocks, possibly including deeper Cambrian limestones. Water ascends via a series of parallel faults ("Lava Hot Springs Fault Set") and discharges through the overlying conglomerate, sand, silt and clay of the Miocene Salt Lake Formation, and unconsolidated alluvial sediments in the Portneuf River valley.

In 2002, St. Marie had the following recommendation for the City of Lava Springs and the Idaho Department of Water Resources: "The city of Lava Hot Springs sits on a highly attractive geothermal resource. However, the intimate economic ties that the city has to that resource make it difficult to recommend further development because of the potential effects on the existing uses. This is not a simple case of conflicting water rights, but a potential irreversible damage to the city's livelihood."

In 2004, The Lava Hot Springs Geothermal Energy Team agreed: "Future planning for the utilization of the resources for community-wide benefits is critical for successful management and use of the resource. Long-range planning must be based on a solid understanding of the physical environment of the geothermal resource and the impacts that might occur if changes happen to the current system." and "There are two primary barriers to future development and use of the geothermal resources in Lava Hot Springs. The first is the lack of knowledge about the resource itself. A geologic investigation should be undertaken to fully understand the characteristics, availability, and limits of the geothermal resource. The second barrier is a lack of available funds to support research or, once the research is done, to use that knowledge for future development."

It remains to be seen if and how will the City and the Lava Hot Springs Foundation change its current utilization of hot springs, including potential additional taping into the geothermal energy potential of the area.

9.6 Steamboat Springs, Colorado

Old Town Hot Springs is a historic all-natural hot spring and recreational facility in the heart of downtown Steamboat Springs, Colorado. It is a 501(c)3 non-profit, multi-use complex open seven days a week, year-round and has eight pools, including two 230-foot waterslides, a 3,000 square foot hot activity pool, an aquatic rock-climbing wall, the historic Heart Spring pool, eight lap lanes, and massage. On its website (https://oldtownhotsprings.org/) one can read: "The Heart Spring is the reason that Old Town Hot Springs is here today. This all-natural mineral hot spring discharges approximately 220 gallons of 102-103 degree water out of the ground per minute and eventually feeds all of the pools at our facility. The Heart Spring has been flowing consistently for more than a century.

Figure 9.37 The main hot pool at Old Town Hot Springs provides a family friendly environment for everyone to relax and play. The water in the pool hovers around 98 degrees and is treated with chlorine to ensure a sanitary and safe environment for members and guests. There are multiple fountains in this pool, and one can swim under two bridges. Left photo: The all natural Heart Spring. Text and photos courtesy of Management, Old Town Hot Springs.

The fact that the water just happens to come out of the ground at this temperature is of unique importance. Unlike other hot springs, we do not have to dilute our mineral content by mixing our water with cooler river water in order to be tolerable. The Native American Ute Indians who first settled the area knew them as "medicine" springs, frequenting them for sacred physical and spiritual healing. Later the pools were likely a gathering and bathing place for the first homesteaders. We are lucky to have the famous Heart Spring right in downtown Steamboat Springs. The Heart Spring contains all natural minerals and is not chlorinated. The water in the pool turns over completely approximately every 15 minutes."

The name Steamboat Springs came from early French trappers who thought they heard steamboats chugging up the Yampa River. It was actually the town's hot springs bubbling, but the name stuck.

The timeline of the Steamboat Springs thermal springs development including historic photographs is explained at https://oldtownhotsprings.org/history/. Based in downtown Steamboat Springs, Old Town Hot Springs has been luring visitors to its cozy pools since 1885 when the City's founder, James Crawford, built the first log structure over the "Bath Spring". Fast forward to 1931 when H.H. Gossard surrounded the original Bath Spring with a stone wall in the shape of a heart and renamed it Heart Spring. He named the development around it *The Rocky Mountain Miriquelle Spa* with the plan to bottle the mineral water as a health product. The Great Depression ruined the plans. In 1935 Gossard returned control of the hot springs to the Steamboat Springs Company (Figure 9.38), who then sold it to the newly formed non-profit corporation, Steamboat Springs Health and Recreation Association SSHRA. At the time, SSHRA also owned the Strawberry Park Hot Springs located 6 miles from downtown. In 2006, SSHRA adopted the business trade name "Old Town Hot Springs" which is how it is known today.

Figure 9.38 Steamboat Springs hot springs circa 1935. Photo courtesy of https://oldtownhotsprings.org/

Figure 9.39 Privately owned Strawberry Hot Springs are a short 6-mile drive or shuttle trip from downtown Steamboat Springs and the Steamboat Ski Area. Courtesy of https://strawberryhotsprings.com/

9.7 Glenwood Hot Springs, Colorado

Glenwood Hot Springs resort is in downtown Glenwood Springs, a 36-mile drive from Aspen Airport via CO-82, and a 157-mile drive from Denver via I-70. Amtrak's California Zephyr runs the line from Chicago–Denver–Glenwood Springs–San Francisco. The train stops just across the river from Glenwood Hot Springs, where passengers can take the pedestrian bridge over to the resort.

On the resort's webpage (https://www.hotspringspool.com/) one can read:

"Rejuvenating mind and body since 1888. A source of relaxation, exhilaration, and breathtaking vistas, we are one of the original attractions in Colorado. Our historic setting is located between Aspen and Vail, just a short walk across the pedestrian bridge to downtown Glenwood Springs. The Resort is home to the world's largest hot springs pool, a full-service Athletic Club, Gift Shop, Grill and 107-room Lodge.

The Ute Native Americans called our source spring "Yampah" or "Big Medicine". The 15 minerals found in our water create a unique blend of natural spring water that relaxes, soothes and restores the body, mind and spirit. Our water in the Grand Pool and Therapy Pool is filtered and purified 24 hours a day, to ensure you experience the cleanest, healthiest water possible. You can experience a range of temperatures as you move through the water of the magnificent Grand Pool, and alternate with a soak in our hot Therapy Pool. Come enjoy the water of the historic Glenwood Hot Springs and find yourself restored."

Figure 9.40 Glenwood Hot Springs Resort in Glenwood Springs, Colorado, hosts the largest thermal pool in the world and many other amenities. Photographs courtesy of https://www.hotspringspool.com/gallery

For Ute people, who are considered the oldest residents of this region — long before it was known as the states of Colorado, Wyoming or New Mexico — these mineral waters are sacred. “Since time immemorial, we've always used hot springs in this region,” said Cassandra Atencio, historical preservation officer for the Southern Ute Native American Tribe.

For Ute people, both hot and cold springs are known as “grandmother water,” the “life giver.” Atencio said the exact way hot springs and vapor caves are used spiritually by each tribe is sensitive information, but she said Ute people enter hot springs with reverence and intention — even if a hot spring is crowded.

“These places are considered sacred places and it connects the tangible — what you can feel and see — to the intangible, which is that spirituality,” Atencio said. “And so when we talk about creator and we want to connect with them, we do that outside.”

It is through those connections, Atencio said, that the ancestors understood the different properties of hot spring water.

Stephanie Rivera, Colorado Public Radio

9.8 Murrieta Hot Springs, California

Murrieta Hot Springs, the recipient of the 2024 USA Today Readers’ Choice Award for 10 Best Spa Resorts in the country (10 best spa resorts across the United States for 2024 (usatoday.com), is in Murrieta, 66 miles from the San Diego Airport via I-15, I-295 and CA-261 (Murrieta Hot Springs Road).

“For over a century, Murrieta Hot Springs has been Southern California’s sanctuary of relaxation. Nestled amid a mountainous backdrop and towering palms, our resort offers a timeless escape from the everyday where our mineral-rich hot springs have been helping people unwind and feel better for generations. Immerse yourself in our oasis of tranquility and discover a new perspective on well-being.”

Nestled within Southern California’s picturesque landscape, our resort boasts over 50 pools—all but eight with 100% pure geothermal water—alongside cold plunges and enchanting water features.” murrieta-hotsprings.com

Figure 9.41 Murrieta Hot Springs Resort. Photo courtesy of Kevin Eassa.

Figure 9.42 Map of the Murrieta Hot Springs Resort. https://www.murrieta-hotsprings.com/springs/pool-details-map/

In 1873, Juan Murrieta and his partners purchased a large area of land, in a region known as Temecula Rancho and renamed it Murrieta Hot Springs. In 1902, after hearing of the area's curative water and healing attributes, German immigrant Fritz Guenther bought a section of the land surrounding Murrieta Hot Springs with the vision of developing it into a world-class health spa resort. In 1904 the Monterey Hotel was added to the property with rooms complete with running water and modern bathroom fixtures, followed by the California Hotel. By the late 1920's, a new Mineral Bath House was built, with a floor dedicated to a state-of-the-art gymnasium. Over the ensuing decades, the property was expanded with bungalows, employee quarters, and Cottage Row.

More on the history of the Murrieta Hot springs is provided in an excellent article by Christopher Reynolds published in the Los Angeles Times and accompanied by photographs by Myung J. Chun, available at https://www.latimes.com/travel/story/2024-01-17/murrieta-hot-springs-temecula-geothermal-pools-wellness.

"Our water comes out of the ground at about 125 to 130 degrees, depending," said Dr. Marcus Coplin, the resort's medical director, noting that the water is cooled to 104 degrees or less before guests bathe. The property also has several cold-plunge pools whose water is 54 degrees or less. According to the resort's promotional materials, the waters "enhance circulation, reduce inflammation, uplift mood, and support cellular health."

9.9 Langford Hot Springs, Texas

Langford Hot Springs is in Big Bend National Park (https://www.nps.gov/rigr/index.htm) in remote southwest Texas, about four miles upriver from Boquillas Canyon and the Mexican village of Boquillas. The crystal-clear water of the spring issues, at near constant temperature of 105 degrees Fahrenheit (40.5ºC), from Boquillas limestone on the north (left) bank of Rio Grande river, near the confluence of Tornillo Creek and the Rio Grande.

Big Bend National Park, the adjacent Big Bend Ranch State Park, and the Spring are among this author's favorites because Big Bend (named for the vast curve of the Rio Grande) is a geologist's and a naturalist's paradise, while the setting of the Spring and the overall experience seem like a beautiful, peaceful dream. Much has to be said about getting to Big Bend which is an adventure in and of itself. First one must choose driving, or flying to the nearest well-served airport (Midland-Odessa) and then driving 220 miles through the endless expanses of southwest Texas. A stop at San Solomon Springs in Balmorhea (Chapter 5.6), Davis Mountains State Park, and perhaps spotting the mysterious and elusive Marfa lights could be on the itinerary. After another 1.5 hour drive Terlingua Ghost Town makes a great stop. It is the funkiest little town in the country, a favorite base for both National Park visitors and many colorful characters from all over the world.

Below are a few excerpts from the fascinating story of Langford Hot Springs as told by Park Ranger Jeannette Woerner of the National Park Service (Hot Water, Health, & History (U.S. National Park Service) (nps.gov).

"The hot springs of Big Bend have long been a focal point for tourists and travelers in the desert. But these hot mineral waters represent more than just a destination for visitors to the National Park. For J.O. Langford and his family, they represented health, business and home. And for several decades in the early 20th century, the hot springs were also the center of a desert community.

Figure 9.43 The original bathhouse built by Langford over the main hot spring. Today only remains of the foundation are visible (see Figure 9.46). Courtesy of NPS.

In 1909, J.O. Langford was sitting in the lobby of the Alpine Hotel when he overheard someone discussing the miraculous healing properties of the hot springs in the Big Bend country. Another person might have been skeptical of claims that the mineral water could cure any disease, but Langford had been ill since contracting malaria as a child, and had been looking for relief from his pains and sickness ever since. In fact, he was so interested in these springs that he immediately set out to purchase the land surrounding them, down in a remote, lonely country that he'd never even laid eyes on.

Langford set out two weeks later with his pregnant wife Bessie and their young daughter Lovie, and traveled for ten days before finally reaching their new home on the Rio Grande. Regaining his health was a priority, so as soon as they arrived, Langford began his treatment: For 21 days, he drank and bathed in the mineral water of the spring, which at its source reaches 105 degrees, and soon he felt healthier and stronger than ever. Langford recognized the value of the springs and he immediately set up a business. He built a bathhouse (Figure 9.43) and developed his land into a desert health resort. Word-of-mouth recommendations soon brought people from across the country to find health at the springs, and many claimed to have been cured of skin diseases, rheumatism, stomach troubles, and chronic pain.

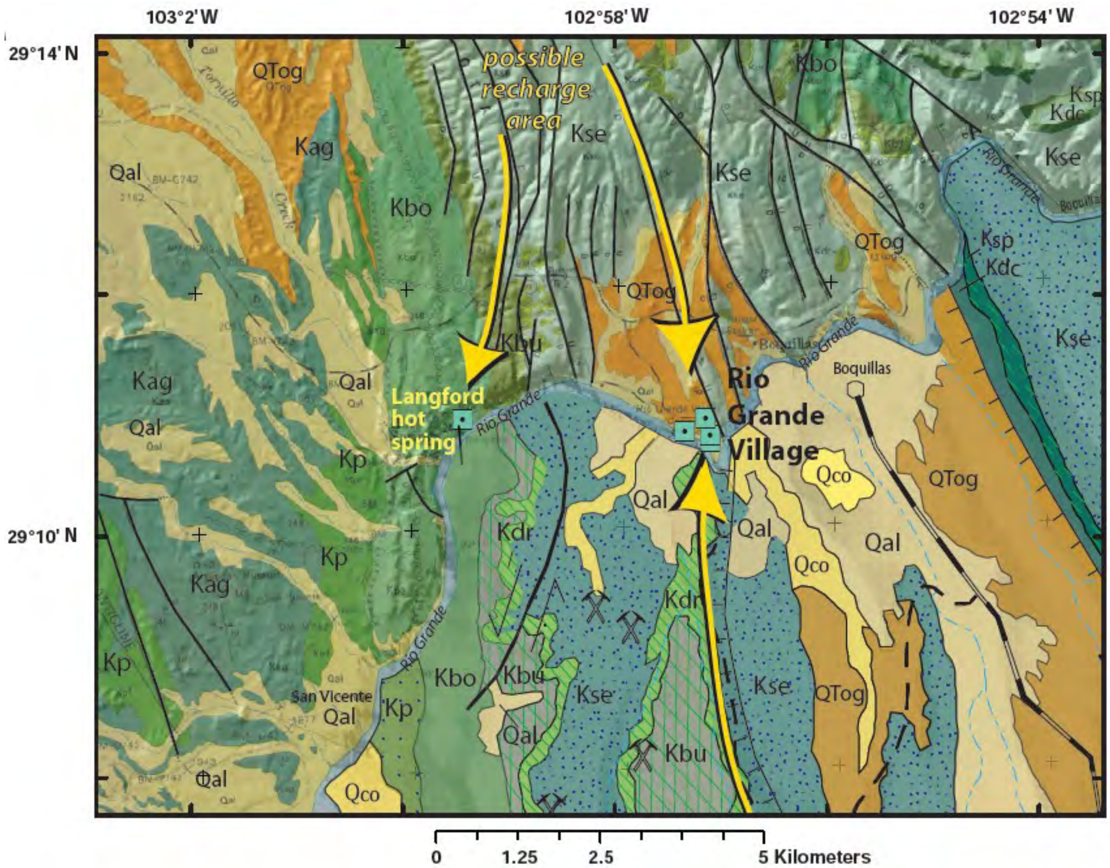

Figure 9.44 Geologic and shaded relief map of the Rio Grande Village (RGV) area. Turquoise square symbols indicate water samples. Geologic units are: Qal, Quaternary alluvium; Qco, Quaternary colluvium; QTog, Quaternary to Tertiary older gravels; Tacb, Tertiary Alamo Creek Basalt; Tasb, Tertiary Ash Springs Basalt; Tig, Tertiary igneous rocks; Tch, Tertiary Chisos Formation; Tcf, Tertiary Canoe Formation; Tbmb, Tertiary Bee Mountain Basalt; Tbr, Tertiary Brown Rhyolite; Twsf, Tertiary Wasp Spring Flow Breccia; Kag, Cretaceous Aguja Formation; Kp, Cretaceous Pen Formation; Kbo, Cretaceous Boquillas Formation; Kbu, Cretaceous Buda Formation; Kse, Cretaceous Santa Elena Formation; Kdr, Cretaceous Del Rio Formation; Kdc, Cretaceous del Carmen Formation; Ksp, Cretaceous Sue Peak Formation; Kjf, Cretaceous Javelina Formation. Big Bend National Park geology from Maxwell and others (1967). Mexican geologic mapping from Servicio Geológico Mexicano (2003). Note location of Langford hot spring, west of RGV, the hottest thermal water spring in the Park at 40.1°C. Water samples at Rio Grande Village are all thermal waters similar in composition, but somewhat more diluted than Langford waters. Hot spring water is probably recharged about 5 km north of RGV in higher ground of the Cretaceous Santa Elena limestones and flows along N-S fault zones (yellow arrows) to the hot spring sites. Possible recharge sites to the south in Mexico also are shown. Mine symbols (crossed picks) indicate fluorite mines. From Shanks et al., 2008.

Langford and his family lived and prospered in the Hot Springs area until 1942, at which time he sold the land to the state of Texas. The purchase was made in hopes of one day protecting the area, and two years later, Big Bend National Park was established.

While the buildings have been abandoned since the 1950s, they still stand as a reminder of the community they once supported. To this day, you can visit the remains of the general store and motor court. A walk just a quarter mile down the river will bring you to what is left of the main bathhouse, and you too can relax and soak in what J.O. Langford and many other West Texans considered to be healing waters."

Figure 9.45 *Left*: Post office near Langford Spring in the 1930s. Courtesy of NPS. *Right*: Post office building in 2017.

Figure 9.46 Langford Hot Spring in Big Bend National Park in November 1997 (left), and March 2017 (right).

Native Americans used the hot springs area as a homestead well before Europeans arrived in this part of Big Bend. The steep rocky cliffs provided shelter, as well as a canvas. Rock art, including pictographs and petroglyphs, adorn the limestone walls. Aprons of rock jutting into the Rio Grande reveal bedrock mortar holes once used for grinding mesquite beans and other seeds. J. O. Langford found that Native Americans had bathed in the hot springs where the hot water "...poured off a lip of rock and into the casket-like bathtub that the Indians built sometime in the past by chipping out and enlarging a fissure in the flat layer of sedimentary rock." The later construction of the bathhouse covered that historic tub (NPS).

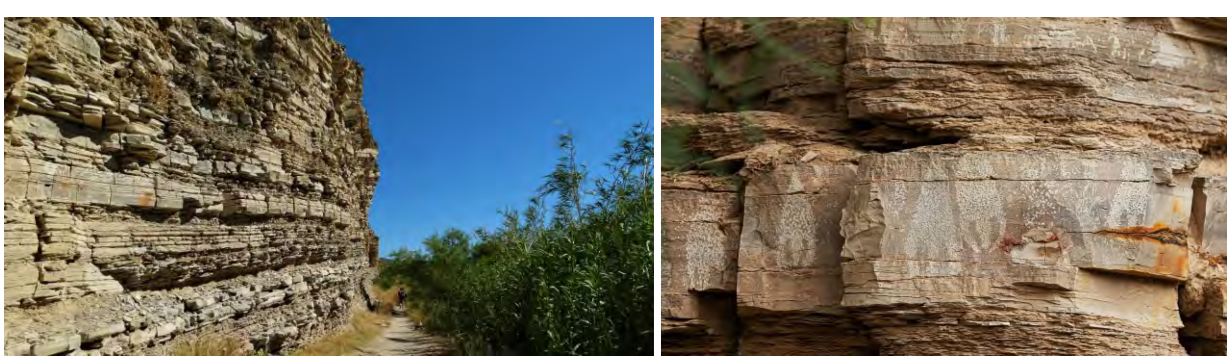

Figure 9.47 Cliff of Boquillas limestone near Langford Hot Spring. Right photo, courtesy of CA Hoyt, NPS, shows petroglyphs of arrowheads.

An extraordinary number of publications about Big Bend, including historic brochures and documents, can be found and downloaded at npshistory.com. This resource is unrivaled by any other National Park in the country.

The park visitor guide, *The Paisano*, provides a wealth of information on visiting Big Bend, park activities, articles, and trip planning ideas: Park Newspaper - Big Bend National Park (U.S. National Park Service) (nps.gov)

Figure 9.48 Mule Ears, twin volcanic dikes, the most prominent landmark in the eastern part of the Park.

Figure 9.49 *Left*: Willow Mountain, north of Study Butte and east of the Alpine entrance road. This is the most spectacular display of rock joints in the southern Big Bend area. The mountain mass is an intrusive magma plug, which cooled below the surface and was uncovered by weathering and erosion which removed the soft rock areas and revealed the joint pattern. *Right*: Cerro Castellan (or Castolon) Peak is a butte capped by remnants of a Miocene-age lava flow overlying volcanic ash and stream deposits of the Chisos Formation.

Figure 9.50 Terlingua, Texas, the funkiest little town in the country.

Figure 9.51 Photographs from the Big Bend area taken in March 2017.

9.10 Hot Springs, Arkansas

As explained by Thornberry-Ehrlich (2013) in an excellent, comprehensive publication on the geology, hydrogeology, origin of geothermal springs, and other features of Hot Springs National Park, the park encompasses approximately 5,550 acres of steep ridges and valleys in Garland County, Arkansas and is centered in downtown Hot Springs. The 47 natural, geothermal hot springs inspired the creation of the park and they remain the park's primary natural resource, although not preserved in a natural state. A series of pipes, flumes, and tanks are in place to collect, cool, and transport water from the springs; they allow the park to conserve and manage the production of uncontaminated hot water for public use.

The groundwater at Hot Springs National Park descends to estimated depths of 4,400 to 7,500 ft below the surface and is heated under a normal geothermal gradient (Bell and Hays, 2007). When the water is heated, it is less dense and rises rapidly to the surface along a narrow "escape route" of fracture zones in the Hot Springs Sandstone member of the Stanley Shale to emerge as artesian geothermal hot springs, at a temperature of 143°F (62°C). Of the 16 units in the NPS with significant geothermal resources, Hot Springs National Park is the only one not associated with igneous activity.

The mechanics of the geothermal system at the park, including its recharge area, are still being studied. From precipitation at the recharge surface area of approximately 1,100 ft in elevation, the water is funneled downward along faults, fractures, and bedding planes. Crucial to the system, a southwest-tilted, overturned anticlinal fold structure slowly directs the groundwater to great depths where it is heated and then ascends towards the surface thanks to a thrust fault that separates Hot Springs and West Mountains and creates a barrier to groundwater flow.

This barrier causes the hot springs to emerge on the southwestern slopes of Hot Springs Mountain near the axis of the anticlinal fold between two thrust faults (Bedinger et al., 1979; Sniegocki, 1996). During the Ouachita Orogeny, the barrier thrust fault transported impervious rocks (possibly Precambrian crystalline basement rocks) toward the surface, juxtaposing them against the Paleozoic bedrock in which a fractured zone in Hot Springs Sandstone provides outlets for the water (Thornberry-Ehrlich, 2013).

Figure 9.52 The bulk of the thermal water flowing each day from Hot Springs Mountain is collected from 27 of the 47 presently active springs. Each spring in the collection system has been sealed and covered with a green box about four feet square with a metal cover, chain, and padlock. The green boxes on the lower west slope of Hot Springs Mountain and the heat exchange units at the north end of Bathhouse Row are the most visible components of the thermal water collection and distribution systems and represent its source portion. Not all the boxes indicate a spring; some hold only valves and collection plumbing.

Analyses of silica in the thermal spring water reveal that the maximum temperature reached by the water is no more than a few degrees higher (151.9°F or 66.6°C) than the temperature at which the springs emerge (143°F or 62°C), which indicates that water rises quickly to the surface to discharge (Bedinger et al. 1979; Sniegocki 2001; Bell and Hays 2007).

Isotope dating with tritium (3H) and radiocarbon (14C; “carbon-14”) indicates the thermal water emerging from the springs is approximately 4,400 years old, whereas a small (less than 10%) cold water component is approximately 20 years old (Bedinger et al. 1979; Sniegocki 1996, 2001).

The springs, located on about 2.8 acres along Bathhouse Row and the Grand Promenade, at the base of Hot Springs Mountain, discharge water at a varying rate; in the early 2010s they have averaged between 655,000 and 710,000 gallons per day (Thornberry-Ehrlich, 2013).

Figure 9.53 Hot Water Spring Cascade. The park supports a flowing display spring at Arlington Lawn to demonstrate how much of the entire hillside might have appeared if the hot springs were still flowing freely. The feature is plumbed to mix hot and warm waters to a safe temperature, and blocks of tufa were put in place to resemble a natural flowing hot spring. Photograph taken in September 2023.

Figure 9.54 Thermal springs issue from Hot Springs Sandstone shown here exposed at a parking lot in downtown Hot Springs.

The history and culture of Hot Springs are explained by the National Park Service and accompanied by nice visuals and photographs at the Park’s website. Hot Springs National Park has a long and colorful history, beginning long before its designation as Hot Springs Reservation in 1832.

Native Americans came here for thousands of years to quarry novaculite for their tools and weapons. The Dunbar-Hunter Expedition came in 1804, sent by President Thomas Jefferson to explore the southern reaches of the Louisiana Purchase. Soon a bustling town grew up around the hot springs to provide services for health seekers. The resultant bathing industry led to Hot Springs becoming known as the "American Spa."

The area now known as Hot Springs National Park first became a United States territory in 1803 as part of the Louisiana Purchase. The first permanent settlers to reach the Hot Springs area in 1807 were quick to realize the springs' potential as a health resort. By the 1830s, log cabins and a store had been built to meet the needs (albeit in a rudimentary way) of visitors to the springs.

Figure 9.55 Painting of the hot springs in 1834. National Park Service image from HOSP archives.

To protect this unique national resource and preserve it for the use of the public, the Arkansas Territorial Legislature requested in 1820 that the springs and adjoining mountains be set aside as a federal reservation (not to be confused with the Indian reservations being established around the same time). On April 20, 1832, President Andrew Jackson signed legislation to set aside "...four sections of land including said (hot) springs, reserved for the future disposal of the United States (which) shall not be entered, located, or appropriated, for any other purpose whatsoever." This makes Hot Springs National Park the oldest national park among current National Park units, predating Yellowstone National Park by forty years.

Unfortunately, Congress failed to pass any legislation for administering the site. As a result, no controls were exerted in the area, and people continued to settle there, building businesses around and over the springs.

On August 25, 1916, Congress established the National Park Service, and Hot Springs Reservation came under its administration. Stephen T. Mather, head of the new organization, took a serious interest in the development of Hot Springs leading to its designation as the eighteenth national park on March 4, 1921.

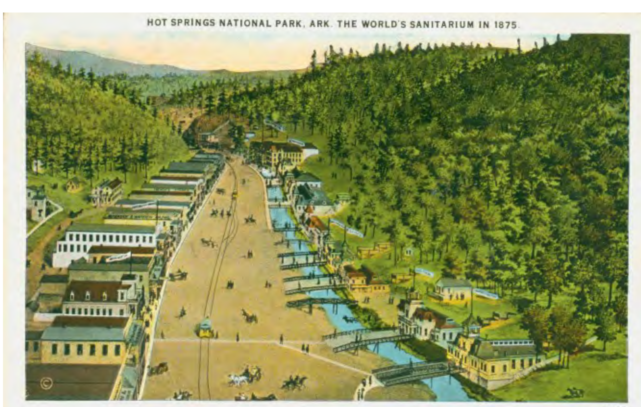

Figure 9.56 Color Postcard of Bathhouse Row along Hot Springs Creek (1875) before the archway was built. In 1882-83 the government enclosed Hot Springs creek in an underground arch for flood and sewerage control. The arch was then covered with earth, and the area above it was landscaped to create a pleasing park bounded with Lombardy poplars. Courtesy of NPS.

By 1901 all the springs had been walled up and covered to protect them. Between 1912 and 1923 the wooden Victorian bathhouses built in the 1880s were gradually replaced with fire-resistant brick and stucco bathhouses, several of which featured marble walls, billiard rooms, gymnasiums, and stained-glass windows. The new Bathhouse Row was completed when the Lamar Bathhouse opened its doors for business in 1923.

Bathhouse Row today consists of eight bathhouse buildings that were constructed between the years of 1892 and 1923, two of which are functional and offer the experience of bathing in thermal water — Buckstaff Bathhouse, and Quapaw Bathhouse. The Bathhouse Row area along with the Grand Promenade was designated as a National Historic Landmark District in 1987.

Figure 9.57 Buckstaff Bathhouse. NPS photo by Mitch Smith. The Buckstaff is the only bathhouse that offers a traditional bathing experience for people 10 & older. It has been in continuous operation since opening its doors in 1912. [Visit the Buckstaff Baths website to learn more about taking a bath.]

Figure 9.58 The Quapaw Bathhouse offers modern day spa services with amenities like roman-style open thermal pools, private baths, massages, facials, and other services for people 14 & older. Photo courtesy of Quapaw Bathhouse and Spa. https://www.quapawbaths.com/

By the 1960s the bathing industry in the park and in the city had declined considerably. On Bathhouse Row, the grand bathhouses that had been thriving since their construction in the first three decades of the century suffered from the decline and closed, except for the Buckstaff Bathhouse which has been continuously operating, and Quapaw Bathhouse which reopened in 2008 as a family-oriented spa.

Figure 9.59 The Park's Museum hosted in Fordyce Bathhouse includes display of the original rooms and equipment for using thermal waters. *Left*: "The most attractive feature in the basement is the enormous hot water spring, which was developed while excavating. This (display) is covered with glass so patrons and visitors can see the hot water as it bursts bubbling from the earth." (Hot Springs New Era 1915). *Right*: Steam Cabinet Room. The temperature of the steam in a vapor cabinet varied from 115 to 140ºF. A vapor bath caused profuse sweating, rapid pulse, and higher body temperature.

9.11 Warm Springs, Georgia

Thermal Warm Springs, made famous by President Franklin D. Roosevelt, are in the City of Warm Springs, little over an hour drive south of Atlanta via I-85 and US-27, or via GA-85 and GA-27. The Springs are located in the Roosevelt Historic Pools & Warm Springs Museum complex which showcases the history and significance of the warm springs that have been a popular destination for visitors seeking relaxation and healing for generations. Visitors can learn about the therapeutic properties of the mineral-rich waters and the connection to former President Franklin D. Roosevelt, who frequented the pools for treatment of his polio. The pools are not in function anymore (Figure 9.58) and their thermal water is reportedly re-directed for use in the modern therapeutic pools at Roosevelt Warm Springs (RWS) which is not open to the general public. RWS continues a tradition of compassion and quality care that spans over 90 years. Founded by Franklin Delano Roosevelt in 1927 to treat patients who had contracted polio, the campus continues to provide services to Georgians with disabilities (see Roosevelt Warm Springs | Georgia Vocational Rehabilitation Agency).

It is said that Native American warriors of the Creek and other Indian nations sought out the natural warm springs of Pine Mountain in the belief that they held special medicinal properties that helped with the healing of battle wounds and other injuries. This belief was passed on to early settlers and in 1832 a man named David Rose first tapped the springs for use as a health resort. Over the century that followed, thousands of people in need of either healing or rest from their daily lives came to Warm Springs for help and renewal. Among them was Franklin Delano Roosevelt, a man destined to become the 32nd President of the United States (Historic Pools Museum - Warm Springs, Georgia (exploresouthernhistory.com)).

Figure 9.60 Historic pools which were fed by thermal waters of Warm Springs in the past. They are now part of the Roosevelt Historic Pools & Warm Springs Museum and are not in function. Photo courtesy of presidentsusa.net

Figure 9.61 Franklin Delano Roosevelt, the 32nd President of the United States, by the Thermal Springs pools. Roosevelt, the Democratic candidate for vice president in 1920, had contracted polio in 1921. Three years later he visited Warm Springs. After a few days at the pools, he felt that his legs had improved more than they had in the previous three years. Other polio patients began to arrive in the spring of 1925, after an article appeared in the Atlanta Journal about Roosevelt "swimming his way to health." Photo courtesy of Roosevelt's Little White House Historic Site.

In a section of their 1937 report on "The Warm Springs of Georgia" entitled *Measures for Improving The Warm Springs*, Hewett and Crickmay of USGS give all the key facts about the thermal springs at the time:

It was the hope of the officials of the Georgia Warm Springs Foundation that, as the result of this investigation, ways might be found by which the temperature of the water and perhaps the discharge, might be increased. The investigation shows that about two-thirds of the total supply of warm water in the area, or about 550 gallons a minute, has an observed temperature ranging only between 87.7° and 88.2° F, and that it issues from a fractured zone in the quartzite scarcely 25 feet wide. The other one-third of the water issues from numerous outlets in alluvium, within 250 feet east or west of the main source, and with temperatures as much as 9 degrees lower than that of the main source.

Doubtless all sources of warm water should be controlled sooner or later, but at present the warmest two-thirds should be segregated from the sources of cooler water. It seems that the minor sources of water that issues from local alluvium may be regarded as leakage from a central or main conduit. It would therefore be advisable to enclose the minor sources in walls of impermeable material, making a tight seal with the bedrock and rising above the present outlets so as to form pools in which water levels would lie several feet above the present outlets. Back pressure would thus be created, which would tend to force the water to rise in the central conduit, probably at the present temperature of that portion. The question has been raised whether it would be possible by drilling to intercept the main or central conduit at depth and permit the water to rise directly to the surface, probably with less loss of heat than takes place in the natural conduit. All that can be learned of the local geology and inferred concerning the path of the rising water indicates that the chance of intercepting the natural conduit at a depth, say, of 500 feet, by one or a few vertical holes, is very small. For the increase in temperature that might be expected, it seems that the expenditure would not be warranted.

The geologic map and cross section in Figure 9.62 illustrate the main hydrogeologic conditions for the emergence of Warm Springs. The arrows on the cross section show the probable path of water discharged by the springs. Starting as rain on parts of Pine Mountain where the dense middle member of the Hollis quartzite has been removed by erosion or is sufficiently fractured to permit some downward percolation, the water moves into the permeable basal beds of the Hollis quartzite and then moves northward through these beds to depths of approximately 3,800 feet below the local surface (based on the dip of the geologic units). There, water becomes heated by the natural geothermal gradient. The geothermal gradient measured at two deep wells near the towns of Griffin and LaGrange was 0.95°F and 1.20°F for each 100 feet in depth, respectively.

From the structure of the rocks, it can be concluded that the water then flows northward up to the Towaliga fault and then upward under artesian pressure through fractures in the dense middle member of the Hollis quartzite, into the upper permeable beds of this formation which are confined by the nearly impermeable middle member below and by the nearly impermeable Manchester schist above. As suggested by Hewett and Crickmay (1937), in its upward course, before it reaches the surface at a temperature of 88°F, the water flows mainly through one or more natural conduits, which may have been produced largely by the solvent action of the water.

Hewett and Crickmay were right on target when they referred to the likely presence of natural conduits, more than 60 years before hydrogeologic investigations at nearby Blue Springs (see map in Figure 9.60) proved that they indeed can be formed in quartzite. This high-flow (500 gpm) cold water spring at Calloway Gardens also issues from the Hollis quartzite. The spring pool is approximately 30 feet across, and its depth near the orifice is about 30 feet. The spring is connected into a cave system that plunges downward to a considerably greater depth.

Below excerpts are from a letter report written for Calloway Gardens by Dr. Thomas Brewer of Hidell-Eyster International in 2001, regarding "some of the remarkable aspects of Blue Spring":

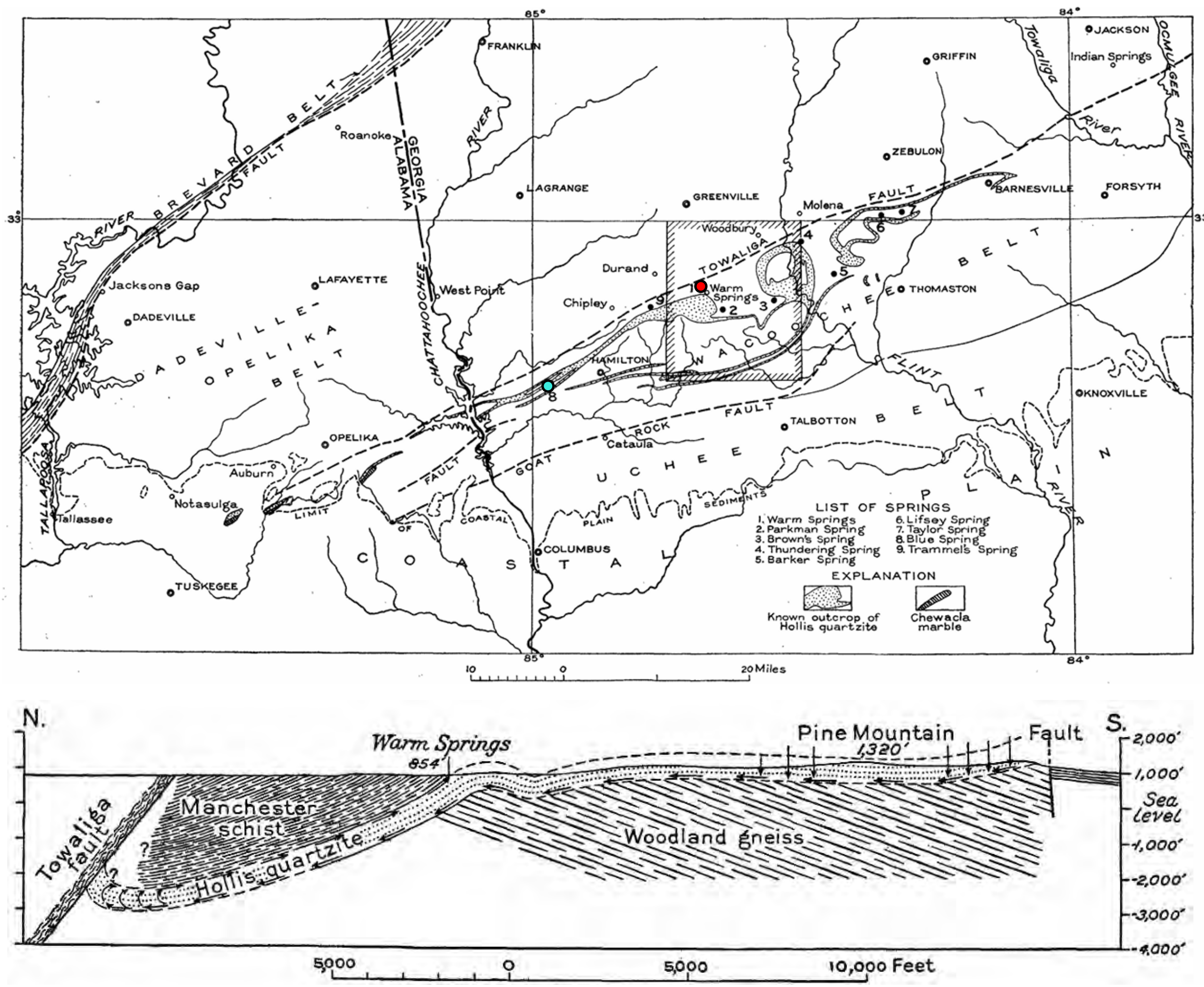

Figure 9.62 *Top*: Generalized geologic map of west-central Georgia and east-central Alabama, showing location of Warm Springs Quadrangle (shaded area) and principal springs(numbered). Red dot: Warm Springs (#1). Blue dot: Blue Spring in Calloway Gardens (#8). Dots are added to the original map for emphasis. *Bottom*: Cross section through Pine Mountain and Warm Springs, showing geologic structure and (by arrow) probable course of the water which enters Hollis quartzite as rain on Pine Mountain and is discharged at Warm Springs. From Hewett and Crickmay, 1937.

I have been performing spring investigations for more than 30 years, and in that time I have seen springs in many different geological settings in the United States and abroad. Blue Spring is unique in several respects:

Most high flow bedrock springs are found in areas underlain by carbonate bedrock such as limestone or dolomite. Blue Spring is a high flow bedrock spring that emanates from non-carbonate bedrock. With a flow rate of about or in excess of 500 gallons per minute, this is the highest flow non-carbonate spring that I have directly observed.

The spring issues from a large cave. Caves are normally characteristic of carbonate terrain because they result from the slow dissolution of the carbonate rock. The solubility of carbonate rock is why limestone springs normally have a high dissolved solids content. The cave from which Blue Spring emanates is formed in quartzite, *a highly resistant rock that is nearly insoluble. Karst Environmental Service, Inc., a company that specializes in underwater cave exploration, has explored and mapped the Blue Spring cave. The portion of the cave that allows for exploration consists of two rooms with a total length of 300 feet, and a maximum width of about 40 feet. There is a passageway that leads out of the lower part of this area and the total additional extent of the cave is not known. Karst Environmental Services representatives have told me that this is the only significant non-carbonate cave of which they are aware.*

The geology of this cave is therefore quite unique. The cave is located near a major ancient fault zone, which likely has something to do with the origin of the cave. The precise mechanism by which the cave formed is not clear.

Carbonate springs frequently have poor quality water for bottling purposes. This is because the high dissolved solids leads to scaling in the hot side of water dispensers, and because the rapid passage of water through limestone terrain frequently (almost always, in our experience) leads to high bacterial counts.

The total mineral matter in Blue Spring (as indicated by the total dissolved solids analysis) is remarkably low and should not present scaling problems. In addition, US consumers generally prefer the flavor of water with low mineral content.

In order to extract water from this spring, we have installed a deep well that penetrates into the lower parts of the cave. This will extract water some distance from the cave orifice and at a depth where the water is well protected from surface influence. Artesian conditions at the spring prevent the entry of surface water into it. (Brewer, 2001).

Although large caves developed in quartzite are indeed rare, some mechanisms of their development are relatively well understood. This includes arenization, or corrosion along grain contacts leading to loosening of the rock mass and making grains available for transport (Sauro, 2014; Piccini and Mecchia, 2009; Wray and Sauro, 2017).

Figure 9.63 Blue Spring, Calloway Gardens. Sampling of water at the bottom of spring pool with a snap sampler during initial hydrogeological assessment in 1998.

9.12 Warm and Hot Springs, Virginia

As described by Stearns et al. (1937), the principal group of thermal springs in the Appalachian Highlands is in Virginia and West Virginia. The thermal springs of Virginia are the best known and have been studied the longest of all springs in the southeast Atlantic States. The contributions by Prof. William Barton Rogers are the most important. Rogers was appointed the geologist for the Commonwealth of Virginia. He headed the state's geological survey from 1835 to 1841 and was the Professor of Natural Philosophy at the University of Virginia.

Although Professor Rogers listed more than a score of thermal springs in Virginia, including several in West Virginia, giving temperature and other data on each, the thermal springs of Warm Spring Valley, including the Hot, Warm, and Healing Springs in Bath County, have the highest temperatures and are best known. The temperature of most of the others is only a few degrees above the annual atmospheric mean.

"The linear grouping of the springs has long been recognized, and Professor Rogers early showed that the more decided thermal springs issue along or near lines of anticlinal axes. They are regarded as due to fractures or zones of crushing which may not always be visible at the surface. Those of the Warm Spring Valley rise along the west limb of the fold through steeply dipping nearly vertical beds of Cambro-Ordovician limestones." (Stearns et Figure al., 1937; Figure 9.64).

Warm Spring Valley has resulted from deep erosion of the crust of Warm Springs Mountain, a conspicuous anticline of the Appalachian type (usually referred to as Warm Springs anticline; Figure 9.65), composed of Silurian sandstone or quartzites and shales overlying Cambro-Ordovician limestones. Steep dips, nearly vertical in places, characterize the west limb. The waters rise to the surface along fracture/fault or slip/bedding planes in the limestone (Figure 9.65-*Right*).

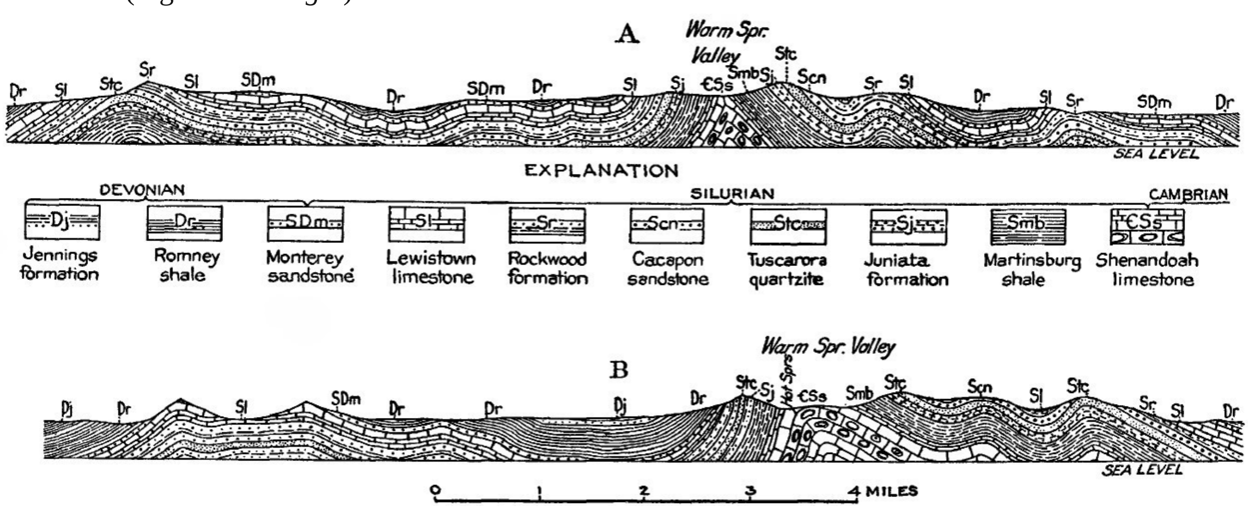

Figure 9.64 Geologic cross sections showing general structure at thermal springs in the Virginia region. A, Section along a line a short distance north of Warm Springs, Bath County; B, section along a line 3.5 miles farther south and a short distance north of Hot Springs. (Figure 9 from Stearns et al., 1937.)

In the town of Hot Springs, on the property of what is now Omni Homestead Resort, eight thermal springs were documented by Reeves in 1932 (Figure 9.66). Spout Spring had the highest temperature, discharging 36 gpm at 105.8°F. Notably, a spring with this name is not listed in the 1979 report by Hobba et al. of USGS; the highest temperature reported in Hobba et al. was 39.9°C at Boiler Spring and only two other thermal springs are mentioned and sampled: Octagon Spring (36.5°C), and Hot Sulphur Springs (36.5°C).

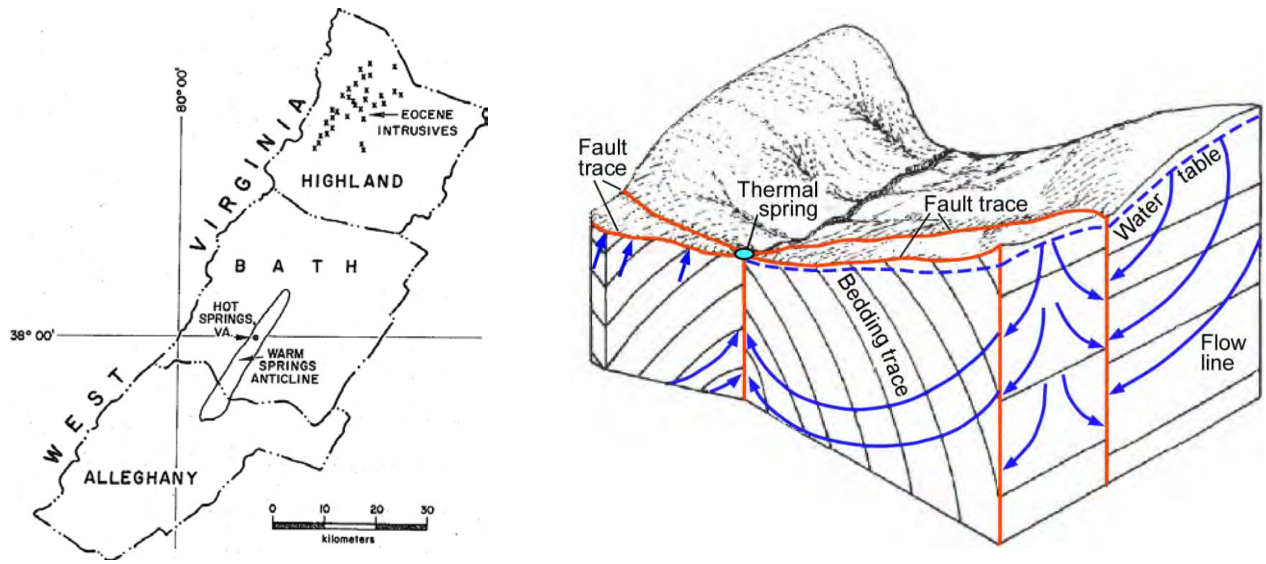

Figure 9.65 *Left*: Location of Warm Springs anticline in Bath and Alleghany Counties, Virginia. From Costain et al., 1976, *Right*: Possible circulation of water to a warm spring located near the crest of an anticline at the intersection of two faults. Much of the flow is into the plane of the figure along open tension fractures, bedding, or fault planes and upward beneath the spring. From Hobba et al., 1979; modified for clarity.

Ladies' pool at Warm Springs, 0.6 mile northeast of Warm Springs post office Bath Co.	Feb. 22, 1928 Sept. 12, 1928 Nov. 2, 1928		94 ° 95.3° ----
Drinking fountain at Warm Springs, 0.6 mile northeast of Warm Springs post office, Bath Co.	Feb. 22, 1928 Sept. 12, 1928 Nov. 2, 1928	1,000 to 1,200	95 ° 95.3° 95.5°
Gentlemen's pool at Warm Springs, 0.6 mile northeast of Warm Springs post office, Bath Co.	Feb. 22, 1928 Sept. 12, 1928 Nov. 2, 1928		95.2° 96.2° 96 °
Meadow spring at Warm Springs, 0.4 mile northeast of Warm Springs post office Bath Co.	Mar. 21, 1928. Sept. 12, 1928	100 100	91 ° 91.2°
Octagon Spring, Homestead Hotel, Hot Springs, Bath Co.	Feb. 22,1928 Sept. 12,1928 Nov. 2, 1928	67 67 67	95.1° 98.6° 98.6°
Boiler Spring, Homestead Hotel, Hot Springs, Bath Co.	Feb. 22, 1928 Sept. 12, 1928 Nov. 2, 1928	168 168 168	104 ° 104.9° 104.5°
Hot Sulphur Springs, Homestead Hotel, Hot Springs, Bath Co.	Feb. 22, 1928 Sept. 12, 1928 Nov. 2, 1928	40 40 40	97.3° 98.5° 97 °
Magnesia Spring, Homestead Hotel, Hot Springs, Bath Co.	Feb. 22, 1928 Sept. 12, 1928 Nov. 2, 1928	30 30 30	95.8° 96.5° 95.9°
Spout Spring, Homestead Hotel, Hot Springs, Bath Co.	Feb. 22, 1928 Sept. 12, 1928 Nov. 2, 1928	36 36 36	103 ° 105 ° 105.8°
Soda Spring, Homestead Hotel, Hot Springs, Bath Co.	Dec. 4, 1928	140	72.2°
Warm Spring, Homestead Hotel, Hot Springs, Bath Co.	Feb. 22, 1928 Sept. 12, 1928	15 15	90 ° 91.8°

Figure 9.66 Portion of Table 4 from Reeves (1932) which shows individual springs of Hot and Warm Springs with date of sampling, flow rate in gallons per minute (3rd column) and temperature in degrees Fahrenheit (4th column). From Lange and Andrews-Jones, 1973.

The group at the town of Warm Springs is made up of three springs within about 100 feet of each other, and a fourth about 0.2 miles to the southwest (Figure 9.66). The two largest springs were developed into Gentlemen's Pool (sometimes referred to as "Gentlemen's Bath House"), the oldest spa structure in the country, built in 1761 and continuously operating ever since, and Ladies' Pool built in the mid-1870s.

Some earlier studies suggest that the reasons for the emergence of the thermal springs in Virginia are normal, natural geothermal gradient and deep circulation of groundwater (e.g., Reeves, 1932; Hobba et al., 1979). In contrast, studies based on geophysical surveys (e.g., Dennison and Johnson, 1971; Lange and Andrews-Jones, 1973; Costain et al., 1976) point to several regional geophysical anomalies centered around the thermal area suggesting a causal relationship with the springs. These include an unusual thickening of the crust to 60km (greatest in the U.S.), deduced from travel-time delays of seismic waves; broad gravity and magnetic lows; an absence of seismicity; and an extreme damping of response from distant earthquakes. In addition, geomorphic evidence points to an uplift of the Eocene erosion surface in the vicinity of the springs. The evidence is corroborated by the presence of outcropping volcanics of Eocene age (47 million years) at the north end of Warm Springs anticline (Figure 9.65-*Left*). These are the youngest igneous rocks found east of the Mississippi.

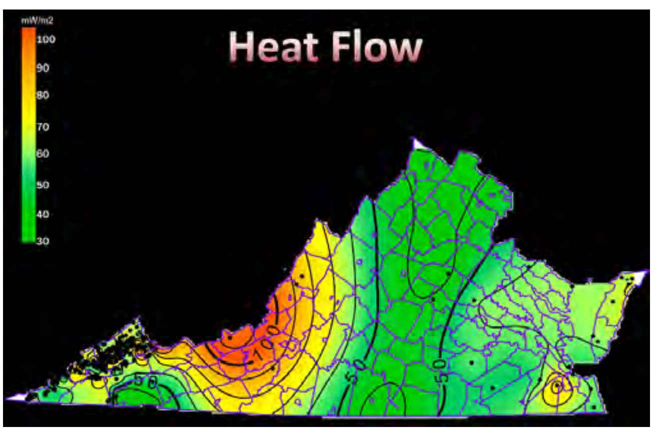

Figure 9.67 Heat flow, the ability of bedrock to conduct heat, is greatest near Bath County. Source: Wendy Kelly, 2013. Geothermal Resources for the Eastern United States. Division of Geology and Mineral Resources, Virginia Department of Mines, Minerals, and Energy.

Dennison and Johnson (1971) conclude that heated pluton underlies the area. Local upward migration of magma in the past would account for the presence of the volcanic outcrops. Such ascendants today would result in localized heating of the subsurface and deeply penetrating groundwater. Rising magmatic waters may also contribute to the temperature and composition of the springs. As suggested by Costain et al. (1976), the likely seat of a geothermal reservoir is the buried paleokarst of the Ordovician Beekmantown formation

An article by Eli Kintisch published in the October 2010 issue of *Science* cited research by geologists at Southern Methodist University (SMU) in Texas and caused quite a bit of excitement at the time: *West Virginia Is a Geothermal Hot Spot. Researchers have uncovered the largest geothermal hot spot in the eastern United States. According to a unique collaboration between Google and academic geologists, West Virginia sits atop several hot patches of Earth, some as warm as 200˚C and as shallow as 5 kilometers. If engineers are able to tap the heat, the state could become a producer of green energy for the region.* (West Virginia Is a Geothermal Hot Spot | Science | AAAS).

With a little delay of 13 years or so after the results of this study, the United States Department of Energy provided over $7 million to West Virginia University, to drill 15,000 feet deep in 2023 to assess if deep wells in the eastern United States could provide a reliable supply of geothermal energy near Morgantown, West Virginia. The results of this study are not yet made public.

Warm Springs

The Warm Springs thermal springs are in the town of Warm Springs, seat of Bath County, 93 miles west of Charlottesville via I-64 and VA-42S (VA-39), at the intersection of two major transportation routes: the north-south corridor of US-220 (Sam Snead Highway) and the east-west corridor of VA-39 (Mountain Valley Road). Warm Springs Bath Houses (Gentlemen's and Ladies' Pools) were listed on the National Register of Historic Places in 1969 (008-0007 (virginia.gov)).

All who have described this noble fountain, write with enthusiasm; nor is it indeed to be wondered at, for the world may well be challenged for its equal. Its temperature, buoyancy, refractive power, transparency – all invest it with indescribable luxury to the feelings and to the sight.

William Burke

Figure 9.68 Edward Beyer's print of Warm Springs published in 1857. The largest building is the Warm Springs Hotel which served as a Confederate Hospital from July 1861 until June 1863.

The history of Warm Springs from the very beginning is explained in detail in the updated nominating form for a listing in the National Register of Historic Places, which was approved in 2019 and is now available at 008-0007 (virginia.gov)

Here is just one of many interesting details that abound in the form:

At the Warm Springs, many went to their own cabins to cool down: in the same document, Prolix advised visitors how to handle the Warm Springs bath: Stay in the bath fifteen minutes, using very little exercise whilst in the water. As soon as you come out, hurry to your cabin, wrap yourself in a dry night-gown, go to bed, cover up warm, go to sleep, get into a fine perspiration, grow cool by degrees, wake up in half an hour, dress and go to dinner with what appetite you have.

Figure 9.69 Gentlemen's Pool, Warm Springs, 2010

Equally resourceful is a collection *Medicinal Springs of Virginia in the 19th Century* housed at Historical Collections at The Claude Moore Health Sciences Library, University of Virginia. The collection is also available digitally at https://exhibits.hsl.virginia.edu/springs/warm/index.html

The building known since the 1870s as the Gentlemen's Pool has a long and complex history. It was originally known as the Warm Springs Bath or the Great Bath. During its first decades the octagonal bath was not covered with a building, but was masked from view by a fence or hedge. The frame bath house was added over the octagonal basin in the mid-to-late 1820s. It was enlarged over the next thirty to forty years until it took the form shown in Figure 9.69, photograph taken in 2010.

Figure 9.70 The Warm Springs thermal spa pools were completely renovated in 2022-2023. The scope of work encompassed preserving and/or replacing in-kind the historic wood structure, windows, doors, siding and roofing along with repairing the foundation piers of both baths and the reception house. In preparing the plans, the rehabilitation team focused on maintaining the existing character of the Warm Springs Pools, referencing the structures as they were when the resort acquired them in 1925. Both pools are open to general public for a fee. Reservations are required well in advance because of a great deal of interest from out-of-state and international tourists visiting the area and boosting the local economy. Ladies' Pool is on the left, Gentlemen's Pool is on the right. Courtesy of the Omni Homestead Resort.

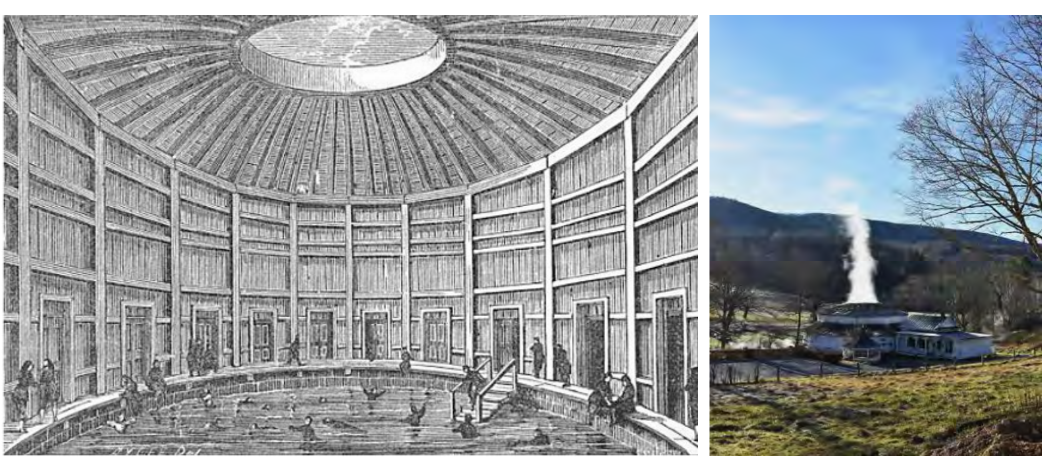

Figure 9.71 *Left*: "Warm Springs, Bath County, Virginia: In New Hands and Greatly Improved. Open on the First Day of June. Gary's Steam Printing Est., 1875." *Right*: The Warm Springs Ladies' Pool in late fall of 2002 with the steam from the thermal spring escaping through the oculus. Courtesy of United States Department of the Interior, National Park Service, National Register of Historic Places; listed on 9/25/2018. Photographs courtesy of NPS, National Register of Historic Places.

The first references to the polygonal Ladies' Bath (Figure 9.71) are found in promotional publications issued by post-civil-war proprietor John L. Eubank for the renamed "Warm Sulphur Springs." The Ladies' Bath was celebrated in a brochures of 1875 and 1884. Both brochures used identical language to describe the facilities; "The Ladies Bath is a circular bath, fifty feet in diameter and one hundred and fifty in circumference. As a swimming pool it is very attractive and many ladies learn to swim..." (NPS, National Register of Historic Places).

Hot Springs

Thermal springs in the town of Hot Springs are on the property of Omni Homestead Resort, about 5 miles southwest of the town of Warm Springs via US-220. The Homestead, together with the thermal springs, was listed on the National Register of Historic Places in 1984. In the nominating form for the listing, one can read the following (008-0025_The_Homestead_1984_Final_NRHP_Nomination.pdf (virginia.gov)):

"The Homestead is one of the finest resort hotels in the nation. Situated at Hot Springs, Virginia in the Alleghany Mountains, the Homestead provides luxurious accommodations, excellent cuisine, and beautiful natural scenery for its internationally famous guests. Although the present hotel dates from the first decades of the twentieth century, the Homestead had its beginnings in the mid-eighteenth century as a health resort. As early as 1766, a small hotel, also known as the Homestead, was built to accommodate travelers who visited Hot Springs hoping to procure health from the thermal springs.

As a health or pleasure resort, Hot Springs suffered in competition with nearby Warm Springs until the hotel was purchased by Dr. Thomas Goode in 1832. Dr. Goode was responsible for promoting the resort chiefly as a health spa by placing large ads in popular periodicals of the day such as Mr. Godey's Lady Book and Harper's Weekly, claiming the waters at Hot Springs were recommended for any number of maladies from gout to spinal irritations.

During the first half of twentieth century, the Homestead enjoyed a national reputation as an outstanding year-round resort. It received additional notoriety as the site of the International Food Conference in 1943. This conference, attended by representatives of forty-four countries, can be regarded as a precursor to the later founding of the United Nations.

The Homestead has attracted many of America's most prominent twentieth-century citizens including Henry Ford, John D. Rockefeller, Paul Mellon, Mrs. William K. Vanderbilt, and Mrs. Cornelius Vanderbilt, the famed New York City social queen, who made the Homestead her summer headquarters in the 1930s. All but three twentieth-century American presidents have been guests at the Homestead.

https://exhibits.hsl.virginia.edu/springs/hot/index.html

Figure 9.72 The Hot Springs resort as drawn by Porte Crayon in 1857. The large hotel, the Homestead, was built by Dr. Thomas Goode in 1846. Courtesy of Medicinal Springs of Virginia in the 19th Century, Historical Collections at The Claude Moore Health Sciences Library, University of Virginia.

They include William McKinley, William Howard Taft, Woodrow Wilson, Warren G. Harding, Calvin Coolidge, Herbert Hoover, Franklin D. Roosevelt when governor of New York, Harry Truman as a senator, Dwight D. Eisenhower after his retirement from the presidency, Lyndon B. Johnson, Richard M. Nixon when vice-president, Gerald R. Ford when vice-president, and Ronald Reagan as a governor of California. Many other governors, senators, dignitaries, and ambassadors are included in the Homestead guest files. The Homestead today remains an internationally famous resort offering some of the best accommodations, cuisine, sports activities, and leisurely pursuits available in the world."

Figure 9.73 Omni Homestead Resort in 2024. Courtesy of The Omni Homestead Resort | Resorts in Virginia (omnihotels.com)

Figure 9.74 *Left*: "The Octagon Pool enjoys the longest recorded history of the many natural mineral springs that abound throughout our mountains and valleys. Native Americans began appreciating its virtues some nine thousand years ago as they explored, hunted, fished and relaxed among the forests, rivers and meadows. Colonial surveyors and settlers found it to be a perfect source of relaxation after arduous journeys. The Octagon Pool was our original soaking pool, and in Colonial times, Homestead guests simply walked up to it, disrobed and enjoyed "taking the waters." The modesty of Victorian times brought an end to that practice, and The Octagon Pool became an attraction of purely historic interest. We invite you to divest yourself of the bonds of shoes and socks, and soak your feet in its soothing waters." (Text is from metal plaque by the pool). Right: Homestead's indoor pool at the Spa, fed by the Boiler Spring.

Figure 9.76 *Spring on the Left*: "The Boiler Spring's naturally hot mineral waters have made The Homestead internationally renowned as a Spa Resort since 1766. These clear waters emerge from deep beneath the earth, flowing constantly at 105°F year-round, and have been greatly favored for their "curative" powers. In 1832 Dr. Thomas Goode began to direct these waters into pool houses through underground pipes made of hollowed-out Chestnut logs. This natural, thermal spring water continues to be conveyed underground to our historic Spa, where it provides today's Homestead guests with the very same absolute relaxation that was described by a noted physician in 1867 as "exceeding all expectation." (Text on metal plaque by the spring). *Spring on the Right*: "Hot Sulphur Spring. The crystal waters of this natural mineral spring are actually warm, rather than hot as its name suggests. They flow constantly at 97° F, and enjoy a mild Sulphur content, which made them popular for both bathing and as a drinking spring. From the earliest recorded uses of springs in America, through the early 20th century, physicians routinely advised patients to drink certain types of waters, as well as soak in them. Although consuming warm sulfur water is no longer popular, this spring house will help you enjoy the heritage of Taking the Waters at The Homestead, a tradition that began in 1766." (Text from metal plaque by the spring).

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EPILOGUE

Thanks to its size and remarkably diverse geology, hydrogeology, and climate, the Unites States is blessed with some of the largest and most beautiful springs in the World. Many springs that did not make it into this book are as beautiful and as important as those that did.

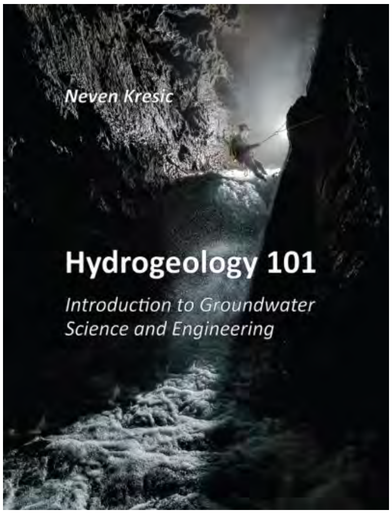
For countless years springs provided a lifeline to Native Americans who cherished them. They built their camps by the springs, used their waters to irrigate crops, and healed their bodies and souls in spring waters. Then the newcomers from the old world came and were astonished to see so many magnificent springs, spouting water more generously than any fountain they ever built. The newcomers also used the crystal-clear waters to irrigate their crops and built their towns and cities because the springs provided plentiful, clean water. They used the springs to power their machines and they too used springs to heal their bodies and souls.

Tragically, many of our Nation's springs including the most magnificent and beautiful, have died or are dying in front of our eyes, silently, because of what we have been doing to them, and because they cannot speak for themselves. It is now our turn to do the healing and to help them survive and thrive again, for the generations to come.

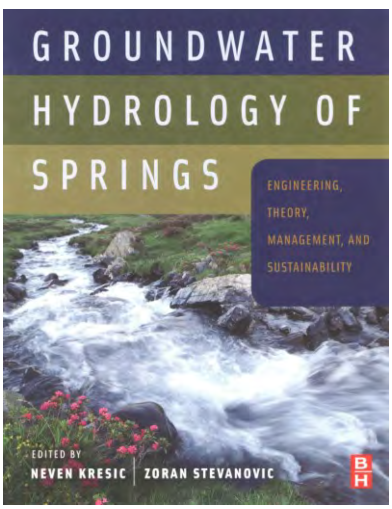
More than once, while working on the book and seeking materials from my colleagues and springs enthusiasts, I was asked about the meaning of "notable". Perhaps the best answer are the following words by Dr. Robert Knight, Director of The Howard T. Odum Florida Springs Institute, cited in the Introduction and repeated here:

> *Everyone I know sees and loves springs differently. But based on what you hear today and what your own eyes tell you, I hope that you will leave with a renewed commitment to act on behalf of your springs and the life they support.*

Other Books by Neven Kresic

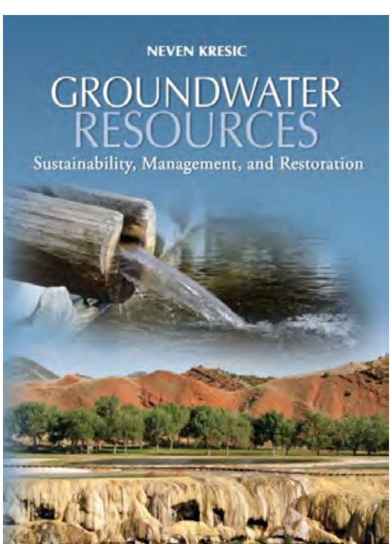


Hydrogeology 101 is a college textbook introducing basic concepts in groundwater science and engineering with 16 lectures, the duration of a typical one or two-semester course at American universities. It covers Introduction to Hydrogeology, Groundwater Use, Porosity and Characteristics of Porous Media, Groundwater Flow, Aquifers and Aquitards, Groundwater Recharge and Discharge, Flow in Unsaturated Zone, Groundwater Chemistry, Groundwater Contamination and Remediation, Field Investigations, Groundwater in Water Supply, and a guest lecture on Groundwater Drought in California by Alex Mikszewski. It includes hundreds of full color illustrations and photographs. This college textbook is available for free download and unrestricted reposting and dissemination for all non-commercial uses. 2023, Blue Ridge Press, ISBN 979-8-218-06984-1



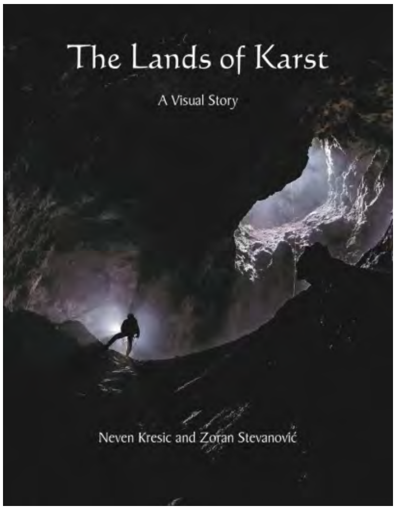
Edited by two world-renowned hydrogeologists, *Groundwater Hydrology of Springs: Engineering, Theory, Management, and Sustainability* provides civil and environmental engineers with a comprehensive reference for managing and sustaining the water quality of springs. With contributions from experts from around the world, this book covers many of the world's largest springs, providing a unique global perspective on how engineers around the world are utilizing engineering principles for coping with problems such as mismanagement and overexploitation and their impacts on both water quantity and quality.

This book explains the theory and principles of hydrology as they apply to springs and provides a rare look into the engineering practices used to manage some of the most important springs from around the world. 2010, Elsevier Butterworth-Heinemann, ISBN 978-1-85617-502-9



Groundwater Resources is a reliable, one-stop guide providing all the information needed to succeed in groundwater management and development projects. It covers virtually every aspect of the subject, from how to characterize groundwater and evaluate its resources to determining the interactions between surface water and groundwater.

Packed with hundreds of illustrations, this expansive guide reviews both established and innovative aquifer restoration techniques and technologies, including the control and remediation of contaminant sources and groundwater contaminant plumes. Written by a recognized expert in the field, *Groundwater Resources* provides the last word on the all-important subject of how to evaluate and manage the most precious natural resource. 2009, McGraw-Hill Companies, ISBN 978-0-07-149273-7

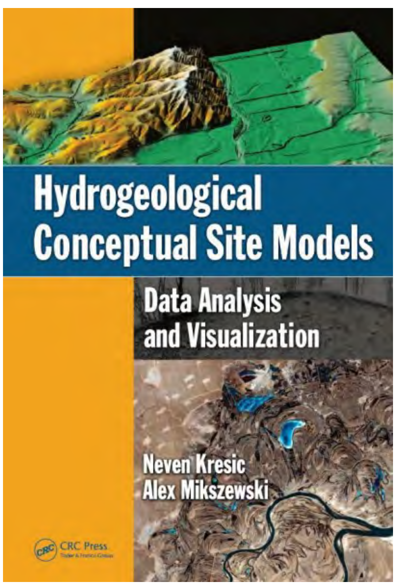


This visual story of the *Lands of Karst*, where the term karst originated, includes hundreds of color photographs contributed by over 70 karst enthusiasts from Slovenia, Croatia, Bosnia and Herzegovina, Montenegro, Serbia, and North Macedonia.

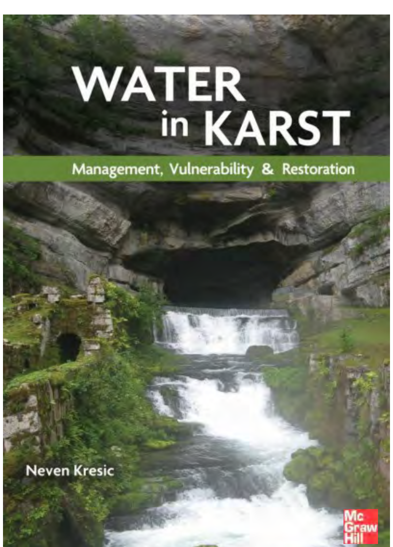
Featured are all types of fascinating landscapes and life: Wild Mountains, Noisy Rivers, Silent Lakes, The Sea, Limestone Walls, Rough Surfaces, Fountains of Life, Windows to Unknown, Magic Chambers, Underground Creatures, Wildlife, and Human Inhabitants in the Past and Present.

The long-awaited visual story, never told before, is finally here.

This book is available for free download and unrestricted reposting and dissemination for all non-commercial uses. 2021, Blue Ridge Press,
ISBN 978-0-578-32045-8

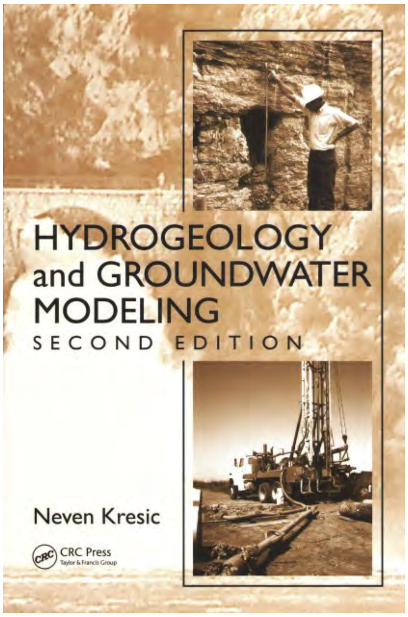


A reference for students, researchers, and environmental professionals, *Hydrogeological Conceptual Site Models: Data Analysis and Visualizations* covers conceptual site model development, spatial data analysis, and visual data presentations for hydrogeology and groundwater remediation. Written by expert practitioners, this **full-color** book demonstrates how fundamental hydrogeological concepts are translated into quantitative, high-resolution graphics. The authors explain analytical methods such as kriging, geospatial processing with GIS, and groundwater modeling through practical real-life examples. Data-rich case studies in groundwater remediation and water resources illustrate the controversial connections between conceptual site models and environmental policy. This visually powerful text contains over 500 illustrations and includes a companion DVD with animations, references, modeling software, and more. 2013, CRC Press Taylor & Francis Group, ISBN 978-1-4398-5222-4



Water in Karst; Management, Vulnerability & Restoration is a complete guide to the engineering and scientific aspects of management and restoration of water in karst environments.

Written by the former co-chair of the Karst Commission of the International Association of Hydrogeologists, this book addresses the unique challenges related to characterization, management, and protection of karst aquifers, which are present on all continents and numerous oceanic islands. *Water in Karst* describes karst hydrogeology and hydrology, surface water-groundwater interactions, site investigation, data collection, delineation of drainage areas, groundwater extraction, regulatory issues, and water vulnerability and restoration. Predictive modeling methods and solutions to restore contamination and overexploitation are included. Photos, diagrams, and an eight-page color insert illustrate the concepts presented in this practical, comprehensive reference. 2013, McGraw-Hill Companies,
ISBN 978-0-07-175333-3



Coupling the basics of hydrogeology with analytical and numerical modeling methods, *Hydrogeology and Groundwater Modeling, Second Edition* provides detailed coverage of both theory and practice. Written by a leading hydrogeologist who has consulted for industry and environmental agencies and taught at major universities around the world, this unique book fills a gap in the literature on groundwater studies.

Reflecting nearly ten years of new scholarship since the publication of the bestselling first edition, this second edition is wider in focus with added and updated examples, figures, and problems, yet still provides information in the author's trademark, user-friendly style. No other books offer such carefully selected examples and clear, elegantly explained solutions. The inclusion of step-by-step solutions to real problems builds a knowledge base for understanding and solving groundwater issues. 2007, CRC Press Taylor & Francis Group, ISBN 978-0-8493-3348-4

This book explores cold and thermal springs in the United States: their origin, characteristics, historical and current uses, and significance. Some of these springs are among the largest and most spectacular in the world and many were and are sacred to Native Americans. Contemporary and historic photographs reveal their beauty and maps, diagrams, and materials from scientific publications and historic chronicles are included to tell their stories. A must read for groundwater professionals as well as spring or nature enthusiasts. The book is also a call to action to protect springs for their unique beauty and to help everyone and everything that depend upon them.

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