International Association of Hydrogeologists

Ian Simmers
Fermín Villarroya
Luis F. Rebollo
(Editors)

Selected Papers on Aquifer Overexploitation

Volume 3
1992

from the
23rd International Congress
of the I.A.H.
Puerto de la Cruz, Tenerife (Spain)
April 15-19, 1991

Volume 3
1992

HEISE

Volume 3, 1992
Hydrogeology, Selected Papers

HEISE

International Association of Hydrogeologists

Ian Simmers
Faculty of Earth Sciences
Free University
Amsterdam (The Netherlands)

Fermín Villarroya
Departamento de Geodinámica
Facultad de Ciencias Geológicas
Universidad Complutense
Madrid (Spain)

Luis F. Rebollo
Departamento de Geoligía
Facultad de Ciencias
Universidad de Alcalá de Henares
Madrid (Spain)

(Editors)

Selected Papers on Aquifer Overexploitation

from the 23rd International Congress of I.A.H. Puerto de la Cruz, Tenerife (Spain) April 15-19, 1991

Volume 3, 1992
Hydrogeology, Selected Papers
Verlag Heinz Heise

Die Deutsche Bibliothek – CIP-Einheitsaufnahme

Selected papers on aquifer overexploitation: Puerto de la Cruz, Tenerife (Spain), April 15 - 19, 1991 / International Association of Hydrogeologists. Ian Simmers ... (ed.). - Hannover: Heise, 1992
(Hydrogeology; Vol. 3) (... International Congress of the IAH; 23)
ISBN 3-922705-62-6
NE: Simmers, Ian [Hrsg.]; 1. GT; International Association of Hydrogeologists: ... International Congress ...

(The designations employed and the presentation of material throughout the publication do not imply the expression of any opinion whatsoever on the part of IAH concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries.

The use of trade, firm, or corporate names in the publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by IAH of any product or service to the exclusion of others that may be suitable).

Volume 3, 1992
Hydrogeology, Selected Papers
I. Simmers, F. Villarroya, L.F. Rebollo (Editors)
ISSN 0938-6378
ISBN 3-922705-62-6
Printed by R. van Acken GmbH, Josefstraße 35, D-4450 Lingen (Ems), West Germany

TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

TABLE OF CONTENTS (continued)

PREFACE

This volume contains 30 papers from 16 countries, selected from the articles presented at the **23rd International Congress of I.A.H. held at Puerto de la Cruz**, Tenerife (Canary Islands) Spain, April 15-19, 1991.

More than 50 countries were represented at the event and over 260 participants from all over the world attended. The topic discussed was 'Aquifer overexploitation' and the themes were:

- Characteristiscs of aquifer overexploitation; hydrogeological and hydrochemical aspects
- Environmental effects related to overexploitation
- Legal and socio-economic problems related to aquifer overexploitation
- Protective and corrective measures in cases of overexploitation
- Overexploited aquifers in water resources management
- Case histories with special emphasis on developing countries

Nine keynote papers were presented by J. Margat (France), E. Custodio (Spain), M.R. Llamas (Spain), J.W. Lloyd (U. Kingdom), A. Sánchez (Spain), R.A. Young (USA), K.S. Johnson (USA), J.H. Lehr (USA), and S.S.D. Foster (U. Kingdom).

One of the sessions was devoted in its entirety to the IAH Burdon Commission and participants from India, Venezuela, Argentina, Nigeria, Uganda, Algeria, Yemen, Mexico, Egypt and China presented their country's paper. Their presence at the Congress was made possible thanks to financial support obtained from UNESCO, UN/DTCD and WMO.

The total number of papers presented was 91 and all appear in the proceedings of the Congress edited by the Spanish National Committee of IAH.

The present edition of Selected Papers (Volume 3) provides a view of the wide spectrum of issues relating to aquifer overexploitation and illustrates the great interest shown in defining and analyzing the positive and negative effects of overexploitation present in different parts of the world.

We strongly believe that this volume contains some outstanding scientific papers, that it represents an important contribution towards solving groundwater management problems, and gives an excellent idea of the state-of-the-art and the direction this subject will take in the future.

Ian Simmers, Fermín Villarroya and Luis F. Rebollo

ACKNOWLEDGEMENTS

The Editors would like to express their appreciation to the Scientific Referees for this Volume, viz: W. Back (USA), E. Custodio (Spain), J. Day (U. Kingdom), R.A. Downing (U. Kingdom), M.A. Kerr (Canada), A. Sahuquillo (Spain), and J.M. Sharp Jr. (USA), for their excellent and conscientious efforts.

Because this volume arises from the Tenerife Congress, thanks must also be expressed to all the people who helped make the event possible;. members of the Organizing Committee, Local Committee, Scientific Committee, Authors and the Secretariat Staff.

It would not have been possible to organize the Congress without the vision and support of the Spanish National Committee, and the financial assistance of the **Consejería de Obras Públicas, Vivienda y Agua del Gobierno de Canarias**, and other national and local institutions.

The present book, devoted to Selected Papers, was composed thanks to the efficient secretarial and editorial work done by the sisters María José Campos and Mercedes Campos.

Elizabeth Lowndes and Enrique Guerrero are also acknowledged for their efforts with correcting the non-native English articles and further reviewing all the papers.

Section 1:

CHARACTERISTICS OF AQUIFER OVEREXPLOITATION: HYDROGEOLOGICAL AND HYDROCHEMICAL ASPECTS

HYDROGEOLOGICAL AND HYDROCHEMICAL ASPECTS OF AQUIFER OVEREXPLOITATION

E. CUSTODIO
Department of Geo-Engineering
Civil Engineering School, Polytechnic University of Catalonia
Gran Capitán, s/n, Mod. D-2, 08034 Barcelona, Spain.

ABSTRACT. Aquifer and groundwater overexploitation is a relatively new, ambiguous and controversial concept in Hydrogeology. Its definition is difficult due to the many different aspects it involves and the variable perception by different technical and social groups. Overexploitation is commonly referred as to the adverse effect of groundwater exploitation, although a balanced view should also consider the beneficial side. It is closely related to safe yield or other similar terms used to try to quantify the exploitable resources of a given aquifer. These concepts are highly dependent on which kind of adverse effects are considered and when they are taken into account. Also, the pattern and time distribution of abstraction play an important role in the effects. The definition of overexploitation by comparing abstraction with recharge is not straight-forward and sometimes unfeasible due to the uncertainty of recharge calculations, the importance of long transient effects, the changes in recharge due to human activities and the possibility of modifying it by artificial methods. But water quality changes, mainly due to mixing with natural saline water, are important issues to be considered in the evaluation of aquifer safe yield and overexploitation situations, especially taking into account the possibly long delay in the appearance of the effects and the difficult monitoring. In any case, overexploitation refers mainly to long-term trends. The new Spanish Water Act introduces the concept of overexploitation. This is discussed and some reflections on the situation in Spain are presented.

INTRODUCTION

Although many aspects of what can be called aquifer overexploitation are not new in Hydrogeology, this concept is still poorly defined, and subjected to varying interpretation by the different kinds of specialists, managers, policy makers and the public. The early works of Meinzer (1920), when considering groundwater resources of semiarid Western United States, include considerations that can be related to aquifer overexploitation, but the term does not appear explicitly.

A set of terms, not always fully equivalent, are in use for concepts related to aquifer overexploitation, such as overpumping, overdraft, overdevelopment and groundwater mining. It is common to apply them looking preferentially at the real, imagined or foreseen adverse aspects involved (Custodio, 1991). The term groundwater mining is used when conscious and planned abstraction rate greatly exceeds aquifer recharge (UN, 1992). Very frequently hydrogeological situations dealt with refer to shallow aquifers, well replenished by rain or by rivers on a annual basis, in which the main problems are related to the wells themselves, interferences between them and with the rivers, and groundwater quality issues - mainly due to pollution - or consider aquifers close to natural conditions, or focus on other problems. This explains why hydrogeological literature has rarely made use of such terms (Custodio, 1989b). Groundwater quality problems due to excessive abstraction, such as seawater intrusion, is seldom qualified as overexploitation, although in many aspects consequences are closely-related (Custodio, 1988; Custodio & Bruggeman, 1988). The overexploitation problem is specially sensitive in small islands (Falkland & Custodio, 1991).

Massive use of groundwater from large systems is something relatively new, except in some areas in or near the arid belts. Most of them are related to well-established extensive irrigated agricultural developments or huge conurbations, such as those in the S and SW United States, NW Mexico, Mexico City, Israel and S and insular Spain. In the last decades new regions have been added, such as Jordan and other areas of the Arabian Peninsula, areas of India, Pakistan and China and Southern Lybia. See UN (1991) for further details.

Hydrogeologists and groundwater managers working in the dry parts of North-America were concerned about the sustainable economic output when there is excessive groundwater withdrawal. They developed the concept of 'safe yield', which will be considered later. This is mainly a concept introduced by groundwater developers, managers and engineers. Conversely, overexploitation is largely a point of view referring to the consequences of intensive groundwater use, as perceived by environmentalists, sociologists, news media and the public in general, and places more emphasis on the adverse or detrimental aspects. Sometimes the concept is used with apocalyptic undertones, and perhaps neo-malthusian connotations.

Overexploitation was converted into a legal term in the Spanish Water Act of 1985, but no clear definition is included. In some way this is the result of an over-reaction to presumed critical situations found in intensively pumped aquifers in some areas of continental and insular Spain. This will be explained later on.

To evaluate a situation that could be termed as 'overexploitation', not only hydrogeological aspects have to be taken into account, but also economic, social and political ones, as well as the point of view of the persons concerned (groundwater exploiters, water administrators, water managers, land-use planners, economists, local people, environmentalists).

Llamas (1984a and 1984b) explains some aspects of overexploitation as ill-transposed surface-water hydrology concepts by engineers, planners and decision makers with poor training in groundwater resources.

SAFE YIELD, OVEREXPLOITATION AND GROUNDWATER MINING

After Meinzer (1920), the 'safe yield' of an aquifer can be defined as the water that can be abstracted permanently from an aquifer without producing undesirable results. This concept has been widely used by the American Association of Civil Engineers (ASCE, 1972). In order to take into account the influence of exploitation pattern, Todd (1976) introduced the concept of 'perennial yield': the flow of water that can be abstracted from a given aquifer without producing results which lead to an adverse situation. A given aquifer has different safe yields, depending on the way it is exploited, changes in natural recharge due to land-use modifications and the introduction of engineered changes in the recharge, such as the different forms of artificial recharge (Custodio, 1986).

The most difficult aspect of such definitions is reaching an agreement on the meaning of undesirable results or adverse situations. The evaluation may be very different from the point of view of the exploiter itself, of the other exploiters, of government officials for water administration and management, of environmentalists and even of the public. The groundwater exploiter is generally concerned about the possibility of getting the desired water with a given quality during the life of the installations, and about the resulting costs. Other exploiters center their concern on the deepening of groundwater level, which increases their own expenses in energy or decreases the yield of the wells, drains or water galleries, or in possible groundwater quality deterioration as the result of aquifer exploitation. Managers and government officials may be more concerned about the possible decrease in river and spring flow, how to solve water conflicts, how to re-allocate changing water resources, and the compliance with regulations. Environmentalists may be concerned about the impact on water table-dependent vegetation and wetlands, the impact of decreasing spring and river flows, or possible land subsidence and collapse problems. Public concerns depend largely on their own perception of the water resources system. In this respect, people from rural areas are generally more sensitive to real problems than are people from urban areas, who rarely understand the behaviour of natural systems, have sectorialized opinions and are highly dependent on the kind of mass-media information they receive, which may be easily biased or laced with intentional or unintentional erroneous concepts. In this respect information and basic training are key factors to redress such possible deviations.

The above comments refer mainly to 'quantity' aspects and the related economic consequences, which are easy to understand and may be observed in a relatively short time, making it easy to relate cause and effect. 'Quality' aspects are as important and sometimes more serious in the long-term, especially in coastal areas and small islands, but also in thick aquifers, where other existing saline waters may encroach the exploited aquifer. The appearance of groundwater quality problems are usually delayed for long periods. It is difficult to prove a cause-effect relationship. Commonly, quality changes present a more widespread impact, and as a consequence they are more difficult to control and solve, and are not well perceived and understood by the public, mass-media and even decision makers, engineers and hydrologists. But some 'quantity' aspects also share misconceptions when long transient periods are involved; even qualified persons fail to recognize them properly, as will be commented later on.

To evaluate possible aquifer (hydrogeological point of view) and groundwater (managerial point of view) overexploitation, not only detrimental (negative) effects have to be considered, but also beneficial (positive) effects. Otherwise a biased assessment may be reached. In many cases beneficial aspects may dominate over detrimental ones.

When there is a continuous watertable lowering due to groundwater abstraction greatly exceeding recharge, aquifer reserves are being used in a process similar to mineral mining and, more precisely, to oil and gas mining. Once the aquifer is depleted, in arid areas it will take generations or even centuries to recover. In many situations the storage of fresh groundwater was formed under wetter environmental conditions milleniums ago, when recharge was greater.

Since fresh groundwater in the aquifer is not beneficial to any one, except to sustain some environmental conditions, in principle there is no objection to 'mine' the reserves for beneficial use if environmental values and the rights of future generations are duly considered, and if it is well known that the resource is limited in quantity and in time. To be confident that such a policy is not against the general interest, an economic study has to be carried out to determine:

(a) the interest rate during the period which is sufficient to repay capital investment;
(b) local benefits;
(c) general interests satisfied by the groundwater development;
(d) the foreseeable consequences deriving from the progressive reduction in the availability of water, including ecological impacts;
(e) equity considerations with respect to future human generations.

A frequent decision in coastal aquifers is to overpump, until the aquifer is sea-water encroached. This may be a reasonable kind of groundwater 'mining' if carefully planned.

Near large urban areas aquifers are important from the security and strategic point of view, in the event of failure or major contamination of other water-supply sources. This has to be considered and evaluated before deciding to 'mine' an aquifer. Conservation may be a wiser alternative under many circumstances.

Groundwater mining is well known in North Africa (mainly in Libya, with the 'man-made river' from the Sahara Desert to the Mediterranean coast) and in the Arabian Peninsula (Margat & Saad, 1982; Margat, 1990).

Well planned 'groundwater mining' is possible, and economically and socially correct. It is not to be considered 'overexploitation' if things go as planned, even when the effects are the same. It may be termed overexploitation when there are serious deviations from what was planned or when there is no planning at all.

DURATION OF TRANSIENT STAGES

Any change in the aquifer input or output produces a transient situation until a new steady state is attained, if it is possible. Transient stages are the necessary response to abstraction, being it 'excessive' or not. This refers to both groundwater levels and the position of the boundaries between different groundwater bodies, e.g. the contact between fresh and salt water.

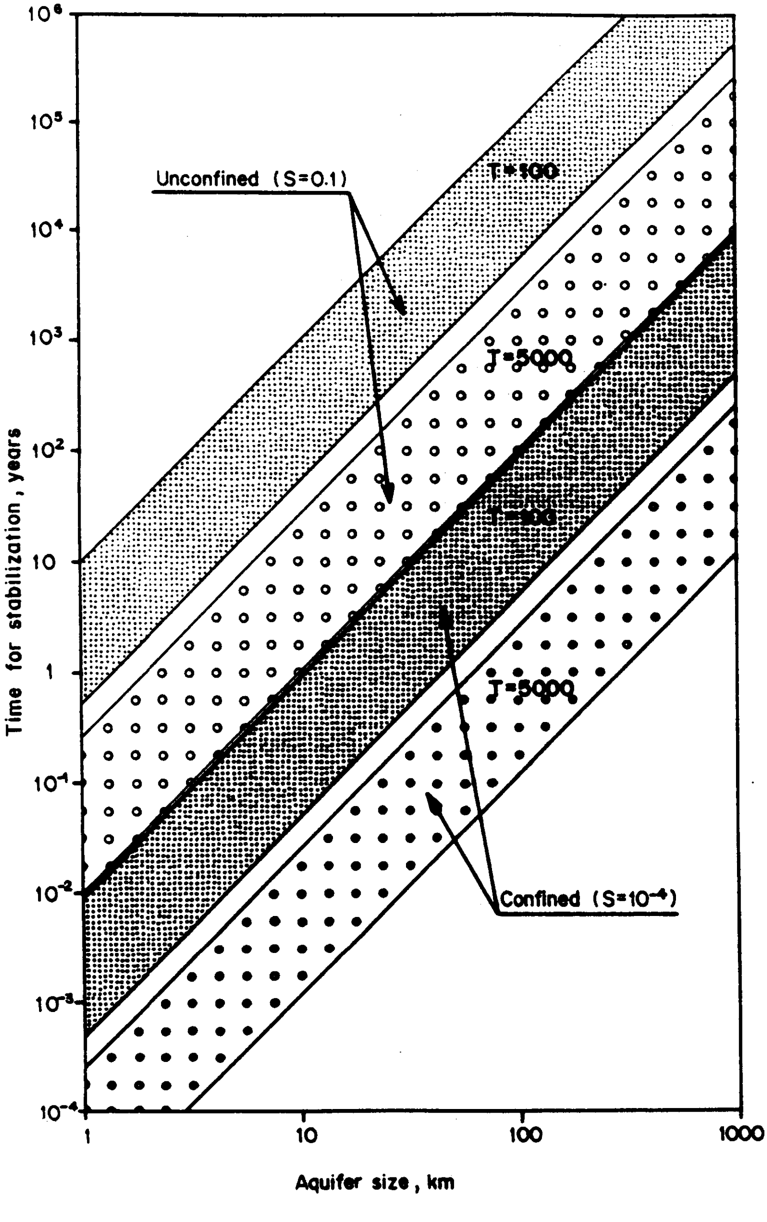


Figure 1: Time for stabilization of drawdowns (in years) in an aquifer after a sudden change in the water balance, according to size (L, in km) and as a function of transmissivitivy (T, in m^2/day) and the storage coefficient (S). The time is proportional to L^2S/T.

The transient stage ends when no further changes in mean groundwater level or interface positions are noticed. This is not a precise definition since it depends on the magnitude of the total change, the accuracy of monitoring and the obscuring effect introduced to other groundwater level fluctuations. Thus, only margins of magnitude can be given if conditions are not clearly defined.

Piezometric level evolution after a perturbation is dependent upon the parameter $\alpha = L^2S/T$ (Custodio & Llamas, 1976; Freeze & Cherry, 1979; Rorabaugh, 1960; Lloyd & Miles, 1986), in which:

L = measure of the dimension of the aquifer
T/S = aquifer hydraulic diffusivity
T = transmissivity
S = storage coefficient

A perturbation practically disappears after a time $t = \beta.\alpha$, in which ß varies in the range 0.5 to 2.5 under most practical circumstances, including islands.

Figure 1 shows how aquifer size effects the duration of the transient stage for high and low transmissivity, unconfined and confined aquifers.

It is clear that in medium to large sized, low transmissivity aquifers, the observation of a continuous drawdown of groundwater levels is not enough to conclude that abstraction exceeds recharge, especially if monitoring has been carried out for only a few years (Custodio, 1991; Margat, 1991). In reality overexploitation is not necessarily the case where abstraction exceeds recharge, but refers to the non acceptability of the consequences of exploitation, such as groundwater level reduction.

In aquifers bounded at the top or at the bottom by aquitards, after a fast rate of groundwater level drawdown, related to the aquifer elastic storage coefficient, a period of slow continuous drawdown follows, generally after what seems to be a temporal stabilization. This is the result of the system behaving as a water table aquifer in the long-term. This situation is common in heterogeneous aquifers in which well yield comes dominantly from a small thickness of the aquifer.

When overexploitation is related to undesirable quality changes, other considerations must be taken into account, such as the physical displacement of salinity fronts inside the system. Assuming as a first approximation that piston flow displacement is an acceptable description of front movement, according to Darcy's law the velocity is $v = k.i/m$, in which:

v = velocity of front displacement
k = permeability (hydraulic conductivity) in the direction of v
i = hydraulic gradient
m = kinematic porosity

Figure 2 shows the time needed for the horizontal displacement of a front, depending on permeability, for a given value of the hydraulic gradient times the kinematic porosity.

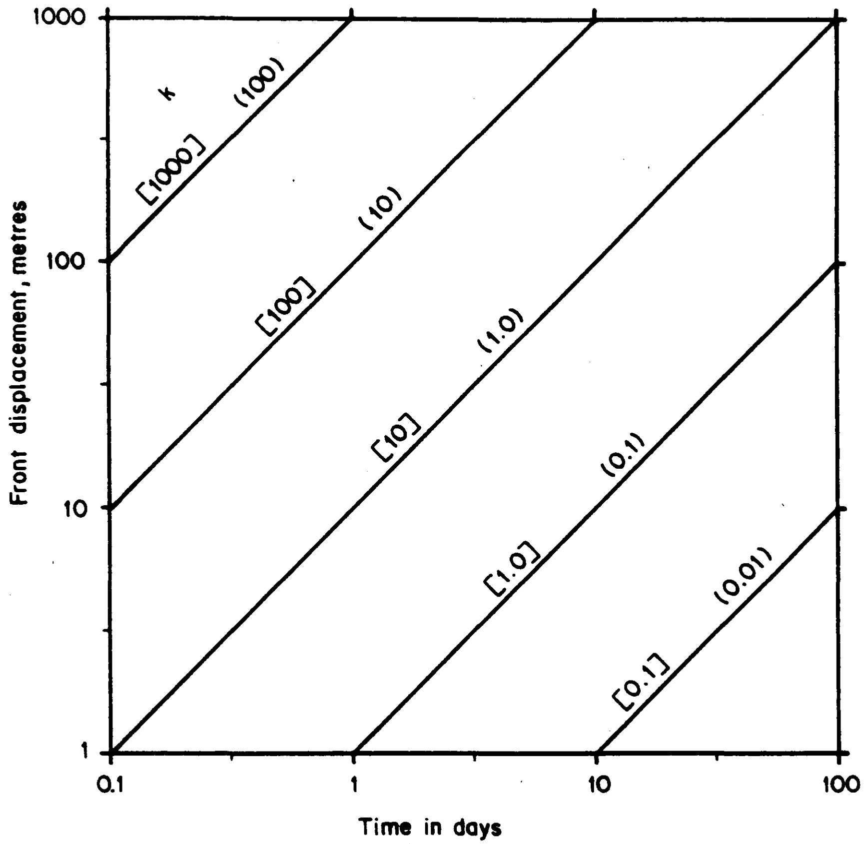


Figure 2: Time for horizontal displacement of a front or interface in an aquifer. k is permeability in m/day. [ ] is for m.i=3.10^{-4} (e.g., m=0.15 and i=0.002) and ( ) is for m.i=3.10^{-4} (e.g., m=0.25 and i=0.002).

A displacement time of a few years is a matter of concern and easily leads to situations that may be termed as overexploitation, but hundreds or even thousands of years may be equivalent to permanent protection. In any case, the dominant -and frequently unknown or unsuspected- influence of high permeability paths is something to be considered. It is difficult to characterize and recognize heterogeneities in detail. The actual gradient producing the front movement is the result of a given exploitation situation and must be deduced by careful flow modelling, or calculated by means of mass transport modelling.

When a variable density fluid is considered, as in the case of seawater intrusion, the situation is more complicated due to the influence of water density in the hydraulic head distribution. In coastal aquifers a landward hydraulic gradient is a clear indication of overexploitation danger, but even maintaining a seaward gradient may produce salinization problems, due to the higher density of sea water (Custodio & Llamas, 1976); (Custodio & Bruggeman, 1988).

UNDESIRABLE EFFECTS OF OVEREXPLOITATION

Most situations in what can be termed undesirable results of groundwater overexploitation are related to the following trends along the years:

(a) groundwater level deepening, continuously or with fluctuations due to changes in recharge and/or exploitation,
(b) spring and river flow diminution or/and wetland surface reduction,
(c) degradation of groundwater quality, either salinity increase or the increase of certain undesirable constituents in the water,
(d) land surface changes in the form of generalized or local land subsidence, or ground collapse.

These changes produce a series of undesirable results with the following aspects:

(a) hydrological aspects: groundwater level decrease reduces transmissivity in water table aquifers, and the yield and specific yield of wells. This is more acute in thin heterogeneous aquifers and in fractured rock aquifers. Groundwater drains and shallow galleries reduce flow or become dry. Well and water galleries have to be deepened or redrilled. Pumping machinery becomes inadequate, works outside their performance range or have to be replaced. Their energy supply facilities have to be enlarged or substituted. There is a decrease in spring and river flow and uptakings reduce their yield or decrease the flow frequency distribution. The entire water resources system is changed.
(b) water quality aspects: wells and water galleries have to be abandoned due to deteriorating water quality, and some treatment has to be introduced before use, including in some cases desalination facilities. The repeated use of low quality groundwater may seriously damage agricultural soil, vegetation, animal raising and industrial production, and in some cases may be the cause of health problems. In coastal aquifers variable groundwater deterioration may appear as the result of the formation of saline upconings.
(c) economic aspects: as groundwater level and well specific yield reduce, exploitation becomes more costly energywise and also new investments are needed for well and gallery deepening or substitution, for pumping machinery and energy facilities, and for new water transport lines. The other conditions being unchanged there is a groundwater level depth beyond which exploitation is economically unsustainable, if the aquifer is not already dry.
(d) environmental aspects: shallow water table aquifers from which natural vegetation or agriculture draw water may suffer a watertable reduction, killing phreatophytes or plants able to use capillary water during the growing season. This is especially noticeable in wetlands and ripanian vegetation belts. In low-lying small coral islands, coconut trees can easily be affected by water table reduction and the related possibility of increased groundwater salinity. Some trees and shrubs are able to extend their roots downwards if groundwater level drawdown is not too fast and not too much, but many other plants are not able to do so. Drought-resistant riparian vegetation also suffer since the equivalent result is extended drought periods to which this vegetation may not be used. The

fauna associated with the affected vegetation is equally damaged, and non migratory animals may disappear from the area.

(e) morphological and geotechnical aspects: this is mainly related to undesirable regional or local land subsidence in unconsolidated sediments, and/or ground sinking by collapse in shallow carbonate or gypsum formations. The results are damage to buildings, structures, basements, roads, railways, canals, etc. and increased risk of inundation after heavy rains, storm surges and high tides. Abandonment of wells in low-laying, intensively exploited areas may produce the inundation and uplift of constructions made when the water table was artificially lowered. This is an undesirable after-exploitation effect.

(f) legal aspects: water rights and pumping capacity of other abstractors, public or private, may be actually or presumably affected. Depending how existing water rights are considered, a normal hydrodynamic evolution may be termed overexploitation and thus, under given legal prescriptions, lead to the introduction of restrictions. An insidious side effect is the extraordinary increase in complaints and legal litigation.

(g) social aspects: the increased cost of obtaining water, water quality deterioration and the possible, or actual, water availability reduction may create social unrest and/or accelerate the loss of employment, eg. by moving agriculture, industry or tourism to other areas. But existing experience is not so dramatic. In most cases there is an adaptation, easy or painful, and no major catastrophic situations are actually known, in spite of predictions in heavily 'overexploited' areas (Custodio 1989a). Nevertheless, non or little renewable groundwater reserve consumption by the present generation is a loss of opportunities for the coming generations, and this is an economical and specially an ethical issue to be carefully considered. However, there will be no future generations if the present one is not capable of living and developing.

It is important to note that the effects of aquifer exploitation do not only depend on the volume being abstracted but also on the time distribution of withdrawals and the well pattern. Thus, the 'safe yield' of an aquifer is a complex function that changes with time. It cannot be considered as a fixed value for an aquifer. Besides, water needs change as the socio-economic framework develops and adapts to variable water availability and costs. Economic impact can be conserved and even increased with less water if new processes are introduced. Therefore, overexploitation is not a permanent situation, even for a fixed bulk abstraction from a given aquifer.

Perhaps the most detrimental cause of everexploitation is the ignorance of what is happening, and the negligence in getting the needed data to correctly evaluate the hydrogeological and economical situation. In the long run a balance will somehow or other be reached, or the exploitation will be finally abandoned (a rare situation), but meanwhile a major investment in money, in effort, and in hope, will be lost (Foster, 1991).

Another detrimental effect of what some call overexploitation is the irresponsible overreaction of water authorities, especially when they are poorly informed or lack the scientific or technical skills to evaluate the physical problem. To try to protect existing shallow wells and galleries or flowing wells in a discharge area the decision to avoid further groundwater level decline usually leads to the interdiction of drilling new wells there or nearer the aquifer recharge one. This decision may prove to defend existing interests, but the aquifer may be underexploited, losing large quantities of water since the first by law have installations that do not allow correct exploitation of aquifer resources.

BENEFITS OF GROUNDWATER OVEREXPLOITATION

Beneficial aspects of groundwater exploitation, mainly from the economic point view, can be summarized as follows:

(a) development in simple stages, drilling new wells only as the need for additional water arises. This allows for a better fit between demand and supply, progressive rather than costly intensive financing and the payment of works from revenues of the part of the project already finished.

(b) little surface area is needed for wells and related water winning facilities, new surface area is more easily acquired, there is no displacement of towns, agricultural lands or transportation ways, and rivers are much less affected.

(c) local manpower can be used, maintenance costs are low and may be solved locally. In remote rural areas pump maintenance and energy supply may be a major problem, but when investment costs and risks of failure are considered groundwater is still most suited if the savings and benefits are used to create maintenance and energy services. They contribute to the development of the area, as well.

(d) water resources availability is increased by evaporation reduction. Evaporation may be enormous in shallow surface water reservoirs, sometimes leaving a brackish residuum.

(e) besides, the lowering of groundwater levels allows for valuable utilization of shallow groundwater, which, under natural conditions, would be lost through evaporation. Abstraction in an alluvial aquifer creates a storage capacity for flood water to infiltrate.

(f) groundwater is in most instances suitable for human consumption and safe without or with only simple treatment if wells are properly constructed and maintained.

(g) wells may produce water close to where it is needed, thus saving costly-to-install and to-maintain water lines, the aquifer playing this role, at least to some extent.

(h) groundwater is generally more efficiently used in the rural world since it is close to the user. Also complex and sometimes unfair subsidizing can be avoided or reduced, and administration can be made easier.

These benefits are not absolute and have to be weighed against other alternatives, case by case, taking into account local physical, human, economic, environmental and legal circumstances.

Benefits exist even if exploitation lead to some kind of overexploitation. What is needed is to know the consequences and extract a part of the benefits -or of the subsidies that would come- to compensate for them, now, or in the future, when investments begin to produce the expected economic return.

In most instances groundwater allows the temporary solution of acute problems of urban population or of abandonment of rural areas. It is better to give some water to the suburbs of fast expanding large conurbations, or to start irrigation or animal raising activities in rural areas, than to leave them to starve or to be deserted, awaiting for difficult, long-term, expensive and uncertain alternatives on the basis of presumed aquifer overexploitation problems, often overstated. This does not mean a simple 'laissez faire' since the aquifers have to be studied and monitored, undesirable effects corrected to the maximum, and provisions be made to cope with groundwater reserve depletion and serious ecological impacts.

The possibility of avoiding some megaprojects for water supply that cripple the economy of developing countries, increase external debt unnecessarily -generally need financing from other countries or international Institutions- have an uncertain output -failures are frequent- and need years, even decades to be completed, is something of uttermost importance. The negative consequences are more easily, clearly and readily corrected when groundwater is used, if there is the will to do it. In some cases, concerning megaprojects there are interests from other countries, local meganomania, ill-conceived politics for big works, and also corruption. Aquifer overexploitation evils are frequently lesser ones, although still they are evils to cope with.

Overexploitation is an acceptable policy if planned with specific aims and as long as the negative consequences have been technically evaluated by those who make the decision and they are economically and socially acceptable. Even so, the issue of intergenerational equity can arise. Some measures valid for surface water reservoirs also apply to some extent to aquifers. Thus, an aquifer that is always full is almost as badly utilized as one which is almost always empty, but some economical (cost of water abstractions) and ecological (maintaining water in some natural outlets such as rivers, springs or water-table-dependent vegetation areas) measures have to be carefully considered.

It may happen that, applealing to its pejorative and emotional meanings, the term 'overexploitation' is used as a political weapon to get other unrelated goals or as a means to justify other water projects, generally much more expensive, that need higher external financing, technology and knowhow, that burdens unnecessarily the economy of developing regions, and that are more prone to under-the-table payments and tips to local, national and foreign receivers.

WHAT IS OVEREXPLOITATION?

Aquifer overexploitation is commonly defined by comparing abstraction to some given quantity and/or considering that some detrimental effects have to be avoided. The most common reference quantity is aquifer recharge.

However the undesirable results of before mentioned have not been defined comparing bulk groundwater abstraction with bulk aquifer recharge. All of them may occur as the result of long transient stages (see respective section), in which recharge is not necessarily exceeded, but yielding similar behaviours during a long series of years. Even when a state of equilibrium is finally attained, there may be a permanent drawdown, flow reduction or groundwater quality deterioration that people can term overexploitation, as far as they remember of the past situation. Then, overexploitation is more an economic, social, environmental and behavioral situation than a hydrogeological one, that may not be clearly related to aquifer recharge.

In many cases a fraction of aquifer water resources are used, as a necessary consequence of overexploitation. When abstraction exceeds recharge there is a permanent decrease in aquifer water reserves until the aquifer becomes depleted, well yield reduction makes them unattractive, further abstraction becomes economically unsustainable or groundwater quality has deteriorated beyond a bearable limit.

In some cases, as in coastal aquifers, it is worth comparing freshwater abstraction with freshwater recharge, since total recharge includes the penetration of sea water or of low quality water from other aquifers or from other surface sources. In that case the drawdown trend may cease after some time but not the progressive degradation of abstracted water quality.

Groundwater recharge is one of the most difficult values to know for a given aquifer. In most cases, available figures are at best assumptions with large uncertainties. Only careful studies based on adequate monitoring of water level, quality and abstraction can produce accurate results. But it has to be borne in mind that results refer to a given volume and pattern of exploitation, and may change with time.

Recharge is not a constant value for a given aquifer, but changes according to exploitation and land use pattern, and can be influenced by artificial interventions. Land-use changes influencing recharge include urbanization, changes in vegetal cover, river channel erosion, coastal erosion or excavation of inland harbours or navigation lines. Forests are effective in evaporating soil water, thus reducing aquifer recharge, other circumstances being the same. Forest destruction or burning, and reforestation of large areas, may have an impact on aquifer and total water resources. The final effect is not easy to predict. The possible increase in recharge by forest cut down cannot be naively taken as a positive effect. Studies carried out in the Murray basin (Australia), shows that formerly slowly downward moving brackish water in the unsaturated zone (the result of low recharge) is now moving faster, after forest clearance, polluting some river reaches and aquifers. This problem will last until the large store of brackish water has been leached down from the unsaturated zone and discharged (Simpson & Herczeg, 1991).

Since problems of overexploitation are predominantly of an economic nature, it could be expected that after economical studies it would be possible to specify the rate of pumping -by geographic area, if appropriate- which maximizes the net present economic value accruing to the groundwater asset, subject to avoidance of damage to third parties. The result can be expressed by a decision rule, which specifies the desired pumping rate. Within this framework, aquifer overexploitation is defined as extraction in excess of that specified by the decision rule, not as pumping in excess of recharge.

However pure economical treatment of aquifer exploitation is not an easy task. It is necessary to consider not only the quantity of water being abstracted but groundwater level, and also groundwater quality when it is variable or may change as a consequence of exploitation. To the physico-chemical parametres an economical one has to be added, represented by the discount rate. Its value may greatly influence the results. A lot of simplifications have to be introduced and then results may easily be naive and unrealistic.

The discount rate to be used does not necessarily coincide with the rate being applied to other economic goods, since the social value of water has to be taken into account. Assigning a value is not only an economical issue but a political one. Water is needed for life and has no other substitute.

Furthermore, it has to be borne in mind that a given economic analysis is not permanent, since parametres may change with time. The reference figure to define overexploitation is then variable. This figure can be given by politicial decree and then overexploitation is simply the situation that overcomes the fixed value. But this may distort market forces, produce loss of oportunities and protect inefficient situations.

Refering to definitions concerning undesirable effects, it has to be borne in mind that the perception of what is an undesirable effect has not been always the same. Some decades ago drainage and desiccation of wetlands was a priority to which land reclamation offices were devoted. Recently, the real need for environment, genetic diversity and natural wildlife preservation has reversed the trend. Many of the remaining wetlands have been converted into protected areas in which such interests frequently clash with often short-sighted development plans involving intensive use of surface and groundwater (Llamas, 1988 and 1989). What decades ago was considered a desirable side effect of 'overexploitation' is now an undesirable consequence. This illustrates the changing perception of what overexploitation is and the difficulty of obtaining a permanent definition. Definitions have to be updated periodically and adapted to new situations, to the better understanding of aquifer systems as exploitation progresses and monitoring is improved, and to the growing concern about environmental protection.

As a conclusion it can be said that a precise definition of aquifer and groundwater overexploitation does not seem possible. It is much better to make a balance of beneficial and undesirable results for a given situation and then decide the technical administrative and legal steps to be followed. Existing legislation has to allow such flexibility and at the same time protect against possible deviations and abuses. Social and political factors play a decisive role.

INTRODUCTION TO THE OVEREXPLOITATION CONCEPT IN SPANISH WATER LEGISLATION

Spain has recently introduced the term overexploitation into its water legislation, thus converting it into a legal term. In the following section this example will be developed, but to understand it an introductory view of water resources in Spain is given below.

As a whole, Spain is the most arid country of the European Community, although large variations can be found in the about 500,000 km^2 territory, from areas with rainfall higher than 1,000 mm/year to areas as low as 100 mm/year in the SE Iberian peninsula and in the Eastern Canary Islands. Good climate and well established long agricultural traditions have helped in developing a prosperous irrigated agriculture over large surfaces, many of them in formerly semi-deserted areas. Many large urban areas, some of them with industrial belts or tourist resorts, are close to the coast, generally in low rainfall regions.

Present groundwater development accounts for 20% of water use, or about 5,000 million m^3/year, of which 85% is used for agriculture; also, 70% of the townships are supplied by groundwater. Abstraction sites have been selected mostly on a local basis, in the absence of a rational planning process.

The 'official' tradition has been the development of surface water resources by mean of dams, canals and some interbasin water transfers. Parallelly, private interests have developed groundwater intensively, more efficiently and to the point of converting economically depressed regions into prosperous ones. About 1 million ha are irrigated with groundwater, and 2,2 million ha with surface water, part of which depends on spring flow.

The intensive exploitation of groundwater, poorly controlled, is not without problems of excessive drawdown -more than 300 m in some aquifers in the SE peninsula and in Gran Canaria and Tenerife islands- loss of well yield, saline water intrusion, groundwater quality impairment and deterioration of valuable wetlands.

There is a long tradition of water administration under scarcity conditions, mainly for irrigation. Local communities developed their rules, well known in the Mediterranean side and in the Canary islands. In Valencia, a popular Water Court has been working uninterrupted for more than 7 centuries.

Unitarian currents in the 19th century stemming from highly centralized governments then in fashion promoted the need for a Water Act enforceable over the whole State Territory, respecting as far as possible old traditions. This produced what is now called the Old Water Act.

After diverse changes and political adaptations, the old Spanish Water Act, first drafted in 1866, was finally enacted in 1879 (see Pallardó, 1976 and Guaita, 1987 for details). Most regulations referred to surface water, which was declared public property. Groundwater was the property of the abstractor and thus was considered as private. A few regulations protected public groundwater, and registered groundwater abstraction works, against the detrimental effects of new abstractions at a close distance, generally 100 m. It is worth noting that when the Water Act was enacted the common water extraction method available was the waterwheel. Piston pumps moved by bulky steam engines were just appearing, drawing from large diameter wells, mostly in alluvium, which could be afforded only by large industrial or municipal supplies. At that time the present development of groundwater, and the possibility of abstracting large flows from small diameter wells (boreholes), by means of deep turbine pumps driven by electrical motors, was hardly imaginable. Even with these handicaps, this Act has been largely recognized as an excellent piece of legal work, that has produced good results during the more than 100 years during which it has been in force.

Actually important groundwater winning schemes were developed, mainly by the private sector, under a Water Administration preferently devoted to surface water, and often ignorant of hydrogeological principles and little interested in them. This situation was further complicated by the antagonism between different sectors of the Administration after splitting the former Ministry of Public Works ('Fomento'), under which the Water Act was enacted, into different Ministerial Departments. Some groundwater administrative competences were given to some of them, while others received the administrative task of applying the Act. As a consequence, and in order to avoid interdepartmental conflicts, some provisions in the Water Act capable of coping with conflicting situations of groundwater exploitation were seldom applied. Also many officials did not know how to apply them correctly due to the lack of adequate hydrogeological training, technical support and groundwater monitoring networks.

At the same time, mainly after 1960, some aquifers were showing problems of what was gradually termed 'overexploitation', e.g., depletion of alluvial aquifers (Middle Besós basin, Barcelona), sea water intrusion (Llobregat and Besós deltas, Barcelona; Palma de Mallorca; Tarragona Plain; Empordá lowlands, Girona; etc.), continuous large groundwater level drawdown (Gran Canaria and Tenerife islands; Campo de Dalías and Campo de Nijar, Almería; areas of Alacant and Murcia; Tarragona Plain; etc.), and depletion of springs and discharges to important wetlands (Tablas de Daimiel, Ciudad Real; Doñana National Park, Huelva and Sevilla; some areas in the Duero Basin as Villafáfila, etc.). Some intensively exploited areas of Murcia (Gutiérrez-Escudero, 1985) were presented as clear examples of the bad consequences of uncontrolled private groundwater exploitation and human greed. Many of the available technical studies showed the problems but were not deep enough to give the quantitative descriptions of the transient stages of the hydrogeological systems. Thus, the apparent consequences were known but not the dynamics. Consequently the best ways to cope with them were unclear. It was difficult to separate local problems created by excessively concentrated abstractions, inadequate well design and construction or misoperation from true regional problems. The common hydrogeological ignorance of groundwater owners added to this, and as a consequence some basic data were unavailable, unreliable or concealed, and independent monitoring was missing or insufficient.

Under these circumstances 'special laws', or regulations to try to solve problems by restricting new abstractions in problematic areas, were enacted as Decrees or Orders of some Ministerial Departments, which were sometimes difficult to apply and even ignored by other Ministerial Departments, or plainly not taken into account by the Civil Courts when apparently in conflict with other regulations, such as the Civil Code.

All this created the environment and expectancy under which the new Spanish Water Act was shaped. It was drafted by government officials, some of them with managerial knowledge of the areas with conspicuous 'groundwater problems', largely biased towards surface water problems and many of them with only occasional training in groundwater. Overconcerned officials tried to get easier control of what they considered catastrophic situations. This explains the introduction of the terms 'overexploitation' and 'risk of salinization' of aquifers in the legal text, although no clear definitions are provided.

In the drafting of the new Water Act some general ideas pre-dominated: the whole water cycle must to be public; users must participate in the Water Administration (later somewhat downscaled); quality aspects are important; Spain is full of groundwater problems which need urgent solutions. Apparently some principles were relaxed in order to conserve competences of some Ministerial Departments, thus avoiding their opposition to the Water Act or reducing the time required to enact it, a political goal at the time. This also explains the reduced possibilities provided for public discussion of it (Llamas & Custodio, 1985; Llamas, 1987). It seems that the Water Act was produced in a hurry.

Special hydrogeological conditions exist in the Canary Islands, mainly rather low permeability volcanics. They are of small size, have a strong orographic effect on rainfall (from 100 mm/year at the Southern coastal areas up to 1,000 mm/year in the northern slopes of the high islands), and still stronger on recharge, and high abstraction rate. In some areas of Tenerife and Gran Canaria islands a continuous groundwater level decline -up to 10 m/year- is being observed, with total drawdown of several hundred metres, recharge being close or less than abstraction. There is a long lasting, transient situation, and with existing water-gallery and well pattern, the final result is high abstraction costs, non-recoverable loss of yield in some areas, and water quality degradation by sodium-bicarbonate or saline water. The old Water Act was adapted to cope with local problems, concentrating water management in only one Institution. The new Spanish Water Act made provisions for a separate Water Act for the Canaries, respecting the general directives. This regional Water Act was enacted with provisions for tight control and intervention of the well-established and popular private water rights -something deeply rooted in the social context- and poor public hearing. When it was enacted public reaction was so strong that the Regional Government fell and the new one won the elections with the promise of changing the Water Act. It was finally done (Ley 12/1990) after overcoming legal difficulties. Some old rights have been preserved, such as the existence of companies created to explore, drill and sell groundwater, and more power is given to island governments to organize their own water plans.

The islands with 'excessive' groundwater exploitation (Gran Canaria and Tenerife) are suffering a series of problems and there is serious litigation, but they have developed their economy and have been able to provide a reasonable standard of living for their inhabitants, which shows no signs of serious deterioration due to groundwater 'overexploitation'. High water demanding crops are being substituted for others less demanding and/or with high added value, in which water cost is not as important. Desalination plants have been introduced, some using brackish groundwater to supply agricultural farms. Reuse of urban sewage water for irrigation, gardening and some urban services is being introduced. Actually, in Gran Canaria groundwater abstraction has been clearly reduced without preventing economic development.

OVEREXPLOITATION IN THE 1985 SPANISH WATER ACT

For a better understanding of the overexploitation legal concept in the new Spanish Water Act, enacted in 1985 (Ley 29/1985), some sections are given below (as translated in MOPU, 1990). Section 54 says:

'1.- The appropriate Drainage Basin Authority, after the Water Council has been heard, may declare underground water resources in a particular area to be overexploited or in danger of being overexploited. At the same time, the Authority must establish comprehensive rules for all kinds of uses in order to achieve more rational exploitation of the resource and make the necessary revision of the Hydrological Plan'.

'4.- The implementing Regulations shall set out the procedures to declare an aquifer to be overexploited and to determine the perimeters referred to in the foregoing paragraphs'.

Accordingly, the Regulations of the Water Act added some details. So, Section 171 of the Regulation of the Public Water Domain (Real Decreto 849/1986) tries to define a little what overexploitation means (author's translation):

'2.- It will be considered that an aquifer is overexploited or in danger of being overexploited when, as a consequence of practising yearly abstractions greater or very close to the mean value of yearly renewable resources, the endurance of existing aquifer abstractions are being put into immediate danger, or a serious water quality deterioration is occurring'.

Also 'the existence of the danger of overexploitation will be considered when the volume of extractions, referring to aquifer renewable resources, produces an aquifer evolution which endangers the long-term endurance of existing abstractions'.

Point 4 of the same Section details the action to be taken in order to comply with section 54.1 of the Water Act:

'4.- The provisional declaration [of overexploitation] will include the perimeter of the affected area and, in the field of application, will have the following effects:

(a) to bring to a standstill all procedures for permits to investigate or for concession of groundwater.

(b) to withhold the rights to start new abstraction works as stated in section 53.3 of the Water Act ['in the case of water reserved or included in a State plan which is not to be brought into immediate use, interim concessions may be granted which will not grant any right whatsoever or give rise to compensation if the Drainage Basin Authority reduces this volume or revokes the authorization']. While the overexploitation situation is in force, this type of use is subjected to the authorization regime specifically established for this situation in the declaration.

(c) to bring to a standstill all procedures for modifying groundwater concession characteristics.

(d) to constitute an aquifer Users Association, if not already existing, applying section 79 of the Water Act ['the users of one and the same hydrogeological unit or the same watercourse shall, upon request from the Drainage Basin Authority, form a users association. Said Authority shall, at the request of any interested party or ex-oficio, set forth its limits and establish the system of joint use of the waters']'.

'5.- The Drainage Basin Authority, after consulting the aquifer Users Association, shall prepare a Plan to arrange abstractions in order to overcome the problems. This Plan must be submitted to the public and to the judgement of the basin Water Council'.

'6.- The Governing Board of the Drainage Basin Authority shall approve, if suitable, the arrangement plan, which involves the aquifer being declared definitively overexploited. This declaration involves the immediate application of the Plan'.

'7.- When an aquifer is definitively declared overexploited or in danger or being overexploited, the Water Plan of the Basin, if existing, must be revised as regards the area overexploited. The Water Plans issued after this declaration shall explicitly mention its endurance or modification'.

'8.- As a common rule, to adequately control groundwater abstractions, the final declaration can force the installation of measuring devices at the outlet of the abstraction works'.

'9.- If at the end of the term established for carrying out the Plan the desired objectives have been met, the By-Laws of the Association shall be adapted to the new exploitation regime of the aquifer. If not, the Government Board of the Drainage Basin Authority shall grant biannual extensions of the Plan, with the necessary changes'.

Section 84 of the Regulations of the Public Administration of Water and of the Water Plan (Real Decreto 927/1988) adds:

'2.- The Water Plan shall include the list of overexploited aquifers or those in danger of being overexploited, as well as those in process of being salinized, or declared as such by the Drainage Basin Authority'.

'3.- Also, basic criteria for protecting groundwater against saline intrusion or other causes of deterioration shall be determined'.

APPLICATION OF THE OVEREXPLOITATION CONCEPT AFTER THE SPANISH WATER ACT

Recent studies (López-Camacho *et al.*, 1991) divide the Spanish peninsular territory and the Balearic Islands in 369 aquifer units. The study shows that 78 of them present exploitation problems and in 42 of them there is an excess of abstraction over estimated recharge. The total deficit in a surface of 23,000 km^2 is 650 million m^3/year, or about 13% of total groundwater abstraction. That overexploitation has been the motor for development in many areas of SE Spain that have passed from a depressed situation to quite good economic achievements. Reserves are expected to last only a few decades in some areas, but solutions are being sought since now the existing wealth allows for the development of new water resources -even interbasin transportation- or the introduction of less water demanding new crops, that before were unthinkable.

It is interesting to note that, at national level, overexploitation in Spain is not extraordinarily high, although it may be of some concern under the special conditions of the Balearic and Canary islands. The Ogallala aquifer, in Southern United States is more 'overexploited' and has produced less official 'nervousness'. It underlies some 135,000 km^2. Following the droughts of the 1930s, irrigation from groundwater was developed rapidly, at a rate exceeding replenishment by a factor of 6 to 16 (to 8,000 million m^3/year for the irrigation of 1.8 million ha in 1980). In nearly half of the region, water levels declined by 3 to 15 m by 1980 and by 15 to 30 m in 20% of the area. Enormous benefits have been derived for the region and exploitation will continue but at a decreasing rate. Only New Mexico, one of the three States involved, has declared groundwater public domain, and even with this provision only special areas are under strict control.

In some aspects Spain can be compared to California (Llamas, 1984b): 500,000 km^2 *s.* 400,000 km^2; 40 million inhabitants *vs.* 25 million; climate varying from wet to desert, although California as a whole is slightly more humid than Spain. California uses as much as twice the surface water and 3 to 4 times more groundwater than Spain. Aquifer water mining reached 5,000 hm^3/year, although at present is reduced to 2,500 hm^3/year, still much higher than in Spain. Out of 392 groundwater basins (369 in Spain), 42 are considered overexploited (42 in Spain), 11 of them critically (about 15 in Spain). This situation is considered bearable and controllable.

The Spanish Water Act relies heavily on the Basin Water Plans and on the National Water Plan, which after six years from the enactment of the Act, and about 12 years from the start of their drafting, are still not ready, although the Basin Authorities have just produced guidelines -or are asked to produce them very soon-. In short, the National Water Plan will be passed to the Parliament. Afterwards the Basin Water Plans have to be definitively approved. It seems that there is no much room left for public debate. In the meantime, several provisional declarations of an aquifer being overexploited or in danger of being overexploited have been made.

Overexploitation is provisionally declared by the Basin Water Authority, using its data and studies. The definitive declaration is done by the National Water Council -or the corresponding body of the Regional Goverments when they have competence to do it- with the advice of official Institutions and some time for public hearing. As shown in section 7, the declaration of overexploitation binds the constitution of groundwater users associations, implies changes in groundwater abstraction -quantity and pattern- and modifies the Basin Water Plan (if it exists). Furthermore, such a declaration obliges the Water Administration to make studies, controls and management, but in reality it is understaffed and short of the economic resources necessary to carry out the task effectively.

At the moment there are 13 provisional declarations of overexploitation (López-Camacho *et al.*, 1991), affecting some 9,000 km^2 of territory and 460 million m^3/year of the 650 million m^3/year of excess abstraction over estimated recharge. Only 7 out of the 13 areas declared provisionally overexploited have a clear deficit. Actually 3 of them have still a clear excess, the declaration being produced due to other circumstances or to political pressure. In fact, in the only aquifer already declared definitively overexploited abstraction is less than 40% of assumed recharge, there is no clear trend in groundwater levels and overexploitation has been called 'temporal'. The objective has been environmental, to maintain water flow to some lakes. This case is the subject of wide argument. The 'temporal' overexploitation concept does not agree with what usually is termed overexploitation and does not conform to the long-term effects indicated in the Regulations of the Water Act.

Overexploitation criteria applied in these decrees seem rather heterogeneous and erratic. In some cases 'overexploitation' is probably used as the 'magic word' that allow the Administration to intervene in a given situation under the umbrella of the new regulations. These interventions may be technically, socially and even politically justified and may be needed to correct a given adverse situation, but they are generally not supported by sound hydrogeologic, economic, social and land-planning studies and analyses, and lack the support of a widely accepted and publicly discussed Water Plan and its social support.

Some of the areas which many feel as -but not necessarily are- heavily 'overexploited', such as Gran Canaria and Tenerife islands, some areas of Mallorca and Menorca island, Eibissa (Ibiza) island, the surroundings of the Doñana National Park, the Tarragona Plain, etc., have not been declared overexploited although special provisions are being taken or are being prepared to cope with existing problems. The ITGE (1991) has listed some of these areas. Some regional administrations try to avoid such declaration due to the legal consequences and the responsibility passed to under-staffed, under-equipped and unprepared Administrative units. Problems are being solved with milder instruments, trying to gain the cooperation of groundwater users.

It has been argued that the way 'overexploitation' has been handled in the Spanish legislation, drafted by lawmakers and administrators not fully informed on groundwater matters, is not entirely satisfactory, and that its lack of clarity may generate difficulties. For example, a lowering of water levels and an increase in salinity is not necessarily a sign of the 'overexploitation' which the law is trying to avoid. In fact, some of the measures which are proposed by the legislator could lead to a worsening of the situation. For example, the closing of salinized wells or a reduction of abstraction may be detrimental if wells actually reducing saltwater head are suppressed.

The Water Act mentions the need for good and adequate monitoring and make Basin Authorities responsible for it. The regulations do not deal adequately with this aspect, and no clear provisions are established for manpower, economic resources and training. A possible approach for solving part of the problem is to incorporate groundwater users into the process of data gathering and evaluation, and in the process of preparing management rules. This needs some kind of users associations or water districts, and some kind of quality assurance of data being produced.

The users associations, as shaped in the Water Act, seem adequate for these purposes if they have a technical staff and are convinced that the protection of their own resources has a cost, all or a part of which they have to support, in order to preserve the benefits they are obtaining from groundwater use. Users associations are taken into consideration in the Water Act, and some successful trials were carried out before it was enacted (Ferret, 1985;

García-Gallego & Galofré, 1989), mainly near Barcelona. New ones are being constituted, fostered by the Water Authorities, but this shows as a slow process, complicated by a shortage of adequately trained personnel. But it seems that a sector of the Water Administration prefers keeping their role without the challenge of users being too close to its decision-making bodies, sharing some of its power and reducing its free-hand decision capability.

To counterbalance for users associations natural tendency for overprotection, public water managers and administrators have to compensate for it. The Water Act gives the elements to do it, but there is little practical experience and no trained personnel.

Aspects of groundwater quality are much more difficult to consider, and the Water Act and its Regulations only provide general declarations. Also there is little experience in the application.

In many situations, necessary monitoring data are missing or simply cannot be obtained due to the lack of wells in critical areas, or at the required depth, or tapping the level of interest. A simple increase in salinity is an alarm, but without knowing the origin of the salt and the most likely process of salinity penetration it is difficult to take the right technical, legal and administrative actions to protect the aquifer. Some simple solutions may be detrimental, such as the closing of salinized wells or a general reduction of abstraction, if wells reducing saltwater head are suppressed. Such measures have little effect when salinization is produced by the infiltration of return irrigation flows or by wells partly open in a salinized deep aquifer.

Quality problems due to infiltration of polluted water or by pollutants cannot normally be linked to overexploitation, although some consider them overexploitation problems if the penetration is the direct result of abstraction, as in the case in which a discharging (effluent) river is converted to a losing (influent) one due to groundwater drawdown.

CONCLUSIONS

Aquifer overexploitation, a relatively new concept in hydrogeology, can be defined from the point of view of the groundwater abstractors or can be related to the results of these abstractions. Common groundwater overexploitation aspects focus mainly on the most negative consequences, as seen by the different social groups involved. However, a balanced evaluation needs to consider the frequently important beneficial results.

Overexploitation is not necessarily a situation in which abstraction is greater than recharge, nor is this situation necessarily overexploitation. Overexploitation is not an easily bounded concept. It depends on the perception of the short and long-term consequences of groundwater abstraction, on the quantity and quality of the aquifer groundwater and on the related environment.

To make an assessment of the consequences of exploitation of an aquifer, and to decide whether it is overexploited under a given set of conditions, it is necessary to have a good and quantitative understanding of the behaviour of the aquifer or the aquifer system. This understanding has to be checked periodically as new data are gathered and exploitation progresses. It is not rare for a given situation to be qualified differently when new data are available, priorities change or human intervention changes input and output factors.

Simple observations of groundwater level changes and quality (mainly salinity) are not sufficient to decide whether an aquifer is overexploited or not, provided some definition is given, but point to the convenience of specific studies and detailed monitoring. In large and low permeability aquifers the start of groundwater exploitation iniciates a transient stage that may last years, decades and even centuries, leading to major changes in groundwater storage and quality, even when abstraction is less than recharge. Whether this is overexploitation or not has to be decided according to the evaluation of the consequences.

But without a well bounded definition of overexploitation there is a large range for personal interpretation and a wide area for argument, but it is probably not possible to make a well bounded definition of overexploitation. Instead, some guidelines on undesirable effects that should be avoided would be welcome. These guidelines probably have to change from area to area. Some of them may be quite general but others would probably be specific for a given area.

Criteria based on comparison of abstraction with recharge must be used carefully since recharge is difficult to measure accurately, and even its order of magnitude may be controversial. Also, recharge is exploitation-dependent, as in the case of aquifers linked to rivers, and it can change over time due to human activities, which are related or unrelated to water resources. If such criteria are used, they must be very flexible, easily updated, and acceptable and clear for managers, administrators, lawyers and groundwater users.

The new Spanish Water Act has introduced the term overexploitation, and the related salinization risk. These now have legal implications. Under these provisions some aquifers have been declared overexploited, but the real benefits are still unclear, since the designation has been used without clear definitions and in some aspects without the support of adequate hydrogeologic, economic and social studies. Nevertheless, it is something to be followed in order to draw technical, managerial, administrative, legal and social consequences.

ACKNOWLEDGEMENTS

The CICYT (Spanish Interdepartmental Committee for Science and Technology) Project PB87-0842 on Doñana Wetlands Hydrogeology, and the Department of Geo-Engineering of the Civil Engineering School of the Polytechnic University of Catalonia have provided the necessary resources and support for the preparation of this paper. The ideas expressed in it are those of the author and do not necessarily coincide with those of these organisations.

REFERENCES

ASCE 1972. Ground water basin management. *Manuals and Reports on Engineering Practi-*

ce, 40. Am. Soc. Civil Engineers. Washington; 20-21.

Custodio, E. 1986. Recarga artificial de acuíferos. *Boletín de Informaciones y Estudios*, 45. Servicio Geológico, MOPU, Madrid.

Custodio, E. 1988. La intrusión marina y los perímetros de protección en la nueva Ley de Aguas. In: *Jornadas sobre la Aplicación de la Ley de Aguas en la Gestión de las Aguas Subterráneas*, F.J. Martínez Gil *et al.* (eds), Asociación Internacional de Hidrogeólogos (Grupo Español), Madrid, vol. I; 111-137.

Custodio, E. 1989a. Strict aquifer control rules versus unrestricted groundwater exploitation: comments on economic consequences. In: *Groundwater Economics*. Elsevier, Developments in Water Science, 39; 381-395.

Custodio, E. 1989b. Consideraciones sobre la sobreexplotación de acuíferos en España. In: *La sobreexplotación de Acuíferos*, A. Pulido *et al.* (eds), Asoc. Intern. Hidrogeólogos (Grupo Español) - AEHS, Madrid; 43-64.

Custodio, E. 1991. Characterisation of aquifer over-exploitation: comments on hydrogeological and hydrochemical aspects: the situation in Spain. In: *Aquifer Overexploitation*, L. Candela *et al.* (eds), Proc. XXIII Congress International Assoc. Hydrogeologists. Puerto de la Cruz, Tenerife, Spain, vol. I; 3-20.

Custodio, E. & Llamas, M.R. 1976. *Hidrología Subterránea*. Ediciones Omega, Barcelona, 2 vol. (2nd printing, 1983).

Custodio, E. & Bruggeman, G.A. 1988. Groundwater problems in coastal areas. *Studies and Reports in Hydrology*, 45, UNESCO Press., Paris.

Falkland, A. & Custodio, E. 1991. Hydrology and water resources of small islands: a practical guide. *Studies and Reports in Hydrology*, 49. UNESCO Press, Paris.

Ferret, J. 1985. *L'aprofitament de les aigües subterrànies del delta del Llobregat, 1933-1983*. Comunitat d'Usuaris d'Aigües de l'Area Oriental del Delta del Riu Llobregat, El Prat de Llobregat, Barcelona.

Foster, S.S. 1991. Unsustainable development and irrational exploitation of groundwater, resources in developing nations: an overiew. In: *Aquifer Overexploitation*, L. Candela *et al.* (eds), Proc. XXIII Congress Intern. Assoc. Hydrogeologists, Puerto de la Cruz, Tenerife, Spain, vol. I; 385-402.

Freeze, R.A. & Cherry, J.A. 1979. *Groundwater*. Prentice Hall, Inc., Englewood Cliffs, New Jersey.

García-Gallego, E. & Galofré, A. 1989. Consideraciones generales sobre las aguas sub terráneas en Catalunya y algunos aspectos administrativos y técnicos en la transmisión de los expedientes iniciados al amparo del régimen transitorio de la Ley de Aguas de 1985. In: *Las aguas subterráneas en la Nueva Legislación de Aguas*. Real Academia de Ciencias, Madrid.

Guaita, A. 1987. *Ley de Aguas y reglamento del dominio público hidráulico: nota preliminar*. Biblioteca de Legislación, serie Menor, 93, Editorial Civitas, Madrid.

Gutiérrez-Escudero, J.D. 1985. La sobreexplotación de acuíferos: Cuenca del Segura. *Tecnología del Agua*, 21; 59-71.

ITGE 1991. *Aquifer overexploitation: conceptual analysis/Sobreexplotación de acuíferos: análisis conceptual*. Instituto Tecnológico GeoMinero de España, Madrid.

Johnson, K.S. 1991. Exploitation ot the Tertiary-Quaternary Ogallala aquifer in the High Plains of Texas, Oklahoma and New Mexico, Southwestern USA. In: *Aquifer Overexploitation*, L. Candela *et al.* (eds), Proc. XXIII Congress Intern. Assoc.

Hydrogeologists, Puerto de la Cruz, Tenerife, Spain, vol. I; 313-328.
Ley 29/1985, de 2 de Agosto, de Aguas. *Boletín Oficial del Estado*, 189, de 8 de agosto de 1985; 25123-25135; error corrections in 243, de 10 de octubre de 1985.
Ley 12/1990, de 26 de Julio, de Aguas. *Boletín Oficial de Canarias*; 94, de 27 de Julio de 1990; 2703-2728.
Llamas, M.R. 1984a. Política hidráulica y génesis de mitos hidráulicos en España. *Cimbra*, 218; 16-25.
Llamas, M.R. 1984b. Las aguas subterráneas en la política hidráulica española. *Tecnología del Agua*, 15; 71-82.
Llamas, M.R. 1987. Las aguas subterráneas en la Nueva Ley de Aguas española. *Tecnología del Agua*, 41; 54-67.
Llamas, M.R. 1988. Conflicts between wetland conservation and groundwater exploitation: two case histories in Spain. *Environ. Geol.*, 11(3); 241-251.
Llamas, M.R. 1989. Wetlands and groundwater: new constraints in groundwater manage ment. In: *Groundwater management: quantity and quality*, A. Sahuquillo *et al.* (eds), Inter. Assoc. Scientific Hydrology, 188; 596-604.
Llamas, M.R. & Custodio, E. 1985. *El proyecto de Ley de Aguas: informe científico-técnico*. Instituto de Estudios Económicos. Madrid.
Lloyd, J.W. & Miles, J.C. 1986. An examination of the mechanisms controlling groundwater gradients in hyper-arid regional sedimentary basins. *Water Resources Bull.*, 22(3); 471-478.
López-Camacho, B., Sánchez González, A. & Batlle, A. 1991. Unidades hidrogeológicas con problemas o riesgos de sobreexplotación (territorio peninsular e Islas Baleares). In: *Aquifer Overexploitation*, L. Candela *et al.* (eds), Proc. XXIII Congress Intern. Assoc. Hydrogeologists, Puerto de la Cruz, Tenerife, Spain, vol. I; 539-544.
Margat, J. 1990. La sobreexplotación de acuíferos: su caracterización a nivel hidrogeológico e hidroquímico. In: *Aquifer Overexploitation*, L. Candela *et al.* (eds), Proc. XXIII Congress Intern. Assoc. Hydrogeologists, Puerto de la Cruz, Tenerife, Spain, vol. I; 21-34.
Margat, J. & Saad, K.F. 1982. Utilisation des resources fossiles: analyse de cas historiques. *Hydrogéologie-Géologie de l'Ingenieur*, Sect. III, (3/4); 289-304.
Meinzer, O.E. 1920. Quantitative methods of estimating groundwater supplies. *Bull. Geological Society of America*, 31; 329-338.
MOPU 1990. *Ley de Aguas/The Water Act*. Ministerio de Obras Públicas y Urbanismo. Madrid.
Pallardó, A. 1976. Legislación de Aguas. In: *Hidrología Subterránea*, E. Custodio & M.R. Llamas (eds). Ediciones Omega, Barcelona, Sect 21(2); 2089-2138.
Real Decreto 849/1986, de 11 de Abril, por el que se aprueba el Reglamento del Dominio Público Hidráulico, que desarrolla los títulos Preliminar, I, IV, V, VI y VII de la Ley 29/1985, de 2 de Agosto, de Aguas. *Boletín Oficial del Estado*, 103, de 10 de abril; 15500-15537; error corrections in 157, de 2 de julio.
Real Decreto 927/1988, de 29 de Julio, por el que se aprueba el Reglamento de la Administración Pública del Agua y de la Planificación Hidrológica, en desarrollo de los títulos II y III de la Ley de Aguas. *Boletín Oficial del Estado*, 209, de 31 de Agosto; 26412-26425; corrections in 23, de 29 de Septiembre; 28420.
Rorabaugh, M.I. 1960. Use of water levels in estimating aquifer constants in a limited

aquifer. *Intern. Assoc. Scientific Hydrology*, 52; 314-323.
Simpson, H.J. & Herczeg, A.L. 1991. Salinity and evaportaion in the river Murray basin, Australia. *Journal of Hydrology*, 124; 1-27.
Todd, D.K. 1976. *Ground Water Hydrology* (2nd edn). John Wiley & Sons Inc., New York.
UN 1992. *Interregional workshop on groundwater overexploitation in Developing Countries*. Gran Canaria, Canary Islands, Spain. United Nations, Department of Technical Cooperation for Development. Prepared by R. Dijon & E. Custodio. New York-Barcelona. U.N. INT/90/R43, New York (in press).

THE OVER-EXPLOITATION OF AQUIFERS

J. MARGAT
Bureau de Recherches Géologiques et Minières
B.P. 6009, 45060 Orléans Cédex 2, France

ABSTRACT. The concept of over-exploitation of an aquifer is ambivalent, and even ambiguous, since it is sometimes applied to the hydraulic concept of unbalanced exploitation and exhaustion of reserves, and at other times to the multi-criterion notion of excessive exploitation with undesirable consequences. Understanding the concept cannot be independent of either the objectives of those exploiting the aquifer or of the hydrogeological conditions. Not all exploitation leading to an abstraction greater than recharge, should necessarily be considered excessive or be prohibited, since the mobilization of the reserve will often play a role in the management of an aquifer. Conversely, exploitation in dynamic equilibrium is not necessarily free of undesirable consequences. The clarification of these concepts should give rise to a consistent terminology.

INTRODUCTION

The debates between experts and decision-makers on the management of groundwater resources, as regards the over-exploitation of aquifers, are based on two main questions:

(a) how should we assess whether an aquifer is being over-exploited, or predict if this may happen as a result of planned new exploitation? According to what criteria?
(b) is the over-exploitation of an aquifer always undesirable, 'bad management' that should be prohibited and prevented, or is it permissible or even advantageous under certain conditions and in certain situations, and what impacts should be be anticipated and compensated for? These are the central themes of the present Congress. It seemed appropriate, however, prior to our debates, to clarify the concept of over-exploitation, upon which, if we refer to the literature (Carrillo, 1989; Custodio, 1989; Margat, 1977 and 1982), there does not seem to be a consensus.

This opening talk will therefore be articulated around three points:

(a) excessive exploitation or nonequilibrium? Is over-exploitation defined as a state or by its consequences?
(b) over-exploitation and ways of using aquifer reserves. The variety of possible hydrogeological conditions.

(c) detrimental consequences of groundwater exploitation.

OVER-EXPLOITATION: EXCESSSIVE OR UNBALANCED EXPLOITATION?

Semantically speaking, over-exploitation is excessive exploitation in relation to the exploitation judged to be the maximum possible on the basis of defined criteria, and therefore bringing negative consequences that are sooner or later detrimental to the operators themselves or to third parties. The assessment of over-exploitation is therefore relative to the criteria used, which are themselves linked to the resource- management objectives for the aquifer in question. According to whether: (a) these objectives are conservative conditions for exploitation at a given stage of development; or (b) we are searching for ways to develop the use of the resource, of which the utilization of water is one factor, by intensifying exploitation (either long-term, and therefore by limiting use to renewable resources, or by temporarily withdrawing part of an abundant non-renewable resource); or again (c) it is a question of minimizing detrimental impacts on the users of surface water or on the occupants of the land; it can be understood that the criteria for assessing over-exploitation will not be the same.

These criteria can therefore be:

(a) purely physical and quantitative: the disruption of the hydrodynamic equilibrium that needs to be preserved; re-establishment of a depleted resource;
(b) qualitative: degradation of water quality due to the effects of exploitation;
(c) economic: exploitation costs outweighing the advantages of developments or which have become non-competitive in relation to other sources of supply, or, more broadly, all the direct costs (for the operators) and 'external costs' (borne by others) greater than the collective advantages (these external costs however, are often difficult to assess or to compare with monetary costs);
(d) social: conflicts of use between unequal developers with detrimental effects suffered by third party users of surface or groundwater;
(e) environmental: damage to the natural environment, especially sensitive aquatic ecosystems.

If one refers to the analysis of the 'resource and utilization system' constituted by an exploited aquifer (Erhard-Cassegrain & Margat, 1983), it can be seen that over-exploitation will, from the point of view of the resource manager, be assessed mainly on the basis of physical, hydraulic criteria favouring the criterion of nonequilibrium (excess demand in relation to supply), and, from the point of view of the operators or the analyst of the utilization system representing all those involved, on the basis of socio-economic criteria, referring essentially to the undesirable or unacceptable nature of the consequences (insufficient supply in relation to demand).

Preserving the conditions for exploiting an aquifer, at a given stage, means maintaining a regime of dynamic or average equilibrium, but not necessarily the maximum exploitation possible, without disrupting the equilibrium. Therefore it is only when the objective is both to maximize and to perpetuate the annual average production of water, by placing a ceiling on the average abstraction without risking depletion of the reserve after too large an increase, that the increase in exploitation and the preservation of the dynamic equilibrium of the aquifer must be reconciled by adjusting abstraction to the average recharge, that is to the conventional 'safe yield'. Over-exploitation would then, and only then, correspond to the condition of abstraction being greater than average recharge, or in other words to an exploitation index (abstraction/average recharge) greater than 1 (or 100%) and therefore to exploitation being both in a unbalanced regime and excessive. The diagnosis of over-exploitation a priori, and especially forecasting it, therefore presupposes independent and fairly reliable knowledge of both the average recharge and the total abstraction that have to be compared, which is often far from practicable with the necessary accuracy. For different reasons, the uncertainty in the assessment is high on both sides, and drawing up a water 'balance' is only a very imperfect way of demonstrating nonequilibrium unless it is very obvious. In practice, over-exploitation is diagnosed a posteriori, on the basis of the observed manifestations of the prolonged maintenance of a unbalanced regime: continuous falls in water level and possible consequences on the flows at the boundaries of the aquifer system and the quality of the water; to be able to do this requires that data on the subject are sufficiently abundant and that their analysis is pertinent.

Of course, this case is real and is analyzed with good reason in different countries. But the identification of the concepts of over-exploitation and of disturbance of the dynamic equilibrium of an aquifer has nevertheless been excessively generalized, leading to a simplistic conception of over-exploitation (as opposed to over-exploitation adjusted to a 'safe yield' related only to the safety objectives of the operators) and to diagnosis of over-exploitation which is sometimes unfounded. We therefore cannot separate the question of over-exploitation from the understanding of the concepts of equilibrium and nonequilibrium in the dynamics of the aquifers.

Equilibrium and nonequilibrium of an exploited aquifer

Is it necessary to repeat? All exploitation in a unbalanced regime -which is revealed by a lowering of water levels and thus a decrease in reserves- does not necessarily imply that abstraction is greater than the average natural recharge of the aquifer. It may be due only to a local increase in abstraction, which is higher than the natural recharge; or it could be due to the fact that the effects of the abstraction on the flows at the boundaries of the aquifer system have still not been fully felt. In a very extensive aquifer with high inertia (for example an unconfined groundwater system), intensive or even stable abstraction may necessitate a long period for re-equilibration. In addition, the effects of exploitation are superimposed upon the natural dynamics of the aquifer, the 'budgetary' equilibrium of which, we well know, is achieved only with reference to a fairly long period, most often several years in the case of unconfined aquifers. The nonequilibrium that can be attributed to exploitation can therefore be demonstrated by its effects only with reference to a significantly longer period than the reference period of the average natural recharge of the aquifer.

To sum up, nonequilibrium in exploited groundwater does not result simply from the relation:

$$P > Qa$$

but from the relation:

$$P > \Delta Qd + \Delta Qa$$

where:

P = average abstraction
Qa = average recharge
ΔQd = induced decrease of the average outflow (natural yield of the aquifer)
ΔQa = induced increase in the recharge flow,

which in all cases implies a decrease in the stored water.

The objective of attaining a balanced 'exploitation account' for an aquifer can therefore only be obtained in a fairly long term. Likewise, an imbalance in the short or medium term is not necessarily caused by exploitation in excess of recharge.

These considerations lead to the conclusion that the notions of **excess** and **nonequilibrium** should be kept separate. All exploitation in nonequilibrium is not necessarily excessive and all excessive exploitation is not necessarily in nonequilibrium.

Thus, if over-exploitation is taken to mean excessive exploitation because its effects do not respect certain constraints, it would be too restrictive to limit this designation only to cases of exploitation which are both excessive and in nonequilibrium; on the other hand generalizing over-exploitation to every case of exploitation in nonequilibrium would be wrong, unless 'over-exploitation' is given another meaning, without a pejorative connotation - that of the exploitation of the reserves of an aquifer-. However, this exploitation is only one aspect of the role that is given more or less intentionally to reserves in the exploitation of aquifers. This will be examined below.

We therefore cannot escape the necessity to solve the semantic dilemma summarized by this table:

Exploitation	Non-excessive	Excessive
In equilibrium	A	B
In nonequilibrium	C	D

Is over-exploitation C + D, or B + D, or just D?

OVER-EXPLOITATION AND THE WAY AQUIFER RESERVES ARE USED

Evidence shows that all groundwater management is necessarily linked with **flow management** and **storage management** in varied and variable proportions as the exploitation progresses; they cannot be disassociated. The 'method of use' of the reserve, the function that it is made to fulfil, is only part, sometimes essential and sometimes an accessory part management of an aquifer.

We know that **all exploitation of groundwater begins with a phase of nonequilibrium** during which part of the volume of water produced is removed from the reserve. The length of this phase depends on:

(a) the rate of abstraction: so long as this increases, no re-equilibration is possible, the same applies if it stabilizes only after the natural recharge has been exceeded.
(b) boundary conditions and the rapidity of compensatory reactions, e.g. reduction in the natural outflow and/or increase in the induced inflow.

Consequently, as has already been stressed, any increased exploitation of groundwater -whether the global abstraction is less or greater than the average flow of the aquifer- is necessarily partly an 'exploitation of reserves', which is significant in the case of unconfined groundwater, but less so for confined groundwater where the aquifer is not dewatered.

According to the exploitation strategies, **three methods of use -of management- of the reserve of an aquifer** are therefore conceivable and practicable, but under certain constraints (Margat & Saad, 1983; Margat & Thauvin, 1989):

(a) a strategy of maximum and lasting exploitation of the renewable resources, in a regime of dynamic equilibrium, with average abstraction ≤ average recharge (possibly enhanced by boundary effects), without taking into account season l or even possible annual variations (increased abstraction in periods of drought). Thus, after a decrease in the initial phase of nonequilibrium, the stabilized reserve is used, usually, as a regulatory factor (annual, multiannual) -its natural regulatory function being amplified- under the constraint of preserving a minimum flow rate at the out flow boundaries of the aquifer (springs, low water level in draining streams, etc.) or preserving the fresh-water/sea-water equilibrium in a coastal aquifer.
(b) a strategy of repeated exploitation of the store and then though flow only, in a prolonged unbalanced regime, that may be 'guided' or unintentional in the initial phase, and in which abstraction (increasing or stabilized) is greater than recharge (even when enhanced by boundary effects). A second phase involves reducing abstraction to restore the equilibrium. In this case the depletion of the reserve contributes largely, sometimes predominantly, to the production of water, during an initial phase of limited medium to long term duration, which is limited either by external constraints (see strategy 1) or by a reduction in the productivity of wells (drawdown excessive, or limited by the base of the aquifer). In the later phase of possible re-equilibration, the reserve may be either
    (i) stabilized, on average, in the condition it has reached, bringing abstraction close to recharge, or
    (ii) in part restored, by reducing abstraction below recharge ('repayment of the loan') and sometimes by artificially increasing recharge, and then stabilizing on average, in this new condition.
(c) a strategy of mining or exhaustion exploitation, with abstraction, increasing or otherwise, in operation from the start and greater, often much greater, than the

average recharge. In this case depletion of the reserve provides most of the water produced and the exploitation is in the long term more or less limited when drawdown becomes excessive without later returning to a regime of re-equilibration. The recovery of the reserve may be too slow and sometimes hindered by irreversible degradation of the storage capacity of the reservoir due to subsidence.

To sum up, by analogy with the management of a financial reserve, we can compare the three methods of managing the reserve of an aquifer to:

(a) the management of a treasury, as 'working capital',
(b) a loan followed or otherwise by repayment,
(c) using up capital or an asset.

Naturally, all aquifers do not lend themselves indifferently to these methods of management:

(a) strategy no. 1 is appropriate for unconfined aquifers of small or medium capacity and of limited thickness, with a high rate of recharge (reserves of the order of one to ten times the average annual volume of recharge), and includes the case where a confined aquifer is exploited near the point where it becomes unconfined. This strategy is used particularly in cases where constraints limit the possible drawdown (to preserve open water bodies or watercourses, conserve hydraulic links with surface water-supply sources, prevent the displacement of the fresh-water/sea-water interface, etc.), whatever the rate of recharge of the aquifer.
(b) strategy no. 2 is more appropriate for unconfined or semi-confined aquifers with high capacity and a small to medium recharge rate (reserves of the order of ten to a hundred times greater than the average volume of annual recharge), without appreciable constraints for the conservation of water levels, for example in aquifers with outlets that are independent of watercourses (areas of evaporation in arid regions).
(c) strategy no. 3 is the only one possible for aquifers of high capacity with very little recharge (reserves of the order of several hundred or thousand times greater than the average annual volume of recharge). Development can take place in the unconfined zone and also the confined zone where the diffusivity is high. This is the case for most of the deep aquifers of sedimentary basins, the most transmissive layers of which drain the less permeable but high-storage layers (aquitards) (Margat & Saad 1983; Margat, 1990).

In other words, the diversity of hydrogeological conditions and types of aquifer, of rates of recharge (which depend on both the geometry and the nature of the reservoirs), and of volumes of recharge, present a large range of possible means of developing aquifers, and of roles which the reserves can be made to play.

How should over-exploitation be placed in relation to this classification of the methods of aquifer management? If we define over-exploitation as 'exploitation of the reserve' (depletion), strategies 1 and 2 would correspond respectively to temporary or permanent 'over-exploitation'. However, if in contrast we define over-exploitation as excessive exploitation in the sense that it has undesirable effects, under regimes both of nonequilibrium and of equilibrium, we could qualify over-exploitation as an uncontrolled slide deterioration effecting a strategy of exploitation different from that desired, e.g. strategy 2 instead of 1, or 3 instead of 2, or the application of a strategy of exploitation which does not suit the aquifer.

Conversely, a diagnosis of over-exploitation based solely on the observation or deduction of dynamic nonequilibrium (assumed to be more or less, long term lasting) could lead to the recommendation of an exploitation strategy in an aquifer which does not suit it and therefore to Malthusian 'under-exploitation'. In particular, refraining from any exploitation in nonequilibrium would be the same as prohibiting the exploitation of non-renewable resources even in cases where it is possible and advantageous (strategy 3). This is the case notably in arid or semi-arid regions where it is already practised anyway (as in Algeria, Saudi Arabia, Libya, Australia and the USA) and where it represents a very substantial part of the water supply. Such exploitation of reserves must nevertheless be intentional and planned.

DETRIMENTAL CONSEQUENCES OF THE EXPLOITATION OF GROUNDWATER

Any exploitation of groundwater with detrimental consequences or impacts, either for the operators themselves or for third parties, can be considered excessive. Such consequences are well known and have arisen many times, generally as a result of intensive exploitation. They are summarised below.

Consequences detrimental to the operators: effects of exploitation on exploitability

(a) normal and direct effects of intensive exploitation, cumulative drawdown, which may reach more than a hundred meters in a few tens of years, necessarily reduces unit production per well -including a reduction in productivity due to clogging- and also increases direct unit production costs -energy costs first of all, plus, beyond certain depth thresholds, equipment transformation costs-. Just one example of this is in a part of the vast Ogallala Aquifer of the High Plains of the Middlewest of the USA, in Floyd County (Texas), where it is exploited intensively for irrigation, and more than 40% of the total volume pumped between 1940 and 1980 was taken from reserves. Abstraction increased from 233 Mm^3 $year^{-1}$ in 1958 to 392 Mm^3 $year^{-1}$ in 1979 and caused drawdown of the order of 50 to 60 m between 1945 and 1984, representing a reduction of two thirds of the depth of the aquifer. Unit production costs rose (in current US$) from 0.31 cents m^{-3} in 1952 to 2.15 cents m^{-3} in 1981, or an increase of 594%, including 302% between 1973 and 1981, in terms of power costs and the depth of pumping. It was calculated that, solely because of the effect of drawdown, the increase in production costs must have been 172% between 1952 and 1981 (Schefter, 1984),

(b) lowering of water level in an aquifer may cause conflict between neighbouring operators, especially when their economic objectives differ and their means of abstraction are different,

(c) local reductions of level in an aquifer may cause clogging of river banks or disruption of the hydraulic link with the surface water supply (reservoirs or rivers), which change the boundary conditions and reduce the supply to the aquifer, aggravating the drawdown even more,

(d) more generally, and particularly in semi-arid areas, regional drawdown, which increases the depth of the non-saturated zone, may reduce the flow percolating into the aquifer, and thus the renewal of the resource,

(e) when the aquifer includes a fresh-water/sea-water interface (generally the case for coastal aquifers), or contains waters with different chemical characteristics (according to the structure of the aquifer, the rocks which constitute it or the soil which covers it, or differing origins for the water), regional drawdown changes the kinetics of flow and the distribution of the water masses of different salinity. This may cause a degradation of the quality of the confined water that can be regarded as 'induced pollution', and relative, like every loss of quality, to the standards of usage (Custodio, 1982 and 1984),

(f) finally, even when intensive exploitation is intended to be temporary -and the more so if it is not- falls in production and unacceptable increases in exploitation costs may occur prematurely and necessitate unforeseen and costly replacements for the source of supply.

In the case of the High Plains in the USA, considered above, to compensate for the reduction in the production of water from the Ogallala Aquifer and to slow down the consequent decline of agricultural production by irrigation, the possibility was studied of taking at least 5 and up to 13 x 10^9 m^3 $year^{-1}$ of surface water from the Missouri-Mississippi, involving transport across distances of 542 to 1836 km and energy costs of 6.6 to 49 million Mwh $year^{-1}$ to raise the water over heights of the order of 1,000 m. The investment required would, according to the projects and objectives, be US$ 3.6 billion (to supply 2 x 10^9 m^3 $year^{-1}$) to US$ 20 billion (1977) (to supply 10.7 x 10^9 m^3 $year^{-1}$), which, taking into account operation and distribution costs, would bring the cost of water supplied to farmers to between $0.06 and $0.2 (1978), and therefore much higher than the cost of producing water from the aquifer (Golubev & Biswas, 1985).

Impacts detrimental to third parties

(a) the principal boundary effect on an aquifer under intensive exploitation in a country with a temperate or moist tropical climate is to reduce outflow, the more so as this reduction is the principal factor in returning the aquifer to equilibrium. This reduction in the yield of springs and in the base flow rate of the water courses tributary to the aquifer may naturally be detrimental to the users of this surface water (by abstraction or *in situ*) or more simply it may damage the aquatic ecosystems which depend on it, reducing the minimum flow rates during low water periods, and therefore increasing the irregularity of flow. The same goes for the open water bodies connected to the groundwater, which are very sensitive to falls in its level,

(b) such impacts also affect the permanent outflows of aquifers in arid zones, where they are particularly serious as springs are rare. For example, in the northern Sahara, the exploitation of the deep confined aquifer of the Continental Terminal in Algeria and Tunisia, which produced about 32 x 10^9 m^3 between 1900 and 1981 compared to recharge of the order of 580 x 10^6 m^3 $year^{-1}$ initially in equilibrium with natural losses, principally in the form of evaporation, caused the partial drying up of some of the artesian outflows from of the system (initially of the order of 5 $m^3 s^{-1}$), whose flow rate decreased by more than 100 $Mm^3 year^{-1}$ and is tending towards zero,

(c) the regional lowering of water levels may in certain cases also destroy the stability of the soil, causing subsidence most often differential and detrimental to the occupants of the land when it is in a built-up area. In many towns throughout the world, intensive exploitation of groundwater for potable water supply and also sometimes for irrigation in the surrounding area, has caused subsidence of a metre or more (the maximum recorded is 10 m, in Mexico), which damages buildings and roads, water and sewerage networks, and of watercourses, which affects the stability of coastal zones and increases the risk of floods, and thus reduces the development potential and therefore the value of the land. Some well known examples of this are Berlin, Milan, Venice, London, and Denver, Houston, San Fransisco and Tucson in the USA, with subsidence of two to nine meters in several towns in California, plus Mexico mentioned above. A report published by UNESCO (Poland, 1985) cites 42 cases throughout the world, including 35 in the industrialized countries of Europe, in the USA and in Japan. The consequences are naturally more serious in a town situated in a low coastal plain, such as Venice,

(d) regional drawdown may also have detrimental consequences on soil moisture and on natural or cultivated vegetation,

(e) lastly, intensive exploitation may paradoxically have negative consequences when it slows down or stops. When drawdown leads to 'external advantages' for the occupants of the dewatered sub-surface, often unaware or forgetful of the benefit derived from such an artificial situation, a situation that has often lasted for a long time, the rise of the water table when exploitation stops becomes a serious problem.

It should be noted that the impact of intensive exploitation of groundwater may be detrimental to the users of surface water or to the occupants of the ground even before its negative effects are apparent to the operator.

Most of the negative consequences of the exploitation of groundwater that have been listed above are independent of the state of hydraulic equilibrium or nonequilibrium. They are mainly due to large drawdowns that exceed certain critical thresholds, with or without stabilization. In particular, a new dynamic equilibrium does not exclude the possibility of the movement of water masses of different salinities within the aquifer, as much more time is required for kinematic reequilibration. In other words, the consequences of hydrogeochemical changes on water quality should not be ignored for a regime in hydrodynamic equilibrium. The same applies to mechanical consequences on ground stability.

We therefore return to the need to distinguish excessive exploitation, with undesirable consequences, from exploitation in a regime of dynamic equilibrium, despite the difficulty of opposing the relatively simple concept of nonequilibrium to that of excess, which is more complex and not unique, as a result of the large number of criteria involved.

The prevention of these undesirable and detrimental consequences will consist, in general, in defining and imposing constraints on the operators, limiting abstraction to limit drawdown. These constraints may be direct, taking the form of a maximum tolerable depth, by area, or of minimum boundary flow rates that must be maintained.

(a) internal constraints which the operators impose themselves, collectively, to 'preserve the resource' (in the sense of potential that can be exploited long-term in both quantity and quality) and productivity, while maintaining the costs at less than the financial benefits, and also individually to avoid conflict.
(b) external constraints protecting third parties, users of surface water and occupants of the land, resulting from arbitration and formalized by regulations.

Any exploitation whose effects do not respect one or the other of these could then be qualified as over-exploitation.

CONCLUSIONS

As far as management of the resource is concerned, two distinct and opposite notions are equally useful:

(a) dynamic equilibrium or prolonged nonequilibrium in an exploited aquifer (opposition between apparently clear and unambiguous hydrodynamic notions, but always relative to a reference period).
(b) consequences that are undesirable and detrimental or otherwise to exploitation (relative to different criteria and different subjects).

To which of these should the opposition exploitation/over-exploitation correspond? For many, it is certainly just a question of words. Is it desirable, however, that a consensus be established so that dialogue is not handicapped by the lack of common language?

It may be preferable to define:

(a) **exploitation of reserves (exhaustion groundwater storage development)**, or even groundwater mining, as exploitation comprising significant, temporary or lasting depletion.
(b) **over-exploitation** as excessive exploitation because of its physical or economic consequences, whoever bears them.

Of course, the two notions partly overlap. Exhaustion may be over-exploitation if it is not desired and is detrimental to the objective of preserving lasting production. But not all exploitation of reserves, necessarly in a regime of nonequilibrium, should be prohibited, just as not every exploitation with undesirable consequences is necessarily in an unbalanced regime.

In this perspective, it can be said that the aquifers most vulnerable to the risk of over-exploitation, in the sense of excessive exploitation, as a result of inappropriate management are principally:

(a) thin aquifers where substantial drawdown reduces productivity, or stratified aquifers with a conductive layer that can be dewatered.
(b) aquifers with high productivity, the groundwater in which is readily accessible by a number of operators, where cumulative abstraction can easily exceed the average recharge.
(c) aquifers recharged from watercourses, the connection with which may be broken in the event of substantial drawdown.
(d) aquifers with important constraints on the conservation of yields on outflows (springs, draining streams).
(e) aquifers with fresh-water/salt-water interfaces (in coastal zones) or with wide-ranging qualities of heterogeneous groundwater bodies, the distribution of which may change under the effects of regional drawdown.
(f) unconsolidated sedimentary aquifers in compactible ground, where drawdown may cause significant ground subsidence.

REFERENCES

Carrillo, J.J. 1989. *La sobreexplotacion en aguas subterráneas. Una definición del concepto*. Instituto de Geofisica, UNAM, Mexico.

Custodio, E. & Bruggeman, G.A. 1982. Groundwater problems in coastal areas. *Studies and Reports in Hydrology*, 45, UNESCO, Paris.

Custodio, E. 1984. Salinización de acuíferos por sobreexplotación/Salinisation des aquifères par surexploitation. *Mediterránia*, 4; 37-54.

Custodio, E. 1989. Consideraciones sobre la sobreexplotación de acuíferos en España. In: *La Sobreexplotacíon de acuíferos*, A. Pulido *et al.* (eds), Asoc. Intern. Hidrogeólogos (Grupo Español) - AEHS, Madrid; 43-64.

Erhard-Cassegrain, A. & Margat, J. 1983. *Introduction à l'économie générale de l'eau*. Masson, Paris.

Golubev, G.N. & Biswas, A.K. (eds) 1985. *Large scale Water Transferts: Emerging environmental and social experiences*. UNEP, Water Resource Series, 7, Tycooly Publ. Lim. Oxford.

Margat, J. 1977. De la surexploitation des nappes souterraines. In: *Eaux souterraines et approvisionnement en eau de la France*, Ed. BRGM, Orléans; 393-408.

Margat, J. 1982. Exploitation ou surexploitation des réserves d'eau souterraine? In: *Le calcul du bilan des eaux souterraines*. PHI/UNESCO, Varna, Thème C.2.

Margat, J. & Saad, K.F. 1983. Concepts for the Utilization of Non-renewable Groundwater Resources in Regional Development. *Natural Resources Forum*, vol. 7, 4; U.N. New-York.

Margat, J. & Thauvin, J.P. 1989. Las reservas de agua subterránea. Nociones esenciales y formas de utilizarlas. In: *La sobreexplotacíon de acuíferos*, A. Pulido *et al.* (eds), Asoc. Intern. Hidrogeólogos (Grupo Español) - AEHS, Madrid; 593-603.

Margat, J. 1990. Les gisements d'eau souterraine. *La recherche*, 221; 590-596.

Poland, J.F. (ed) 1985. Guidebook to studies of land subsidence due to ground-water withdrawal. *Studies and Reports in Hydrologie*, 40, UNESCO, Paris.

Schefter, J.E. 1984. Declining Ground-Water Levels and Increasing Pumping Costs: Floyd County, Texas. A Case Study. National Water Summary 1984. Hydrologic Perspectives. U.S.G.S., *Water Supply Paper* 2275, Washington.

OVEREXPLOITATION EFFECTS ON THE AQUIFER OF MAR DEL PLATA (ARGENTINA): MARINE INTRUSION AND GROUND WATER DECLINE

M. A. HERNANDEZ
CONICET & Cátedra de Hidrogeología, Fac. Cs. Naturales
Univ. Nac. de La Plata, Paseo del Bosque, 1900 La Plata, Argentina.
J. L. FASANO & E. M. BOCANEGRA
CONICET & CIC. Centro de Geología de Costas y del Cuaternario
Univ. Nac. de Mar del Plata, C.C. 722, 7600 Mar del Plata, Argentina.

ABSTRACT. Present day conditions in Mar del Plata city, located at the Atlantic coast, produced by the overexploitation of an aquifer are herein described. This aquifer is the only available water source for domestic, industrial and agricultural supply in the area. The hydrodynamic evolution is analyzed in terms of: (i) the structural geological control and (ii) the requirements for growth, by means of a numerical simulation model, using the method of finite elements for an unsteady regime.

INTRODUCTION

The city of Mar del Plata is the main Atlantic touristic center of Argentina and the most important fishing port, with a stable population of 500,000 inhabitants that, in summer months (January-February), receives up to 2,000,000 tourists.

Climate is humid/sub-humid with oceanic influence, with a mean annual rainfall of 795 mm and a mean annual actual evapotranspiration of 713 mm, with a surplus of 82 mm/year. The precipitation is evenly distributed throughout the year. Maximum and minimum precipitation occur in autumn and winter, accounting for 27.8 % and 21.8 % respectively of the total annual rainfall. Consequently, water surplus is only available from July to September, in accordance with decreasing evapotranspiration values. The mean annual temperature is 13.8 °C. January is the hottest month with a mean temperature of 19.7 °C; July is the coldest month with a mean temperature of 8.2 °C.

Since 1913, Mar del Plata has a running-water supply system, through the exploitation of a Quaternary semiconfined aquifer which, starting in 1943, shows a saline intrusion effect, favoured by genesis of large drawdown cones, with an apex at 27 m below sea level. The development of a series of wells in the Camet area, north of Mar del Plata, and its alternating operation with the original water system, stopped the saline intrusion, although problems related to overexploitation are still persisting. Such problems are discussed in this paper.

GEOLOGY AND HYDROGEOLOGY

The base of the Cenozoic clastic deposits, in which the main aquifer is developed, are Early Paleozoic quarzites (Groeber, 1954), known today as the Balcarce Fm. (Dalla Salda & Iniguez, 1979). These rocks outcrop in different areas of the city, overlying Precambrian metamorphic rocks that have been recognized only in the substratum. The quartzitic massif has been affected by three fault systems, with NW-SE, NE-SW and E-W orientation, respectively. These fractures are normal faults with dominant vertical displacement and slight tilting, which generate a geologic structure defined by tectonic horst and grabens. The grabens have been uncomformably infilled by Miocene marine sediments, known as Parana Fm., with a reduced thickness in the area. These deposits have been uncomformably covered by loessoid sediments, aeolian sandy-silts with intercalations of clayey beds and development of calcareous (caliche) layers. This Pliocene- Pleistocene sequence includes the main aquifer of the region, reaching a thickness of up to 70 m, which increases northwards, towards the Salado Basin axis. To the south, this sequence is well exposed along the sea-cliffs (Zárate & Fasano, 1989).

The resulting landscape on this structure is undulating, with outcropping of horst and relatively plain areas, that are located at the grabens, filled by Cenozoic units (Hernández & Ferrante, 1987; Hernández *et al.*, 1989).

From the hydrogeological point of view, it is an anisotropic sequence of medium permeability (Sala *et al.*, 1980). The permeability values are in the range of 10-15 m day^{-1}, the transmissivity coefficient is between 500 to 700 m^2 day^{-1}, and the storage coefficient is around 1.10^{-3}. The Paleozoic quartzites present a secondary permeability derived both from fracture and bedding planes. Till now, no attempts have been made to evaluate the hydrogeological significance of this unit.

The non-saturated zone thickness, originally of 5-10 m, has been expanded as a consequence of the drawdown cones formation under the influence of descending leakage.

GROUNDWATER

According to the information available since the early 1900s, the original groundwater flow direction was seaward, with isopiestic lines running subparallel to the shoreline. A regional drawdown cone was formed by the coalescence of several smaller cones which in turn were caused by the first exploitation wells. The former includes secondary apexes which are conditioned by the geological structure and the catchment geometry. In 1953 two main depression cones were observed: one close to the port area and the other, of greater extent, to the north, corresponding to the more densely populated area. The lowest piezometric levels were situated at 2.0 and -3.5 m above mean sea level, respectively (Groeber, 1954).

As a consequence, marine intrusion occurred from 1943 (Ruiz-Huidobro, 1971), leading to the end of exploitation of the coastal wells. Wells with water showing high chloride content -greater than 700 mg l^{-1}- were abandoned. In some cases, chloride concentrations reached as much as 6,000 mg l^{-1}. By the year 1976 the saline front was 2.5 km inland from the coast. Due to the abandonment of 33 salinized pumping wells and the progressive shifting of the well field to Camet since 1969, ground water levels experienced pronounced declines and recoveries (Fig. 1). The 0 isopiestic line continuously migrated northward and westward. This is particularly evident between 1979 and 1983. During this interval, a 5.5 km migration was recognized (Bocanegra *et al.*, 1985). One of the main modifications related to the new pumping scheme was the enlargment of the area limited by the -10 meter isopiestic line in the Camet well field.

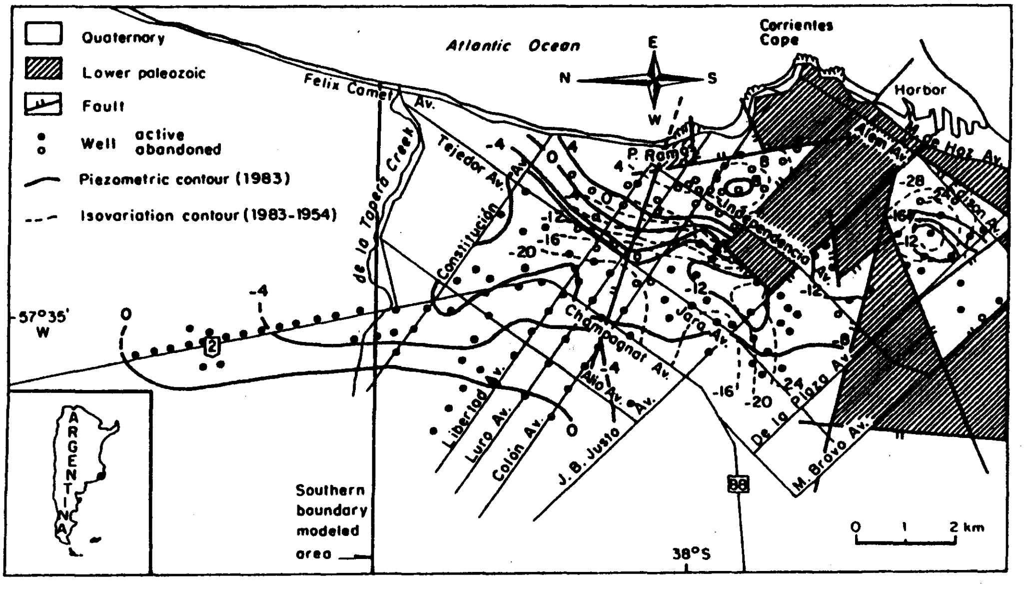


Figure 1: Piezometric and isovariation lines. Main geologic features (modified after Bocanegra *et al.*, 1985).

Fig. 1 shows the piezometric state from 1983 together with the 1954 and 1983 isovariation contours, the latter showing recoveries of up to 10 m at the coastal sector and a depression of about 20 m towards the northwest with a local maximum of 28 m near the port area (Bocanegra *et al.*, 1985). It seems probable that the depression cone close to the harbour area, located in a graben, is evolving independently.

The main consequences of overexploitation are:

(a) increase in the pumping costs by excessive drawdown.

(b) saline intrusion affecting the city center. Intrusion was mitigated since the 80's by the Camet battery operation and by the winter season stoppage of central urban wells operations.

(c) subsidence in some areas, mainly on structural depressions, as a result of drawdown by continuous pumping.

(d) negative effects in piezometric recovery on the building structures in the central-coastal area. Because most of the building in Mar del Plata were constructed under drawdown level conditions, recovery affects their ground-structure (basement, parking lots, etc.) as well as their foundations and other facilities.

A numerical simulation model using the finite-elements method was applied for the Camet area in order to forecast the aquifer behaviour and to optimize the exploitation strategies so undesirabile effects are avoided (Fasano *et al.*, 1989).

This method was assumed to be more efficient for the treatment of irregular geometries and grids because it allows the utilization of smaller surfaces in the vicinities of the wells (Fig. 2). Boundary conditions correspond to the prescribed hydraulic potential ($h = 0$ m in the western limit; $h = 30$ m in the eastern limit) and the prescribed yield ($\delta h/\delta n = 0$) both in the northern and southern limit, in agreement with the flow lines.

The equation employed for a non-steady regime is (Fasano *et al., op. cit.):*

$$- \frac{\delta}{\delta x_i} (T_{ij} \frac{\delta h}{\delta x_j}) + (S + S_y) \frac{\delta h}{\delta_t} = Q\ (x_1,x_2,t) - I\ (x_1,x_2,t)$$

where T_{ij} is the transmissivity tensor, S the storage coefficient, S_y the phreatic storage coefficient, Q the well volumetric flow per containing element surface unit, and I the infiltration. Also it is considered that $h_a \approx h_b \approx h$, where a and b represent the aquifer base and the phreatic surface, respectively.

The results of the numerical simulation of the piezometric surface corresponding to 1969, when only 3 pumping wells in the southern extreme of the modeled area were operating, is shown in Fig. 2 (Fasano *et al.*, 1989). In a period of 13 years (1970-1983) a considerable water table lowering has taken place due to the 51 wells battery installed. Water levels at Camet declined about 30 meters, or at a rate of about 2.3 meters per year. Since 1983 till now, the piezometric surface seems to be stabilized.

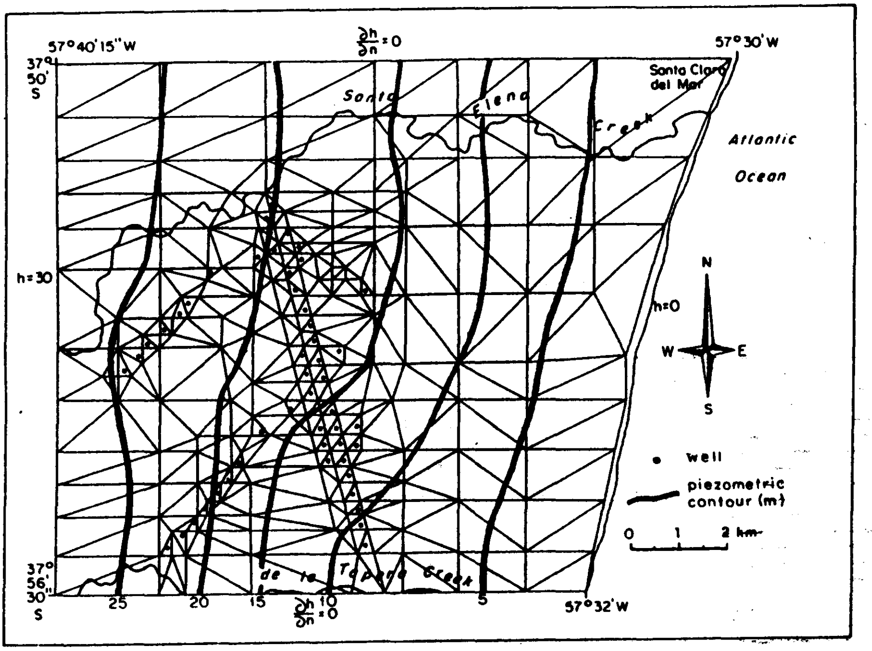


Figure 2: Finite element grid and well locations, Camet. Simulated piezometric surface corresponding to 1969 (after Fasano *et al.*, 1989).

CONCLUSIONS

Although marine intrusion caused by overexploitation has been mitigated by new catchment geometry, subsidence and ground-structure floodings do still occur because of level recovery due to the lack of operating wells in the central urban area.

In order to control these floodings or to plan an eventual artificial recharge project, the optimal critical level of the phreatic surface should be established.

The model described will help in designing exploitation strategies, including correction and prevention of non-desired effects in the Camet area and in the central urban sector.

REFERENCES

Bocanegra, E. M., Cionchi, J. L., Fasano, J. L., Osterrieth M. L. & Schnack, E.J., 1985. Geología ambiental del área urbana marplatense, Provincia de Buenos Aires. Caracterización preliminar. *In: I. Jor. Geol. Bonaerenses*, Actas, CIC, La Plata: 663-682.

Dalla Salda, L. & Iniguez, M. 1979. La Tinta. Precámbrico y Paleozoico de Buenos Aires. In: *VII Congr. Geol. Arg.*, Actas I, Buenos Aires; 539-550.

Fasano, J., Bocanegra, E., Suárez, M & Hack, H. 1989. Simulación numérica por elementos finitos del flujo estacionario del acuífero de Camet, Mar del Plata, Argentina. In: *Proc. UNESCO Intern. Symp. on Hydrology of Flat Lands* (in press).

Groeber, P. 1954. Geología e hidrogeología de Mar del Plata en relación con el problema de suministro de agua potable a la población urbana. *Rev. Mus. Cienc. Nat. y Trad.*, vol. 1 (2); 5-25.

Hernández, M.A. & Ferrante, V. 1987. Saline intrusion in the Mar del Plata aquifer (Argentina): presents days situation. Studies and measures undertaken. Groundwater Problems in coastal areas. *Studies and reports in Hydrology*, 45, UNESCO, París; 494-498.

Hernández, M.A., Fasano, J. & Bocanegra, E. 1989. Prevención de riesgos en la recuperación de niveles piezométricos en áreas urbanas de Argentina. In: *Segunda Conferencia Latinoamericana de Hidrología Urbana*. ALFHSUD - IDRC - UBA, Buenos Aires.

Ruiz-Huidobro, O. 1971. La intrusión de agua de mar en el acuífero de Mar del Plata. *In: I Congr. Iberoamer. de Geol. Econ.*, Madrid, vol. 2, Sec.3; 845-858.

Sala, J. M., Hernández, M. A., González, N., Kruse, E. & Rojo, A. 1980. Investigación geohidrológica aplicada en el área de Mar del Plata. *Con. Obras Sanitarias de la Nación-Univ. Nac. de La Plata*. Inf. inédito. Mar del Plata.

Zárate, M. A. & Fasano, J.L. 1989. The Plio-Pleistocene Record of the Central Eastern Pampas, Buenos Aires Province, Argentina: the Chapadmalal Case Study. *Palaeogeography, Palaeoclimatolog, Palaeoecology*, 72; 27-52.

EVALUATION OF HYDROTHERMAL SOURCES THAT SUSTAIN AN OVEREXPLOITED AQUIFER AT SAN LUIS POTOSI, MEXICO

I. HERRERA, R. MEDINA, L. CHARGOY & J. CARRILLO
Instituto de Geofísica, UNAM, Mexico City
Apdo. Postal 22-582, 14000 Mexico, D.F., Mexico

ABSTRACT. A numerical model is implemented for the aquifer of the City of San Luis Potosí, which takes into account the contribution of an underlying thermal source. Previously, it was thought to be overexploited. By means of the numerical model, it is shown that this is not the case, because there is a contribution from the underlying thermal source. Since the properties of the thermal source are not known, the procedure used to incorporate them is to adjust the values of the vertical hydraulic conductivity between the thermal source and the aquifer until the actual piezometric levels in the aquifer were reproduced. For this case study, such a procedure has produced useful results.

INTRODUCTION

The Valley of San Luis Potosí, is located in the high plateau of the Republic of Mexico (Fig.1) and it lies in the semi-arid region. The water demand of the City of San Luis Potosí, capital of the state of the same name, for agricultural, urban and industrial uses, has been steadily increasing. Most of the water supplied to the city is from underground sources, because due to the reduced rainfall, the surface water contribution is small (only 8 %).

There is concern with respect to the future evolution of the aquifer, because in the last few years the observed speed of drawdown has reached the rate of 1.3 m year^{-1}. However, if the hydraulic balance of the aquifer is carried out taking into account only what is known about the aquifer, the predicted rate of drawdown is even larger. On the basis of thermal, chemical and hydraulic evidences, in a previous study: Instituto de Geofísica, UNAM (1988), it was established that the differences between the observed and the predicted rate of drawdown is due to water supplied by deeper geological formations with thermal activity.

Taking into account these facts, it was decided to implement a numerical model of the aquifer to improve the understanding of its behavior, specially with respect to the deep thermal sources, and to predict the system behavior under different exploitation policies for the next twenty years.

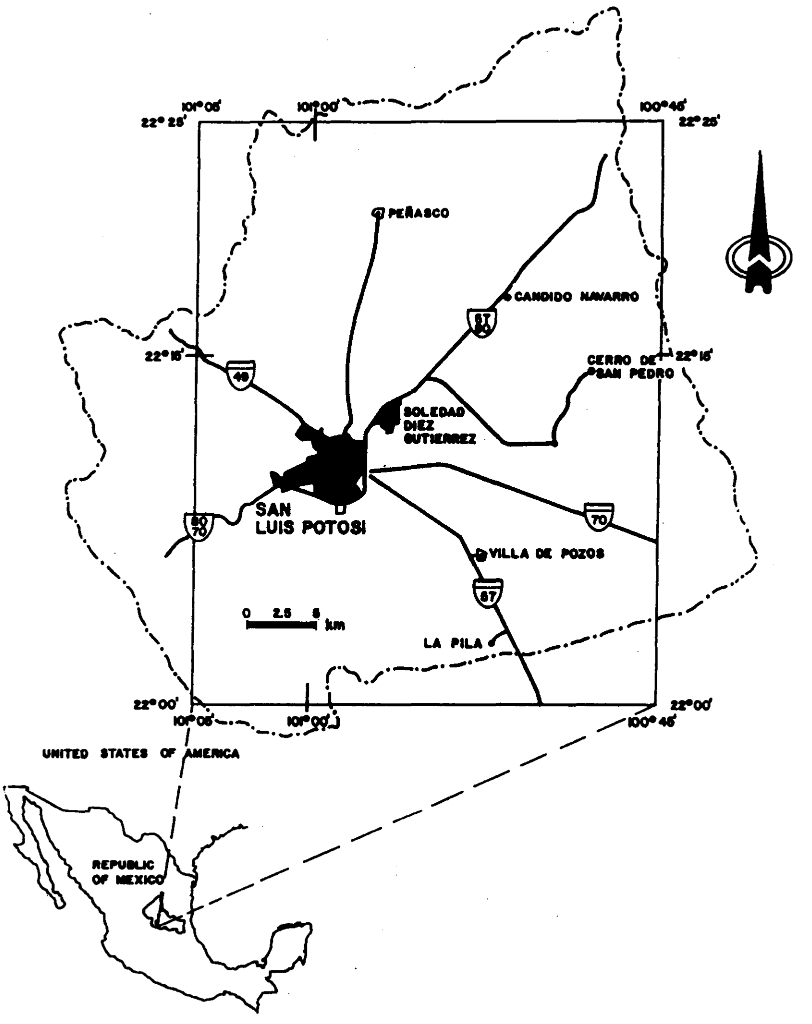


Figure 1: Location map of San Luis Potosí Basin.

HYDROGEOLOGIC MODEL

On the basis of the available geological, geophysical, piezometric and hydrochemical information, the proposed hydrogeological model of the system includes a "shallow aquifer" of reduced yield and poor quality water. This aquifer overlies a "clay formation" which in turn confines a deeper aquifer. Most of the water is produced at this "deep aquifer", which has thermal activity (Fig.2). Below it, lay the "thermal sources".

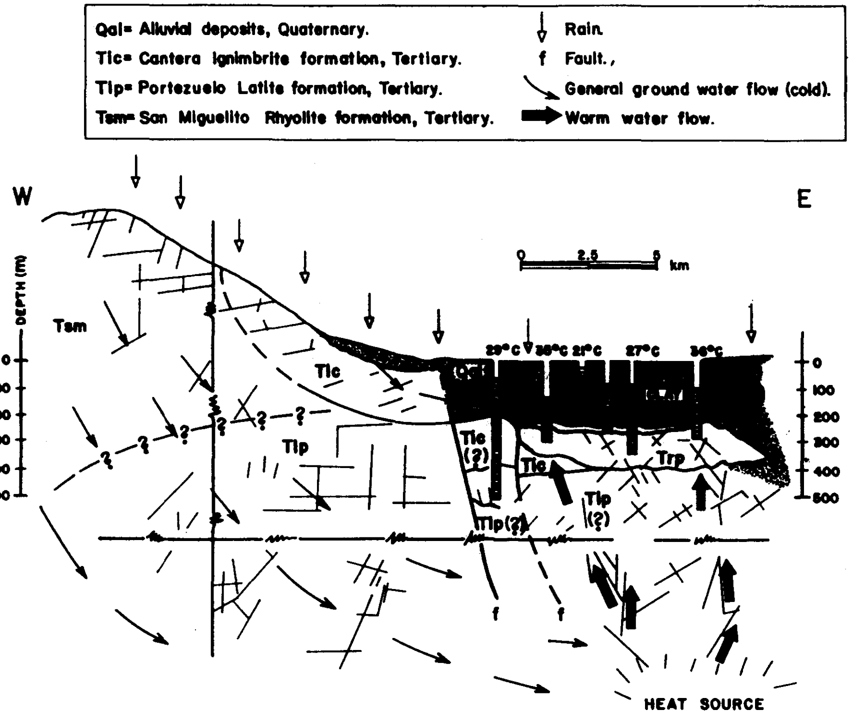


Figure 2: The hydrogeological model.

In this figure, it can be observed that the system of regional flow is important for aquifer performance, producing a vertical component of hot water. For a detailed geological description of the system, the reader is referred to the previous study: Instituto de Geofísica, UNAM (1988).

MODELLING OF THE SYSTEM

For the implementation of the numerical model, a conceptual model of its behavior was defined, suitable differential equations were adopted, a computer program was selected and its calibration was carried out using the available information. The piezometric levels produced by the program were interpolated using the package SURFER: Golden Software, Inc., (1989) to obtain a more convenient graphical representation.

The conceptual model

The limits of the area included in the model, are shown in Fig. 3 and were based on geological considerations.

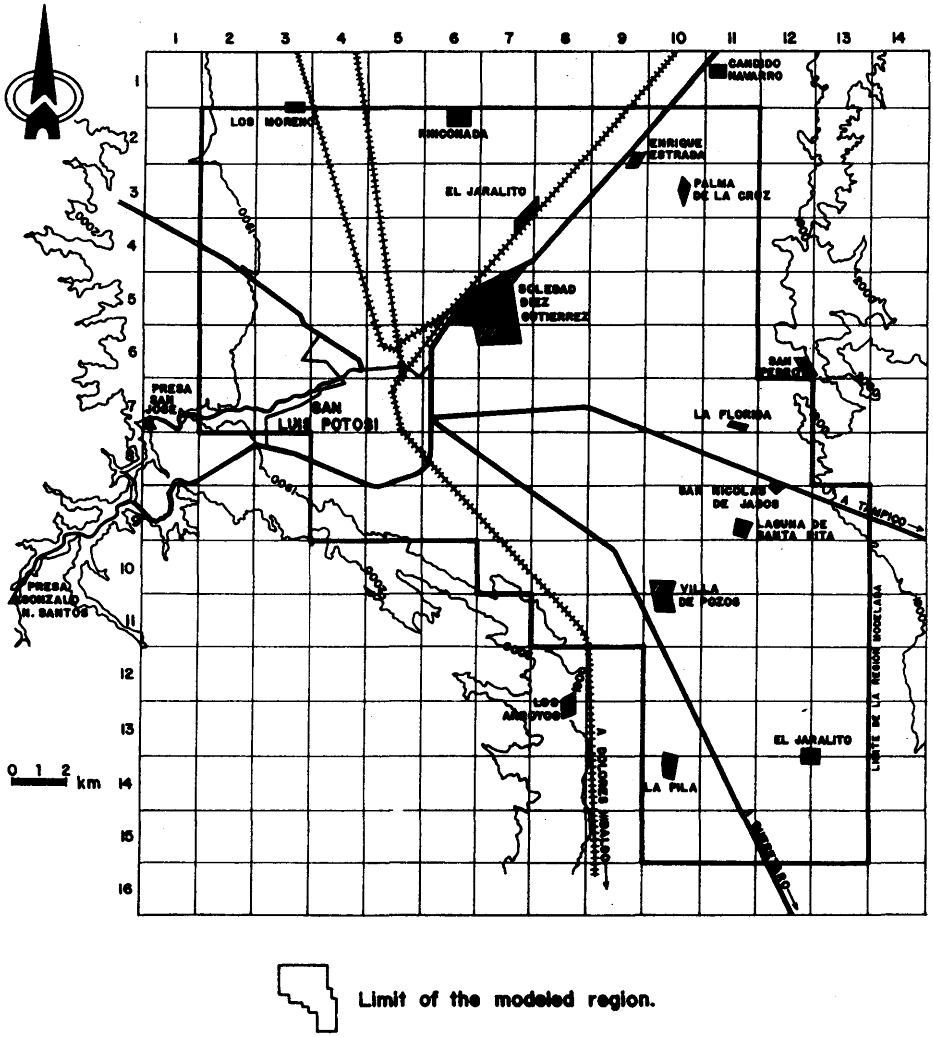


Figure 3: Grid used in the numerical simulation.

The San Miguelito range at the west and the San Pedro range at the east, constitute natural boundaries because they present conditions of no flow, and at some places constant head (Fig. 4).

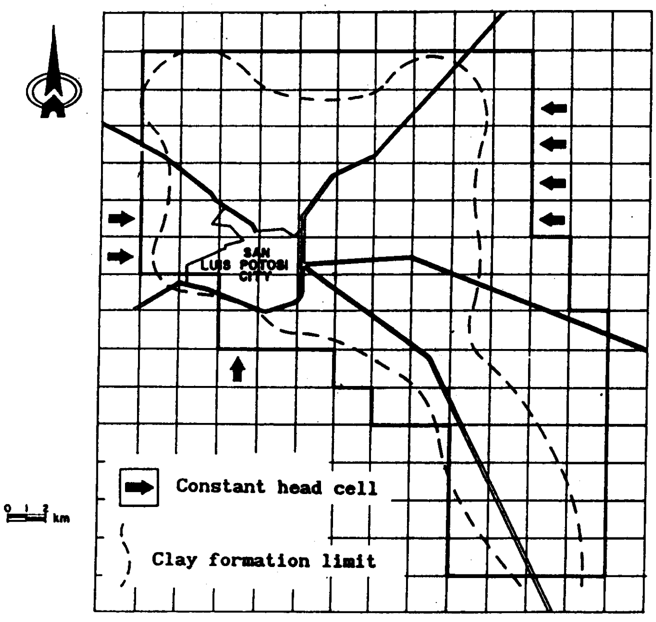


Figure 4: Area covered by the clay formation

The northern and southern limits were selected on the basis of the piezometric information that was available and they were taken as impermeable, because there is evidence that the flow there is negligible. The shallow aquifer, located on the upper part of the system, functions as a unit independent of the deep aquifer, because the clay layer that separates them is sensibly impervious. Taking into account that most of the water is produced at the deep aquifer, the purpose of the model is the prediction of its behavior exclusively, leaving aside the shallow aquifer.

The basic Equation

The governing equation used was:

$$\frac{\partial}{\partial x}\left(Kx\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(Ky\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(Kz\frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t} \qquad (1)$$

where Ss = specific coefficient of storage $[L^{-1}]$

K = Hydraulic conductivity $[LT^{-1}]$

h = Hydraulic head $[L]$

t = Time $[T]$

However, the analysis of the flow was mainly two-dimensional, because only two horizontal layers were incorporated in the model.

The computer code MODFLOW: McDonald & Harbaugh, (1984), was used in all calculations. This model applies the cells method which yields finite difference approximations.

The deep aquifer can be satisfactorily modelled using a 2x2 Km grid and applying finite difference schemes on them, as illustrated in Fig. 4. Layer I includes the best known part of the system, where the value of the hydraulic properties are known or at least can be estimated. Layer II was introduced to model the deeper, less known geological formations which supply the thermal water. The flow and interaction between layers I and II is due to the differences of hydraulic head between them. In layer II, it was assumed a constant hydraulic head that remained greater than the head of layer I, throughout the runs. This induces a vertical component of flow whose magnitude can be adjusted varying the ratio of the hydraulic conductivity (Kz) to the thickness of the layer where the flow takes place.

An upper boundary condition of no flow was considered in layer I, which corresponds to the clay layer whose hydraulic conductivity is neglected. In the horizontal limits of the aquifer, either constant head or no flow boundary conditions were considered, as indicated in Fig. 4.

CALIBRATION

In the period January 1987- July 1989, heads were measured monthly in observation wells distributed throughout the region that was modelled. At the same time, the pumping rate was measured in some cases and estimated by indirect means in others.

In addition, the piezometric head distribution corresponding to 1960 is available and there are estimates of the historical evolution of the pumping rates.

The hydraulic properties of the known part of the aquifer were obtained by means of pumping tests and also some pumping tests available from previous studies were interpreted. Transmissivity varies between $1x10^{-5}$ and $8x10^{-4}m^2s^{-1}$. The calibration for layer I started with these values and then were modified on the basis of the results of the calibration. The properties of layer II were adjusted until the behavior of the system was reproduced in a satisfactory manner.

In spite of the additional piezometric information that was available, the calibration was based on the period 1987 - 1989, which covers 30 months only. This was due to the better quality of the data for that period. Once the results of the calibration were obtained, the data of less quality that were available for the period 1960 - 1988 were used to verify it.

In the evaluation of the storage coefficients of the region modelled, 10 values that were determined by pumping tests were incorporated. The extension of the confining clay layer was determined by means of the analysis of the prevailing geological conditions (inferred from well logs) and geophysical surveys. The values of the storage coefficients that were used for the cells that behave as confined are between $2x10^{-4}$ and $7x10^{-3}$. In the case of cells that perform as unconfined, values between 0.02 and 0.15 were used.

The initial runs, using the estimated values of S and T, led to the distribution of the piezometric heads shown in Fig. 5.

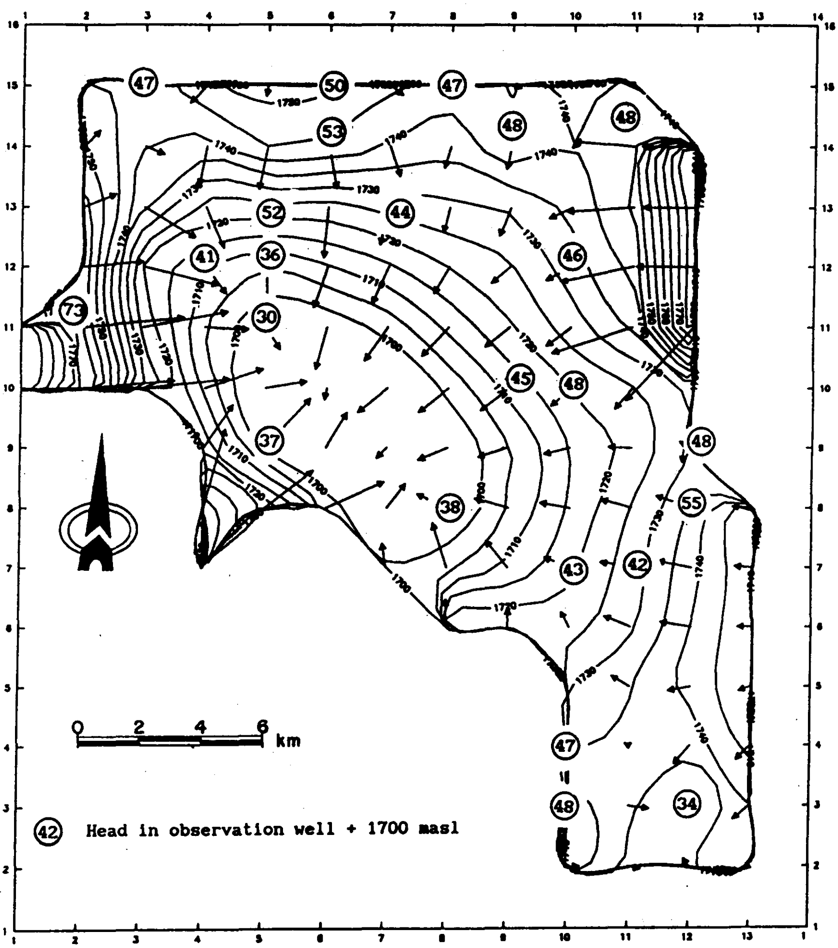


Figure 5: Contour map of predicted piezometric heads, without thermal sources.

In this figure the predicted drawdowns deviate drastically from those observed, the greatest deviations occurring in the area where the thermal manifestations have been observed (Fig. 6).

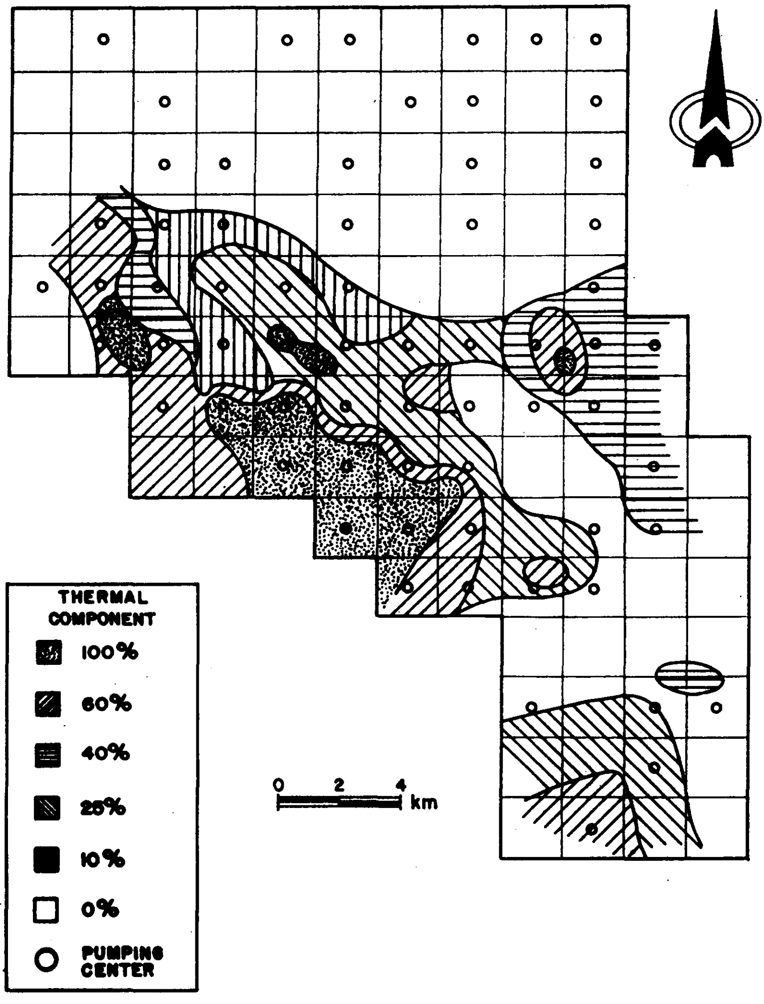


Figure 6: Location of thermal sources.

The general conclusion drawn from these results was that the observed behavior cannot be predicted satisfactorily using the observed values of S and T, when only horizontal flow is modelled. The yield of the actual system is much larger than the one obtained in such model.

The discrepancy between the observed and predicted heads can be reduced in one of the following manners:

(a) increasing the storage coefficient of the aquifer, considering it as unconfined in all the region modelled;
(b) incorporating additional sources of water in the cells, where required.

The first option is unrealistic, since it contradicts geologic evidence directly supplied by well logs and must be discarded, in spite of the fact that it was used in a previous study: Niedzielsky, (1990).

On the other hand, the inclusion of additional sources in the model is fully justified by the hydrochemical and thermal evidence : Cardona (1990), Carrillo-Rivera (1992). They represent the vertical component of the regional system of flow that has been observed in the thermal area of the Valley of San Luis Potosi (Fig. 6). Therefore, this was the option that was adopted in the model. It was incorporated by means of an additional layer (layer II) whose properties were adjusted in the calibration of the model, assuming the piezometric head of that layer is constant.

Since the hydraulic properties of the main aquifer (layer I) are the best known, in the calibration emphasis was placed in determining the properties of the thermal sources. A first guess of the values of the hydraulic conductivity in the vertical direction (Kz) between layers I and II, based on the temperatures and well discharges measured in the field, was used in the initial simulations, and then they were adjusted until the actual piezometric distributions in the thermal area were reproduced. The stopping criterion for the calibration process was that the actual heads should be predicted with an error of less than one meter in the thermal zone, as shown in Fig. 7.

Using the calibrated model, a global mass balance of the region was carried out. The results obtained are listed in Table 1.

Table 1: Mass Balance of the Aquifer.

Concept	$Q(m^3s^{-1})$	%
Aquifer storage	0.34	13
Lateral recharge (cold water)	0.36	14
Upward supply (hot water)	1.90	73
Total well extraction	2.60	100

The distribution of the supply shows clearly that the most important contribution comes from the vertical flow which originates in the regional system and exhibits thermal anomalies.

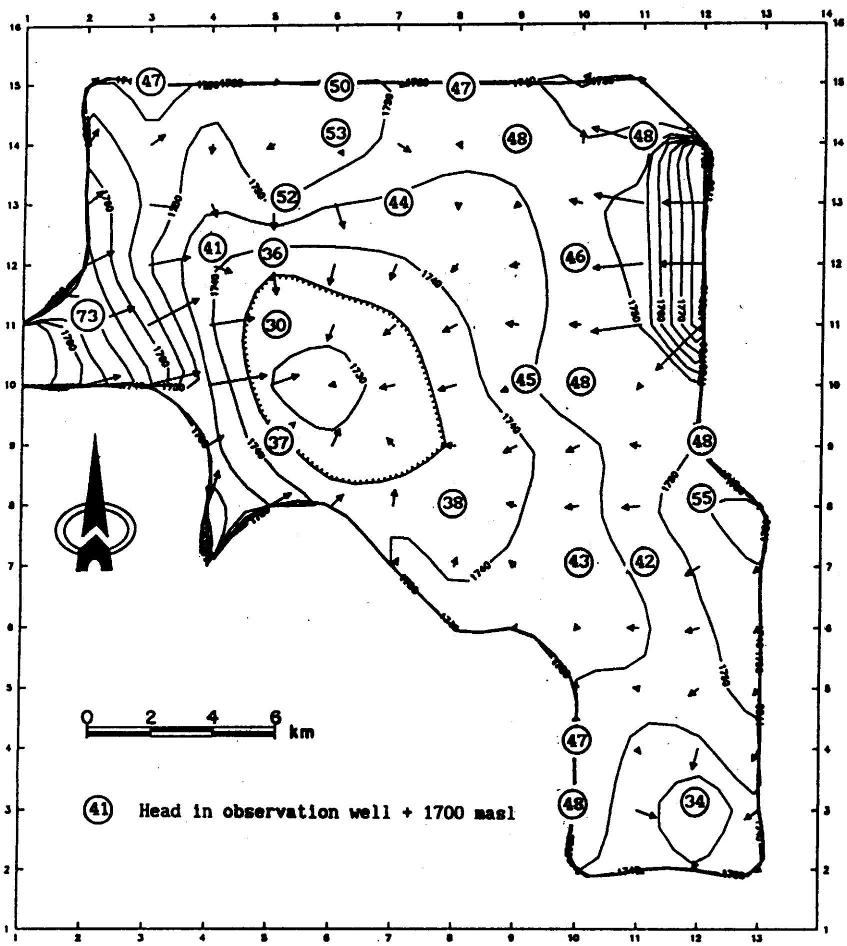


Figure 7: Contour map of predicted piezometric heads, after calibration.

Long period verification

As was already mentioned, the information available for the period 1960 - 1988 was used to test the results of the calibration. Thus, after the calibration was completed, a run covering that period was carried out.

Taking the known initial conditions for 1960 and estimating the evolution of the rate of pumping in the period, the piezometric heads were predicted using the calibrated model. The results of the simulation after 29 years had differences of less than 3 meters between the observed and computed heads in the thermal area. This indicates, specially taking into account the low quality of the information available for the period, that the parameters that were obtained in the calibration are acceptable to make predictions of the behavior of the system within a moderate range of accuracy.

TESTING DIFFERENT PUMPING POLICIES

The analysis of a wide range of exploitation policies of the system is necessary, to quantify the potential of the thermal sources as a water supply for the city of San Luis Potosi.

Predictions of the behavior of the system for a period of 21 years (1989 - 2010) under different exploitation policies were carried out. The options considered were:

- I.0- Keeping the present extraction rate fixed during the whole period.
- I.1- Increasing the rate of extraction 5 % every 5 years.
- I.2- Increasing the rate of extraction 10 % every 5 years.
- I.3- Increasing the rate of extraction 20 % every 5 years.

- II.1- Increasing the rate of extraction in the thermal area exclusively (13 cells) 5% every 5 years.
- II.2- Increasing the rate of extraction in the thermal area exclusively (13 cells) 10% every 5 years.
- II.3- Increasing the rate of extraction in the thermal area exclusively (13 cells) 20% every 5 years.
- II.4- Increasing the rate of extraction in the thermal area exclusively (13 cells) 40% every 5 years.

In Table 2 the results obtained for the different policies that were tested are shown. For each policy the total volume extracted during the period of 21 years is given and then the percentages which originate in the thermal sources, the storage of the aquifer and the neighboring regions is indicated. Finally, in the last column the total volume of drawdown produced during the whole period in the modelled region is given in millions of cubic meters. These results are also illustrated in graphical form in Fig. 8. Clearly, to ensure a drawdown as low as possible, locating the additional demand in the thermal region is the best option.

Table 2: Predictions for the period 1989-2010 under different policies.

Policy	Total Pumped Volume (m^3x10^6)	Of Thermal Origin (%)	From Aquifer Storage (%)	From the Boundary (%)	Drawdown Volume (m^3x10^6)
I.0	1698	81	3	16	3440
	When increments in pumping are uniformly distributed				
I.1	1915	81	5	14	6000
I.2	2153	76	7	17	8800
I.3	2702	77	11	12	16000
	When all increments of pumping are taken from thermal area				
II.1	1866	83	4	13	4800
II.2	2069	81	5	14	6400
II.3	2184	82	6	12	7600
II.4	2946	82	8	10	13600

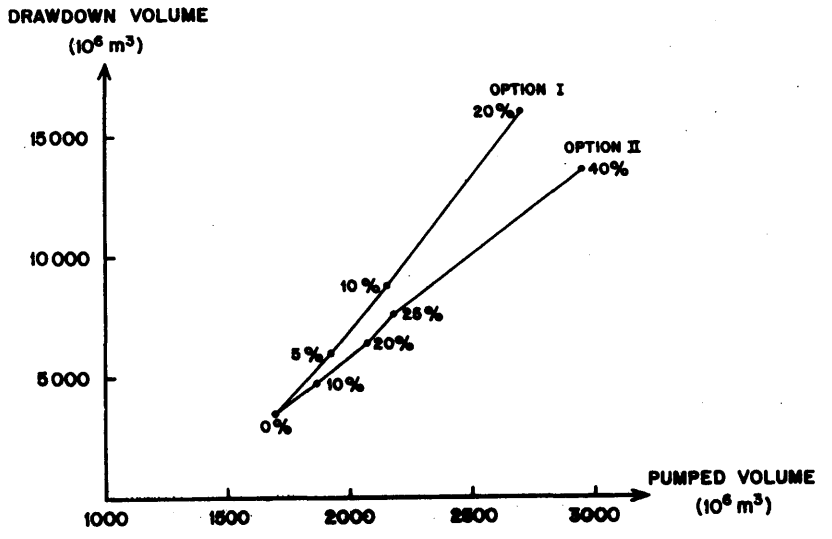


Figure 8: Comparison of simulated policies.

CONCLUSIONS

A numerical model that takes into account the contribution of thermal sources was developed, and using it, different operation policies have been tested for the aquifer of the City of San Luis Potosi.

Initially, it was intended to implement a model without thermal sources. However, it turned out to be impossible to achieve a model capable of predicting the observed behavior when only horizontal flow was modelled. This pointed out the need of incorporating thermal sources in the model, in order to explain the vertical flux coming from deeper geological formations whose hydraulic properties are unknown. This vertical supply was incorporated in the model, introducing a layer of constant hydraulic head in the lower aquifer.

Since the properties of such layer were unknown, it was necessary to derive them during the calibration process. The main parameter that was adjusted was the vertical hydraulic conductivity that exists between layers I and II. At the same time, the hydraulic properties, T and S, of the aquifer and the boundary conditions were also adjusted. The fact that an additional parameter was introduced in the calibration made this process more complicated than is usual for this kind of application . However, this form of proceeding is similar to what is usually done when applying modelling techniques in the horizontal plane, for which it is standard to eliminate neighboring regions with insufficient hydrological information by imposing suitable boundary conditions. In many cases, the supply coming from such regions is quite significant for the behavior of the part of the aquifer which is modelled.

The results of the calibration were satisfactorily verified by reproducing the observed behavior in a longer period (1960-1988) of exploitation of the aquifer, for which incomplete hydrometric information was available. The results of this study indicate that the procedure used here to study a deep geological formation for which no information is available, may be useful more generally. In particular, in the case study here reported, in spite of the insufficient knowledge of the deep formation it was possible to make recommendations for the policies to be followed in the production of the aquifer. These recommendations are better founded than if the lack of information about the thermal sources had inhibited the development of such model.

The distribution of piezometric heads predicted on the assumption that the present rate of pumping is continued through the whole period 1989 - 2010 (Fig. 9 option I.0) indicates that the present extraction can be continued without producing exceedingly large drawdowns.

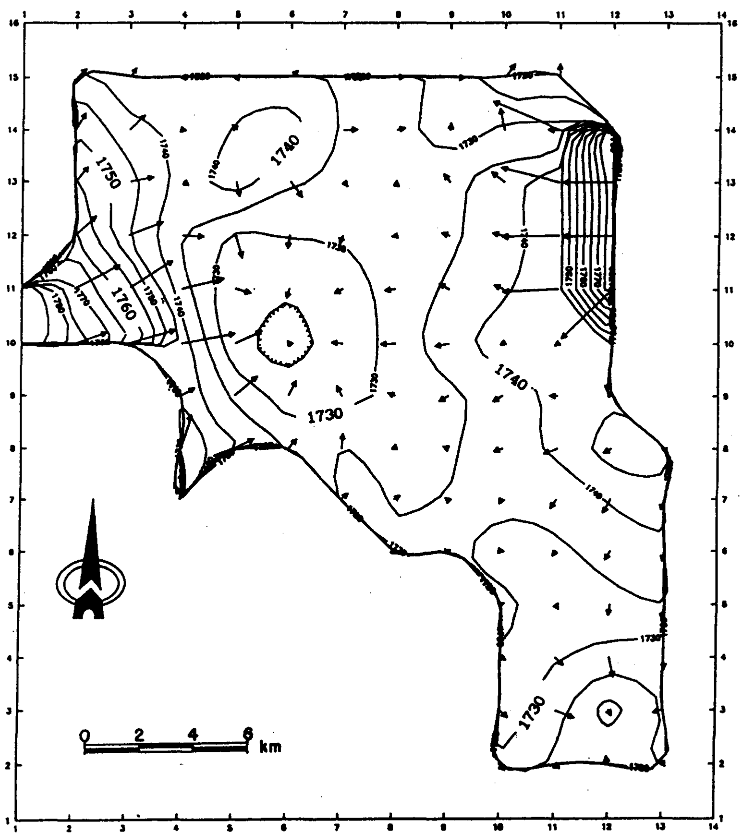


Figure 9: Contour map of predicted piezometric heads (1989 pumping rate).

Figure 8 clearly illustrates the fact that if the pumping rate is to be increased, the most convenient option from the point of view of keeping the drawdowns as small as possible is to concentrate the demand in the thermal area. However, if such policy is adopted, the supply would contain a greater volume of thermal water, which would deteriorate its quality. Thus, in such case, it would be important to monitor the dissolved ions and the water temperature. If this is done, it should be recommended that the information gathered in this manner be used to improve the numerical model and to test the assumptions on which it is based.

REFERENCES

Cardona A., 1990. *Caracterización Físico-Química y origen de los sólidos disueltos en el agua subterránea en el Valle de San Luis Potosí: su relación con el Sistema de Flujo*. M.S. Thesis, Universidad Nacional Autónoma de Nuevo León, México.

Carrillo-Rivera J.J., 1992. *The hydrogeology of the San Luis Potosí area*. Ph. D. thesis, London University, U.K.

Golden Software, Inc., 1989. Surfer reference manual. P.O. Box 281, Golden, Colorado 80402 U.S.A.

Instituto de Geofísica UNAM, 1988. *Estudio geofísico-geohidrológico del Valle de San Luis Potosí*: Contrato cc-86-3140, Informe Interno Secretaría de Agricultura y Recursos Hidráulicos, México, D.F.

McDonald M. & Harbaugh A., 1984. *A Modular three-dimensional finite-difference ground-water flow model*. U.S. Department of the interior U.S. Geological Survey, National Center, Reston, Virginia.

Niedzielski H, 1990. Perspectivas del suministro de agua a la Ciudad de San Potosí. Ciencia, *Revista de la Academia de la Investigación Científica. vol 41*, No. 5 México, D.F. 153-162.

THE RISK OF OVEREXPLOITATION OF A MULTI-LAYER HETEROGENEOUS AQUIFER SYSTEM. HYDROGEOLOGICAL CONSIDERATIONS IN MAJOR GREEK BASINS

P. MARINOS
Geotechnical Division. Department of Civil Engineering
Nat. Tech. Univ. Athens, 42 Patission Str. 10682 Athens, Greece
J. DIAMANDIS
Engineering Geology Lab.,Department of Civil Engineering, University of Thrace
67100 Xanthi, Greece

ABSTRACT. Major parts of neogene and pleistocene basins with a multi-layer confined aquifer system, are subject to overexploitation due to their lithological and structural heterogeneity which obstructs the recharge from the adjacent high potential quaternary aquifers.

INTRODUCTION - GENERAL SETTING

In several extensive regions in Greece, neogene and pleistocene deposits are developed, either forming a hilly environment or covered by the recent alluvia of plains. Those deposits of fluviotorrential or lacustrine origin, consist of alternations of coarse and fine materials, e.g. sands, sandstones, gravels, conglomerates, silty mixtures, clays and marls, forming a resemblance to a multi-layer system.

This system offers a sequence of confined aquifers of significant potential for local use. The recharge of the aquifers (II, III, A, B in fig. 1) is achieved through underground lateral inflows from the termination of the torrential fans at the borders of the basins (I in fig. 1). In the fans, very effective phreatic water tables are developed, recharged mainly by infiltrations from the river beds. In some cases, the multi-layer system communicates laterally with the limestones of the borders which discharge their karstic waters in the form of huge springs; a dynamic hydraulic continuity from the karst to the porous media is then established.

Wells of depths between 100 and 200 m are found to deliver yields from 50 to more than 300 $m^3 h^{-1}$ However, after several years of exploitation of the ground-water of these regions, a general decline is observed which cannot be attributed only to the construction of new wells or the aging of the old ones. Many of these regions are already under a regime of overexploitation and new irrigation plans will be mainly based on water from surface reservoirs.

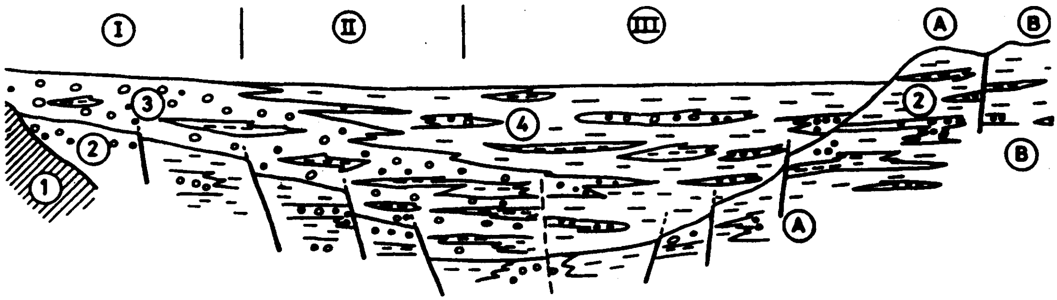


Figure 1: The structure of the multi-layer system. Heterogeneity and discontinuities. 1: basement, 2: neogene or pleistocene deposits, 3: torrential fans, 4: quaternary deposits in the extension of fans; I, II, III, A, B.: hydrogeologic zoning, see text and fig. 2. (Not to scale).

OVEREXPLOITATION. REASONS AND RISKS

The reason for the drop of potential is the hindering and obstructive connection of the confined aquifers with the recharging sectors. This is due to the discontinuities of the permeable horizons provoked by (fig. 1):

(a) the lithological heterogeneity and the non-development of persisting typical strata imposing an anarchy and discontinuities in the distribution of the coarser material. The irregularities are greater in the cases where there is a sudden transition from the torrential to the completely runoff regime.

(b) the tectonic discontinuity generated by the neotectonic extentional fault activity which is of high frequency and intensity in the area of Greece ('back-arc' regime).

(c) the frequent erosion-filling of the occasional recent paleogeographic relief, as a result of the continuous changes of the geographic base level.

The wells during the pumping tests and also during the first period of their exploitation, provide a false view of their real capacities which can lead to overexploitation. The connection between permeable horizons takes place through complex paths, due to the very strong lateral changes already mentioned. The transmissivities obtained from short-term pumping tests may baffle the modeling of the system.

ILLUSTRATIVE CASES

The Thessaly plain

This plain of 3,500 km², the biggest in the country, extends within the Pinios river basin (fig. 2). Most of the groundwater reserves are in the alluvial field of the two depressions of neotectonic origin; they are separated by a hilly ridge where, besides the alpine basement, the neogene deposits outcrop too. The western part is rich in aquifer resources with a total of 800×10^6 m³ annual

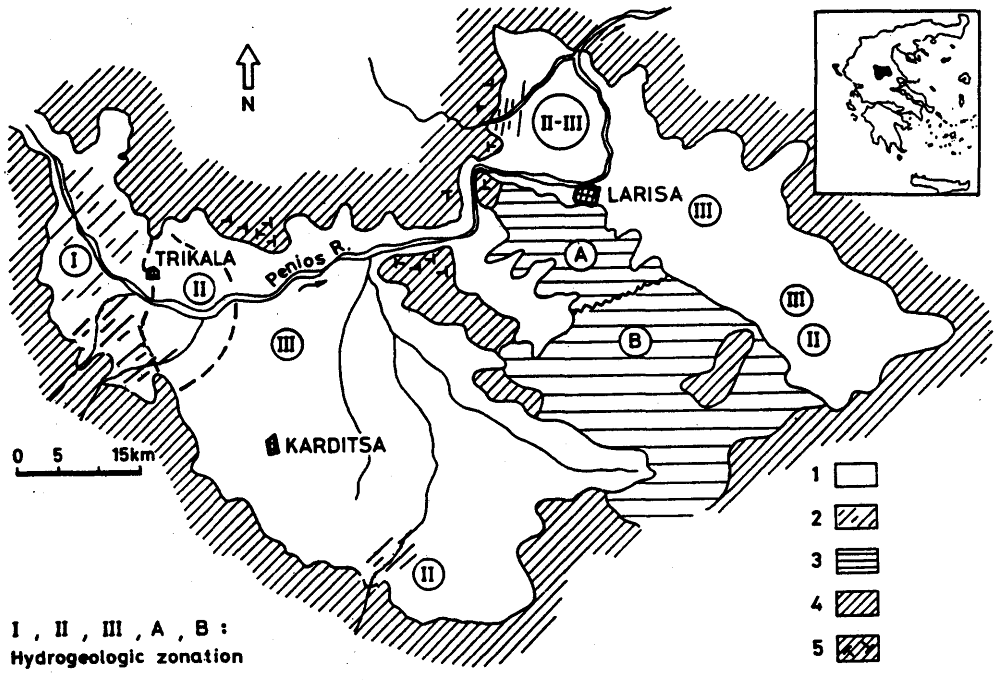


Figure 2: A sketch geologic map of the Thessaly plain. 1: quaternary deposits, 2: fluviotorrential fans, 3: neogene multi-layer systems, 4: alpine basement, 5: basement with karstic inflow; I, II, III, A, B, see fig. 1.

underground inflows (70% from infiltration from rivers). 90% of these inflows are concentrated at the most eastern part, where the fans still persist (I in fig. 2). A portion, 60-70%, of the inflow quantity is collected again on the surface by sponteous outflow in the riverbed, feeding downstream schemes but an important quantity of 150×10^6 m^3 of groundwater can be annually exploited by wells. (Anon, 1974; Konstantinidis, 1978; Konstantinidis & Pergaliotis, 1983). Downstream of the zone I, the structure of the filling presents the irregularities and discontinuities described before; here the potential is low and overexploited sectors can be observed.

In the hilly neogene area (fig. 2), alternations of strata-like horizons of 1-15 m thickness are developed. The permeable strata have always a clay portion which is becoming more apparent towards the south (B in fig. 2). The annual quantities pumped from the wells are estimated to 20×10^6 m^3. The overexploitation of the reserves is a fact. Figure 3 shows the changes from the pumping tests in 1974-75 to the estimated production in 1983, by using a pseudo-specific yield $z = Q/H$ (Q being the pumping yield and H the corresponding dynamic depth). The yields diminish from 150-300 to 70-200 m^3 h^{-1}(zone A) or from 40-80 to 20-50 m^3 h^{-1}(zone B in remote areas). In fig. 4 a comparison is shown between the changes of the level of a karstic aquifer (1) and the multi-layer aquifer of Neogene (2).

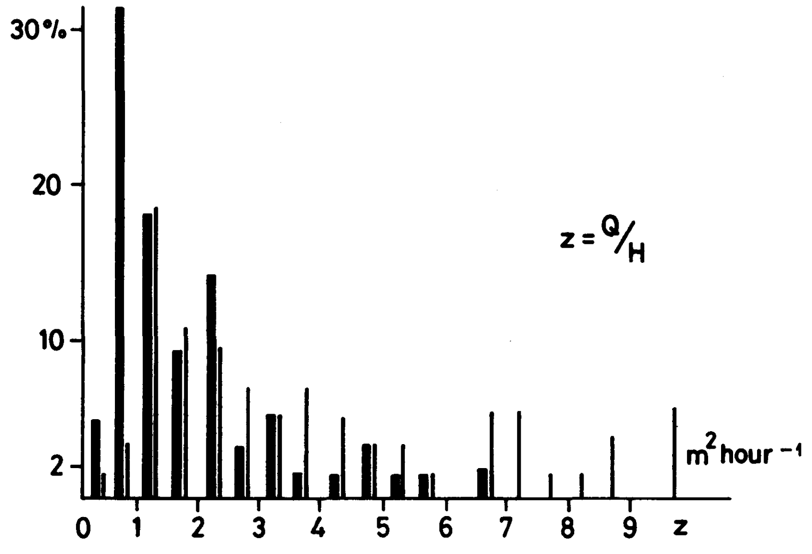


Figure 3: Changes in production of wells in zones A and B of fig. 2. Thin columns: data from pumping tests in 1974 - 75. Thick columns: estimated production from 1983.

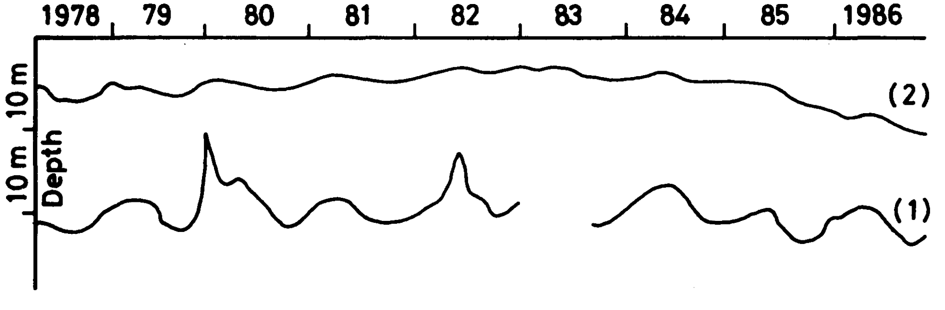


Figure 4: Piezometric levels. (1): well in a karstic aquifer, (2): well in the porous multi-layer system.

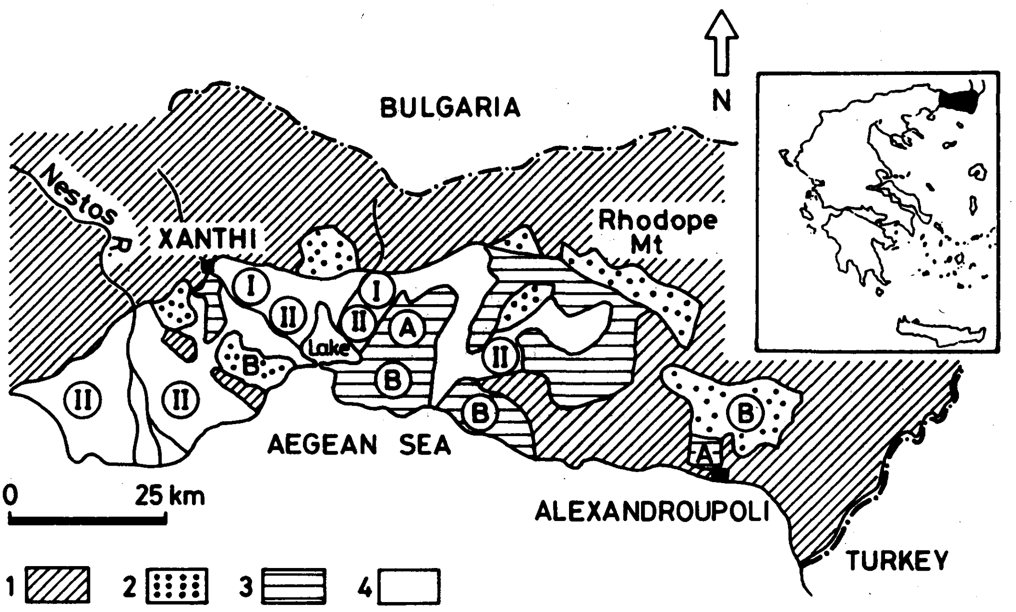


Figure 5: Sketch geology for Thrace. 1: crystalline basement, 2: paleogene multi-layer system, 3: neogene multi-layer system, 4: quaternary deposits, I, II, A, B, see fig. 1 and text.

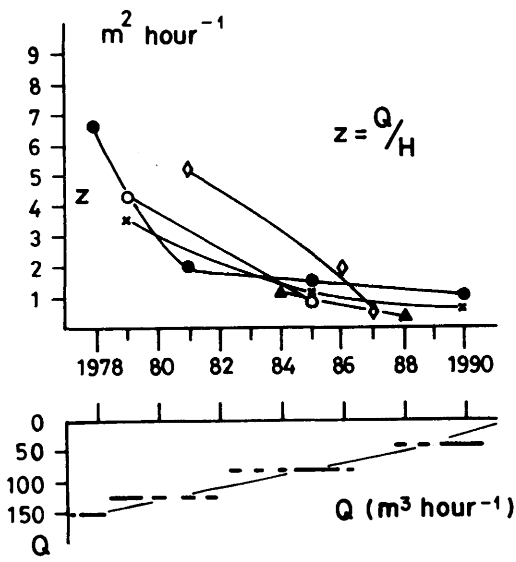


Figure 6: Overexploitation of the ground water reserves for the city of Alexandroupolis (see fig. 5).

Thrace

In the coastal area of Thrace a series of tertiary clastic sediments overlay the crystalline basement, and form a hilly environment eroded by the main rivers of the province (fig 5). The heterogeneity is considerable due to the absence of an intermediate regime of sedimentation, from the torrential to the deltaic conditions; high rates of neotectonic subsidence have also ocurred (Marinos *et al.*, 1981 and Diamantis, 1978). In this region the most attractive part for exploiting is located in selected zones of torrential fans and ancient river bed axes. In the neogene sediments (approx. 150 m thick) wells of yield up to 300 m^3 h^{-1} present, after two years of exploitation, a 20 m drop of piezometric level. This drop is only partly due to the construction of new wells.
Further eastwards, the city of Alexandroupolis is located in an area with no major aquifers. The city is supplied from the aquifers of neogene and the underlying paleocene deposits, fed mainly by moderate inflows from the adjacent fissured crystalline rocks. In fig. 6 the dramatic drop due to overexploitation during 1978-90 is clearly shown. This drop imposed low rates of exploitation after three to four years of operation. No other wells were constructed in the area to influence the above pumping rates.

CONCLUSIONS

In areas with high lithologic, tectonic and geomorphologic heterogeneity, an important drop of ground water potential can be observed and an overexploitation could be established, if the management of the confined aquifers is based only on data from short term pumping tests. The hydrogeologic investigation of the greater surrounding recharging area must always be insisted on.

REFERENCES

Anon. 1974. Ground-water development project of the plain of Thessaly. Sogreah, Grenoble; 1-235.
Diamandis, J. 1985. Hydrogeological study of the Vistonis lake basin. PhD, Univ. of Thrace; 1-265.
Konstantinidis, D. 1978. Hydrodynamique d' un système aquifère heterogène. Thessalie orientale. Disertation Université de Grenoble.
Konstantinidis, D. & Pergaliotis, P. 1983. Ground water development in Thessaly. Mathematical models. Report, Ministry of Agriculture. Athens (in greek).
Marinos, P., Diamantis, J. & Stournaras, G. 1981. Les eaux souterraines dans la région de Komotini, Thrace. *Ann. Geol. Pays Hellen,* 20; 616-636.

Section 2:

ENVIRONMENTAL EFFECTS RELATED TO AQUIFER OVEREXPLOITATION

WETLANDS: AN IMPORTANT ISSUE IN HYDROGEOLOGY

M.R. LLAMAS
Dept. de Geodinámica, Fac. de Geología
Universidad Complutense, 28040 Madrid, Spain

ABSTRACT. Valuable ecosystems conservation is considered an important issue to attain sustainable development. Wetlands are usually included among the most valuable and fragile ecosystems. Groundwater flow changes, caused by its exploitation or by other causes, may induce serious impacts in wetlands natural functioning. On the other hand, the creation of new wetlands demands a good knowledge of the hydrogeological conditions of the site. Therefore, wetlands hydrogeology will become an important issue in the near future. The problems in the two relevant wetlands in Spain are summarized. The sizes, hydrogeological and ecological characteristics and the legal frameworks of both wetlands are significantly different, as are their respective degrees of deterioration, but the common cause of this deterioration is the depletion of the water table induced by pumpage for irrigation purposes.

INTRODUCTION

This article is a partial and updated reproduction of other article (Llamas, 1991b) published in the Proceedings of the 23rd International Congress of the International Association of Hydrogeologists (Puerto de la Cruz, Spain, April 1991). The topic of that Congress was aquifer overexploitation. The invited papers and communications included in those proceedings will be a relevant reference for some years. Immediately after the Congress, the Department of Technic Cooperation for Development of the United Nations jointly with the Spanish Government organized at Gran Canaria (Spain) an Interregional Workshop on Groundwater Overexploitation in Developing Countries. The corresponding report (UN/DTCD, 1991) will probably constitute a landmark for those interested in groundwater management.

The first part of the previous paper (Llamas, 1991b) was devoted to comment the diffuse character, and almost impossible practical definition, of the word overexploitation, that is often charged with emotional or negative overtone which does not respond to the physical or socioeconomic reality. Sometimes this concept has been used with sectarian purposes. Therefore, it was suggested to eliminate the use of the word 'overexploitation' from the scientific and technological literature and replace it by other expressions which describe reality more accurately. This topic will not be treated here again. The interested reader is refereed to Custodio (1992), Llamas (1992) and mainly to UN/DTCD (1991).

AIM AND SCOPE

Wetlands are almost universally considered a scarce and valuable resource* which is diminishing because of the impact of anthropic actions. The actual trend in developed countries is that wetlands surface should be conserved (no net loss) or even increased (net gain). This paper will summarize the importance of groundwater for the hydrological functioning of wetlands ecosystems. The ignorance or neglect of such reality may cause serious ecological impacts. Two cases in Spain will be described. Groundwater exploitation has virtually destroyed one of them: the National Park of the Tablas de Daimiel wetland and will probably cause a great deterioration in the second one: the National Park of Doñana. The latter is the most important National Park in the whole European Community. In both cases, these impacts have already induced a relevant reduction in groundwater exploitation and more restrictions in groundwater use will be probably required in the near future.

SUSTAINABLE DEVELOPMENT AND ECOSYSTEMS CONSERVATION

The general awareness of the importance to humanity of the correct compatibility between nature conservation and economic development has been constantly increasing throughout the last two decades. On the level of principles, almost everyone admits that solidarity, an international consensus, is necessary to achieve a sustainable development, since some important environmental problems clearly transcend national policies. The report entitled 'Our Common Future' (UN, 1987) presented an interesting panorama of the world state of development and environmental conflicts. However, some researchers have considered that the subject of water resources was not covered sufficiently in this report. In fact the World Meteorological Organization (WMO) has organized an International Conference on Water and the Environment (Dublin, 26-31 January 1992) with the purpose of preparing a more complete information for the UN Conference on Environment and Development which is to take place in Brazil in June 1992.

One practical consequence of this large-scale awareness of the importance of nature conservation is the demand for environmental impact assessments to be made prior to the approval of a large part of development plans or projects (transport, agriculture, urban planning, etc.). This demand was imposed in North America back in the 70s, in most of the European Community countries only in the 80s. For this reason it is not surprising that the ecological concern of some of the people responsible for water policy in Europe is still only small, although the situation does seem to be changing more or less quickly. Thus in 1990 the European Community Government decided to create an Agency for the Environment but it has not started to operate yet.

WETLANDS: TYPES, IMPORTANCE AND LEGAL DEFINITION OR DELINEATION

Types

Within the broad field of nature conservation 'Our Common Future' (UN, 1987) places special stress on avoiding the destruction or degradation of certain ecosystems considered to be particularly valuable. Among the ecosystems of singular interest are wetlands. These ecosystems can be very varied in nature and are often given different names: swamps, peatlands, bogs, fens, mires, marshlands, etc. Wetlands include some of the most productive ecosystems of world.

According to Gosselink & Maltby (1990), wetlands occupy about 6 per cent of the world's land surface. Their types vary according to many different factors, such as clime, topography, surface and groundwater hydrology (quantity and quality), dominant vegetation and others. But in all these ecosystems water is the dominant factor in their origin and functioning. Wetlands are usually sustained by water resources other than direct rainfall.

Tidal salt marshes and coastal tropical mangroves are among the most important wetlands but present less interest in our case. Non-tidal, continental fresh or saline wetlands are usually more related to groundwater flow. Also, here there are a great variety of types: from tundra to tropical peatlands, from bottomland hardwoods along the great America rivers to playa lakes or sebkhas in arid regions or to "pothole" ponds on the Canadian prairies.

This is not the right place to present a detailed classification of the numerous types of wetlands. There exist recent and good publications on this subject, e.g. Dugan (1990) and Maltby (1991a).

Importance

The relevance of these aquatic ecosystems is related to their functions and values, which have been described in a good number of recent papers (Maltby, 1991b; Burke *et al.*, 1988; Dugan, 1990). Some are hydrological: flood mitigation, groundwater discharge (or recharge) places, traps of sediments and pollutants; other are ecological, such as sites of great biomass production, habitats for endemic or unique (endangered) species, and in general sites with great biodiversity; recreational and educational values of wetlands have steadily increased during the last decade in most countries.

Among the values of wetlands there is one that probably will acquire more importance in the near future. Natural and constructed wetlands may provide a relatively simple and inexpensive solution for controlling many water pollution problems facing small communities, industries, and agricultural operations. Nevertheless, according to Hammer (1990), adoption of this technology has been inhibited in the USA by the lack of guidelines and adequate information on important system components and on basic wetlands ecology.

The published studies about the economic value of wetlands seem to be scarce. Whitehead & Lonquist (1991) present an analysis in which they introduce the notion of economic value of the pure existence of wetlands and also the importance of information on wetlands and related environmental values on the "willingness to pay" of the general public in order to conserve one of such ecosystems.

Legal definition or delineation

The general feeling of the need for protection of wetlands has led to policy actions and the corresponding regulations. In a certain number of cases, economic or social conflicts may rise between certain land use developments and wetlands conservation. Therefore is important to define what is a wetland from the legal point of view. Probably the country in which this process is more advanced is the USA. In 1989 four federal Agencies with responsibilities in wetlands Administration published a Manual for identifying and delineating jurisdictional wetlands (USEPA, 1989).

According to Lehr (1991) the 1989 Manual for delineating jurisdictional wetlands (USEPA, 1989) is mired in a swamp of controversy because with its definition of wetland condemns as much as 1.20 million km^2 of mostly private property to a useless future in spite of the fact that it may appear high and dry to the 'untrained' eye. The main concern of Lehr (*ib.*) is that, in the 1989 wetland Manual (and its new May 1991 draft), land which has a high water table saturating the surface up to 14 days a year during the growing season and containing hydric soil, which support hydrophilic vegetation, is to be considered wetlands. According to Lehr (*ib*) this is a new 'dry and often barren' type of wetland. It seems that during the next years a probably fruitful discussion is going to take place in the USA about how to define a wetland and when the conservation of a wetland should be preferred to other possible uses of such land. In many cases, good knowledge of the hydrogeologic characteristics of the area will be a crucial factor in order to make a sound decision.

WETLAND LOSSES AND THREATS

The destruction or degradation of wetlands has been considerable as from a century ago in almost all the industrialized countries. There have been different types of causes for these losses. According to Dugan (1990), the most frequent have usually been: a) surface drainage of marshlands to transform them into arable land; and b) the contamination of surface water as a result of urban or industrial activities.

The main interest for hydrogeologists is in inland freshwater wetlands which comprise most of the world's wetlands; for example: according to Gosselink & Maltby (1990), in the United States more than 90 per cent of wetlands are interior. The largest single cause of loss of these wetlands between the 1950s and 1970s (80 per cent of the total loss) was conversion to agriculture. In Europe the pattern of conversion began much earlier than in the United States, with impounding and draining being well under way in medieval times. According to Dahl (1990) wetland losses in the U.S.A. between 1880 and 1980 were about 53%, but in California were 91%. In the USA conversion of inland marshes to agricultural production reflects two different processes. The first is the purposeful draining of marshes via surface ditches, subsurface tiles, impounding and pumping to make them suitable for cultivation. Tax incentives and drainage improvements associated with new highways are contributing factors. The second process is more subtle. The expansion of irrigation systems, especially the development of centre-pivot irrigation, had a twofold effect. Small wetland pools became sources of irrigation water, for example in the playa region of the Texas highlands. Further, subsurface pumping, mostly for irrigation, reduced ground water levels. This tended to dry out many isolated wetlands in the Midwest, making them easier to convert to agricultural production. A further complication of irrigation practices in arid regions is the fate of return flows. Water flowing across arid fertilized land accumulates various chemicals. In California, loss of wetland habitat for migrating waterfowl has concentrated remaining populations into a few remaining areas such as the Kesterson Wildlife Refuge. Agricultural return flows into this refuge have high selenium concentrations, which cause high egg mortality rates and severely malformed chicks. The refuge has been closed until some solution to this problem can be found.

On a world scale there still seem to be only a few well-documented cases where the destruction or deterioration of wetlands can be attributed to the extraction or contamination of groundwater. In fact, the only example of this type quoted by Dugan (1990) is the case of the Tablas de Daimiel National Park in Spain which will be discussed in this paper. Zimmerman (1990) studies the Cheyenne Bottoms wetlands which are in trouble because of water table drawing down to grow crops.

The demand for groundwater is particularly important in arid or semi-arid countries. The existing cases of 'water mining' are almost only found in these countries and involve the corresponding significant depletion or drawdown of the water table. The fact that there hardly seem to exist any well-documented cases of wetlands being deteriorated as a result of groundwater pumping in the arid regions of western USA still does not seem to have any clear explanation. According to Llamas (1989), there are two possible factors which might explain this situation: 1) in the US as a whole the proportion of wetlands in arid or semi-arid zones is very small in relation to the abundance of wetlands that exist in its cold, temperate or tropical zones; 2) furthermore, probably most of the destruction of wetlands as a result of intensive groundwater extraction took place before the 70s when public interest over the conservation of these ecosystems virtually did not exist.

WETLANDS HYDROLOGY

There are numerous natural factors affecting the hydrological regime of a wetland. Mention can be made of precipitation, evapotranspiration, topography, geology, soil and vegetation. In addition the hydrological regime in the particular wetland zone is often affected by the general regime of the basin and/or of the regional hydrogeological system.

Undoubtedly Hydrology plays a fundamental role in the way wetlands function. The role of surface water in the functioning of wetlands has generally been admitted and can easily be observed. On the other hand, there is still frequent ignorance about the role of groundwater or even this role is incorrectly understood (Kusler, 1988; Llamas, 1990; Winter, 1988). This situation will probably improve quickly in the near future. Among the reasons for this can be mentioned the fact that the US legislation considers 'Hydrology' as one of the three basic criteria to determine whether a zone is legally a wetland or not (USEPA, 1989). The other two criteria for defining a wetland are the existence of certain types of vegetation and/or soils. Genetically speaking, both the soil and the vegetation are a consequence of the water regime in the zone. Wetland administrators are usually better schooled in Biology, or Soil Science, than in Hydrology (Kusler, 1988) and this may explain why USEPA (1989) emphasizes the criteria related to the vegetation and soils more than those referring to Hydrology.

According to USEPA (1989), the legal existence of a wetland requires the presence of water in the form of permanent or periodic inundation, or saturation of the soil over a sufficiently long time (at least one week) during the period of vegetational growth; according to Lehr (1991) this time will be probably increased to two weeks. All wetlands ought therefore to be in connection with surface or groundwater at least periodically.

Many wetlands are located on flood plains bordering rivers, lakes or estuaries; on the other hand, others are formed in closed basins or depressions where surface runoff accumulates or groundwater flow emerges; finally others appear on slopes with where the saturated zone stays close to the topographical surface and gives rise to a spring or simply to an area of active evaporation. In short, in almost all the cases, the wetlands are going to be characterized by having the aquifer water table very close to the topographical surface. Practically the only exception to this situation consists of the small closed basins which are perched over local phreatic surfaces and therefore constitute recharge areas for the underlying aquifer and not discharge areas as the cases mentioned earlier. In these recharge zones the soils may not be hydromorphic and the saturated zone may only lie close to the topographical surface for a short time.

For the purposes of this paper it is important to bear in mind that a general drawdown of the water table will usually lead to drastic changes in the hydrological functioning of the overlying wetland. Generally speaking the wetland will be transformed into a groundwater recharge area instead of continuing to be a discharge area of the aquifer, which is the usual situation in arid or semi-arid climates. This transformation may also involve significant changes in the chemical properties of the water.

The characteristic plants of wetlands are very varied and their types not only depend on the moisture of the soil but also on the chemical composition of the water (Bernáldez *et al.*, 1988). Therefore changes in water chemistry introduce changes in vegetation which in turn cause modifications in the fauna of the ecosystem (Schot *et al.*, 1988).

TWO SPANISH CASES OF CONFLICTS BETWEEN GROUNDWATER EXPLOITATION AND WETLAND CONSERVATION

Two Spanish cases will be presented where groundwater exploitation has undergone or is soon about to undergo important restrictions as a result of its ecological impact on some ecosystems considered of relevance on a world scale. It is important to stress that in both cases this ecological impact or deterioration occurred before other effects became apparent which could be considered typical of aquifer 'overexploitation'. In other words, a depletion of the water table, which proves almost irrelevant from the point of view of Technology or the economics of groundwater extraction, can give rise to real ecological catastrophes.

The cases presented here are the National Parks of the Tablas de Daimiel and Doñana. They are the only Spanish national parks located in wetlands. The classification of land as National Park **theoretically** implies the maximum legal protection possible in Spain. Furthermore, in 1982, both zones were included by the Spanish Government in the RAMSAR list, the international agreement for the protection of habitats for migrating birds. Both places have also nominated Biosphere Reserves by UNESCO.

The two cases have considerable analogies and also important differences, both from the hydrological and socioeconomic/legal points of view. Hence their analysis and comparison is of interest. The publications on the Hydrogeology of both National Parks are relatively abundant but the conclusions of the authors do not always coincide. For the benefit of those who cannot read in Spanish, almost all the references in this paper correspond to articles in English. However a large part of the basic data are published in articles in Spanish or in reports by the corresponding Spanish Agencies (ICONA: Nature Conservation Institute, ITGE: Technological and Geological Institute and MOPU: Ministry of Public Works). In Suso & Llamas (1990) many of the references for these documents in Spanish are included.

The Tablas de Daimiel National Park

The 'Tablas de Daimiel' form a marshlands in the confluence of the Rivers Guadiana and Gigüela (Fig. 1); at its most extensive times this zone covers some 15 km^2. The swamps of the Tablas used to be covered all the year round by a layer of water almost 1 m deep, except during summers in very dry periods. The Tablas occur in the discharge zone of the western Mancha calcareous aquifer which extends over an area of 5,000 km^2 and has high transmissivity (Fig. 2). The average recharge has been estimated at some 200-300 Mm^3 per annum. The water of the Tablas came also from the stream flow of the Rivers Gigüela and Guadiana. The first of these rivers is mainly fed by surface runoff; the second is basically groundwater fed by the western La Mancha calcareous aquifer (Llamas, 1989, 1991; Hollis & Jones, 1991).

An intensive exploitation of the western La Mancha aquifer for irrigation purposes has been carried out over the last two decades, increasing from 200 Mm^3/year in 1974 to some 600 Mm^3/year in 1987. This exploitation has given rise to 1) a progressive decline in the water level in the wells, which have gone down as far as 20-30 m in some points (Fig. 2); 2) the disappearance of the emergences of the River Guadiana from the 'Ojos del Guadiana' sources to the Tablas since 1983 and 3) the change of the Tablas into a 'gigantic recharge pond' for the surface waters of the River Gigüela instead of being a discharge zone of the western La Mancha aquifer. This intensive irrigation was fundamentally financed by the local farmers themselves. Irrigated agriculture has been the most important factor in the economic development of this region.

The ecological impact caused by this intensive pumping on the National Park became obvious in the last decade: the 'Tablas' became dry a great part of the year and the River Guadiana 'disappeared', since 1983. In 1986 and 1987 two fires occurred, possibly the result of arson, which destroyed a large part of the Park. Independly of those two large fires, the peatland which covers most of the 20 km of the former thalweg of the Guadiana river -totally dry since 20 years ago- undergoes a slow process of spontaneous combustion. This process which practically can not be stopped has an obvious visual and economic impact.

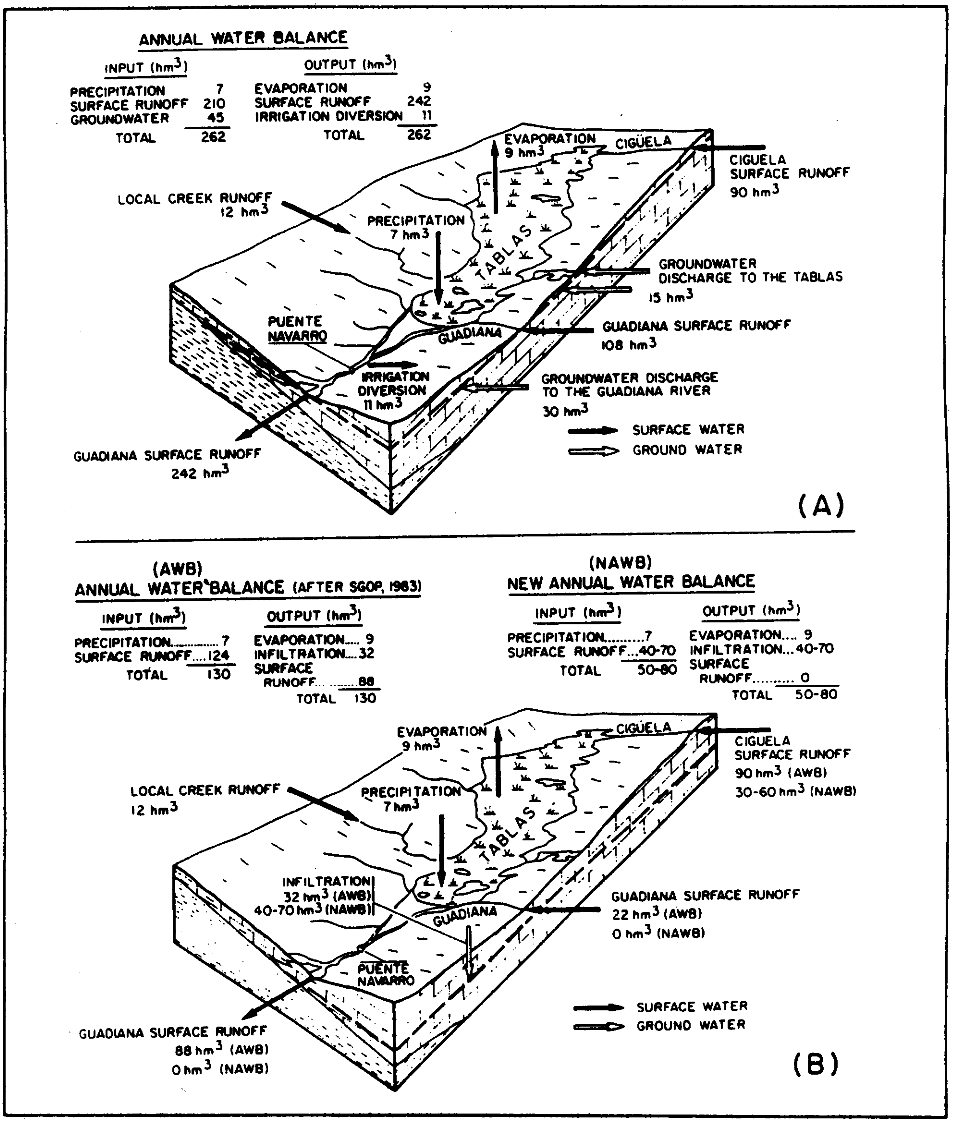


Figure 1: Hydrological functioning and Water Balance of the Tablas de Daimiel National Park Wetland. A) average situation under practically undisturbed conditions; B) probable new situation because of watertable depletion after a report of the Servicio Geológico de Obras Públicas (SGOP) and (NAWB) after Llamas (1989).

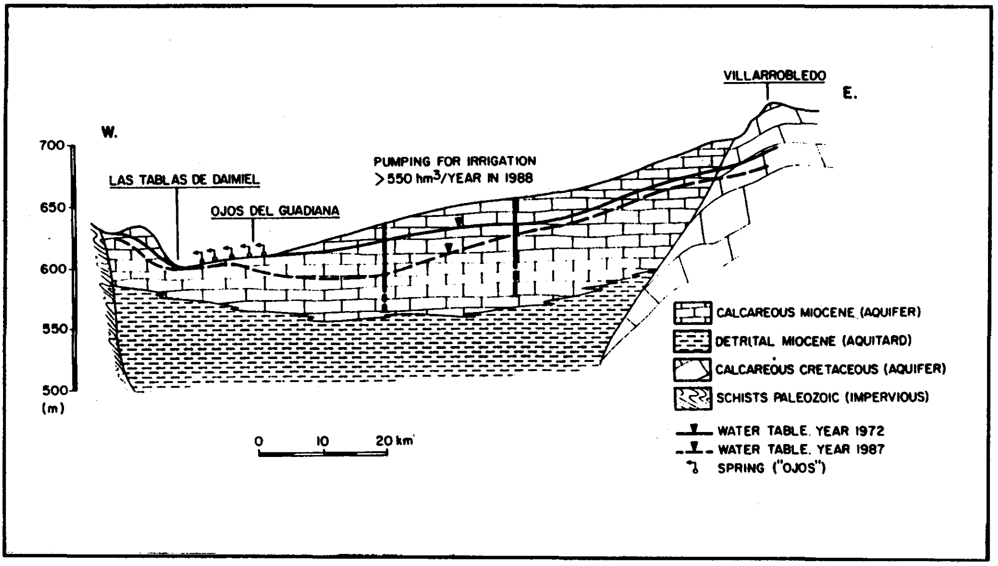


Figure 2: Schematic Hydrogeological profile of La Mancha aquifer.

In february, 1987, the Mancha aquifer was officially declared **overexploited** according to the 1985 Spanish Water Law. A declaration of overexploitation requires the drawing up of a groundwater management plan which must be carried out jointly by the Guadiana Basin Water Authority and by the 44 Groundwater Users Communities which should be formed (one for each municipality of the zone declared overexploited). It was therefore first necessary to create these Users Communities which did not exist in the past. Apparently the farmers have been putting up considerable resistance to forming such Users Communities. At the end of 1991, less than one fifth of the total number of Users Communities had been legally constituted.

Under the pressure of the protests of national and international ecological groups, an experimental three-year plan for the hydrological regeneration of the National Park was approved in 1988 by the Spanish Government. This plan essentially consisted of three actions: a) drilling of some emergency pumping wells within the Park; b) the experimental transfer of up to 60 Mm^3 of water from the Tagus-Segura Aqueduct to the Gigüela over the three-year period (1988-90); and c) the construction of a new reservoir in the River Bullaque, a tributary of the Guadiana, to carry water to the Tablas. Prior to this one small concrete dam (some 8 m high) had been built at the downstream border of the National Park to retain the incoming surface waters inside the Park. Other two smaller earth dams have been built inside the Park, in order to better manipulate the scarce surface water coming into the marshlands.

The results of the experimental hydrological regeneration plan could be summarized as follows: 1) at the end of 1990, the flooded area of the Park had been reduced to some 0.7

km^2 (5% of total marshlands); 2) the emergency wells had been drilled but for reasons not well known have not been practically operated to supply water during this critical period; 3) over these three years some 40 Mm^3 of water have been transferred from the River Tagus to the Park; the maximum amount planned was not reached because the first two years were relatively wet ones. 4) Apparently the idea of building a reservoir in the River Bullaque has been abandoned for both hydrological and political reasons; the possibility is now being studied of building a reservoir on the head waters of the River Gigüela which would possibly be mainly aimed at storing water from the Tagus-Segura Aqueduct.

The official Government stand has been that the hydrological regeneration plan for the Tablas de Daimiel has been a success. For this reason, at the beginning of 1991 it was decided to extend the transfer of water from the Tagus for a further three years. This has undoubtedly pleased the farmers in the area who find their water resources increased by this 'artificial recharge'. Apparently most ecological groups are also pleased with this extension of the hydrological regeneration plan, possibly because they have not studied the ecological impact of the water transfer on other wetlands along the River Gigüela. The first regeneration project budget was some 10 million dollars and it can be assumed that its extension for a further three years involve a similar cost. The scientific data on the water regeneration plan made public are still incomplete not only from the hydrological but also from the ecological point of view. The changes caused in the vegetation and fauna seemed to be so significant that some ecologists have stated that the Tablas de Daimiel National Park has become an 'ecological desert, even though sometimes it has water'.

The situation of the Tablas de Daimiel National Park could be summarized by saying that an extraction of groundwater exceeding the natural recharge by some 200 to 400 Mm^3/per annum has given rise to the virtual disappearance of the Guadiana river (16,000 km^2 of watershed surface and about 240 Mm^3/year stream-flow) and to a far-reaching ecological deterioration of a National Park and of the nearby wetlands. To pretend to solve this problem essentially by means of a costly import of water which barely reaches 10% of the water deficit is to try to achieve the impossible. It would probably have been more effective to invest this money (some 20 million dollars in six years) in other actions, for example: 1) in encouraging a technological reconversion of the irrigated land to crops requiring less water, without prejudicing the economic standard of the farmers; 2) in intensive campaigns of hydrogeological education in order to convince the farmers of the urgent need to form Users Communities to manage groundwater better.

It does not seem exaggerated to say that the Tablas de Daimiel National Park is in a state of 'ecological coma'. Recuperation from this 'coma' is extremely difficult, unless agricultural practices are changed and a substantial improvement in the hydrogeological education of the farmers is carried out.

The Doñana Park

The problems of Doñana have been considered an emblematical case in nature conservation of the European Community by the President of its Parliament (Llamas, 1991). This National Park covers an extension of 500 km^2 of Parkland proper and 230 km^2 of Prepark or buffer land. It has three main ecosystems (Fig. 3) (Llamas, 1989 and 1990): a) the marshlands, b) the stabilized eolian sands or 'cotos' and c) the moving dunes. The ecological function of these three ecosystems is intimately linked to the surface and groundwater hydrological system of the lower Guadalquivir basin which, in addition to the River Guadalquivir, includes the River Guadiamar and the La Rocina stream. Beneath all this physiographic unity lies an extensive Plioquaternary detrital aquifer known as the Almonte-Marismas system, extending over some 3,400 km ^{2}.

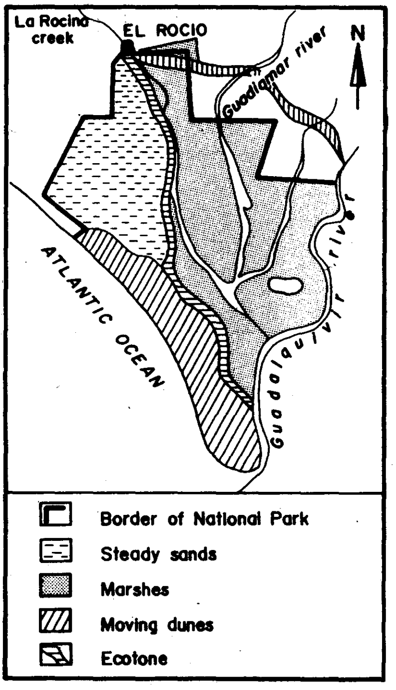


Figure 3: Main ecosystems in the Doñana National Park.

In the 70s the Spanish Ministry of Agriculture designed its most ambitious groundwater irrigation project in this area, known as the Almonte-Marismas Plan (25,000 ha involving a groundwater withdrawal in the order of 150 Mm^3/year). This irrigation zone - and its corresponding wells are located in the border of the National Park. The State investment for this irrigation plan has been in the order of 200 million US dollars. In 1991, there are at least 10,000 ha under irrigation and a groundwater withdrawal of around 60 Mm^3/year. The most important part of the irrigated land corresponds to the Almonte-Marismas project which is currently being managed by the Autonomous Government of Andalusia. Figure 4 illustrates the state of the area known as Sector II of the Almonte-Marismas Plan which is the area which will cause most ecological impact because of its proximity to the Doñana National Park and to the La Rocina creek. This stream is now the main source of

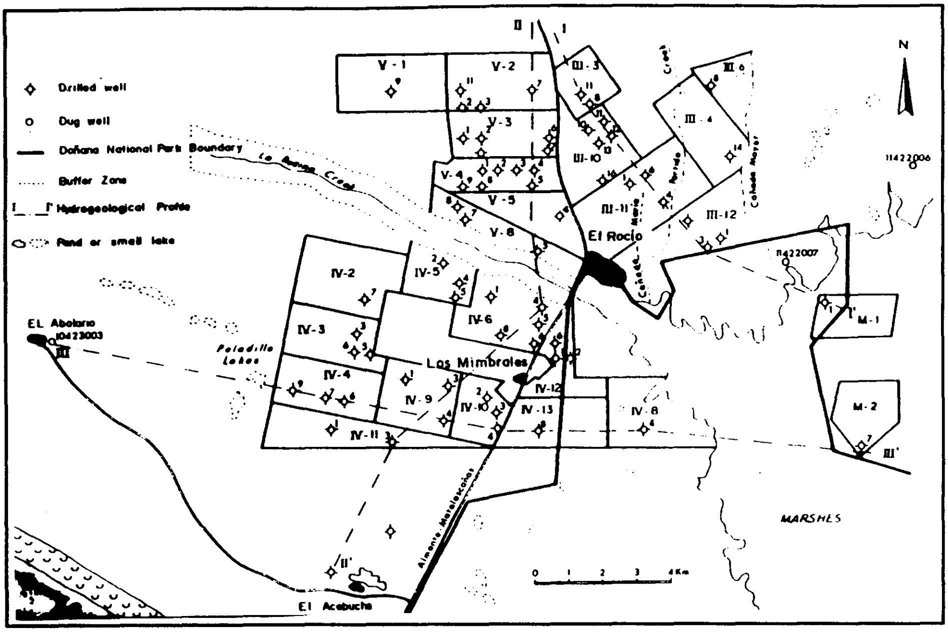


Figure 4: Location of the main observation wells in the Sector II of the Plan Almonte-Marismas (after Suso & Llamas, in preparation).

fresh surface water for the National Park.

The economic return of the Almonte-Marismas irrigation Plan does not appear to be clear. Both in 1989 and in 1990 several multitudinous protests were made by farmers who the Government had taken to the area. They demanded more economic aid from the Andalusian Government (about US$ 40 million) because they consider their operations are ruinous (Llamas, 1991). This problem has not been solved yet. It seems that the Andalusian Government is going 'to rebuy' the land which was previously given free to the farmers.

At least since 1984 the Spanish Ministry of Agriculture has been receiving warnings from scientists that the Almonte-Marismas irrigation scheme could give rise to a serious ecological deterioration in some critical parts of the Doñana National Park. These warnings were mainly based both on the research done by these scientists and on the results of a numerical flow model made in 1982 by the Geological and Mining Institute of Spain (IGME). These warnings were to no avail, possibly because the IGME report had a 'developer's approach' and made no mention of the ecological impact of the pumping operations. Successive research produced more data to further substantiate the hypothesis of a forthcoming 'Daimielization' of Doñana and gave rise to several scientific articles and official communiqués addressed to the Doñana National Park Board. These warnings were not heeded either by the responsible authorities. Perhaps contributing to this lack of acceptance was the fact that a second flow model done by the IGME in 1985 did not appear to give importance to the ecological impact of the groundwater extractions (Suso and Llamas, 1990).

In 1987 the IGME submitted a new report with a flow model that was essentially the same as those of 1982 and 1986 but which now warned of the possible negative ecological effects after 20 or 25 years of pumping activity, and which recommended that the irrigated area then existing (7,000 ha) should not be increased. But this report was not sufficiently clear in indicating that, even with the groundwater extractions required to irrigate 7,000 ha, the depletions of the water table and the deterioration of the Park would be considerable before 20 years transpired (Fig. 5). This proposal was not accepted by the Andalusian Government nor by the Central Government of Spain. In 1991 there are at least 10,000 ha under irrigation in the area.

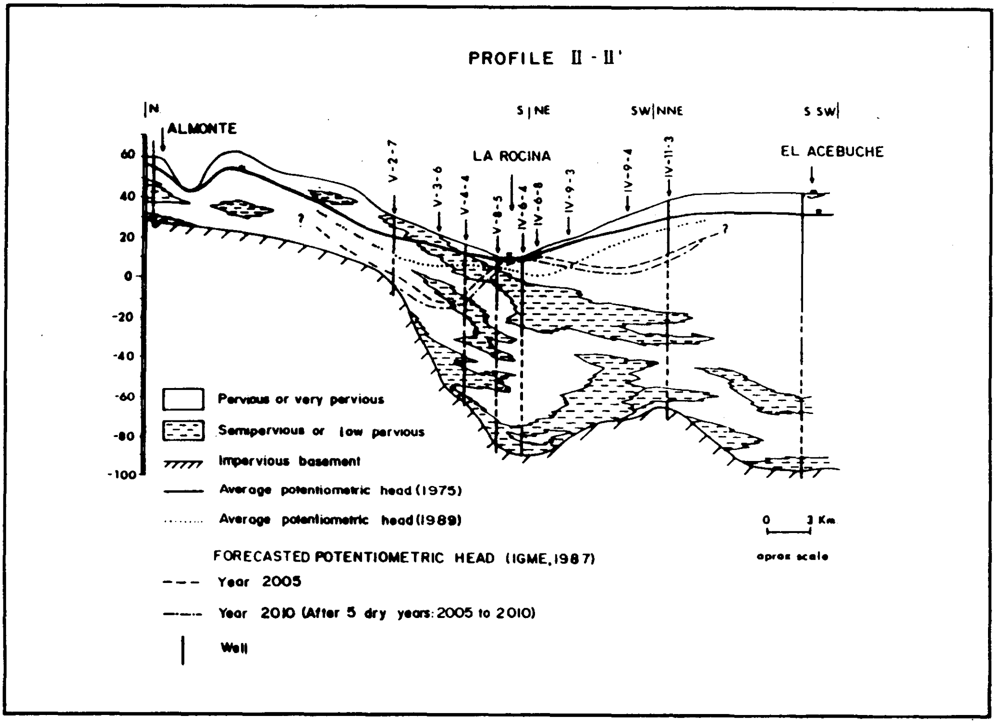


Figure 5: Hydrogeologic profile II-II. Location in figure 4 (after Suso & Llamas, in preparation).

In 1989, at the request of the World-Wide Fund for Nature (WWF), a mission of international experts issued a statement on the consequences of groundwater extraction in the Doñana Park. The mission visited the area for one week in November of 1988. Its report included, in a more implicit than explicit way, all the impact predictions made in previous studies (Suso & Llamas, 1990). These impacts are essentially three: a) desiccation of the groundwater discharge zone known as La Vera ecotone as a result of the drawdown of the water table (Figs. 5, 6 and 7); b) considerable reduction of the incoming supply of fresh water to the swamps through the La Rocina stream and c) entry into the Park of surface water and groundwater contaminated by fertilizers and pesticides used in the areas irrigated by groundwater.

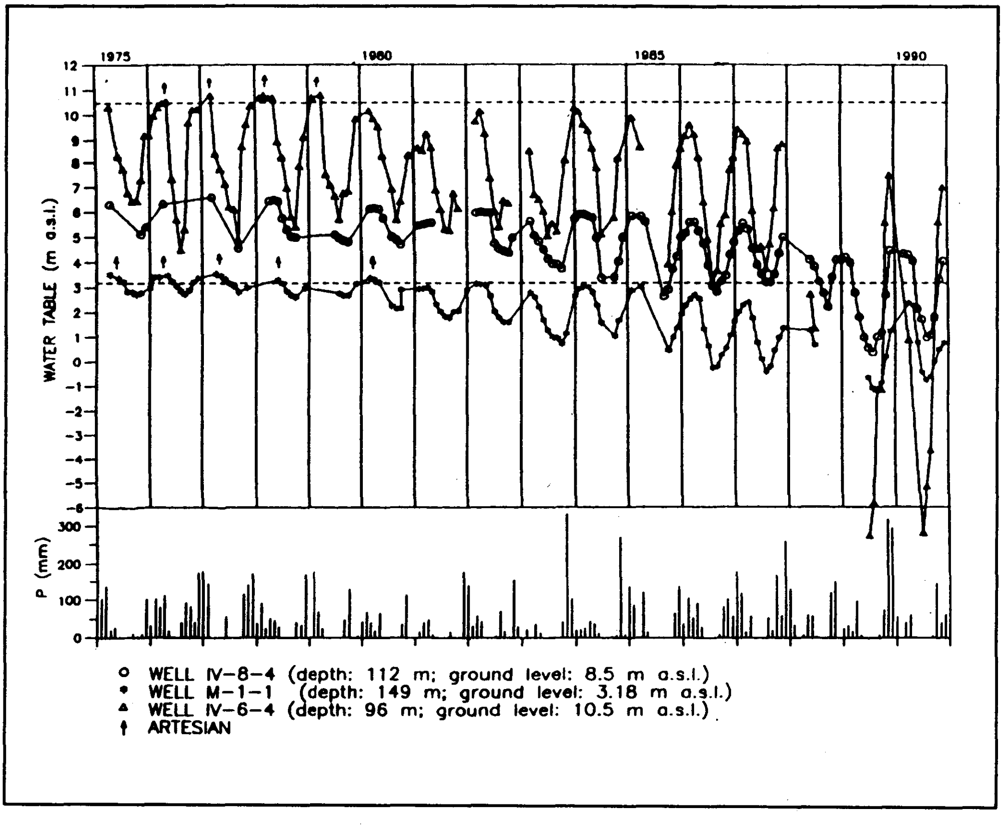


Figure 6: Hydrographs of three observation wells located inside the National Park (IV-8-4 and M-1-1) or near to it (IV-6-4). The situation of the wells can be seen in Figure 4 (After Suso & Llamas, in preparation).

The WWF Report contained some omissions and ambiguous phrases (Suso & Llamas, 1990) but it contributed significantly in creating a greater social awareness of the ecological problems caused by the extraction of groundwater in the area surrounding Doñana Park. It is enough to mention that the problems of Doñana Park have warranted articles in Time Magazine (24, August, 1990) and in New Scientist (November, 1990). A more significant fact would be the letter of requirement sent to the Spanish Government

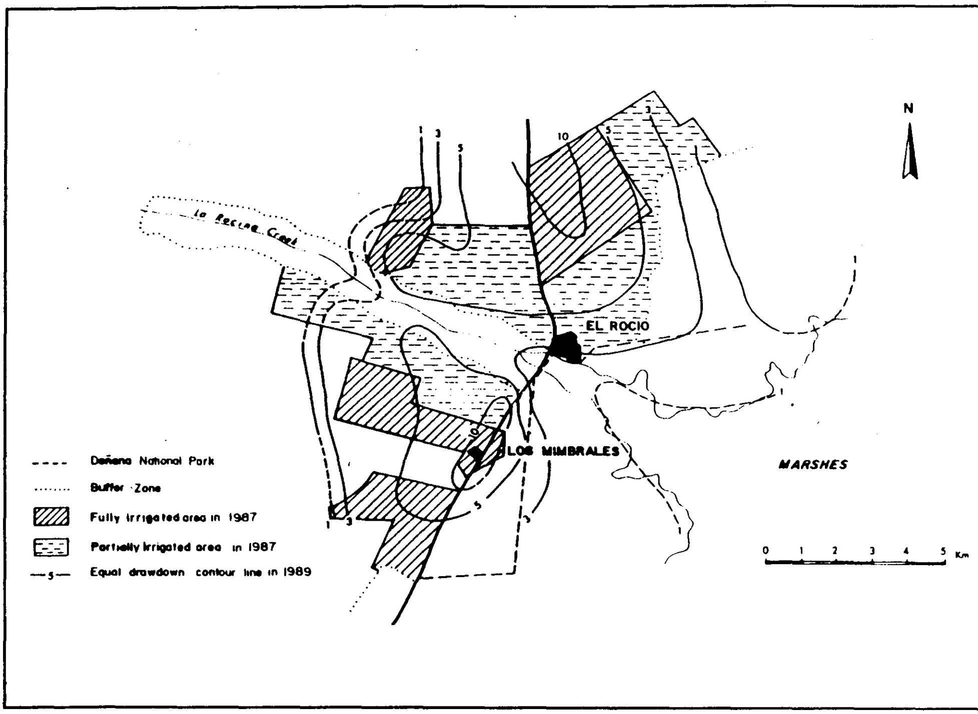


Figure 7: Map of equal average drawdown contour lines between 1975 and 1989 (after Suso & Llamas, in preparation).

by the Commission of the European Communities (CEC) in which it takes into account the claims presented by conservationist groups because of the deterioration of the Doñana National Park. If the Spanish Government's reply to that letter is not considered satisfactory the CEC will take the case up with the Court of the European Community which can end in a condemnation of the Spanish Government. Both the CEC letter and the Spanish Government's reply are still restricted matter and therefore not known officially by the scientific community. In 1990 UNESCO, in charge of controlling the Reserves of the Biosphere, commissioned the Spanish Government to draw up a report on the state of the Doñana National Park. This report has not been made known to the scientific community at the end of 1991.

In the 23rd IAH International Congress, Olías *et al.* (1991) presented a short paper with the first results of the project entitled 'Ecological Effects of Aquifer Exploitation in the Doñana National Park' which had been funded by the Spanish Government. According to these authors, it seems that there is only one observation well which permits the water table fluctuation inside Doñana National Park to be followed. This well -located in the moving sands- is close to the coast and over 10 km away from the main pumping well fields. It is therefore quite logical that it does not show any declining trend. These facts do not coincide with those of Suso & Llamas (1990) and with those shown in Figures 5, 6 and 7, in which it can be seen that a good number of observation wells exist inside the National Park and that a declining trend exists.

The case of the Doñana Park could be summed up by saying that the ecological impact of the pumping of groundwater is not yet as obvious as in the case of the Tablas de Daimiel National Park and some scientists are expressing doubts as to the existence or importance of this impact. Nevertheless, the great importance of the ecosystems under threat and the direct protagonism of the Spanish and Andalusian Governments as potential aggressors of these extraordinary ecosystems lends special poignancy to the case of the Doñana Park. In any case, it seems obvious that concern over the conservation of these unique ecosystems (and not over the overexploitation in the most usual sense of the word) has already led to the area covered by the Almonte-Marismas irrigation plan being reduced to 10,000 ha, that is to 40% of the 25,000 ha officially planned a few years ago. Furthermore it is likely that a large part of these 10,000 ha will have to be abandoned as a result of their ecological impact on the Doñana Park.

CONCLUSIONS

Sustainable development of groundwater resources is not an easy task, because it requires the participation of a great number of persons or social groups. The number of direct users, or exploiters, who pump groundwater in any important aquifers is frequently in the order of several thousands of farmers, industrialists, small public water-suppliers, and others. Often these users lack an adequate education about the basic principles of Hydrogeology and of Ecology. Therefore, a substantial improvement is necessary in the education of the general public to meet the challenge of achieving a wise use of groundwater.

Wetlands are ecosystems with relevant functions and values from an ecological, hydrological, economic and cultural point of view. Their surface has been steadily diminishing along the last two centuries because of anthropic impacts, mainly agricultural development in industrialized countries. The awareness of the need for protecting these aquatic ecosystems began only a couple of decades ago and has led to different kinds of policies in each country, from **no care** to **no loss** or to **no net loss**. Foster & Rogers (1991) have recently proposed the goal of **net gain** of wetlands surface; this means to restore old wetlands or even to create new wetlands. In most developing countries, the incentives to conserve wetlands are frequently non-existent. To achieve the goals of **no loss, not net loss** or **net gain** some political and economic changes are necessary but also improved research and much public education is needed.

Groundwater frequently plays an important role in the hydrological functioning of wetlands. Sometimes small modifications in the groundwater flow, which can hardly be classified as excessive exploitation, can give rise to serious deteriorations in the ecosystems located on wetlands. For this reason, and especially in arid or semiarid countries, it will be increasingly more necessary to make detailed environmental impact studies of activities which may alter the flow and/or quality of groundwater systems related to wetlands. On the other hand, the creation or restoration of wetlands also requires a detailed knowledge of the hydrogeological characteristics of the site.

REFERENCES

Bernáldez, F.G., Rey J.M., Peco, E. & Levassor, C. 1990. Groundwater indicator plants in the Tertiary aquifers of Central Spain, In: *Selected Papers on Hydrogeology*, Heise, vol. 1; 301-312.

Burke, D.G., Meyers, E.J, Tiner, R.V. & Hazel Groman. 1988. *Protecting nontidal wetlands*. American Planning Association, Washington.

Custodio, E. 1992. *Hydrological and hydrochemical aspects of aquifer overexploitation*, (this book).

Dahl, T.E. 1990. *Wetland losses in the United States, 1780s-1980s*, U.S. Department of the Interior, Fish and Wildlife Service, Whasington DC.

Dugan, P. (ed.). 1990. *Wetland conservation: a review of current issues and required action*. International Union for Conservation of Nature, Gland, Switzerland.

Foster, C.H.W & Rogers, P.P. 1991. *Rebuilding the nation's wetlands heritage: a challenge for the 1990s*. Center for Science and International Affairs Discussion Paper 91-5, Kennedy School of Government, Harvard University.

Gosselink, J.G. & Maltby, E. 1990. Wetland losses and gains, In: *Wetlands: a threatened landscape*. Williams, M. (ed.), Blackwell; 296-322.

Hammer, D.A. (ed.). 1990. *Constructed wetlands for waste water treatment*. Lewis Publishers. Chelsea, Michigan.

Hollis, G.E. & Jones, T.A. 1991, Europe and the Mediterranean Basin, In: *Wetlands*, Finleyson and Moser (ed.). Facts on File, Oxford; 27-55.

Kusler, J.A. 1988. Hydrology: An Introduction for wetlands managers, In: *Wetland Hydrology*, Assoc. of State Wetland Managers, Berne, New York; 4-26.

Lehr, J.H. 1991. Wetlands: a threatening issue. *Ground Water*, vol. 29, 5; 642-645.

Llamas, M. R. 1988. Conflicts between wetlands conservation and ground water exploitation: two case histories in Spain. *Environmental Geology*, vol. 11, 3; 241-251.

Llamas, M. R. 1989. Groundwater and wetlands: new constraints in groundwater management. *Inter. Assoc. Hydrol. Sciences*, Publ. 188; 295-604.

Llamas, M. R. 1990. Geohydrology of the eolian sands of the Doñana National Park (Spain). *Catena Supplement*, 18; 145-154.

Llamas, M.R. 1991. Groundwater exploitation and conservation of ecosystems. In: *Aquifer Overexploitation*, L. Candela *et al.* (eds), Proc. XXIII Congress International Assoc. Hydrogeologists. Puerto de la Cruz, Tenerife, Spain, vol. I; 115-131.

Llamas, M.R. 1992. La surexplotation des aquifers: aspects techniques et institutionnels. *Hydrogéologie*, admitted (preprint-10 pages).

Maltby, E. 1991a. Wetlands and their values. In: *Wetlands*, Finlayson and Moser (eds). Facts on File, Oxford; 8-26.

Maltby, E. 1991b. Wetland management goals; wise use and conservation. *Landscape and Urban Planning*, vol. 20; 9-18.

Olías, M., Cruz, J. Benavente, J., García-Novo, F. & Muñoz, J.C. 1991. New data about the Almonte-Marismas aquifer from the hydrogeological monitoring (1989-1990). In: *Aquifer Overexploitation*, L. Candela *et al.* (eds), Proc. XXIII Congress International Assoc. Hydrogeologists. Puerto de la Cruz, Tenerife, Spain, vol. I; 159-162.

Schot , P.P., Barendregt, A. & Wassen, J.M. 1988. Hydrology of the Naardermeer: influence of the surrounding area and impact on vegetation, *Agricultural Water Management*, 14; 459-470.

Suso, J.M. & Llamas, M.R. 1990. El impacto de la extracción de aguas subterráneas en el Parque Nacional de Doñana. *Estudios Geológicos*, vol. 46; 317-345.

United Nations. Commission on Environment and Development. 1987. *Our Common Future*, Oxford Univ. Press.

United Nations/Department of Technical Cooperation for Development (UN/DTCD).1991. *Interregional Workshop on Groundwater Overexploitation in Developing Countries*, Gran Canaria, Spain, 20-24 April 1991. Publication U.N. INT/90/R43.

U.S. Environmental Protection Agency. 1989. *Federal Manual for Identifying and Delineating Jurisdictional Wetlands*, 3 appendices.

Whitehead, J.C. & Lonquist, B.C. 1991. Measuring contingent values of wetlands: effects of information about related environmental goals. *Wat. Res. Research*, vol. 27, 10; 2223-2231.

Winter, T.C. 1988. A conceptual framework for assessing cumulative impacts on the Hydrology of nontidal wetlands. *Environmental Management*, vol. 12, 5; 605-620.

Zimmerman, J.L. 1990. *Cheyenne Bottoms: wetland in jeopardy*, University Press of Kansas.

THE IMPACT OF THE OVEREXPLOITATION OF THE CAMPO DE MONTIEL AQUIFER ON THE LAGUNAS DE RUIDERA ECOSYSTEM

P.E. MARTINEZ-ALFARO & E. MONTERO-GONZALEZ
Geodynamics Department, Faculty of Geology,
Universidad Complutense, 28040 Madrid, Spain
B. LOPEZ-CAMACHO Y CAMACHO
Geological Service, Dir. Gen. Water Works,
Ministry Public Works & Transport,
Avda. Portugal 81, 28071 Madrid, Spain

ABSTRACT. The River Pinilla, Guadiana Viejo or Alto Guadiana rises in Campo de Montiel (Eastern Mancha Region) at an altitude of some 980 m in the barren plain known as 'Borbotón de las Cobatillas' where de Pinillas springs occur in the contact between the Lias carbonates and underlying the saline, impervious Keuper.

The waters form a small brook which along a 35 km stretch subsequently gives rise to the ecosystem of the Lagunas de Ruidera Natural Parkland. This is a set of some 15 lakes interconnected by channels and/or cascades, each closed off by a natural travertine dam.

The conversion of over 5,000 ha into irrigated land, mostly for corn crops, in this area has caused problems for the lakes and the different water usage involved since it has considerably reduced the water resources on which the latter relied. In 1988 the aquifer was officially declared overexploited.

A digital surface and underground flow model has been used to analyse the effects of the overexploitation on the system and the effectiveness of the possible steps to be taken.

INTRODUCTION

The Campo de Montiel high plateau lies to the south of the Manchegan Plain, in the provinces of Ciudad Real and Albacete, and consists of a barren plain of tabular Jurassic limestone, slightly inclined northwards, averaging around 100 m thick and lying over an impervious substrate of Triassic clays and marls. The plateau altitude rises gently from 700 or 800 m in the northern zone to up to 1,000 m in the south (Fig.1).

This limestone plain gives rise to an unconfined aquifer approximately 2,500 km^2 in area whose groundwater recharge produces numerous springs which in turn start a series of rivers flowing into three different catchment basins: the Guadiana, Guadalquivir and Júcar.

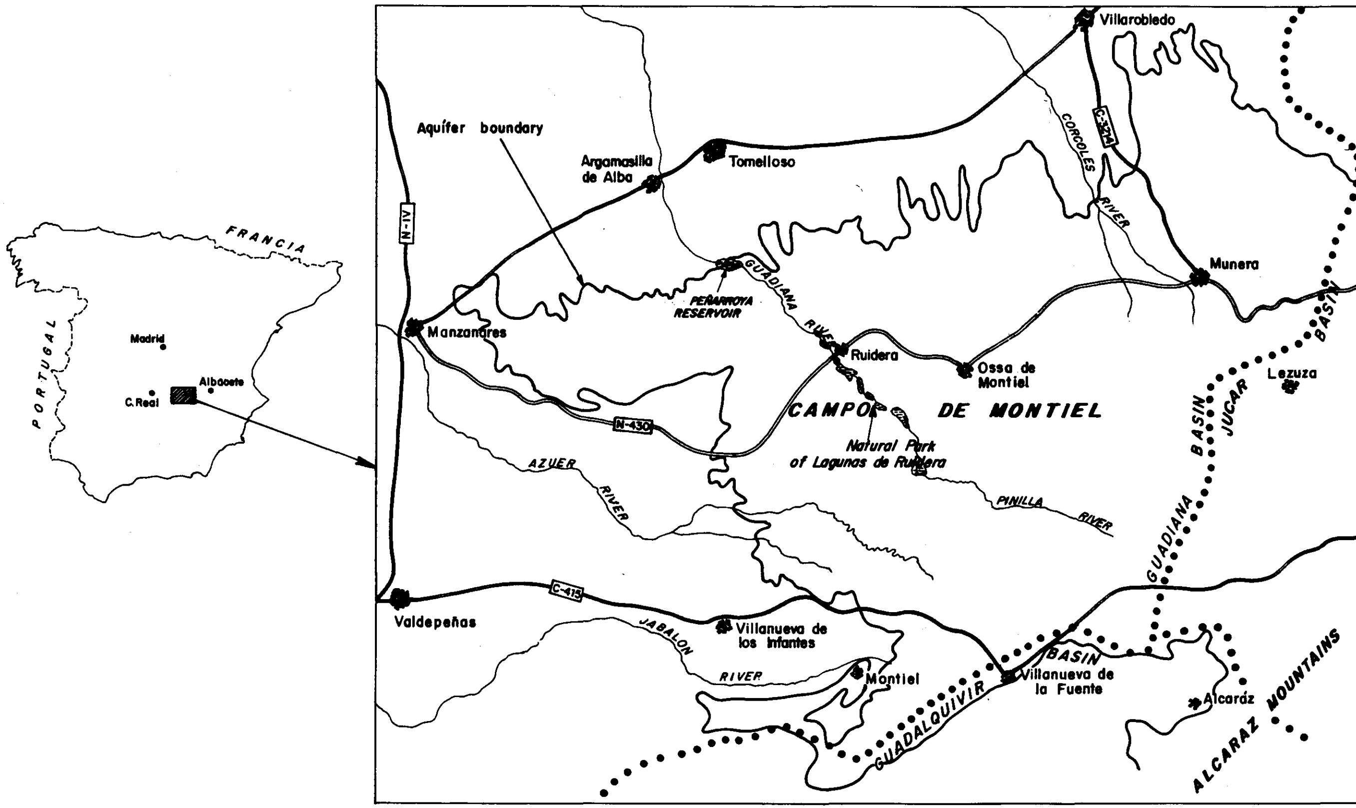


Figure 1: Location map of the study area.

The most outstanding of the rivers flowing across Campo de Montiel is the Guadiana Alto, which rises in the Pinilla springs, at an altitude of 980 m, forming the brook known as Pinilla which disappears as a result of infiltration in some points of its course. Several kilometres downstream its flow suddenly increases and gives rise to the particular system of the Lagunas de Ruidera tarns. During the Second Republic in Spain a Ministerial Order dated 31 October, 1933 declared this area a Natural Location of National Interest. With the promulgation of the Law of Protected Areas it was officially declared Natural Parkland (Royal Decree 26 of 31 July, 1979). This Parkland is subject to a special Protection Plan approved in 1981 and since 1984 the Castilla-La Mancha Communities Board is responsible for its protection.

The main valley comprising the Parkland contains a chain of 15 tarns connected by brooks, gullies, cascades and underground effluents running in a SE-NW direction. They appear in stepped formation over 35 km, with a difference in level between the first and last tarn of approximately 120 m.

Until less than a decade ago Campo de Montiel was a stony, largely untilled plain where the scant cropping that did take place (cereals usually alternated with leguminous crops) required a great deal of labour and produced very poor results. Only in the valley zones did small, irrigated kitchen garden allotments exist where vegetables, fruit and sugar beets were grown. The water supply for these came from spring water and from small wells. Some seven years ago the aquifer began to be exploited as a result of having converted a considerable number of hectares into irrigated land mostly given over to corn crops. In 1987 the total area corresponding to the new crops was 5,225 ha which created a demand of 34 hm^3 $year^{-1}$. The urban demand rose to 2 hm^3 $year^{-1}$ (SGOP, 1988a and b).

As a result of these exploitations, conflicts began to arise amongst the different water users since some villages and fertile plains relying on springs to meet their water demand had seen their resources greatly reduced if not actually exhausted.

In an analogous way the supply of water to some of the tarns has dropped considerably and this, together with the increased nitrates in the water from the springs feeding them, has endangered the existence of the ecosystem. The effect was made considerably worse by a consecutive series of dry years (Montero-González, 1989).

In 1988 the authorities declared the aquifer overexploited.

With a view to protecting the Lagunas de Ruidera Natural Parkland, and in order to guarantee the supply to the users that historically depend on the Peñarroya Reservoir, a digital model was designed to integrate both the surface and underground flow in the basin supplying the ecosystem.

FEATURES OF THE DIGITAL MODEL

The model was designed to cover the following phases:

(a) underground flow simulation,
(b) surface runoff simulation,
(c) simulation of total runoff by integrating the two preceding phases,
(d) analysis of the system's responses to different action proposals.

The 1951-87 period was simulated month by month, taking the aquifer's isopiestic lines as reference for the model calibration, plus the supply from the Peñarroya Reservoir, the only point where past data were available. In addition, since it was the final collective outlet of this particular water system that was under study, it provided a true reflection of the water demands involved in this.

RESULTS OBTAINED

Once the simulation model had been calibrated, two runs were made every month throughout the time period under consideration. The first one assumed there was no exploitation while the second assumed an exploitation equivalent to the one affecting the aquifer in 1987.

The first simulation, the natural regime, allowed the following deductions to be made concerning the properties of the system:

(a) the aquifer recharge occurred almost exclusively between January and March.
(b) the maximum inflow from the Peñarroya Reservoir occurred between September and December.
(c) not one month of the 444 simulated had an average flow under 1 $m^3 s^{-1}$. The annual inflow never fell below 40 hm^3 and the average per year was some 80 hm^3.

The second run, underground water drawdown equivalent to that of 1987 and with the same monthly distribution, produced the following deductions:

(a) the largest drawdown in the Peñarroya supply occurred between May and September during which time the inflow fell by 24% with respect to the supply not affected by pumping.
(b) the average annual inflow into the Peñarroya Reservoir fell by around 22%.
(c) in 39% of the 444 months simulated, the average entry flow into Peñarroya was under 1 $m^3 s^{-1}$ and in 36% of the years studied the annual inflow did not reach 40 hm^3, the figure estimated as the current demand to be met by the reservoir.

From the above a clear water demand can be deduced, both affecting the Natural Parkland and the historic rights of the Peñarroya Reservoir irrigators.

PROPOSALS FOR ACTION

In view of the results obtained, the following action alternatives were analysed using appropriate runs:

(a) General reduction in summer pumping in the Campo de Montiel aquifer. The summer pumping of the aquifer would need to be cut by 75% to cover the objective of the years with under 40 hm^3 supply to Peñarroya (supply failure) reaching 14% of the ones simulated.

(b) Selective reduction of the Campo de Montiel pumping. This would consist of suppressing drawdown in years where the precipitation over the October to February period is below the average for these months in the period under study. This would not provide a clear solution to the problem since, despite the measure proposed, in 20% of the years the demand could not be met from the Peñarroya Reservoir.

(c) Increasing the Peñarroya Reservoir's regulating capacity. Increasing the reservoir's capacity from the current 47,4 hm^3 to 60 hm^3 would make the supply from the reservoir compatible with the current groundwater drawdown, but it would create a water demand in the Natural Parkland when the flowing discharge rates were really low. This could be alleviated in certain points by some complementary measures regarding conservation of volumes and preservation of the chemical quality of the waters involved. What appears to be out of the question, however, is the possibility of increasing the irrigated zone in the aquifer supplying the Lagunas de Ruidera area.

REFERENCES

Montero-González, E. (1989). *Estudio Hidrogeológico del Campo de Montiel*, Degree Thesis (unpublished), Universidad Complutense, Madrid.

Servicio Geológico de la Dirección General de Obras Hidráulicas (SGOP). (1988a). *Informe Hidrogeológico 03/88 sobre las afecciones producidas a manantiales y corrientes superficiales como consecuencia de las extracciones de aguas subterráneas en la zona sur del Campo de Montiel*, M.O.P.T. (unpublished).

Servicio Geológico de la Dirección General de Obras Hidráulicas (SGOP). (1988b). *Informe 06/88 sobre la hidrogeología del Campo de Montiel y la influencia de la explotación de aguas subterráneas sobre el Parque Natural de las Lagunas de Ruidera*, M.O.P.T. (unpublished).

SOME ECOLOGICAL CONSEQUENCES OF AQUIFER OVEREXPLOITATION IN WETLANDS IN SPAIN

T. RODRIGUEZ-ESTRELLA
Empresa Nacional ADARO de Investigaciones Mineras, S.A.
Gran Vía, 42, 1ª Esc. 5º A, 30005 Murcia
F. LOPEZ-BERMUDEZ
Departamento de Geografía Física
Universidad de Murcia C/ Santo Cristo, 1, 30001 Murcia

ABSTRACT. In certain cases where wetlands are due to piezometric surfaces, lowering the piezometric surface as a result of aquifer overexploitation brought about the disappearance of the wet zone and, consequently, serious ecological damage. Some examples of wetlands in the Albacete and Murcia provinces are studied. Piezometric and quality variations in the Quaternary Campo de Cartagena aquifer are also analyzed in relation to the Mar Menor -Spain's largest wetland-. It may be concluded that when aquifer overexploitation occurred, this was beneficial to the wetland.

INTRODUCTION

Waterlogged areas or wetlands, 'humedales' in Spanish (Vélez-Soto, 1979; Llamas, 1984; González-Bernáldez, 1987), are functional systems of landscape of great environmental value. They contain some of the most productive existing ecosystems and perform a wide variety of natural functions of great biospheric interest. Wetlands, moreover, are among the most threatened habitats because of their vulnerability to human activity. This includes massive extraction of groundwater, which causes in general a very adverse impact.

The role of wetlands as resting and nesting sites for migratory birds was recognized at the 'Convention on Wetlands' -signed in Ramsar (Iran) in 1971- as being of international relevance, especially as habitats for aquatic birds. The Convention included a requirement that all wetlands within territory of any of the signing countries, Spain among them, should be subject to 'rational exploitation' (Hollis *et al.*, 1988) and recognized the irreplaceable role played by wetlands in the maintenance of migratory birds.

The origin and functioning of Spain's ecologically interesting wetlands is not very well known, in particular the relationship between surface waters and piezometric levels. Even today, knowledge of the hydrologic aspects of wetlands is scarce (Llamas, 1984).

Indeed, in interpreting the various wetlands within the Iberian Peninsula, the role of underground aquifers has been ignored or underestimated. However, there is increasing evidence relating wetland ecosystems to groundwater flows, as far as the duration of the flooding and mineralizaton and material transfer are concerned. Hydrology is the very foundation and existence of marshy complexes (Custodio, 1987). To a large extent, hydrologic characteristics respond to the conditions, diversity, evolution, contamination and disappearance of these environments; their hydrologic behaviour will be eventually reflected in the water balance (Custodio, 1982). Establishing the water balance, however, is not only difficult but also costly, since a good knowledge of how the whole system works is needed, along with periodical controls of the various parameters involved, adequate simulation models, follow-up of salinity values, nutrient content and of the effect of anthropic action. In addition, parameters and variables should be put together within a single hydrologic functioning framework.

The aim of this work is to discuss briefly excessive groundwater withdrawal and its most apparent effects on a few wetlands of SE Spain. The impact has been so great that in some cases the wetland no longer exists and in others, the ecosystem is being seriously threatened.

ANALYSES OF CASES

Lagoons in the vicinity of Albacete

Genesis and overexploitation. Near Albacete, the Acequión, Ojos de S. Jorge and Salobral lagoons represented the piezometric surface of the Albacete aquifer (López-Bermúdez *et al.*, 1988). The aquifer was composed of Dogger dolomites, Pontian limestones and Quaternary gravels. With massive exploitation initiated at the time of the 1978 drought, piezometric levels steadily decreased by 2 to 3 metres per year (Fig. 1) until, finally, the wetlands dried up.

The Acequión and Ojos de S. Jorge lagoons lay on the fault line between a large, highly transmissible limestone-bearing Pontian outcrop on the south and a less transmissible detrital outcrop of yellow red Miocenic clays and conglomerates, on the north (Fig. 1).

The Salobral lagoon was on Quaternary detrital materials found directly above Dogger dolomites.

The lagoons originated when erosion reached the piezometric surface of the Albacete aquifer; now groundwater flows under them at a depth of 45 m.

Ecological effects. The environmental relevance of wetlands in the La Mancha region has been underlined by numerous investigators (Hernández-Pacheco, 1949; López-Bermúdez, 1978; Cirujano, 1981; Romero & Ruiz, 1986; Herreros, 1987; De la Peña, 1987; Cirujano *et al.*, 1988; Martino, 1988; Tello & López-Bermúdez, 1988; Llamas, 1989), as well as in international conferences which have included this vast steppe within their protection and conservation programmes. Since 1965, the group of Castilian lagoons known as 'the wet Mancha' has been one of the four Spanish zones that have deserved inclusion under the A category of the MAR list and -since 1981- has been nominated Biospheric Reserve within the

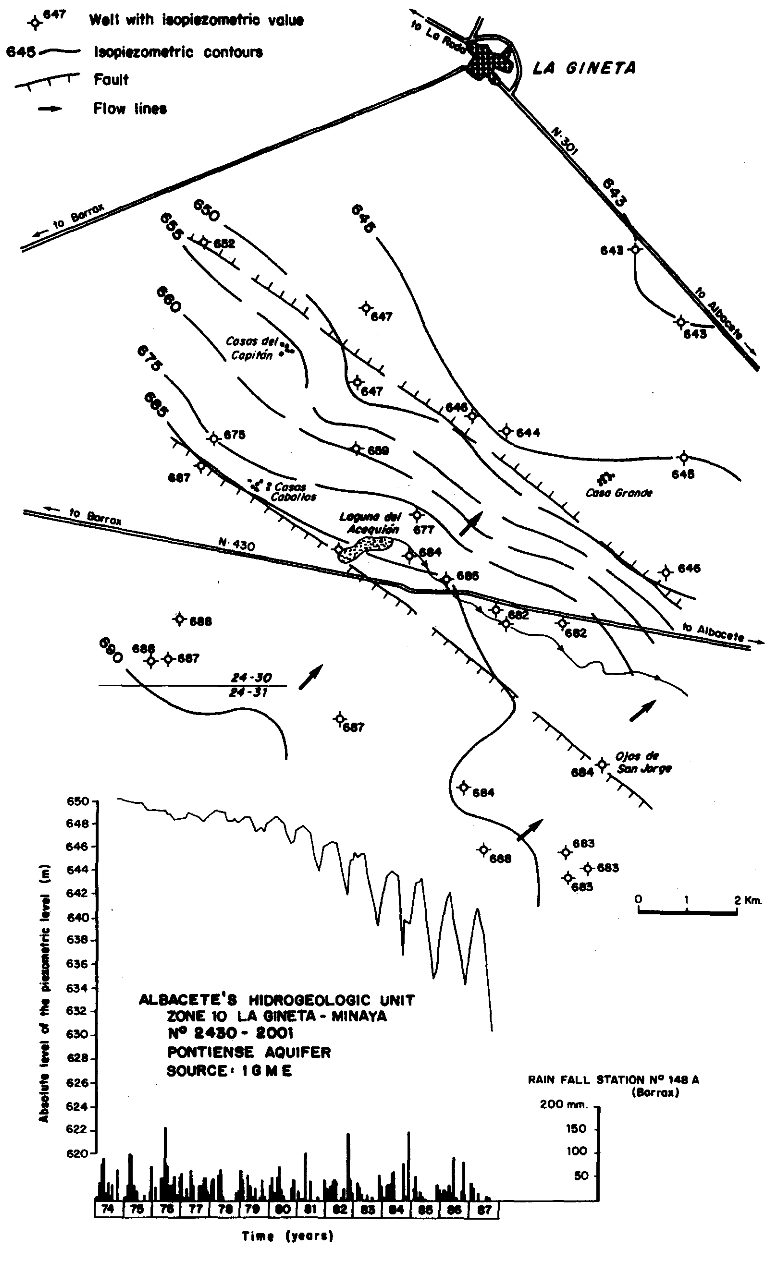


Figure 1: Isopiezometric contours of Pontiense aquifer in Acequion-Ojos de San Jorge pool (Albacete, 1973) and piezometric evolution in the zone.

international network of UNESCO'S MAR programme. The Tablas de Daimiel and the Lagunas de Ruidera are the most environmentally significant wetlands because of their large size and ecological interest.

Of the four provinces comprising the La Mancha region, Albacete contains the largest number and widest variety of wetlands -a little under a hundred according to the inventory made by Cirujano *et al.* (1988)-. The Salobral, Acequión and Ojos de San Jorge lagoons have recently dried up because of aquifer overexploitation. With them have gone their rich and varied flora and their potential use as dwelling sites by a large number of waterfowl species, the most representative of which are: the common gallinula (*Gallinula chloropus*), the mallard (*Anas platyrhyncos*), the widgeon (*Anas penelope*), the shoveller (*Anas clypeata*), the little grebe (*Podiceps ruficollis*), the European coot (*Fulica atra*), and the common pochard (*Aythia ferina*). Apart from waterfowl, excessive groundwater exploitation and the elimination of wetlands have affected other ecological communities such as beetles (carabids).

Degraded or extinct vegetation includes reeds, rushes, bulrushes, grasses and other species tolerant of water and saline soils (*Salicornia*). These different forms of vegetation of the now extinct lagoonal ecosystems supplied optimal dwelling conditions to wildlife.

The Saladar (salt marsh) of Lorca

Genesis and overexploitation. In the tectonic valley of the Guadalentin river (upstream region) in a fault sink, there is an important detrital aquifer that occupies a surface area of 235 km^2 (High Guadalentin), has a thickness of up to 400 m and is composed of Plioquaternary gravels, sands and clays. Some thirty years ago both surface and underground runoff flowed to the low-lying area (north of the Altobardo district and near the small village of Solabrares),that represented the aquifer's piezometric surface, visible once the terrain lay below it through the action of erosion (Fig. 2).

Since the 60 s, intense groundwater draw off has been taking place through wells and bore holes. The result has been overexploitation and a drawdown in piezometric levels which has led to the disappearance of the Lorca Saladar as a wet zone (Fig. 2). However, even today, this area is seasonally flooded after heavy rain, even though its piezometric surface lies at a depth of 150 m. The reason -as already stated- is the low lying position of the zone; to it flows the salt-bearing surface runoff from adjacent mountain ranges, so that evaporites settle in the bottom (just as before, but then they were washed away by fresh groundwater) and form a white impermeable crust that can be seen directly on the terrain and gives the place its name. This interpretation is supported by Salazar (1911) when he states: 'The salinity of this formerly fertile land would be linked to the lack of flood wash and silt that have been retained in the Puentes and Valdeinfierno dams since their construction'.

Ecological effects. The almost complete disappearance of this saline wetland has markedly altered the evergreen plants of chiefly fleshy leaves and stems (*Suaeda vera, Halocnemun strobilaceum*, *Albardinalis* and *Atriplex*.

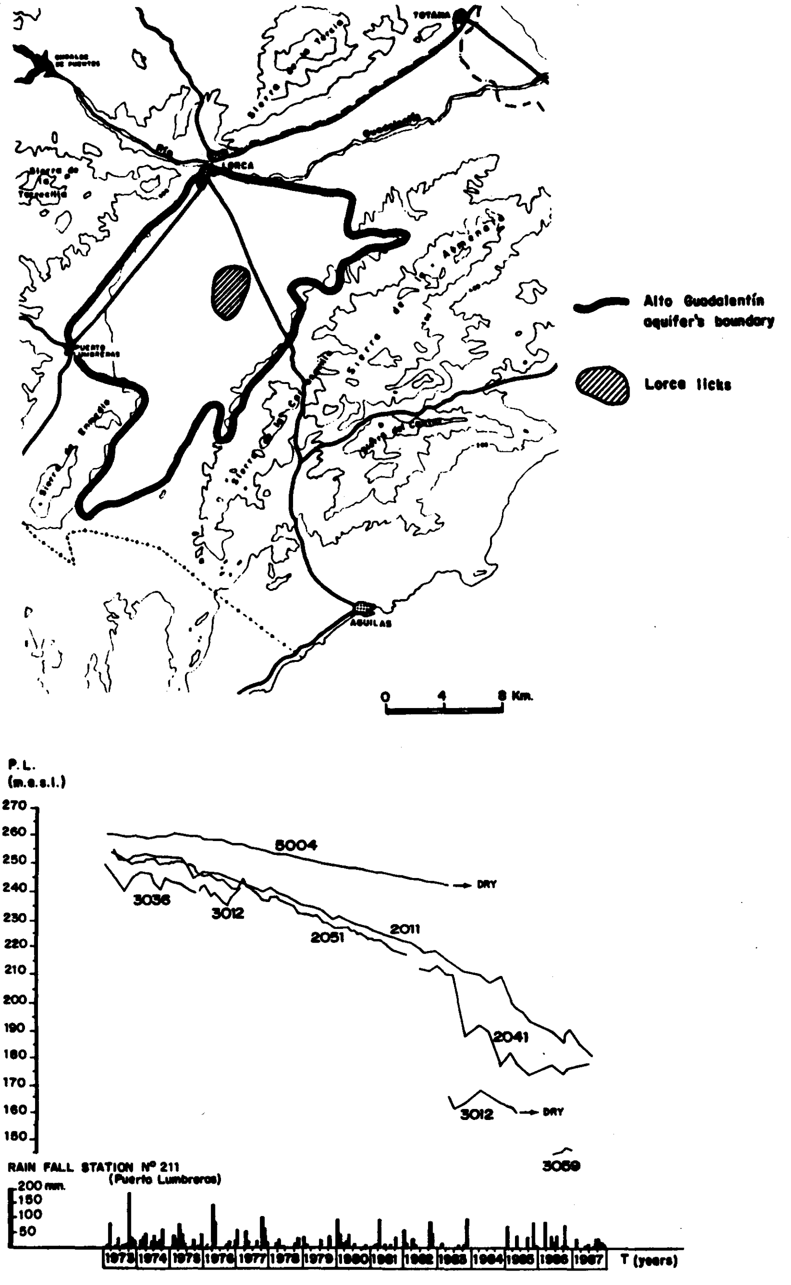


Figure 2: Location of Lorca licks and piezometric evolution in Alto Guadalentin aquifer.

Apart from the botanical value of halophytes, these high-conductivity water areas are remarkably interesting from both a scientific and didactic viewpoint since complex saline crystallization and sedimentation processes occur in them that aid in understanding the origin and formation of evaporitic rocks (De la Peña, 1986). Salt marshes, with their flooding-drying cycles, saline efflorescences, flora species and trophic chains, constitute singular ecosystems worth preserving for their exceptional value. Their extinction, therefore, entails irreversible damage that hinders understanding, study and use as a pedagogic resort.

Fuente de las Anguilas (Eels' spring)

Genesis and overexploitation. South of Pliego (Murcia) lies the Bosque aquifer (75 km^2 in area). Its permeable rocks consist of 150-300 m of pudding stones, algal limestones, sandstones and Oligocene dolomites; limestones exhibit strongly karstic characteristics.
One of the aquifer's natural outlets (together with those of Barbol and Caños) was the Fuente de las Anguilas. The spring's discharge was over 100 l s^{-1} and water issued at the point of contact between Oligocene limestones and Miocene marls. However, with massive exploitation by wells, tunnels and bore holes (as much as 10 hm^3 year^{-1} in 1987 compared with 4 hm^3 year^{-1} of renewable resources) piezometric levels slowly decreased at first and then increasingly fast until they reached 75 m between 1982 and 1985; finally the spring stopped supplying water in 1977 (Fig. 3).

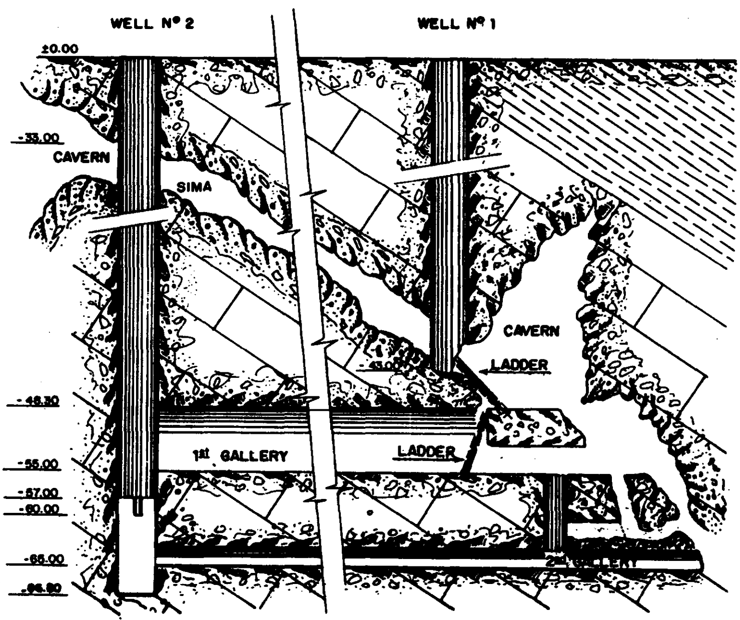


Figure 3: Wells and galleries in Fuente de las Anguilas (Murcia).

Ecologic effects. The 'Fuente de las Anguilas' (Eels' spring) (Rodríguez-Estrella *et al.*, 1986) derives its name from the fact that these teleosts could be found swimming in its clear surface waters. With the decline in levels and the building of wells 1 and 2, the eels were trapped inside, and have not been seen since 1978. If we take into account that the only existing access to the karst -via surface runoff- is through the small streams from which the above-mentioned aquifer springs originate; that these springs have not flowed since May 1977 (100 l s^{-1} did flow out of the 'Anguilas' spring in a month); that the last time eels were seen was in 1978 in the bottom of well number 1, when the person in charge caught a 1-metre long female specimen; and that they must travel to the Sargasso Sea to spawn, it can be concluded that these fish have been trapped inside the wells probably since well number 2 was built in 1960 (to improve water withdrawal) and that -judging from their size- must have grown and developed at a depth of 50 metres for almost 20 years, which is about their life span.

Overdevelopment at this site has thus led to the death and extinction -after 20 years imprisonment inside the caverns- of the eels which gave the spring its name and which -together with other living beings- formed part of an original and beautiful ecosystem.

Mar Menor

Genesis and overexploitation. The unique environmental nature of the Mar Menor (Spain's largest salt wetland) in Murcia makes it one of the most outstanding lagoons in the country. Its waters are shallow, oligotrophic and hypersaline.

The origin and development of the Mar Menor are linked to geomorphological Quaternary dynamics, namely, neotectonic and volcanic activity, eolic and fluvial erosion processes, sediment transport and accumulation and marine dynamics. Renewed activity of old Tertiary faults, especially those of NNW- and SSE-orientation, depressed the eastern block and gave rise to a sedimentary basin into which materials were transported down the western washes (of which the Albujón is the most important). This lagoon, however, would have silted up if -as the sediments were deposited- vertical movements and seismic activity had not occurred.

La Manga, a strip of land 24 km long and 500 m wide on average, separates the lagoon from the Mediterranean. It is composed of Quaternary sandstones and silts and volcanic rocks. In all, four mouths -two natural (Ventosillo and Charco) and two man-made (El Estacio and Marchamalo)- connect this coastal pool with the open sea. Within the Mar Menor five volcanic islands are found -Mayor, Perdiguera, Ciervo, Rondella and Sujeto-. La Manga must have had its origin in a row of interrupted volcanic outcrops, which later, during the Quaternary, became a reef thanks to the marine and eolic sandstone strata which progressively filled in the eruptive band.

To the west of the Mar Menor lies the Campo de Cartagena, a 1,600 km^2 post-tectonic depression with a very marly 1,000 m Neogenic fill interspersed with tracts of permeable materials, the largest of which are Pliocene sandstones (30 m) and Andalusian sandstones (100 m), forming aquifers; of less importance is the Quaternary aquifer composed of not more than 100 m of gravels, sands and limestones.

The latest studies made by the Instituto Tecnológico GeoMinero de España (ITGE) show that no direct relationship exists between the groundwaters of the Pliocene and Andalusian aquifers, on the one hand, and the sea water, on the other, since deep faults prevent it. A hydraulic relationship does, however, exist between the groundwater of the Quaternary aquifer and the water in the Mar Menor. A discussion of this follows, especially of the effects on the Mar Menor caused by aquifer overexploitation during various periods.

In the 60s groundwater was withdrawn from the Quaternary aquifer, because it was less expensive than drawing water off from greater depths. This dried up a large number of wells as a result of aquifer overexploitation, a situation that continued up to the early 70s as shown by the negative piezometric levels of some wells and by poor water quality, a result of the penetration of seawater into the land. Obviously, during that period, the aquifer did not discharge any water to the Mar Menor and there was even evidence of marine intrusion.

During the 70s, as a result of increased agricultural demand in the Campo de Cartagena, deeper holes were bored that drew water from better and more productive aquifers. This brought about less massive exploitation of the Quaternary aquifer and further allowed its recharge with surplus irrigation water from the Pliocene and Andalusian aquifers. A recovery of piezometric levels to pseudoequilibrium was thus observed.

Bore holes, however, were not properly built as the tubing across permeable sections was not cemented. This led to a progressive discharge downwards of water from the Quaternary aquifer through infiltration and finally to depletion without any large water volumes being directly withdrawn from it. During that period seawater again penetrated the aquifer, as the isopiestic lines for the year 1980 illustrate (Fig. 4).

The water diverted from the Tagus basin to the Segura basin in 1979 and 1980 (depending on the individual sector) and its massive utilization by surface flooding meant that the Quaternary aquifer -and the Pliocene aquifer because of the poorly built bore holes- were artificially recharged, which led to a situation similar to the one in 1978 -water flowing out to the Mar Menor and positive piezometric levels-. The severe drought initiated in 1978, which became more pronounced in the years 1983 through 1986, led to a fall in piezometric levels, although the groundwater continued to flow into the Mar Menor. The rain fall in 1986 caused levels to rise by more than 4 m -a trend which has been extended over the last several years, as the isopiestic lines for the year 1989 show (Fig. 4)-. Chloride content also decreased by 50% compared with the amount recorded for 1973.

The water in the Quaternary aquifer is nowadays so high (depth < 1 m) that in sectors such as S. Pedro-S. Javier serious waterlogging problems exist on both housing developments and agricultural land. As a result drains have been built to prevent root asphyxiation; otherwise new wet zones would have originated.

So far it has been shown that an obvious relationship exists between the Quaternary aquifer groundwater and the water in the Mar Menor, overexploitation occurring during the 60s and 70s (with pseudoequilibrium towards the mid 70s) and ending in the year 1979-80. From that year on, water levels began to rise progressively as a result of the above-mentioned transbasin diversion.

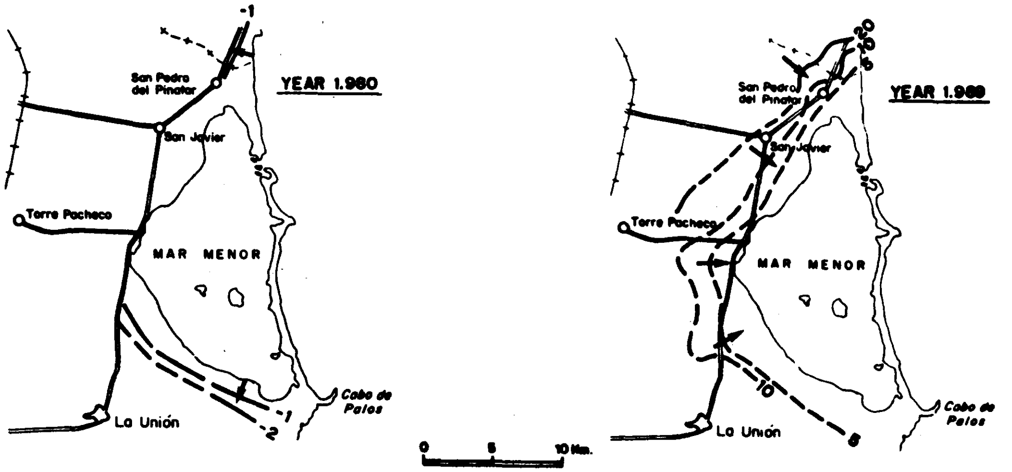


Figure 4: Isopiezometric contours in Campo de Cartagena Quaternary aquifer.

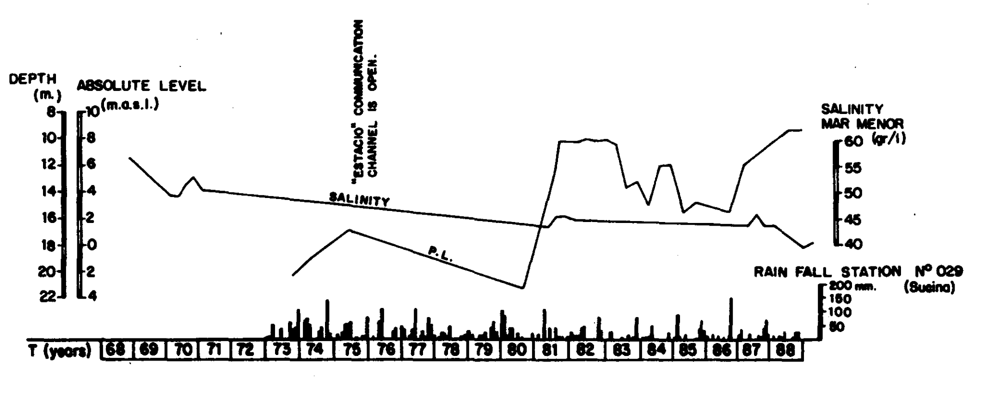


Figure 5: Piezometric variation in the Campo de Cartagena Quaternary aquifer and salinity evolution in Mar Menor.

Decreased groundwater discharge to the Mar Menor during the overexploitation years contributed no doubt to greater salinization of the pond water, as shown by the controls performed by the Murcia office of the Instituto Español de Oceanografía (Spain's Oceanographic Institute).

Salinity values (in g l^{-1}) corresponding to the mentioned controls are given in Table 1.

Table 1: Salinity values (g l^{-1}) in the Mar Menor.

MAR MENOR					MEDITERRANEAN SEA
Year	Winter	Spring	Summer	Autumn	Interannual Average
1968				57	
1970	49.78	49.50	51.77	53.05	37
1971	50.68				37
1973	The "Estacio" mouth was opened				
1981		43.50	45.50	45.50	37
1982	44.88				37
1987		44	46	44	37
1988	43.90				37
1989	40	41			37

As shown in the table, the number of controls available is unfortunately small. Some conclusion can, however, be drawn:

(a) for the Mar Menor there is a difference of as much as two points within the same year between the salinity values for winter and summer; evaporation in this latter season is greater and so is saline concentration.

(b) there is a rise in salinity of almost one point between winter values for the years 1970 and 1971 (from 49.78 to 50.68 g l^{-1}). This is interpreted as being a result of overexploitation, as rainfall during the latter year was greater than during the former. In autumn 1968 the highest salinity concentration was recorded (57 g l^{-1}) coinciding with an overexploitation period.

(c) in 1973 the Estacio mouth was opened to allow the transit of sailing boats. The mouth overtly linked the Mar Menor to the Mediterranean sea and led to a considerable fall in salinity values of almost 10 points (Arévalo & Arabio, 1971; Faraco, 1981; AMBIO, 1981). This sharp change in salinity soon stabilized, so the downward trend seen in the following years should therefore be put down to greater groundwater supply from the Quaternary aquifer once overexploitation had ended.

(d) as stated earlier, the transbasin diversion from the Tagus basin to the Segura basin brought massive supplies of water to the Campo de Cartagena in 1979-80. From then on two new water sources (other than rainfall) have contributed to the reduction of salinity in the Mar Menor, the more important of them being the sea water flowing in through the Estacio and which has a less concentrated salt content than the water within the Mar Menor; the other the fresh groundwater from the Quaternary aquifer as a result of surplus irrigation water leaking through to the aquifer. The value that most clearly reflects this phenomenon is that for the spring of 1981 (43.50 g l^{-1}) which differs by 6 points from that for the 1970 spring.

(e) values between the years 1981 and 1987 are kept within a narrow range (around 44 g l^{-1}), which suggests unchanged conditions.

(f) one of the latest data available is that for the exceptionally rainy 1989 winter, which led to an important fall in salinity of almost 4 points (40 g l^{-1}) with regards to the winter of 1988. The 40 g l^{-1} mark represents a very close approximation to 37 g l^{-1} -the average for the Mediterranean sea-. The isopiestic lines of the Campo de Cartagena Quaternary aquifer for 1989 show that this increase in rainfall, coupled with the effect of infiltration of surplus irrigation water, contributed to a rise in levels of as much as 13 m and to greater groundwater discharge into the Mar Menor.

Ecological effects. As stated earlier, both over- and underexploitation in the Quaternary aquifer have directly influenced salinity in the Mar Menor; what needs to be analyzed now is whether these changes in the original equilibrium have brought with them positive or negative consequences.

With regards to the flora, it is interesting to see that in 1970, when there was overexploitation in the Quaternary aquifer and the Estacio mouth was not yet open, the *Posidonia* alga dwelled in the pond, which was indicative of pollution-free seawater (Departamento de Biología Animal y Ecología, 1989).

Since 1973, the year the Estacio was opened, *Posidonia* has been increasingly replaced -more notably since 1979 when the transbasin diversion ended the overeploitation period- by *Caulerpa prolifera* (hare's-ear) on muddy bottoms. This algae retains sediment and prevents it from being washed away to the Mediterranean by storms, which results in increased silting. Recent work by Pérez-Ruzafa (1989) demonstrates that in 1972 the maximum depth of the Mar Menor was 7 m and its surface area 180 km^2 whereas in 1988 its maximum depth was 5 m and its surface area 130 km^2. Indiscriminate disposal of urban waste has no doubt played the most important part in the silting process, while recreational building within the sea (actually encroaching upon it) and beach reclamation have been the key factors in the decrease in surface area.

As for the fauna, the same species dwell now in the Mar Menor and the Mediterranean. One example is the red mullet, which swims over from side to side with no adaptability problems. However, the number of autochthonous species has become smaller, since *Caulerpa prolifera* does not protect young fish as safely as the dense *Posidonia* prairies. On the other hand, Mar Menor fish and crustaceans such as the mullet, the gilthead or the prawn, which had attained a relevant place within Spanish cuisine for their exquisite taste, cannot now be differentiated from those of the Mediterranean.

In conclusion, it has to be admitted that every time there was overexploitation in the Campo de Cartagena Quaternary aquifer -unlike the majority of cases in which unwanted effects result- it had a beneficial effect on the Mar Menor since one could enjoy the tasty flesh of mullets and sparids and swim in more healthy, less polluted waters, rich in iodine.

REFERENCES

AMBIO (ed) 1981. *Anteproyecto para el estudio del impacto ambiental turístico en el Mar Menor.* Secretaría de Estado de Turismo. Madrid.

Arévalo, J. & Arabio, A. 1971. La salinidad del Mar Menor y sus variaciones. Algunas consideraciones sobre el intercambio de aguas con el Mar Mediterráneo. *Inst. Oceanog.*, 146.

Cirujano, S. 1981. Las lagunas manchegas y su vegetación, II. *Anales Jardín Botánico de Madrid*, vol 38(1).

Cirujano, S., Montes, C. & García, Ll. 1988. Los humedales de la provincia de Albacete. Una panorámica general. Inst. Estudios Albacetenses. *Al-Basit*, 24.

Custodio, E. 1982. Zonas húmedas y explotación de aguas subterráneas: aplicación al litoral catalán. In: *Jornadas sobre Problemática de las Zonas Húmedas en España*, CEOTMA-ICONA-ETSIMt, Madrid.

Custodio, E. 1987. Peculiaridades de la hidrología de los complejos palustres españoles. In: *Bases científicas para la protección de los humedales en España*, Real Academia de Ciencias Exactas, Físicas y Naturales. Madrid.

De la Peña, J.A. & Marfil, R. 1986. La sedimentación salina actual en las lagunas de La Mancha: una síntesis. *Cuadernos de Geología Ibérica.*

De la Peña, J.A. 1987. Las lagunas de La Mancha: Un ejemplo de sales en ambiente continental. In: *Bases científicas para la protección de los humedales en España*, Real Academia Ciencias Exactas, Físicas y Naturales. Madrid.

Departamento de Biologia Animal y Ecología. 1989. *Inventario abierto de los humedales de la Región de Murcia.* Univ. de Murcia (not yet published).

Faraco, F. 1981. Contaminación del Mar Menor: estado actual.*Revista de la Diputación Provincial de Murcia*, 18.

González-Bernáldez, F. 1987. Las zonas encharcables españolas: El marco conceptual. In: *Bases científicas para la protección de los humedales en España*, Real Academia de Ciencias Exactas, Físicas y Naturales. Madrid.

Hernández-Pacheco, E. 1949. *La Mancha.* Real Acad. de Ciencias. Madrid.

Herreros, J.A. 1987. *Introducción al estudio de las zonas húmedas de la provincia de Albacete y su avifauna acuática.* C.S.I.C. Albacete.

Hollis, G.E., Holland, M.M.; Maltby, E. & Larson, J.S. 1988. Explotación racional de los humedales. In: *La Naturaleza y sus Recursos*, vol XXIV, 1. UNESCO, París.

López-Bermúdez, F. 1978. El sector pantanoso al O de Albacete y su desecación. Inst. Estudios Albacetenses. *Al-Basit*, 4(5).

López-Bermúdez, F., Rodríguez-Estrella, T., Navarro, F. & Romero, M.A. 1988. Zonas húmedas y sobreexplotación de los acuíferos subterráneos. El caso del Salobral (Albacete). In: *Internt. Symp. on Hidrolog. of wetlands in semiarid and arid regions*, Sevilla.

Llamas, M.R. 1984. Notas sobre peculiaridades de los sistemas hídricos de las zonas húmedas. In: *Jornadas andaluzas para el estudio de la problemática de las zonas húmedas*, Monografías de la Dirección General de Medio Ambiente, MOPU, Madrid.

Llamas, M.R. 1989. Consideraciones en relación con el impacto negativo de la extracción de aguas subterráneas en dos importantes ecosistemas españoles. In: *Conf. sobre Hidrología General y Aplicada*, Salón Internacional del Agua, Zaragoza.

Martino, P. 1988. *Limnología de las lagunas salinas españolas*. Tesis Doctoral, Facultad de Ciencias, Univ. Autónoma de Madrid.

Navarro, F., Rodríguez-Estrella, T., Romero, M.A. & López-Bermúdez, F. 1988. Zonas húmedas y sobreexplotación de los acuíferos subterráneos. Los casos del Acequión y los Ojos de S. Jorge (Albacete). In: *Internat. Symp. on Hidrol. of wetlands in semiarid and arid regions*, Sevilla.

Pérez-Ruzafa, A. 1989. *Estudio ecológico y bioquímico de los poblamientos bentónicos del Mar Menor*. Tesis Doct., Dep. Ecol., Fac. Biol., Univ. de Murcia.

Rodríguez-Estrella, T., Martínez-Conesa, A. & Solís, L. 1986. Hidrodinámica del Karst de las Anguilas (Murcia): Método de prospección en acuíferos kársticos. *Karst Euskadi*.

Romero, M.A. & Ruiz, A. 1986. El endorreísmo en la provincia de Albacete. Tipología y condicionamientos físicos. In: *I Reunión de estudios regionales de Castilla-La Mancha. El Medio Físico*, Albacete.

Salazar, Z. 1911. *La agricultura en la provincia de Murcia*.

Tello, B. & López-Bermúdez, F. 1988. *Guía Física de España. 4. Los Lagos*, Alianza Editorial, Madrid.

Vélez-Soto, F. 1979. Impacto sobre zonas húmedas naturales. *ICONA, Monografía 20*. Madrid.

ENVIRONMENTAL EFFECTS TO OVEREXPLOITATION IN A KARST TERRANE

P.E. LaMOREAUX & J.G. NEWTON
P. O. Box 2310
Tuscaloosa, Alabama 35403

ABSTRACT. Overexploitation of ground water in karst areas for the development of water for municipal supplies and mine activities are sometimes cause for catastrophic subsidence. Extreme care must be taken to identify the factors that trigger subsidence. These factors include: major changes in rainfall, drainage, construction, explosives, as well as overdevelopment.

Owing to the legal and regulatory aspects involved, extreme care must be exercised by hydrogeologists to identify specific causes and effects and quantify the resulting environmental impacts.

INTRODUCTION

The sudden formation of sinkholes or 'catastrophic subsidence' in recent years has focused attention on a little-understood geologic hazard. Few people realize that thousands of sinkholes have formed in the United States since 1950. Costly damage, some accompanied by injuries and loss of life, has resulted from sudden collapses beneath highways, railroads, bridges, buildings, dams, reservoirs, pipelines, vehicles, and drilling operations. Perhaps one of the most spectacular was the 'Golly Hole' collapse on December 2, 1972 in Shelby County, Alabama; another was the surface collapse of part of a city block in Winter Park, Florida in 1981.

Sinkholes can be separated into categories defined as 'induced' and 'natural'. Induced sinkholes are those caused or accelerated by man's activities whereas natural ones occur in nature. Recognition of induced sinkholes or catastrophic subsidence, the subject of this paper, and their investigation has been confined mainly to this century. Almost all investigations dealing with triggering mechanisms or processes have been made since 1950.

The purpose of this paper is to present a review of geologic and hydrologic mechanisms triggering the development of induced sinkholes resulting from water-level declines and to identify predictive capabilities relating to their occurrence as a basis for relocating a gas pipeline in a highly vulnerable karst setting.

GENERAL HYDROGEOLOGIC SETTING

The terrain chosen to illustrate catastrophic sinkhole development is Dry Valley, Shelby County, Alabama. It is a youthful basin that contains a perennial or near-perennial stream. Water is stored in underlying carbonate rocks and moves through interconnected openings along bedding planes, joints, fractures, and faults, some of which are enlarged by solutioning. Recharge from precipitation, in response to gravity, moves downward into this system of openings or toward the stream channel where it discharges and becomes streamflow.

Water in rocks underlying the basin occurs under water-table and artesian conditions; however, this study is concerned with water-table conditions. The configuration of the water table conforms to that of the topography but is also influenced by precipitation, geologic structure, and water withdrawal. Bedrock openings underlying lower parts of the basin are water-filled and those underlying upland areas north of County Highway 16 are air-filled.

A mantle of unconsolidated deposits resulting from the solution of the underlying rocks, consists chiefly of residual clay (residuum). This clay commonly contains chert debris and covers most of the bedrock surface. Alluvial or other unconsolidated deposits often overlie the clay adjacent to streams. The contact between residuum and underlying bedrock is highly irregular because of differential solution of the bedrock. Unconsolidated deposits commonly fill openings in bedrock to depths of 9.1 m or more.

GEOLOGY OF THE DRY VALLEY AREA

Dry valley is within the Cahaba Valley District of the Valley and Ridge physiographic province which is characterized by northeast-southwest trending valleys and ridges.

The Cahaba Valley was formed by differential erosion of folded and faulted rock formations composed primarily of chert, limestone and dolomite.

Rock formations in the Dry Valley area outcrop in northeast-southwest trending parallel bands. The rocks dip to the southeast at 20 to 60 degrees and range in age from Cambrian to Mississippian. From northwest to southeast, the rock formations include the Copper Ridge Dolomite of Cambrian age; the Chepultepec Dolomite, Longview Limestone, Newala Limestone, Lenoir Limestone, and Athens Shale of Ordovician age; the Chattanooga Shale of Devonian age; and the Fort Payne Chert and Floyd Shale of Mississippian age.

The Copper Ridge and Chepultepec Dolomites form the western boundary of Dry Valley and support a stream-dissected ridge that is locally more than 30.5 m above Dry Creek. The valley of Dry Creek is underlain by the Longview, Newala, and Lenoir Limestones. The Newala is mined from recessed quarries and underground mines in the valley as a source of raw material for the manufacture of cement. The Athens Shale and Fort Payne Chert outcrop in a sinuous, narrow ridge that forms the eastern boundary of the valley.

A mantle of unconsolidated material consisting of residual clay covers the bedrock in the area, obscuring surface exposures of geologic contacts and faults. This unconsolidated material, or residuum, has resulted from the solution of underlying carbonate rocks. It commonly contains varying amounts of insoluble chert debris. Some of this unconsolidated material fills solutionally-enlarged fractures and solution openings in the bedrock underlying the valley floor. Because of differential solution, pinnacles of bedrock extend in places upward into the residuum, and boulders of 'floating' rock occur within the residuum. These may easily be mistaken for the bedrock surface.

WATER LEVEL DECLINE AND CATASTROPHIC SUBSIDENCE

Sinkholes resulting from water-level declines are not unique to the Dry Valley area. Foose (1953), in a study in Pennsylvania, first identified sinkhole activity associated with pumping and a decline in the water table. He determined that sinkholes were confined to areas where a drastic lowering of the water table had occurred and that their occurrence ceased when the water table recovered. He stated that the collapses indicated a lowering of the water table and withdrawal of support. Robinson *et al.* (1953) added that sinkhole occurrence in a cone of depression was related to the increased velocity of ground water. Spigner (1978) attributed intense sinkhole development near Jamestown, South Carolina to a water level decline resulting from pumpage and provided descriptions indicating loss of support and downward movement of unconsolidated deposits due to piping. Sinclair (1982) attributed similar activity in Florida to loss of support and water-level fluctuations.

Cited reports have described only in part the geologic and hydrologic impacts from a decline of the water table that cause the downward migration of unconsolidated material. However, it is important to understand that, in almost all instances, only the unconsolidated overburden becomes unstable and flows downward causing a collapse or failure, whereas the bedrock remains stable. The most common cause of induced subsidence is the decline of the water table as a result of ground-water withdrawal from wells or from underground mines and quarries. This occurred in Dry Valley, Shelby County, Alabama, and similar problems are documented in reports for other areas of Alabama, Pennsylvania, Florida, South Africa, Europe and elsewhere in the karstic areas of the world.

The following processes or activities are recognized as causing or accelerating subsidence following a decline of the water table:

(a) the loss of buoyant support exerted by ground water to unconsolidated materials overlying bedrock. Based on comparative specific gravities, for instance, this support to an unsaturated clay overlying a bedrock opening would amount to about 40 percent of its weight.

(b) an increase in the velocity of ground-water movement resulting from an increased hydraulic gradient toward a discharge point. This water velocity results in the flushing of sediments filling openings in the cavity system. This, in turn, results in the downward movement of overburden into bedrock openings that form a sinkhole.

(c) the weakening of unconsolidated bridging materials and downward erosion of these materials caused by alternate repeated addition and substraction of buoyant support and alternate wetting, drying and lubrication brought about by water-level fluctuations.

(d) induced recharge to previously water-filled bedrock cavities by infiltrating surface water passing through and eroding overlying unconsolidated material downward. This process, most active during periods of heavy or prolonged rainfall, is the same process described by many authors as 'piping' or 'subsurface mechanical erosion'.

(e) grading, ditching, or other man-related disturbances that result in thinning of overburden or concentrations of drainage at the surface or in the subsurface. These activities induce more water to move more rapidly along preferential flow patterns through soils or over-burden and into bedrock. Triggering mechanisms are piping, saturation and loading. Other examples include leaking pools, pipes, gutters, irrigation, and broken lined canals or ditches. Collapses resulting from leakage from underground pipes are well documented in the literature. Such a collapse in a gold mining district in South Africa resulted in the loss of a three story building and the lives of 29 men.

(f) heavy construction, traffic, or explosives that disturb the soil or overburden and trigger its downward movement into solution openings in bedrock.

(g) removal of vegetation or the planting of large deep rooted trees that increases recharge by creating avenues for more rapid movement of water from the land surface through soils and overburden to bedrock.

(h) drilling, augering or coring where surface water gains access to uncased or unsealed holes. These activities cause erosion of overburden into underlying openings in bedrock. This occurrence has resulted in collapses at and near drill rigs or the holes created.

(i) impounding of water results in saturation of overburden and loss of cohesiveness of unconsolidated deposits overlying bedrock openings. This, accompanied by loading caused by the weight of impounded water, results in the collapse of unconsolidated material into a bedrock opening. Similar collapses beneath impoundments are also caused by piping. This occurs where the water table has declined below the top of bedrock and where openings at the surface are interconnected with those in bedrock. Collapses resulting from saturation and loading have been described by Aley *et al.* (1972) and those resulting from saturation and piping have been described by Warren (1974). Collapses resulting in draining of impoundments in cones of depression are not uncommon.

PRESENT CONDITIONS

Present hydrologic conditions in Dry Valley are characterized by a water table that has been lowered by extensive ground-water withdrawals by mines and wells. The approximate decline has been illustrated by Warren (1976). Natural surface water drainage patterns in the Dry Creek area have been extensively modified by road construction and mining operations. Dry Creek is now intermittent north of Shelby County Highway 16 all year because of the small drainage area and rapid downward infiltration of water from the main channel to the lowered water table in bedrock. A tributary of Dry Creek originating from Simpson Spring and an impoundment on the Floyd Shale east of the rerouted pipeline has appreciable flow over the shale during the 'dry season'. However, this flow disappears into induced sinkholes near the contact between the Athens Shale and Lenoir Limestone. This water and that from the upper reach of Dry Creek Valley moves southward in the subsurface to a mine where it is pumped back into a downstream reach of Dry Creek. It then flows southwestward to Spring Creek.

For example, discharge measurements made by the U.S. Geological Survey in October 1973 (low flow period) indicated the runoff from Simpson Spring and the impoundment at 0.002 $m^3 s^{-1}$. A discharge measurement made downstream by the U.S. Geological Survey at Dry Creek on Shelby County Highway 23 in October 1973, indicated the discharge was about 0.91 $m^3 s^{-1}$. At the time of this measurement, Dry Creek north of Highway 16 was dry (Warren, 1976). Therefore, all natural runoff originating in the Dry Valley drainage basin does not flow through this part of the basin as surface water. Stream flow in the area immediately north and south of Highway 16 discharges directly into sinkholes. For example, runoff from the Simpson Spring tributary of approximately 0.14 $m^3 s^{-1}$ on March 4, 1977, was discharging into a recent collapse near County Highway 16 in the SE 1/4 NW 1/4, sec. 18, T. 22 S., R. 2 W. On April 3, 1977, a runoff of about 0.17 $m^3 s^{-1}$ was observed to be flowing into a second collapse farther upstream.

Surface water discharging into sinkholes in the area enters the solution cavity system in the underlying carbonate rocks and, from this part of the karst system, is pumped by dewatering wells into a downstream reach of Dry Creek that is south of Highway 16. Ground-water withdrawals in October 1983 amounted to about 52.99 m^3 $minute^{-1}$ or about 0.91 $m^3 s^{-1}$ (Warren, 1976). This is approximately the same discharge measured in Dry Creek at Shelby County Highway 23 during the same period.

Water-table decline in the area is the result of extensive ground-water pumping from wells, recessed quarries, and underground mines. Water levels at the center of the cone of depression are more than 121.9 m below land surface. The center of the cone of depression corresponds closely with the location of the deepest underground mine in the area.

Variations in pumpage and recharge result in water level fluctuations far greater in magnitude than those occurring under natural conditions. The repeated movement of water through openings in bedrock against overlying unconsolidated deposits causes repeated addition and subtraction of buoyant support to them and repeated saturation and drying. This triggers the downward migration of the deposits that creates or enlarges cavities in the overburden.

The inducement of recharge through openings in unconsolidated deposits interconnected with openings in bedrock also results in the creation of cavities in the unconsolidated deposits. The material immediately overlying the bedrock openings is eroded to lower elevations. The water table, previously located above the top of bedrock, is no longer in a position to dissipate the mechanical energy of downward moving recharge. Repeated rains result in the progressive enlargement of this type cavity. A corresponding thinning of the cavity roof due to its enlargement toward the surface eventually results in collapse. The position of the water table below unconsolidated deposits and openings on the top of bedrock favorable to induced recharge. The creation and eventual collapse of cavities in the deposits by induced recharge is described as 'piping'.

Where the cone of depression is maintained by constant pumpage, all mechanisms described are active. Any one or all mechanisms may be responsible for the development of a collapse at a specific site. For example, in an area near the outer margin of the cone, the creation of a cavity and its collapse can result from all mechanisms. It can originate from a loss of support, can be enlarged by water level fluctuations and by increased velocity of water movement against sediment that originally filled the openings, and can be enlarged and collapsed by induced recharge.

Many induced sinkholes in Dry Valley are near the center of the cone of depression and their locations are controlled by the decline in the water table. The number of sinkholes and related features such as 'pipes' or fractures has increased since 1967. The number, to date, is estimated to exceed two thousand. The big sink or 'Golly Hole' which occurred on December 2, 1972 is approximately 99.1 m long, 91.44 m wide, and 36.8 m feet deep. Other sinkholes or related features are much smaller than the "Golly Hole." They generally range in diameter from 1 to 30.5 m and in depth from 1 to 22.9 m.

A broad definition of remote sensing includes all methods of collecting information about an object without being in physical contact with it. If a more restrictive definition is used, it could include only those methods that employ electromagnetic energy, including light, heat, and radio waves, as a means of detecting and measuring target characteristics (Sabins, 1978). The major types of remote sensing used in carbonate hydrology are aerial photography, satellite imagery, thermography, and radar. Remote sensing techniques or surveys used on the land surface includes sonar, down-hole geophysical logging and television cameras, and seismic resistivity, gravity, magnetic and radar.

PREDICTION OF INDUCED SINKHOLES

Induced sinkholes are predictable in the context that they will occur within the area impacted by activities such as dewatering. In some instances, their alignment with other sinkholes, their shape, size and depth are also predictable. Predictive capabilities would be most significant in the type of terrain described in this paper, and would be dependent on amount of geologic and hydrologic data available.

The most predictable induced sinkhole development is that resulting from water-level declines due to dewatering by subsurface mines, recessed quarries, and wells. This occurs where the water level, previously above the top of bedrock during all or most of the year, is maintained below it by pumping. All mechanisms that trigger sinkhole development in unconsolidated deposits are activated by the decline.

Conversely, the unconsolidated deposits are not impacted and sinkholes will not occur where the zone in which the water level fluctuates is located below the top of bedrock prior to dewatering. Determining the position of the water table in relation to the top of bedrock aids in predicting whether sinkholes will or will not occur at a given site.

Where and when some sinkholes will occur in a dewatered area is also predictable to a limited degree. Many occur where concentrations of surface water are greatest such as streambeds, natural drains, or poorly drained areas. Large numbers occur where natural drainage has been altered and where natural recharge has been increased as a result of activities such as ditching and timber removal. Most of the sinkhole activity occurs during or immediately after rains, especially deluges, when hydrologic stresses to overburden are greatest.

Prediction of size, shape and depth is based on a knowledge of the character of the bedrock, the extent, orientation and size of the solution features, the thickness and stability of the overburden, and the mechanism triggering overburden erosion. Induced recharge in an area prone to flooding, for instance, would assure maximum subsurface erosion of overburden.

REFERENCES

Aley, T.J., Williams, J.H. & Masselo, J.W. 1972. *Ground-water contamination and sinkhole collapse·induced by leaky impoundments in soluble rock terrane.* U.S., Missouri Geological Survey and Water Resources Engineering Geology Series no. 5.

Foose, R.M. 1953. Ground-water behavior in the Hershey Valley, Pennsylvania. *Geological Society of America Bulletin, 64;* 623-645.

LaMoreaux, P.E., & Associates, Inc. 1982. *Reports to the Southern Natural Gas Company.* U.S., Tuscaloosa, Alabama (unpublished).

LaMoreaux, P.E., Wilson, B.M. & Memon, B.A. (eds). 1984. *Guide to the hydrology of carbonate rocks.* Unesco.

Lattman, L.H. & Parizek, R.R. 1964. Relationship between fracture traces and the occurrence of ground water in carbonate rocks. *Journal of Hydrology,* 2; 73-91.

Newton, J.G., 1984, Sinkholes resulting from ground-water withdrawals in carbonate terranes-an overview. In: *Man induced land subsidence,* T.L. Holzer, (ed), Geological Society of America, Reviews in Engineering Geology, vol. VI; 195-202.

Robinson, W.H. Ivey, J.B. & Billingsley, G.A. 1953. Water supply of the Birmingham area, Alabama. *U.S. Geological Survey Circular, 254.*

Sabins, F.F. Jr. 1978. *Remote sensing.* W.H. Freeman. San Francisco.

Sinclair, W.C. 1982. Sinkhole development resulting from ground-water withdrawal in the Tampa area, Florida. *U.S. Geological Survey Water Resources Investigations, 81-50.*

Spigner, B.C. 1978. Land surface collapse and ground-water problems in the Jamestown area, Berkley County, South Carolina. *South Carolina Water Resources Commission Open-File Report no. 78-1.*

Warren, W.M. 1974. Retention basin failures in carbonate terranes. *Water Resources Bulletin,* vol. 10, no. 1; 22-31.

Warren, W.M. 1976. Sinkhole Occurrences in Western Shelby County, Alabama. *Alabama Geological Survey Circular 101.*

AQUIFER OVEREXPLOITATION IN THE PO PLAIN: HYDROGEOLOGICAL, GEOTECHNICAL AND HYDROCHEMICAL ASPECTS

G.P. BERETTA
Unità Operativa 4.3 Politecnico di Milano C.N.R.
Gruppo Nazionale di Difesa dalle Catastrofi Idrogeologiche.
A. PAGOTTO, R. VANDINI, & S. ZANNI
Unità Operativa 4.8 U.S.L. di Modena C.N.R.
Gruppo Nazionale di Difesa dalle Catastrofi Idrogeologiche.

ABSTRACT. In the text the authors explain two cases of overexploitation of Quaternary aquifers placed on the Alpine and Apennine slopes of the Po Plain.

Historical data point out that unplanned ground water abstraction during the last fifty years has determined the lowering of groundwater table, the disappearance of 'fontanili', the presence of pollutants coming from near areas which are industrially developed or intensively agriculturally exploited.

These harmful effects have caused a considerable reduction of water resources and also the subsidence of urban centres.

The situations concerning Milano and Modena areas have been compared and the possibility of an intervention to slow down the phenomena has been taken into account, as already done by reducing the industrial water use.

INTRODUCTION

Two areas in the Po plain have been studied to show the effects of aquifer overexploitation: the first one is the district of Milano, an industrial township; the second one is the district of Modena with a large farming area (Fig. 1).

The Po Plain, the largest flat area in northern Italy, is bounded to the North by the Alps and to the South by the Apenines. High availability of water resources has encouraged human activities and settlements since ancient times.

Groundwater exploitation has been developing step by step with the social and economic improvement. In the last 50 years technological improvement and the modern way of life has increased water consumption with consequent lowering of the water table (about 1 m/year).

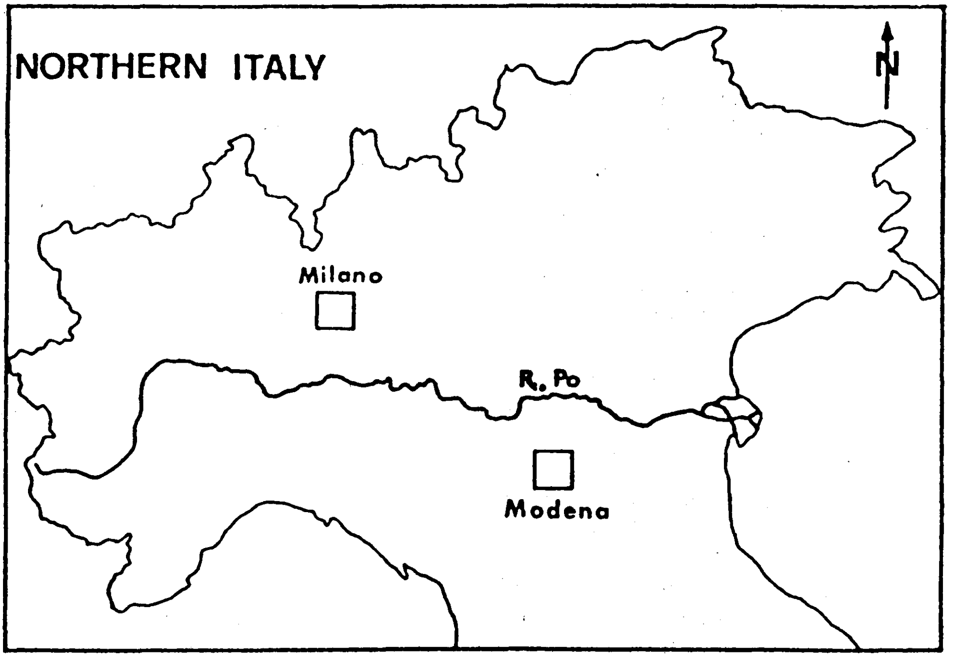


Figure 1: Plan of studied areas.

GEOLOGY

The Po Plain is a regional basin (46,000 km^2) formed by Quaternary sedimentary rocks up to 8,000 m thick.

There are three main geological zones:

(a) the northern part is characterized by glacial and fluvio- glacial deposits, and by alluvial sediments from the left tributaries of the river Po (Milano);
(b) the southern part (Modena), below the Apennines, is formed by the right tributary rivers (alluvial fans);
(c) the central part consists mostly of sands and clays.

In the Milano area, the percentage of gravel and sand ranges between 60 to 80% in the first 100 m of depth. The Pliocene sedimentary rocks are 600-700 m deep.

In the second area examined -the district of Modena- this percentage varies from 20 to 40. The base of the Quaternary sediments is found at a depth of 1,500 m (Fig. 2).

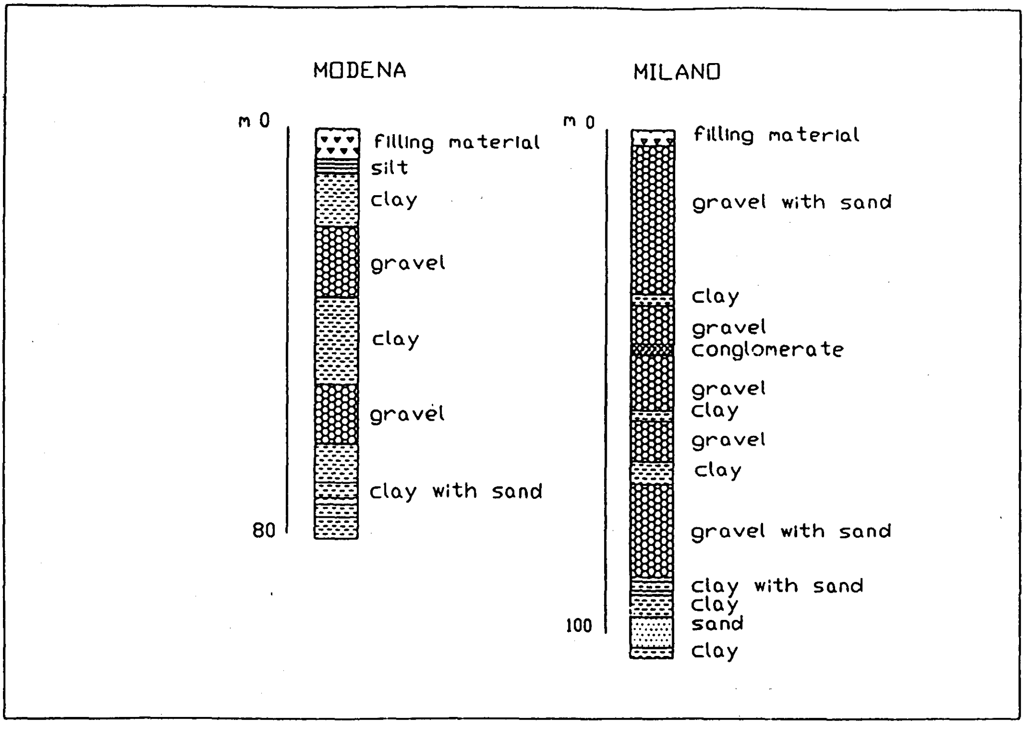


Figure 2: Schematic stratigraphies of Milano and Modena areas.

HYDROGEOLOGY

In the Milano area there are three principal aquifers (Fig. 3):

(a) in the first one (unconfined aquifer; 40-50 m deep) the groundwater is fed by precipitation and effective infiltration from the superficial stream network.

(b) the second aquifer is hydraulically connected to the first and is 100-120 m deep. The feeding areas are located in the nearby mountains, although groundwater recharge is partially due to leakage from the upper aquifer. The first and the second aquifer are considered a single stratum and are traditionally exploited by wells for water supply purposes.

(c) the third aquifer (more than 120 m deep) is partially confined and at present not much exploited due to its rather low productivity.

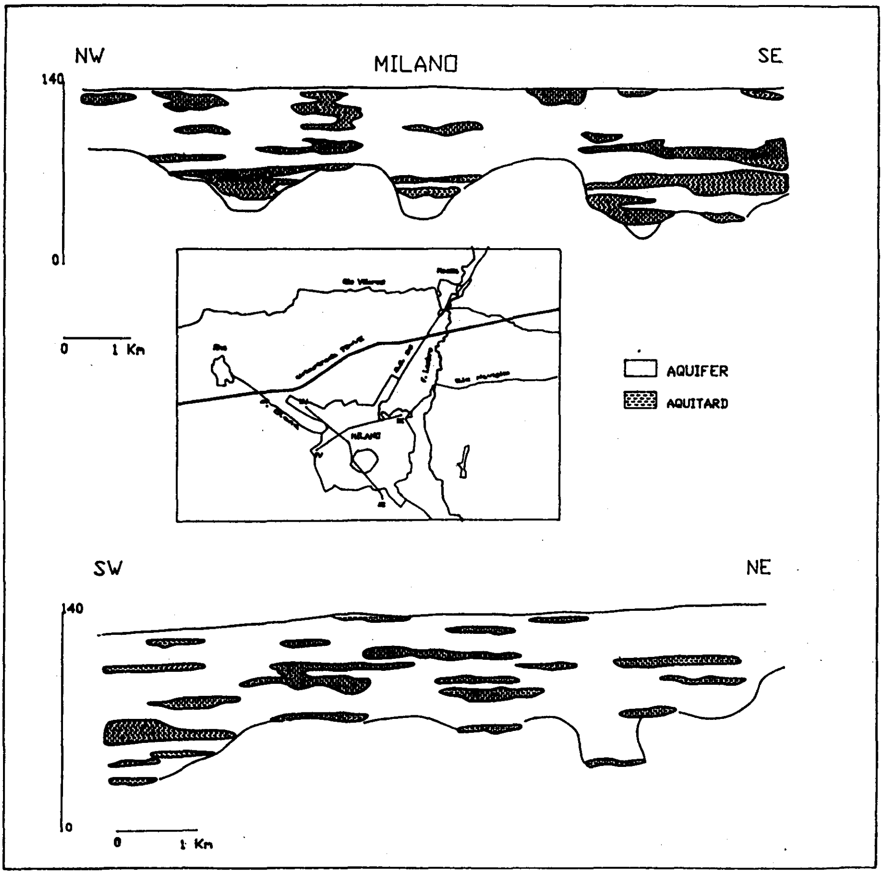


Figure 3: Hydrogeological sections of Milano area.

In the Modena area (Fig. 4) one can recognize four main hydrogeological units consisting of gravel and sand layers of varying thickness; each unit is formed by several layers hydrogeologically interconnected and characterized by different transmissivities.

On the whole the most exploited aquifers (100-120 m) can be considered as partially confined single strata. The aquifers show different hydraulic conditions: in the central area they are confined or semiconfined, whereas to the sides there are water tables hydrologically interconnected with rivers. Both precipitation and infiltration from the river beds help the aquifer recharge.

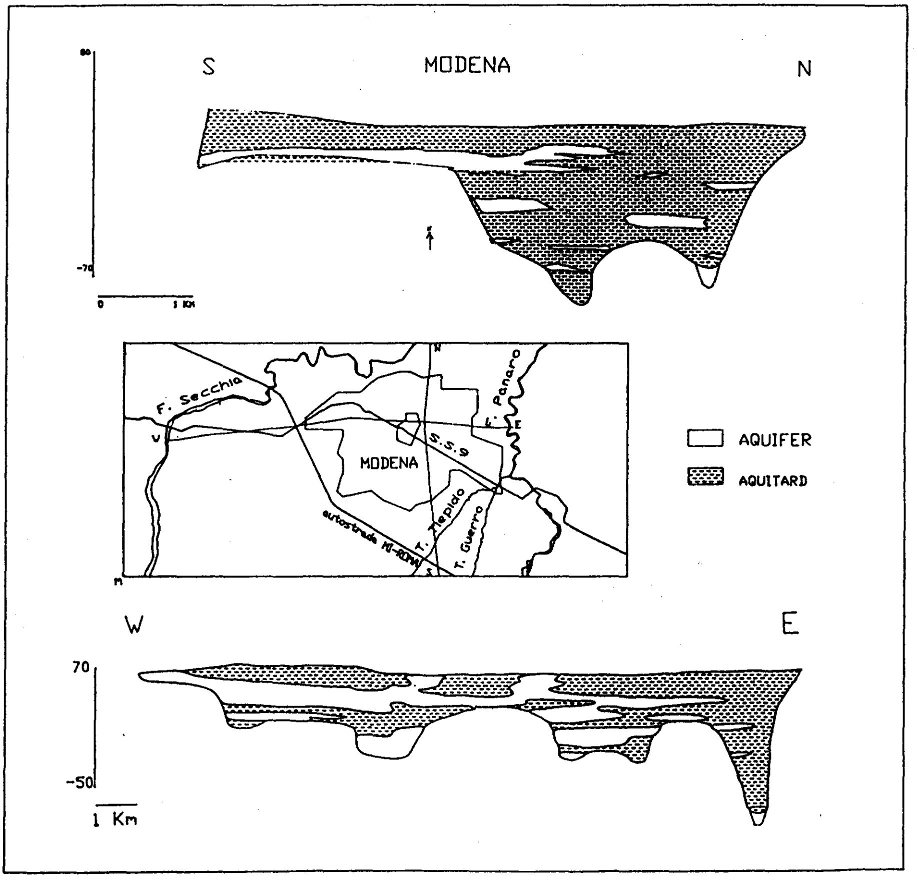


Figure 4: Hydrogeological sections of Modena area.

Piezometric Surface

In the Milano area the piezometric surface in 1952 (oldest available data) was regular, apart from some depressions just below the town centre and the northern industrial area (Fig. 5). The piezometric level varied between 130 and 105 m above sea level.

At present, the trend of the piezometric surface is radial with streamlines converging towards the town centre, with isopiezometric lines creating stagnation areas in some points (Fig. 6).

The piezometric level in this case varies from 118 to 97 m a.s.l.; that means a decrease of about 15 m in the last 40 years.

At present, the regional depression cone has a recharge area 30 km wide to the North of the town.

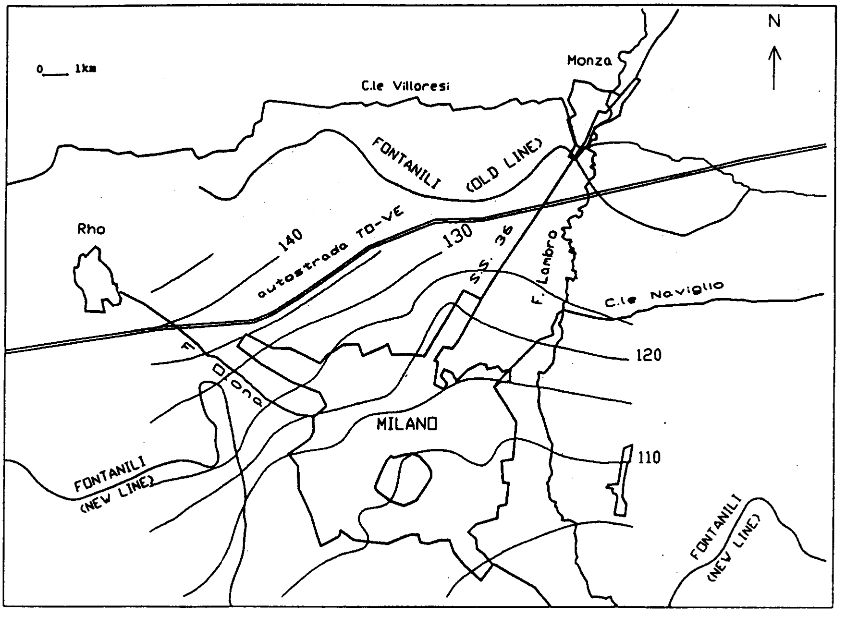


Figure 5: Piezometric map of Milano area (in m a.s.l.) in 1951.

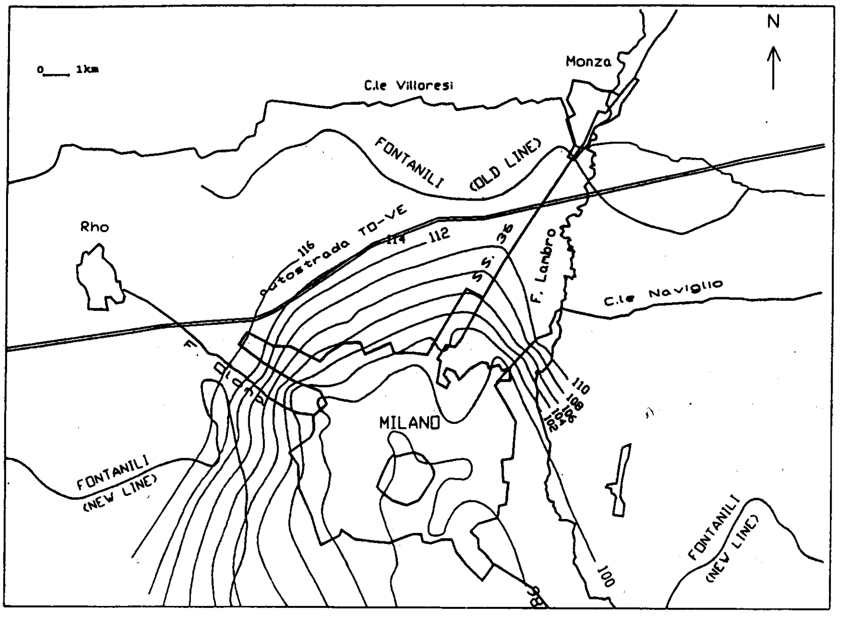


Figure 6: Piezometric map of Milano area (in m a.s.l.) in 1989.

Other hydrographic elements are given by the 'fontanili, (springs situated at the contact between high and low permeable sediments) typical of the Po Plain; these springs are aligned along the 'fontanili line' for 50 km. The 'fontanili' have served as a local water supply for agriculture.

In Modena area the piezometric surface presents the same trend as in Milano area. The trend of the piezometric surface in 1951 showed a low depression just below the town centre (Fig. 7); however the piezometric surface seemed to be influenced by the hydraulic connection with the main rivers and the hydrographic network, rather than by the direct exploitation of groundwaters. The piezometric level varied between 42 and 30 m.

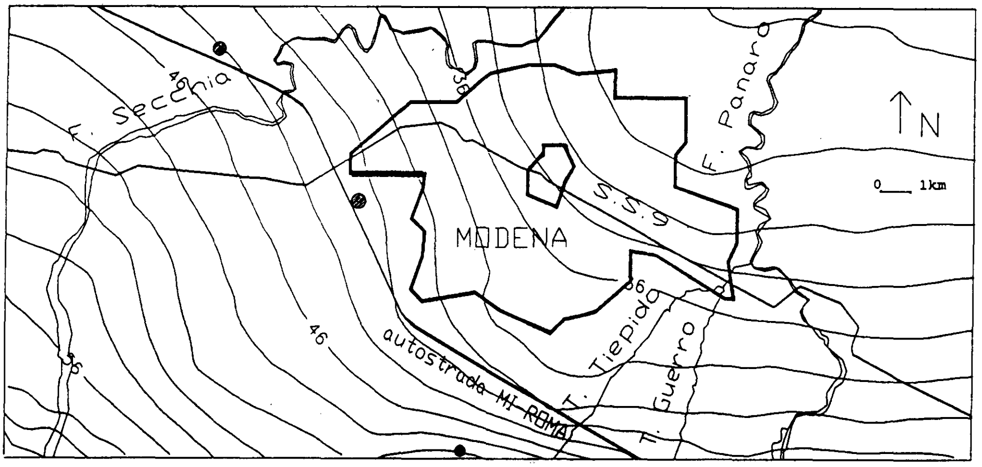


Figure 7: Piezometric map of Modena area (in m a.s.l.) in 1951.

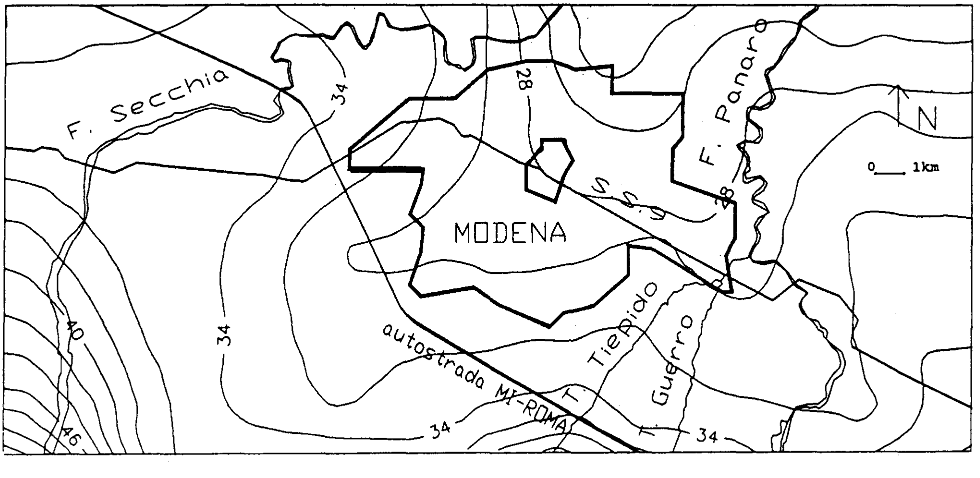


Figure 8: Piezometric map of Modena area (in m a.s.l.) in 1989.

In 1989 the depression cone was spreading as far as the rivers (Fig. 8). The streamlines do not create stagnation points, until they converge. The piezometric levels vary from 31 to 24 m a.s.l.; that means a decrease of about 7 m in the last 40 years.

As for the 'fontanili' we have historical data since roman times; the last observations on these hydrographic elements are found south of the Modena town centre.

Use of Groundwater

Groundwater is the main source for human supply both in Milano and Modena areas.

In Milano area the amount of public consumption is up to 400 million m^3 $year^{-1}$; this value has remained stationary for the last 10 years.

On the other hand, in Modena the volume of groundwater exploited for public purposes has increased in the last few years from 20 to 25 million m^3 $year^{-1}$ (Fig. 9).

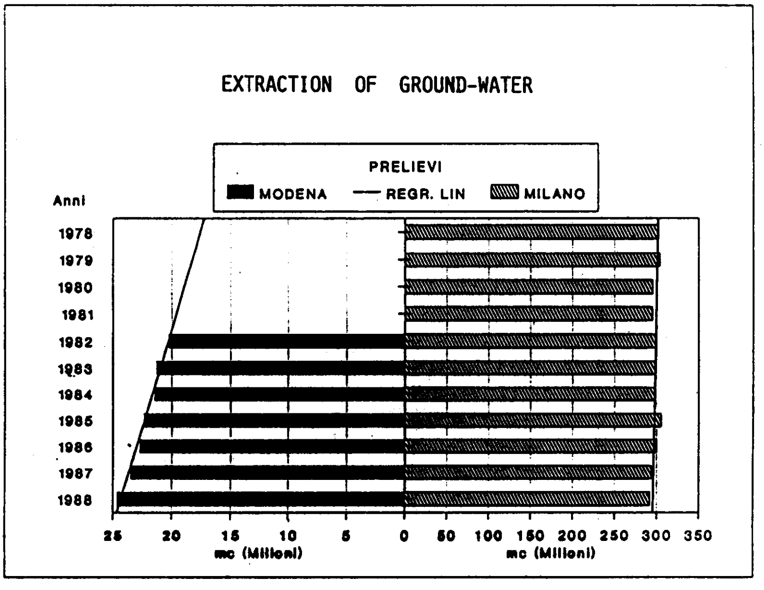


Figure 9: Extraction of groundwater

OVEREXPLOITATION EFFECTS

The intense overexploitation of groundwater in the last 50 years has caused a strong disturbance of the environmental balance.

The most important effects, in addition to the reduction of available groundwater, are:

(a) land subsidence
(b) attraction of pollution
(c) modification of the surface stream network.

Subsidence

The Po Plain is a post-orogenic subsided basin lying between two orogenic belts, the Alps and the Apenines.

Milano area is characterized by moderate soil-lifting due to tectonic causes (0.5 mm $year^{-1}$), while Modena area is affected by general subsidence (0.3 mm $year^{-1}$).

The rate of subsidence increased from 1950 untill 1970. After this time the reduction of man-induced causes of subsidence has resulted in a decrease of this rate.

In Fig. 10 we can see that the main subsided area for the 1952-1972 period is situated in the town centre (10 mm $year^{-1}$). One can observe two further depressions in the western and north-eastern outskirts of the town (4 mm $year^{-1}$).

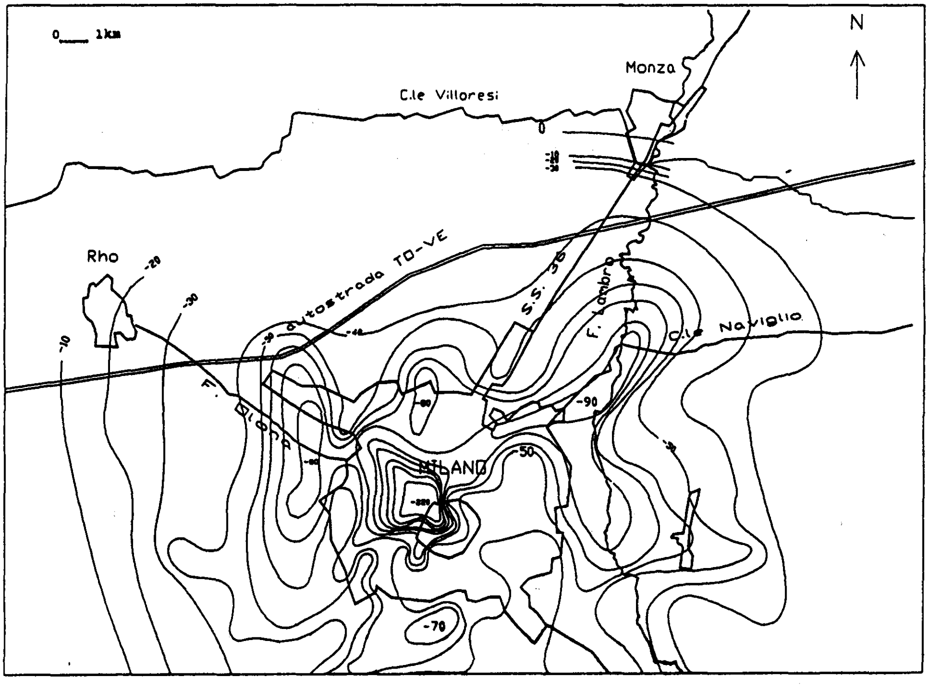


Figure 10: Subsidence map (in mm) in Milano area (1952-1972)

The recent subsidence map (1973-1986) indicates the same sinking areas (4 mm year^{-1}) and a new one in the south-eastern part of Milano (Airoldi *et al.*, 1990). We can further observe that the hinterland is also subjected to lowering (Fig. 11).

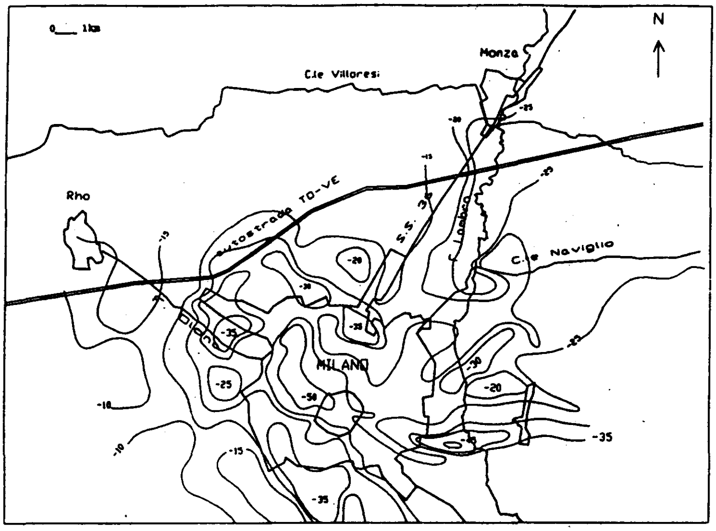


Figure 11: Subsidence map (in mm) in Milano area (1973-1986).

In the next two maps we can see that on the outskirts of Modena (southern) the rate of lowering was 6.5 mm year^{-1} in the period 1950-1981 (Fig. 12), while it was reduced to 3 mm year^{-1} in the following 7 years (1981-1988) (Fig. 13).

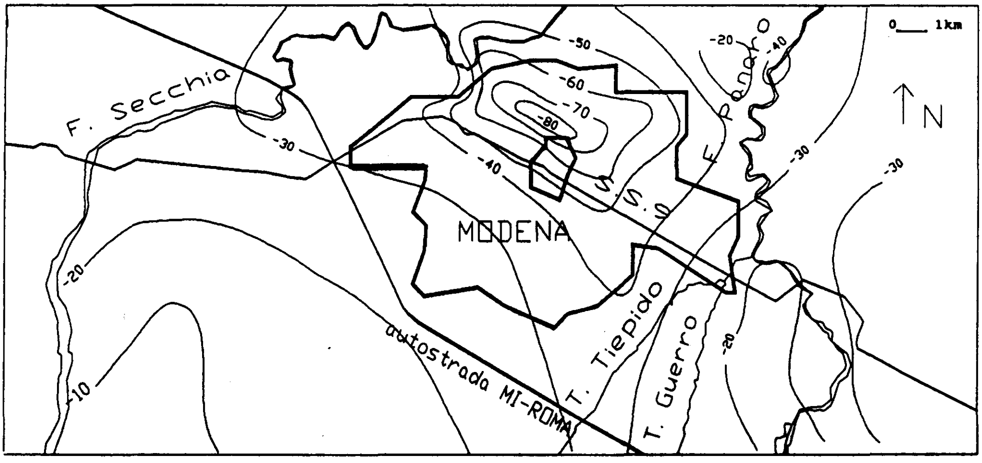


Figure 12: Subsidence map (in mm) in Modena area (1950-1981).

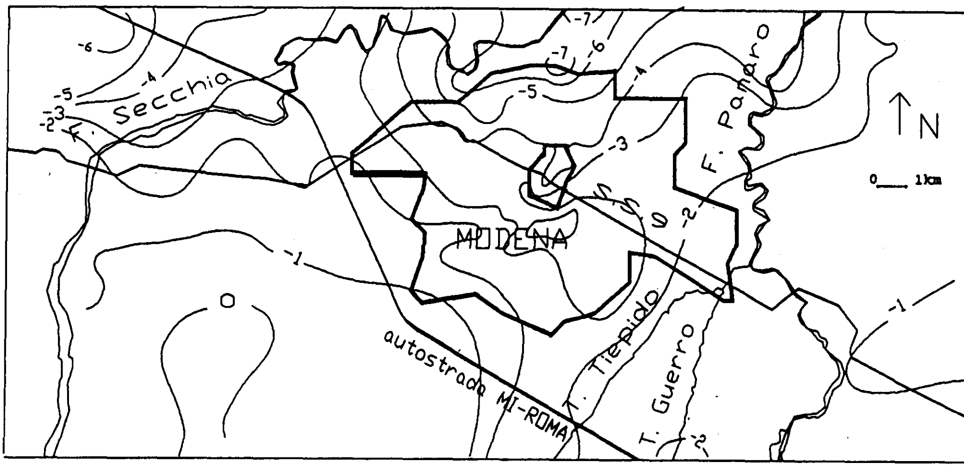


Figure 13: Subsidence map (in mm) in Modena area (1981-1988)

The northern side keeps subsiding because of the natural compaction of low permeability sediments; the highest subsidence rate has been measured in the town area (1950-1979), characterized by a strong decline of the piezometric level, (Cancelli *et al.*, 1984). The same trend continued in the following period (1981-1988) except for the northern area, where the intensive exploitation produced an increase in subsidence of up to 6 mm year^{-1}. The same value is measured in the southern part of Modena.

Generally the values increase northwards to 14 mm year^{-1} in the town centre. The lowest area lies between the Secchia and Panaro rivers as a consequence of the rising consumption of irrigation water in these areas.

Pollution

One of the most notable effects of aquifer overexploitation in Milano area is a depression cone of regional extent. This depression cone, of about 100 km^2, makes groundwater defense from pollutants impossible, especially in highly industrialized areas.

We have studied the polluting substances representative of the social and economic structure of Milano and Modena; halogenated hydrocarbons for the first area and nitrates for the other.

Milano and its hinterland represent an important economic area within the European Community.

In the hydrochemical map one can see several polluting plumes, originating in the hinterland, which are moving towards the depression cone in the town centre. At present we can identify widespread water pollution (Fig. 14).

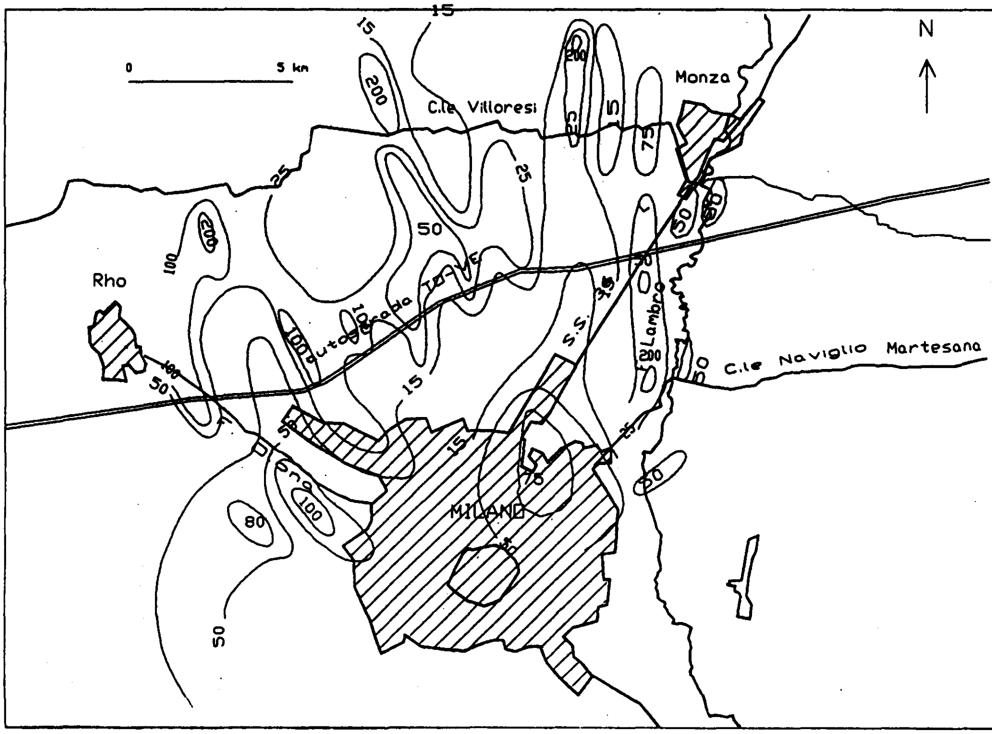


Figure 14: Halogenated hydrocarbons map (in ppb) in Milano area (1989).

Some studies have estimated that about 19% of halogenated hydrocarbons used in Italy are present in the productive activities of Milano and its outskirts. We must remember that there was no regulation until 1976.

The enforcing of a level of 30 mg l^{-1} as the highest allowable concentration fixed by E.E.C. regulations will cause the stoppage of exploitation for 30% of the present wells (Cavallaro *et al.*, 1983).

In Modena area agricultural and farming activities are responsible for the presence of nitrates in groundwaters.

One must also consider that human and economic activities have developed principally in aquifer recharge and highly vulnerable areas. As a consequence there is a nitrate concentration higher than 50 mg l^{-1}; the highest allowable value in Italy (seen in the southern side of the map in Fig. 15).

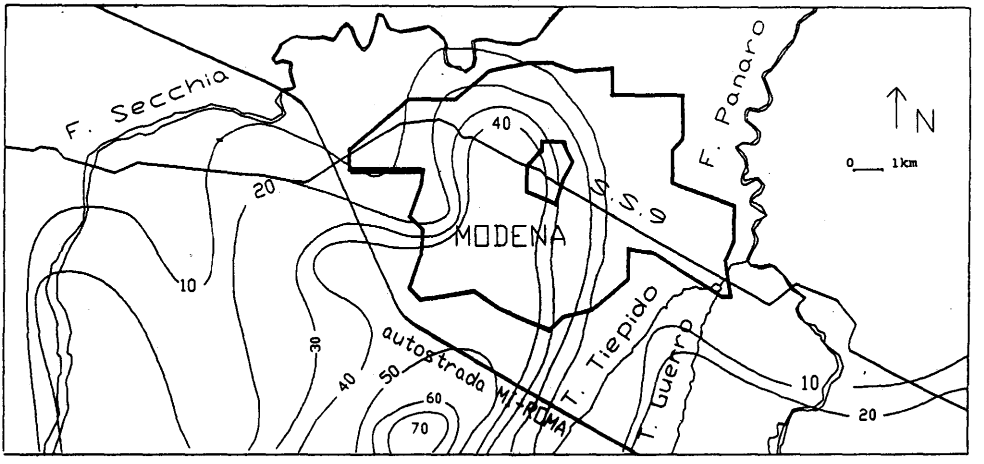


Figure 15: Nitrate map (in mg l^{-1}) for Modena area (1989)

The highest values correspond to the most hydraulically conductive areas where the permeabilty reaches its maximum value (C.N.R.-G.N.D.C.I., 1989).

Along the rivers we can notice the dilution effects due to the infiltration from the river beds. On the contrary, in the northern confined aquifers where recharge is less considerable, dilution is not significant.

Modification of the surface stream network

A considerable modification in the rising of "fontanili" was caused by the lowering of water tables due to groundwater extraction.

In Milano area the 'fontanili line' originally extended 10 km further north than its present position (Figs. 5 and 6); in addition, discharge has considerably decreased and some have even disappeared.

These typical hydrographic elements have disappeared in Modena area too and 'fontanili' no longer exist (Figs. 7 and 8).

PREDICTIONS

After considering overexploitation effects one can postulate the developing trend of problems affecting the two studied areas.

As regards pumping of groundwater one can assume a slight increase of *per capita* consumption proportional to life-quality improvement, but restrained by a campaign for consumption control.

We estimate that pollutants will persist for a long time because it will take many years for groundwater recharge to occur. This situation particularly concerns the Milano area where there are piezometric stagnation conditions.

An improvement of the hydrochemical situation would be possible thanks to the application of national reclamation Plans. Concerning pollutants in Milano, an improvement of the present hydrochemical situation will be possible by way of appropriate groundwater reclamation, while in Modena proper territory management together with regulation of agricultural activities will improve water quality.

The subsidence rate has partly decreased as a consequence of a rising piezometric level following the very high precipitation in 1986.

A high degree of low-permeability soils consolidation has been reached in both towns (90% in Milano and 70% in Modena). In Milano area, however, the future exploitation of deep aquifers, where the thickness of low-permeability sediments is 70% of the total thickness, will probably cause the renewal of subsidence. In Modena area, the final stage of soil consolidation could be contained by well redistribution, differential use of the water resources and the use of surface waters for agricultural and industrial activities.

As regards future predictions, we define analytical relationships for Milano and Modena areas according to historical and geotechnical characteristics of soils.

Considering the values in Table 1 and keeping in mind that:

$$tv = Tv\ (H2/Cv)$$

where
tv = consolidation time (s)
Tv = time factor (dimensionless)
H = compressible layer thickness (m)
Cv = coefficient of volumetric compressibility ($m^2\ s^{-1}$)

Table 1: Geotechnical parameters for (MI)lano and (MO)dena areas

	H(m)	Cv (m^2s^{-1})	tv (years)	tv (years)	tv (years)	Years
			U (%)	U (%)	U (%)	Sub (mm)
MI	10	10^{-1}	2.5	6	40	22
			35	50	90	0.22
MO	60	10^{-6}	10	22	40	30
			35	50	70	0.81

we can get the following relationships which give the consolidation value U (%):

Milano $U (\%) = 1.34\ t + 36.45$
Modena $U (\%) = 1.13\ t + 23.97$

where t is time (years).

The 'natural' contribution S_n (m) can be estimated as follows:

Milano $S_n = + 0.0005\ t$ (rising)
Modena $S_n = - 0.0030\ t$ (lowering)

In this way it is possible to establish the relationships between the maximum piezometric drawdown D_h (m), the time range t (years), the consolidation value U (%) and the natural movement of the soil S_n (m), to interprete subsidence phenomena.

If S_{tot} (m) represents the total variation of the soil level we can write:

$$S_{tot} = A\ D_h + B\ U + S_n$$

in which A and B are coefficients (dimensionless).

Milano $S_{tot} = -0.031\ D_h + 0.0060\ U + 0.0005\ t$
Modena $S_{tot} = +0.088\ D_h - 0.0265\ U - 0.0030\ t$

As said before, we can state that in Modena the subsidence has attained 2/3 of the total value while in Milano it is finished. In both cases this is related to the first 100 m of thickness of the soil surface.

We fear a new start of subsidence in Milano in relation to the exploitation of deep aquifers (over 100 m of depth). The piezometric depression of these aquifers increases the geostatic charge on the clay layers which, between 100 and 200 m depth, constitue 70% of the total thickness. In this situation, should there be a 5 or 6 m piezometric drawdown, we can foresee a variable soil settlement of between 200 and 400 mm in the next 10 years.

CONCLUSIONS

The arrangement of hydrochemical and piezometric networks of control, the periodic monitoring of the subsidence and the examination of the amount of public use of groundwater provide very significant data for the understanding of physical phenomena.

The needs of water supply have prompted the redistribution of wells around Modena and the exploitation of deeper aquifers in Milano area.

The proposals made for Milano could, however, induce the renewal of subsidence in view of the abstraction amount and the geological and geotechnical characteristics of deep sediments.

The results of this research indicate the necessity for the estimation of a water balance in order to programme appropriate water resources management. Correct management in the area will in fact help to reduce overexploitation.

REFERENCES

Airoldi, R., Barzaghi, R., Beretta, G.P., Cabbafoglia, C., Cassano, E., Cassinis, R., Cavagna, B., Cunietti, M., De Haan, A., Ferrari da Passano, C., Forlani, G., Francani, V., Giacometti, E., Longo, G., Mussio, L., Nardon, M. & Salvaderi, R. 1990. Abbassamento del suolo nel territorio metropolitano milanese nel periodo 1973-1986. *Rivista del Catasto e dei Servizi Tecnici Erariali*, Nuova Serie, Anno XLIV, no. 1-2, Roma.

Cancelli, A., Govoni, E., Paltrinieri, N., Pellegrini, M., Russo, P. & Zavatti, A. 1984. A guidebook to the city of Modena land subsidence and the effect on the main historical buildings. In: *Proc. of the Third International Symposium on Land Subsidence*, Venice, Italy.

Cavallaro, A., Corradi, C., De Felice, G., Grassi, P. Mazzarella, S. & Ruota, F. 1983. Case histories: Milano e Provincia. In: *Inquinamento delle acque sotterranee da composti organo-clorurati di origine industriale.* Monduzzi Editore, Bologna.

C.N.R.-G.N.D.C.I. 1989. Carta della vulnerabilità degli acquiferi all'inquinamento: unità idrogeologica conoidi dei fiumi Secchia e Panaro. In: *Studi sulla vulnerabilità degli acquiferi*, no. 2. A cura di N.Paltrinieri, M.Pellegrini & A.Zavatti, Pitagora Editrice, Bologna.

CAUSES AND IMPLICATIONS OF RELATIVE SEA-LEVEL RISE ALONG THE TEXAS GULF OF MEXICO COAST

J. M. SHARP, JR.
Department of Geological Sciences,
The University of Texas at Austin, Austin TX 78713-7909, USA

ABSTRACT. Numerous low-lying coastal areas possess thick sedimentary sections which contain valuable fluid resources--water and petroleum. Their utilization can create a variety of problems including salt-water intrusion, subsidence, flooding, and fault activation. All of these have been documented in the low-lying coasts surrounding the Gulf of Mexico Basin. Fluid extraction has accelerated natural consolidation in Cenozoic clastic units along the northern Gulf. Groundwater pumpage is responsible for most of the very high rates of relative sea-level rise (>12 mm year^{-1}), but it appears that regional depressurization of petroleum reservoirs is very significant on a regional scale. Tectonic processes and natural subsidence are less important in contributing to the high observed rates. These subsidence effects will be exacerbated by predicted eustatic sea-level rise induced by global climate changes. Coastal flooding and erosion in response to subsidence is particularly acute during major storm events. Surface-water resources have replaced ground water in some areas, but high rates of subsidence continue. Impoundments necessary for surface water utilization also store sediment and may, therefore, contribute to the erosion. Groundwater pumping has also activated growth faults and differential subsidence with ensuing engineering problems. Subsidence prediction is difficult, and documentation of subsidence on an areal basis is not now practicable, but new satellite-based methods provide promise. Determination of the fault permeability is critical in controlling differential subsidence. Salt-water intrusion created by aquifer overexploitation is a major problem on Gulf of Mexico barrier islands and along the coast of the Florida and Yucatan peninsulas, which possess extremely permeable carbonate aquifer systems and where surface water supplies are not available. The continued use of groundwater in the Gulf of Mexico region requires careful consideration of integrated hydrological, socioeconomic, climatological, and geological factors to avoid the consequences of overexploitation.

INTRODUCTION

The groundwater resources of the Gulf of Mexico coastal plain are vast (Sharp *et al.*, 1991a). The aquifers of this low-lying coastal plain are not, however, inexhaustible. Aquifer exploitation, coupled with petroleum reservoir depressurization and the geologic setting common to prograding consolidating coasts, has created a high rate of relative sea-level (RSL) rise. The RSL rise (Figure 1) is a combination of eustatic sea-level rise (the absolute rise of sea level with respect to a fixed datum) and subsidence (both natural and anthropogenic). Several recent studies (Germiat & Sharp, 1990); Paine, 1990; Sharp *et al.*, 1991b) indicate widespread rates of relative sea-level (RSL) rise of 5 to 20 mm year^{-1}. These studies analyzed tidal gauge records and relevelling lines. They noted that many of the high rates are in areas with essentially zero groundwater production. The negative effects of RSL rise include water-quality deterioration, salt water intrusion, differential subsidence, coastal retreat/erosion, and flooding/inundation. There are similar low-lying coastal areas near the deltaic areas near major rivers worldwide (Sharp & Domenico, 1976, their Fig. 1). The Gulf coast, however, has already experienced intensive development and may serve as a prototype for the other areas.

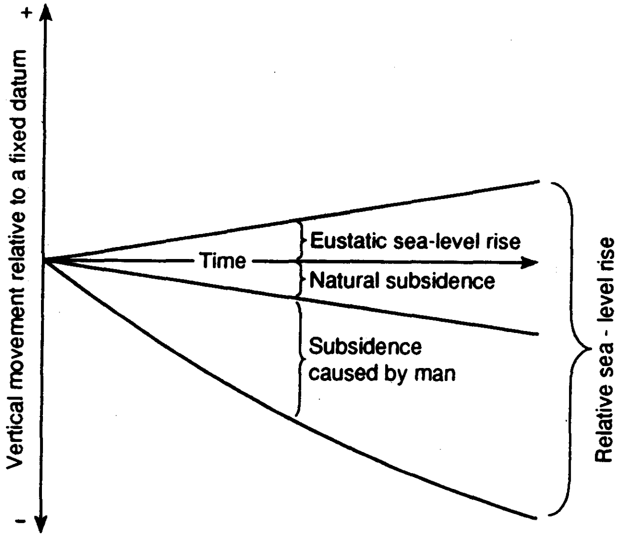


Figure 1: Eustatic sea-level rise, subsidence, and relative sea-level rise.

In this paper, I wish to outline the physical hydrogeologic setting of the northwestern Gulf of Mexico coastal plain (Figure 2), examine the causes of the observed high rates of RSL rise, particularly examine petroleum reservoir depressurization as a cause of regional subsidence, and briefly comment on the environmental/geotechnical effects of rising RSL. The potential effects of future increases in eustatic sea level on these problems must be considered. Special emphasis is placed on the Texas coast which is undergoing rapid and increasing industrial, residential, and recreational development.

HYDROGEOLOGIC SETTING

The chief characteristic of the northwestern Gulf of Mexico is its thick section of clastic sediments. Up to 12 kilometres of sediment have accumulated on a passive continental margin in the last 55 million years. The intercalated sand, silt, and clay layers dip gently coastward unless offset by faulting. The Chicot, Evangeline, and Jasper are the most prolific clastic aquifers. They are generally confined by highly compressible clays. Underneath the fresh-water section is the saline section at depths between 0 and 1,000 metres. Figure 3 depicts the general trends of fluid pressures with depth in the Gulf of Mexico. Shallow reservoirs exhibit nearly hydrostatic fluid pressures, although clayey confining units may be overpressured. At depths of 1,500 to 2,500 metres, the sediments are overpressured (also called geopressures). Fluid pressures approach 90 percent of the lithostatic load which is apparently the pressure at which the sediments fracture hydraulically. These deep, overpressured sediments contain most of the region's immense petroleum reserves.

Important carbonate aquifers are located in Florida, Texas, and the Yucatan Peninsula (Sharp *et al.*, 1991a). The Floridan aquifer consists of up to 1,000 metres of carbonates with both confined and unconfined units. Overexploitation of the Floridan aquifer has caused sink-hole collapse, localized salt-water intrusion, and environmental problems related to the protection of wetlands. The Edwards (Cretaceous) aquifer of Texas borders the clastic sediments of the Gulf of Mexico. Conflicts between competing users are common. Overexploitation problems are somewhat unique--diminution of spring flow, loss of surface-water discharge to bays and estuaries, and protection of a

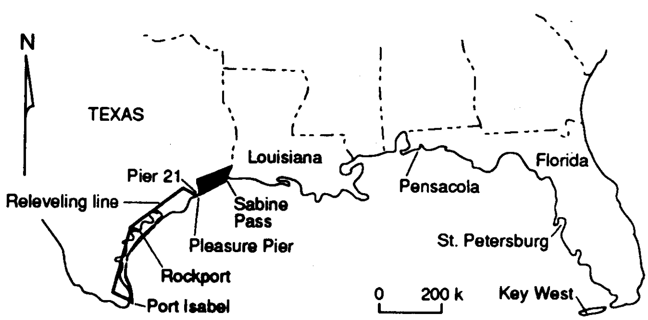


Figure 2: The northwest Gulf of Mexico showing the northeastern study area (in black), the relevelling line of Paine (1991), and utilized tide gage stations.

few endangered species. The carbonate system of the Yucatan is an areally extensive but thin freshwater lens. Here, overexploitation can create rapid salt-water intrusion. Pollution is a problem in these carbonate systems, particularly in the Yucatan because the system is predominantly unconfined and because of inadequate water and sewage treatment systems. Point- and nonpoint-source pollution of both clastic and carbonate aquifers is common, particularly in areas of heavy industry.

Regional subsidence, however, is the most widespread and diagnostic result of aquifer exploitation (and petroleum reservoir depressurization) in the northern Gulf of Mexico basin. Both the aquifers and the reservoirs have been extensively pumped and fluid pressures greatly reduced. This has created significant subsidence. Near Houston, over two metres of subsidence has occurred because of groundwater pumpage (Gabrysch, 1982). Consequently, coastal areas, where possible, have converted to surface-water resources impounded in reservoirs. Petroleum production also contributes; localized subsidence of over 1 metre has long been noted over the Goose Creek oil field (Pratt & Johnson, 1926). Below we examine subsidence effects along the Texas coastline.

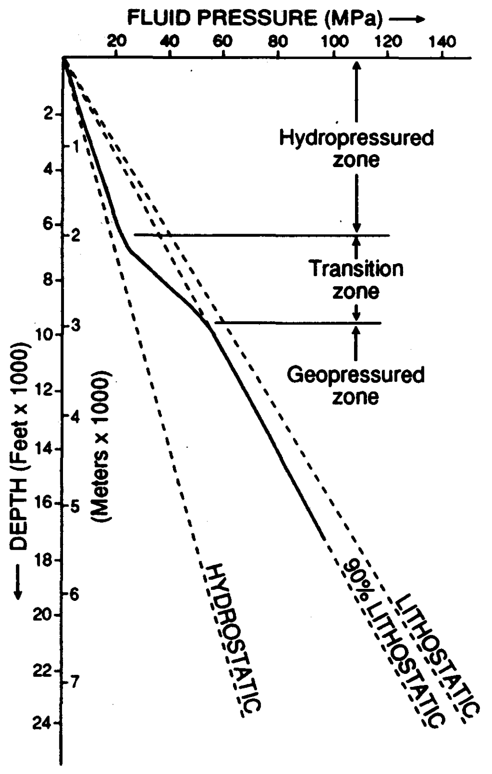


Figure 3: Generalized pressure versus depth for the Gulf of Mexico (Sharp *et al.*, 1988). Thick sections of overpressured sediments exist at depths.

RELATIVE SEA-LEVEL CHANGE AND ITS CAUSES

Recent studies (e.g., Sharp *et al.*, 1991b) at The University of Texas documented unexpectedly high regional rates of relative sea-level rise. Germiat & Sharp (1990) and Sharp & Germiat (1990) studied the northeasternmost Texas coast. Based upon a comparison of tidal gages in Texas and Florida (Figure 4), it is apparent that RSL rise is significantly greater in Texas (6 to 12 mm year^{-1}) than in Florida (2 to 3 mm year^{-1}). Furthermore, a second order regression of the long record at Pier 21 or linear regressions of early data versus data from the last 25-30 years clearly demonstrate an acceleration of RSL rise. The area near Sabine Pass on the Texas–Louisiana border has not been extensively exploited for ground water. This apparent acceleration has been documented over a wide area of the Gulf Coast by Penland *et al.*, (1987), although Turner (1991) contends that this acceleration is only a periodic fluctuation of a long-term trend. The linear regression of Sabine Pass tide gage data yields a 11.4 mm year^{-1} rate of RSL rise. Some of the RSL rise at Pier 21 and Pleasure Pier may be due to ground-water withdrawals in the greater Houston area, but these have been greatly curtailed. Gabrysch's (1982) data yields a linearized RSL rise of 4.1 mm year^{-1} for the eastern edge of the northeastern coastal study area. Studies by Paine (1990 and 1991) investigated the Texas coast from Galveston to the Rio Grande. This work combined, among other items, a correlation of tidal gage data with National Geodetic Survey relevelling surveys. These data are depicted on Figure 5. Paine (personal communication) suggests that RSL rises of greater than 10 mm year^{-1} could correlate with groundwater extraction, but the high rates RSL rise over the entire coast can not be so attributed. The problem of tidal gage location in near harbor and navigational facilities has been addressed by Pirazzoli (1986) and Turner (1991). The relevelling line analyses by Germiat & Sharp (1991) and Paine (1991), however, confirm that the high RSL rise rates are not confined to the areas immediately adjacent to the gages but do indeed reflect regional trends. Consequently, we observe rates of RSL rise of between 20 and 5 mm year^{-1}; rates which have been greater in the past 30 years than in the preceding records or predicted based upon geological observations.

Each of the following processes could be responsible for a portion of the observed RSL rise: natural consolidation of the thick sequence of sediments, tectonic processes, eustatic sea-level rise, pumping of ground water, and extraction of petroleum. Each process is discussed in turn below.

Natural consolidation

Table 1 lists the known estimates of natural subsidence along the Texas Gulf Coast. Based upon the total accumulation of sediment (up to 12 kilometres in the Cenozoic) an average rate of Cenozoic downwarping, if we assume that natural subsidence is keeping pace, a rate of 0.025 mm year^{-1} is readily calculated. The 5 other estimates are more site specific and each could be correct for that specific site. The 1979 estimate of Morton is abnormally high, but it is nevertheless clear that natural subsidence is probably one or more orders of magnitude too low to account for much of the observed high rates of RSL rise.

Table 1: Estimates of natural subsidence along the Texas Gulf Coast.

RATE (mm year^{-1})	SOURCE OF ESTIMATE
0.025	Average rate of Cenozoic downwarping of the Gulf of Mexico Basin
0.06	Paine (1991) - elevation change of marker beds
0.1	Winker (1979) - tilting of the Ingleside shoreline
0.15	Winker (1979) - sedimentary cycle thicknesses
0.3	Bernard and LeBlanc (1970)- present slope of the Beaumont Formation surface
2.5	Morton (1979) - subsided strandline of Holocene Brazos-Colorado shoreline

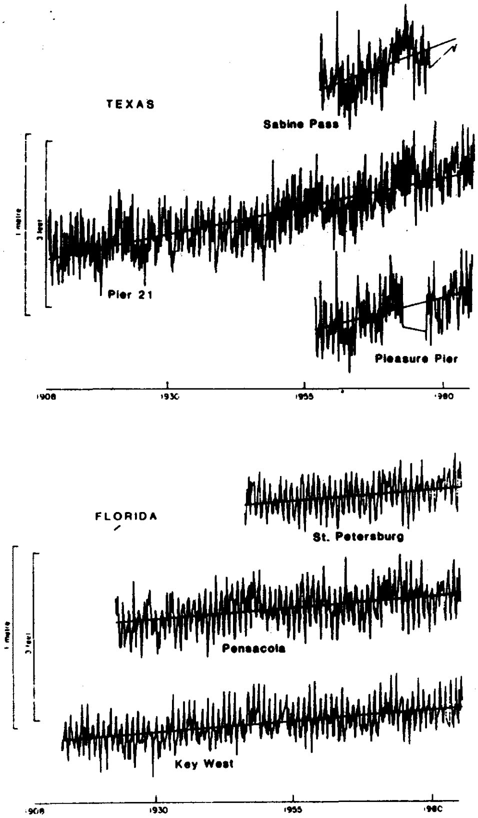


Figure 4: Comparison of Texas (upper) and Florida (lower) tidal gage records. The higher rate of RSL rise in Texas is shown by the steeper lines of linear regression.

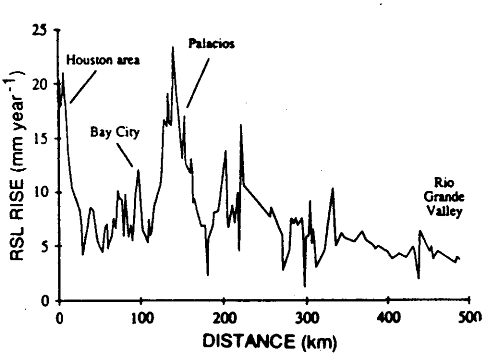


Figure 5: Relative sea-level rise estimates for the relevelling line of Paine; from Sharp *et al.*, 1991b).

Tectonic processes

Coastal areas are, of course, subject to uplift and subsidence from tectonism. Two processes must be considered--regional downwarping and growth faulting. The Gulf of Mexico is an area of tectonic subsidence, created in part by the loading of the thick sequence of Cenozoic sediments. The estimated linear rate of downwarping is shown in Table 1. It is possible that rates have accelerated, but the general concensus is that such rates are relatively constant over 100s or 1000s of years (Holdahl & Morrison, 1974). For instance, near the present locus of sediment accumulation at the delta of the Mississippi River, sediment is accumulating at rates of near 10 mm $year^{-1}$. The Sabine Pass area is indeed the closest to this area. It is still unclear how this vertical strain is transmitted laterally. However, the rate must be significantly less along the Texas Coast because the downwarping is not reflected inland at any significant distance (Holdahl & Morrison, 1974). Furthermore, times of most intense sediment loading on the Texas coast were pre-Miocene (Sharp *et al.*, 1988). The rate of tectonic deformation is neither accelerating or sufficient to account for the observed rates of regional RSL rise.

The effects of growth faulting on the regional subsidence picture is problematic. Ewing (1985), for instance, used reactivated growth faults to infer consolidation and subsidence above the High Island petroleum reservoirs. The geotechnical effects of growth faults, which are activated by declining hydraulic potentials, are well documented. This is presumed to be the result of differential subsidence, but the exact processes are poorly understood. It is also unknown whether or not the activated faults serve as permeability barriers. It is possible that the regional structure of subsidence is altered by differential movement along growth fault blocks, but in areas of high subsidence induced by groundwater pumping the overall bowls of subsidence do not seem to be fault bounded (Gabrysch & Bonnet, 1975). This is an area which needs investigation. Fault controls on overall subsidence will require an accurate regional surveying grid (possibly using GPS, tiltmeters, and occasional high precision relevelling) over several decades.

Eustatic sea-level rise

World-wide estimates of ESL rise are typically on the order of 1 to 1.5 mm $year^{-1}$ (e.g., Gornitz *et al.*, 1982 and 1987), although Pirazzoli (1986) disputes the data. Turner (1991) suggests a higher rate for the Gulf of Mexico and Davis (1987) reports a rate of 2.5 mm $year^{-1}$ along the Atlantic coast, similar to the tide gauge data for the "stable" Florida peninsula which show 2.0 to 2.5 mm $year^{-1}$ RSL rise. Projected rates of ESL rise in response to the Greenhouse Effect are significantly higher than 2.0 mm/yr. These higher rates of inferred ESL rise along the Florida and Atlantic coasts may due to unexpected regional high ESL rise, changing geostrophic currents, or downwarping of the Earth's crust in response to sediment loading by the Mississippi delta. Therefore, combined tectonic/ESL rate of RSL rise in the range of 2 to 2.5 mm $year^{-1}$ is estimated for the Texas Gulf Coast.

Of great significance to problems created by rising RSL along low-lying coasts is the potential for a rise in ESL caused by global climate change (Figure 6). A subjective probability analysis (Sharp & Germiat, 1990) revealed a wide range of estimates with a 50% chance of an ESL rise of 60 centimetres by 2050. This is approximately the same as the extrapolation of observed rates of RSL rise.

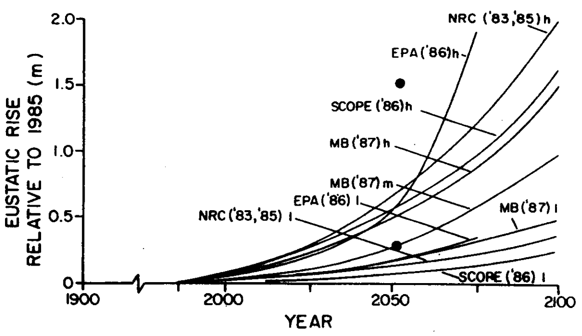


Figure 6: Projections of ESL rise (Sharp & Germiat, 1990). Black dots represent the 10% (upper) and 50% (lower) certainties of ESL rise by 2050 from Sharp & Germiat (1990). Curves represent high (h), middle (m), and low (l) estimates of the Marine Board of the National Research Council (MB, 1987), the Environmental Protection Agency (EPA, cited in Marine Board, 1987), the Scientific Committee on Problems of the Environment (SCOPE, 1986), and the National Research Council Carbon Dioxide Assessment Committee and Polar Research Board (NRC, 1983 and 1985, respectively).

Subsidence from groundwater pumping

Declining potentiometric surfaces for shallow clastic aquifers is well documented, particularly, in the greater Houston-Galveston and, locally, in other Texas areas (Bonnet & Gabrysch, 1982; Gabrysch, 1982; Gabrysch & Bonnet, 1975; Ratzlaff, 1980). The correlation between groundwater pumpage and local subsidence is excellent. This led to a gradual conversion to surface-water resources and the formation of the Houston-Galveston Subsidence Control District. Subsidence from direct aquifer exploitation has been lessened and concentrated farther inland where potential problems of inundation are minimal.

Nevertheless, it is documented that areas of high RSL rise occur in areas with little or no groundwater exploitation (Germiat & Sharp, 1990; Paine, 1991; Sharp *et al.*, 1991b). This is demonstrated by the relevelling from the Rio Grande to Galveston; rates of over 12 mm/yr of subsidence are clearly related to groundwater pumpage. Rates of 5 mm $year^{-1}$ exist near the Mexican border, but extensive areas of the upper Texas coast, where there is virtually no groundwater production, show subsidence rates of 5 to 12 mm $year^{-1}$. The Sabine Pass area with a linear trend of 11.4 mm $year^{-1}$ since 1958 has minimal groundwater production and relevelling analysis indicates RSL rise of similar magnitude southwest to the Galveston region. These observed rates of RSL rise are almost an order of magnitude greater than estimated rates of natural subsidence, which vary from 2.4 to .025 mm $year^{-1}$. Clearly, processes other than groundwater extraction or natural subsidence are indicated. Subsidence created by petroleum reservoir depressurization is the only other logical explanation because world-wide ESL rise is estimated at less than 2.0 mm $year^{-1}$.

Subsidence from petroleum production

Declines in petroleum reservoir pressures has been documented both on a local (Germiat & Sharp, 1990; Pratt & Johnson, 1926) and regional basis (Kreitler, 1989; Sharp *et al.*, 1991b). Most of the studies (e.g., Esaki *et al.*, 1991; Poettgens & Brouwer, 1991) concentrate on relative subsidence immediately above producing reservoirs. The case of the Goose Creek field (Meinzer, 1928; Pratt & Johnson, 1926) is the first well-documented case of oil-field subsidence. Currently, up to 3 metres of subsidence occur locally over the Goose Creek field. Germiat & Sharp (1990) and Sharp & Germiat (1990) used the analytical technique of Geertsma (1973) to analyze potential subsidence of depressurized oil and gas fields along northeastern Texas Coast. They calculated total subsidences of between 1 and 72 cm for the seven fields for which data were obtainable. It must be stressed that Geertsma's analysis calculates elastic compression of an idealized producing reservoir only. These calculations do not account for consolidation of overlying, underlying, or intercalated clay-rich or shaly confining layers. It has been demonstrated in most subsidence areas (e.g., Long Beach, Houston–Galveston, Venice) that the bulk of the strain is produced in the clay-rich layers. This strain is largely nonrecoverable and the consolidation is delayed by the slow rate of fluid flow from the confining layers to the aquifers and/or reservoirs.

Data from the petroleum reservoirs along the Texas coastline (Sharp *et al.*, 1991b, their figure 2) depicts the significant depressurization which has occurred because of production. This fluid pressure must be accompanied by concomitant confining layer dewatering and subsidence. The significant questions which must be addressed are: How regional or local is the depressurization? What is the time lag between reservoir depressurization and confining layer consolidation? And what is the magnitude of the key parameters (e.g., hydraulic conductivity and sediment compressibility) needed for estimating subsidence due to petroleum reservoir depressurization. Sadly, despite the intensive study of the Gulf Coast for petroleum, these important questions have been little studied.

Saleem Ahkter of the Texas Bureau of Economic Geology provided petroleum well shut-in pressure data for the four counties (Orange, Jefferson, Chambers, and Harris) of the northeastern Texas Gulf Coast which are shown on Figure 7. The data cover the last 80 years but are more common recently. It is not yet possible to contour these data areally or as a function of time. It is evident, however, that there has been considerable depressurization. Presumably initial pressures should basically envelop the data in curve similar to the idealized curve of Figure 3. In order to examine whether or not petroleum reservoir depressurization is potentially significant quantitatively a set of scoping calculations were conducted. A uniform percentage of clay/shale with depth is considered. These clay/shale confining layers are divided into arbitrary thicknesses per each 500 feet (152 metres) depth increment corresponding to 1, 10, and 100 layers per increment. The depressurization shown on Figure 7 is uniformly distributed to the reservoirs in each depth increment. The average adjustments of pressure in the confining layers are calculated by the analytical solution presented in Carslaw & Jaeger (1959, p. 100). Consolidation per confining layer is calculated assuming a constant (linear) compressibility. The rate of subsidence is calculated as linear over 30 years, a period corresponding to the start of more intensive offshore petroleum production. Typical conservative input data (see, for instance, Domenico & Schwartz, 1990, p. 65 & 111) and one set of typical results are given in Table 2.

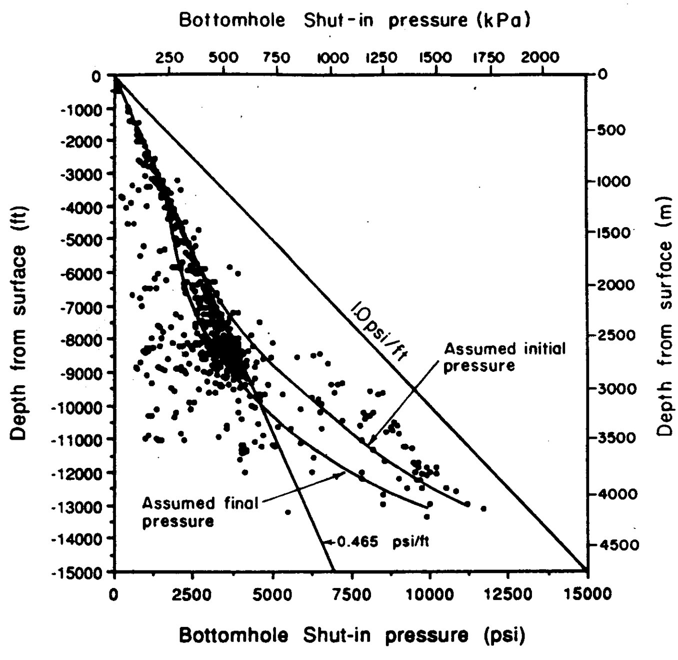


Figure 7: Reservoir pressure versus depth for the northeast Texas coast (courtesy of Saleem Ahkter, Texas Bureau of Economic Geology). Also shown are theoretical values for both hydrostatic pressure (10.51 kPa m^{-1} or 0.465 psi ft^{-1}) and lithostatic pressure (22.61 kPa m^{-1} or 1.0 psi ft^{-1}) and the postulated values of initial and present pressures in the study area.

Table 2: Input data and calculated possible range of subsidence from petroleum reservoir depressurization, northeast Texas coast.

Input data: Hydraulic conductivity = 10^{-11} m s^{-1}
Confining layer compressibility = 10^{-10} m^2 N^{-1}
Percent clay/shale in Gulf Coast sediment sequence = 80%
Depth range of depressurized reservoirs = 3962 m

Confining layer thickness (m)	% pressure equilibration	Total calculated subsidence (m)	Calculated rate (mm $year^{-1}$ for 30 yrs)
122.0	21.3	0.141	4.7
12.2	99.9	0.660	22
1.22	100.0	0.661	22

The calculated subsidence rates of 4.7 to 22 mm $year^{-1}$ demonstrate the potential significance of subsidence caused by petroleum production in contributing to the observed high rates of RSL rise.

Conservative values of hydraulic conductivity and compressibility were input. Subsidence in the reservoir itself, as in Geertsma (1973) or Sharp & Germiat (1990), was also ignored. In addition, the degree of depressurization as a function of depth (Figure 7) was conservative. Nevertheless, it is not known how far vertically and horizontally from the reservoirs the depressurization has reached, how the key parameters actually vary with depth, what is the preconsolidation stress (if any), or to what degree the confining layers have equilibrated to reservoir depressurization. Therefore, these calculations must not be considered as predictive calculations, but only as an indication of the potential significance of this process. More study is clearly needed before a definitive calculation of this process can be conducted.

EFFECTS OF PROJECTED EUSTATIC SEA-LEVEL RISE AND CONTINUED SUBSIDENCE

Figure 6 shows some predictions of ESL rise, based upon assumptions of climatic change, melting of ice sheets and glaciers, and thermal expansion of the oceans. Also shown are two delphic predictions of ESL rise provided by Sharp & Germiat (1990). A linear projection of subsidence (i.e. current RSL rise less 2.5 mm year^{-1} of ESL rise) plus ESL rise projections suggest a reasonable expectation of a RSL rise of up to 1.20 metres in the next 60 years. Significant modern and historical coastal erosion and retreat along the Texas Coast have been documented (Benton & Bolleter, 1987; Germiat & Sharp, 1990; Morton, 1977). We should, therefore, expect accelerated coastal erosion and retreat, inundation and loss of coastal marshes, and periodic storm-induced floods along the low-lying Texas Gulf coast in the next century. Germiat & Sharp (1990) predicted rates of coastal retreat ranging from 0.41 to 30 m year^{-1}. There may be also be exacerbated problems with salt-water intrusion in Florida and the Yucatan. Still speculative is how such a RSL rise will affect the increasing problems of land and water pollution.

CONCLUSIONS

Aquifer overexploitation along the Gulf coast has created a variety of problems. Subsidence is of great concern because of its high rate and lateral extent, as well as the low elevation and low topographic relief of the coastal plain. The need for water resources is growing and, in many areas, surface-water resources are limited. Groundwater pumpage, coupled with extraction of hydrocarbons, has created general regional subsidence plus localized areas of the very rapid subsidence. A conservative "scoping" calculation indicates that regional subsidence created by petroleum reservoir depressurization is indeed a potentially significant process. With the expected advent of global warming and associated ESL rise, the potential exists for coastal land loss, inundation, and associated socioeconomic consequences. Of particular importance is the need to consider all the causes of RSL rise when designing projects to mitigate subsidence and to provide necessary water resources. In some cases we may be needlessly restricting pumpage; in other cases, RSL rise from other causes than groundwater pumping may be great enough to cause deleterious effects. A critical need for future analyses is to obtain data on the areal and temporal extents and magnitude of subsidence, as well as continued monitoring of ESL rise projections.

ACKNOWLEDGEMENTS

Acknowledge is made to the donors of the Petroleum Research Fund of the American Chemical Society for partial support of this research. I also wish to thank Saleem Ahkter and Jeff Paine of the Texas Bureau of Economic Geology, Austin, for providing some of the data. The interpretations of those and other data are strictly those of this author. Past discussions with Jeff Paine, Steve Germiat, and Dick Raymond on the topics of this paper are gratefully acknowledged. Manuscript preparation was supported by the Owen–Coates Fund of The Geology Foundation of The University of Texas at Austin.

REFERENCES

Benton, A.R., Jr. & Bolleter, J.M. 1987. Erosional trends on Galveston Island, Texas. *Bull. Assoc. Engineering Geologists*, 24; 345-358.

Bernard, H. A. & LeBlanc, R. J. 1970. Resume of Quaternary geology of the northwest Gulf of Mexico province. *Recent Sediments in Southeast Texas.* Univ. Texas Bureau of Economic Geology Guidebook #11, Austin.

Bonnet, C. W. & Gabrysch, R. K. 1982. Development of ground-water resources in Orange County, Texas, and adjacent areas in Texas and Louisiana, 1971-1980. *U.S. Geological Survey Open-File Report 82-330*; 46 p.

Carslaw, H.S. & Jaeger, J.C. 1959. *Conduction of Heat in Solids*, Oxford Univ. Press, London.

Davis, G. H. 1987. Land subsidence and sea-level rise on the Atlantic coastal plain of the United States. *Environmental Geol. Water Sci.* 10; 67-80.

Domenico. P.A. & Schwartz, F.W. 1990. *Physical and Chemical Hydrogeology.* John Wiley & Sons, Inc., New York.

Esaki, T., Shikata, K., Aoki, K. & Kimura, T. 1991. Surface subsidence in natural gas fields. In: *Land Subsidence*, A.I. Johnson (ed.), IAHS Pub. 200; 109-118.

Ewing, T.E. 1985. Subsidence and surface faulting in the Houston-Galveston area, Texas--related to deep fluid withdrawal? In: Proc. 6th U.S. Gulf Coast Geopressured-Geothermal Energy Conf., *Geopressured-Geothermal Energy*, Dorfman, M.H. & Morton, R.A. (eds.), Austin; 289-298.

Gabrysch, R. K. 1982. Groundwater Withdrawals and Land Surface Subsidence in the Houston–Galveston Region, Texas, 1906-1980. *U.S. Geological Survey Open File Report 82-571*; 68 p.

Gabrysch, R.K. & Bonnet, C.W. 1975. Land-surface subsidence in the Houston–Galveston region, Texas. *Texas Water Devel. Board Rpt.* 188; 19 p.

Geertsma, J. 1973. Land subsidence above compacting oil and gas reservoirs. *Jour. Petroleum Tech.*, 24; 734-744.

Germiat, S. J., & Sharp, J. M., Jr. 1990. Assessment of future coastal land loss along the upper Texas Gulf coast. *Bull., Assoc. Engineering Geologists*, 27; 263-280.

Gornitz, V. & Lebedeff, S. 1987. Global sea-level changes during the past century. In: *Sea-Level Fluctuations and Coastal Evolution*, Nummedal, D. *et al.*, (eds.), Special Publication No. 41, Society of Economic Paleontologists and Mineralogists; 3-16.

Gornitz, V., Lebedeff, S. & Hansen, J. 1982. Global sea level trend in the past century. *Science*, 215; 1611-1614.

Holdahl, S. R. & Morrison, N.L. 1974. Regional investigations of vertical crust movements in the U.S. precise relevelings and mareograph data. *Tectonophysics*, 23; 373-390.

Kreitler, C. W. 1989. Hydrogeology of sedimentary basins. *J. Hydrol.*, 106; 29-53.

Marine Board, Committee of Engineering Implication of Changes in Relative Mean Sea Level, National Research Council. 1987. *Responding to Changes in Sea Level.* National Academy press, Washington, D.C.

Meinzer, O.E. 1928. Compressibility and elasticity of artesian aquifers. *Economic Geology*, 23; 263-291.

Morton, R.A., 1977. Historical shoreline changes and their causes, Texas Gulf Coast. *Trans., Gulf Coast Assoc. Geological Societies*, 27; 352-364.

Morton, R. A. 1979. Temporal and spatial variations in shoreline changes and their implications, examples from the Texas Gulf Coast. *J. Sed. Petrology*, 49; 1101-1112.

National Research Council, Carbon Dioxide Assessment Committee. 1983. *Changing Climate.* National Academy Press, Washington, D.C.

National Research Council, Polar Research Board. 1985. *Glaciers, Ice Sheets, and Sea Level: Effects of a CO_2-Induced Climatic Change.* National Academy Press, washington, D.c.

Paine, J. G. 1990. Recent vertical movement and sea-level changes, Texas coastal zone [abs.]. *EOS*, 71; 479.

Paine, J.G. 1991. *Late Quaternary Depositional Units, Sea Level, and Vertical Movement Along the Central Texas Coast.* Univ. Texas Ph. D. Dissertation, Austin, Texas.

Penland, S., Ramsey, K. & McBride, R.A. 1987. Relative sea level rise and subsidence measurements in the Gulf of Mexico based on National Ocean Survey tide gauge records--New Orleans, USA, Proc. Tenth Nat. Conf. of the Coastal Society. *Estuarine and Coastal Management --Tools of the Trade*; 66-68.

Pirazzoli, P.A. 1986. Secular trends of relative sea-level (RSL) changes indicated by tide-gauge records. *Jour. Coastal Research*, 1; 1-126.

Poettgens, J.J.E. & Brouwer, F.J.J. 1991. Land subsidence due to gas extraction in the northern part of The Netherlands. In: *Land Subsidence*, A.I. Johnson (ed.), IAHS Pub. 200; 99-108.

Pratt, W. E. & Johnson, D. W. 1926. Local subsidence of the Goose Creek oil field. *J. Geology*, 34; 577-590.

Ratzlaff, K. W. 1980. Land-surface subsidence in the Texas coastal region. *U.S. Geological Survey Open-File Report 80-969*, 19 p.

Scientific Committee on Problems of the Environment (SCOPE) of the International Council of Scientific Unions. 1986. *Greenhouse Effect, Climate Change, and Ecosystems.* John Wiley & Sons, Inc., Chichester.

Sharp, J. M., Jr. & Domenico, P. A. 1976. Energy transport in thick sequences of compacting sediment. *Bull., Geol. Soc. America*, 87; 390-400.

Sharp, J. M., Jr., Galloway, W. E., Land, L. S., McBride, E. F., Blanchard, P. E., Bodner, D. P., Dutton, S. P., Farr, M. R., Gold, P. B., Jackson, T. J., Lundegard, P. D., Macpherson, G. L. & Milliken, K.L. 1988. Diagenetic Processes in Northwest Gulf of Mexico Sediments. In: *Diagenesis, II*, Chilingarian, G.V. & Wolf, K.H. (eds.) Elsevier Science; 43-113.

Sharp, J. M., Jr. & Germiat, S. J. 1990. Risk assessment and causes of subsidence along the Texas Gulf coast. In: *Greenhouse Effect, Sea Level, and Drought*, Fairbridge, R.W. & Paepe, R. (eds.) Kluwer Academic Publishers, Dordrecht, NATO ASI Series 325; 395-414.

Sharp, J. M., Jr., Kreitler, C. E. & Lesser, J. 1991a. Ground water. In: Salvador, A. (ed.) *The Gulf of Mexico, The Geology of North America.* Geological Society of America, Boulder, v. J, p. 529-543.

Sharp, J.M., Jr., Raymond, R.H., Germiat, S.J. & Paine, J.G. 1991b. Re-evaluation of the causes of subsidence along the Texas Gulf of Mexico coast and some extrapolations of future trends. In: *Land Subsidence,* Johnson, A.I. (ed.), IAHS Pub. 200; 397-406.

Turner, R. E. 1991. Tide gauge records, water level rise, and subsidence in the Northern Gulf of Mexico. *Estuaries,* 14; 139-147.

Winker, C. D. 1979. *Late Pleistocene Fluvial-Deltaic Depositions of the Texas Coastal Plain and Shelf.* Univ. Texas M.A. thesis, Austin, Texas.

FLUORIDE IN PALEOCENE AQUIFER IN SENEGAL : AN EXAMPLE OF THE CONTAMINATION OF A CONFINED AQUIFER BY ITS ROOF ZONE, AGGRAVATED BY INTENSIVE EXPLOITATION

Y. TRAVI
Laboratoire d'Hydrogéologie, Faculté des Sciences,
33 rue L. Pasteur, 84000 Avignon
A. FAYE
Département de Géologie, Faculté des Sciences,
Dakar Fann, Sénégal

ABSTRACT. On the western border of the Senegalese sedimentary basin, S. E. of Dakar, Paleocene aquifers, in general discontinuous, present a relative homogeneity.

In this area it is slightly karstified and in part confined under Eocene formations. It is characterised by exceptionally high fluoride concentrations (0,1-13 mg l^{-1}). This aquifer, exploited by numerous rural boreholes, is also strongly influenced by Dakar Water Supply .

A detailed hydrochemical study (major and trace elements) shows a very good agreement between water mineralisation and hydrodynamic characteristics ; in addition, it reveals the influence of the phosphatic roof zone (F, Mg, Na), confirmed by geochemical analyses carried out on the Eocene and Paleocene reservoir rocks.

Piezometric level measurements, F^- diffusion modelling and isotope interpretation (^{18}O, ^{2}H, ^{3}H, ^{14}C) have allowed us to demonstrate that fluoride mineralisation occurs by percolation from the upper level aquifers through the phosphatic Eocene roof zone.

In this context, intensive exploitation could easily aggravate the fluoride contamination. In order to verify this hypothesis we repeated field measurements three years after our earlier investigations. The results clearly indicate :
An increase of fluoride concentration in the confined part of the aquifer that was previously undersaturated with respect to CaF_2 and a progressive advance of contaminated water towards the unconfined part of the aquifer.

Using thermodynamic modelling while taking into account chemical conditions of fluoride transport in groundwater, we were able to calculate the probable maximum fluoride concentration that could arise in the aquifer.

INTRODUCTION

The occurrence of fluoride in high concentrations in the ground waters of the Senegalese basin has been known for over twenty years now.The harmful biological effect of fluoride ion is an important element in the quality of drinking water. Its presence prevents tooth decay ; however, when the quantity is excessive it provokes dental or bone fluorosis.

The World Health Organisation recommends a concentration of 1 mg/l which is adjustable depending on the atmospheric temperatures and fluoride intake from other sources. Observations carried out in Senegal (Travi & Lecoustour, 1982 ; Brouwer *et al.*, 1988) show that harmful effects first appear in concentrations of about 2 mg l^{-1}; serious fluorosis becomes prominent when the level attains 4 mg l^{-1}.

The presence of fluorine is conditioned by the nature of the reservoirs ; however, changes in the concentration are determined mainly by the hydrodynamics of the aquifer and its hydrochemistry. The origin and mechanism of fluoride mineralisation in the Senegalese ground waters have been recently defined (Travi, 1988). From the hydrogeological and hydrochemical results obtained on the Paleocene aquifer, we show in this paper that the exploitation of the aquifer presents a risk of worsening the fluoride contamination. We try therefore to evaluate and quantify the risk.

HYDROGEOLOGICAL AND HYDROCHEMICAL CONTEXT

The Paleocene aquifer, generally very heterogeneous and discontinuous, forms a unit in the region around Mbour, on the western limits of the sedimentary basin. In this sector, the Paleocene formation is composed of limestone and marly limestone horizons, some 100 m thick on the average. Lithologic changes and the presence of a very limited paleokarst have distinguished two zones with different hydrodynamic characteristics (Pitaud 1980). Furthermore, the reservoir, suboutcropping to the West under the Quaternary sand and clay deposits, is rapidly overlain to the East and South East by an increasing thickness of the Eocene formations (fig. 1). The Eocene reservoir contains phosphatic lens and nodules, and its base is characterised by a phosphatic level which is more or less continuous. The aquifer is exploited by numerous rural water supply boreholes; at the same time, it is influenced by the Dakar water supply (Pout). As such, the most permeable zone has formed a drainage axis running NW (fig. 2).

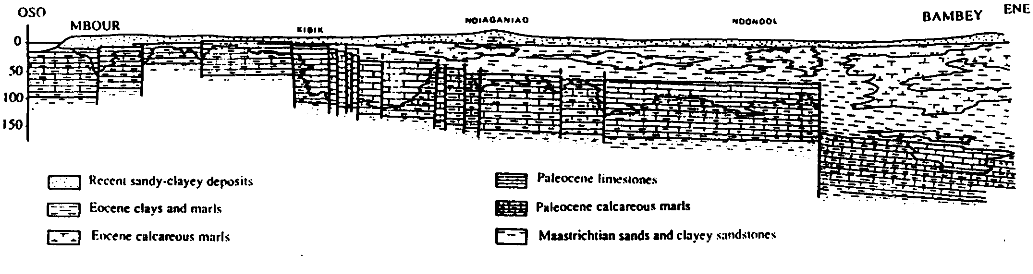


Figure 1: Schematic hydrogeological section across the Paleocene aquifer.

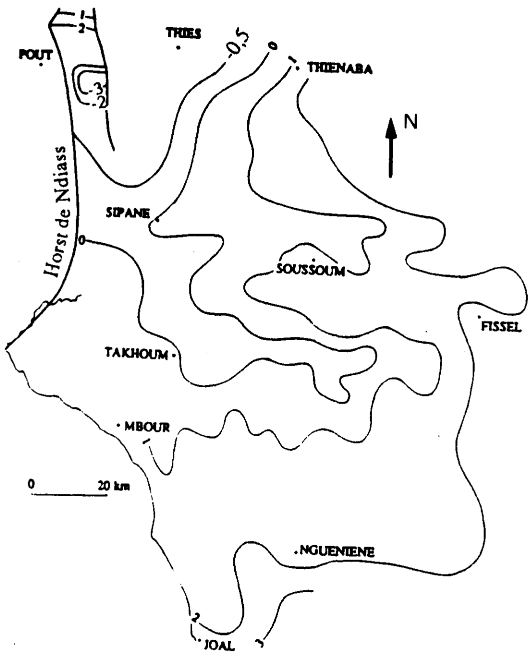


Figure 2 : Piezometric map of the Paleocene aquifer in the region around Mbour, low water level, 1979.

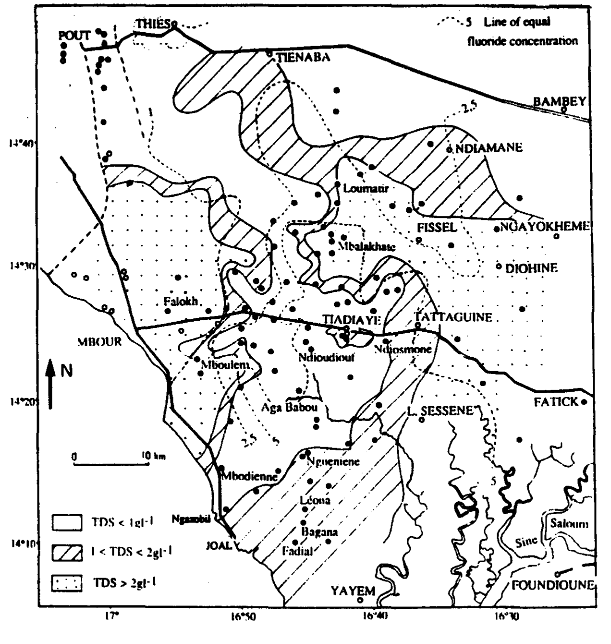


Figure 3 : Map of TDS and fluoride contents in the Paleocene aquifer.

A detailed hydrochemical study (major and trace elements) show a very good relation between water mineralisation and the hydrodynamic characteristics of the aquifer. Hence, in the calcareous and karstified central zone, one finds that the water has a low mineral content ($0{,}4 < TDS < 1\ gl^{-1}$) of a calcium and magnesium bicarbonate type. Here and there, in the more marly aquifer zone, ground waters are highly mineralised, often brackish ($1 < TDS < 10 gl^{-1}$), mainly of a sodium chloride type (fig. 3). The unconfined-confined aquifer boundary is marked by a relative increase, often very pronounced, of Mg^{2+}, Na^{+} and F^{-} concentrations. Fluoride concentrations are particularly high ($0{,}1$-$13\ mg\ l^{-1}$) and are totally independent of the global mineralisation (fig. 3).

MECHANISMS OF FLUORIDE MINERALISATION

Role of the phosphatic roof zone

Some types of reservoir are particularly liable to fluoride contaminations. In sedimentary basins, fluorine comes mainly from fluorapatite present in phosphatic rocks and to a lesser degree from the leaching of marine clays (Travi, 1988). In the Paleocene aquifer the origin of the fluoride has been linked with the phosphatic roof zone, principally for two reasons : first, high concentrations are associated with the confined part of the aquifer and they fall suddenly (factor of 10) as the aquifer becomes unconfined (fig. 4). Second, geochemical analyses realised on borehole cuttings indicate that fluoride levels are, on the average, 10 times higher for the Eocene reservoir (fig. 5, tabl. 1).

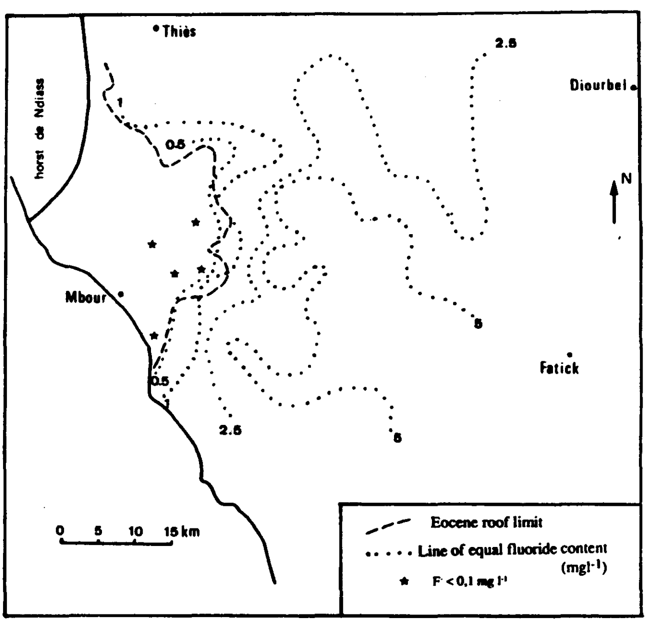


Figure 4: Schematic map showing relationship of fluoride contents and phosphatic roof zone in the Paleocene aquifer.

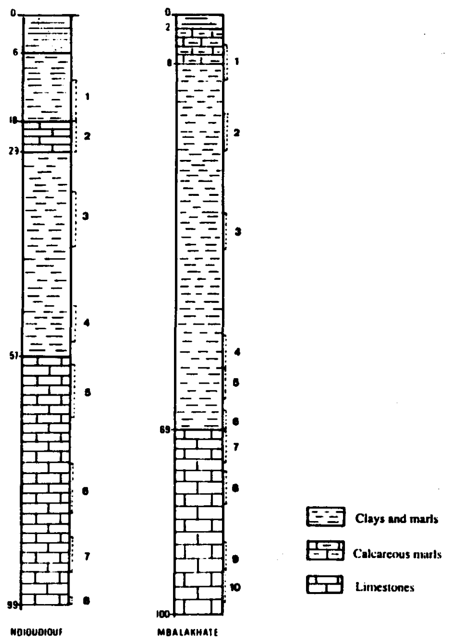


Figure 5 : Lithostratigraphic sections

Table 1: Fluorine geochemical analyses on boreholes cuttings (F^- %).

F^- %	NDIOUDIOUF	MBALAKHATE
1	0,46	0,11
2	0,38	0,40
3	0,40	0,43
4	0,46	0,48
5	0,052	0,57
6	0,035	0,52
7	0,013	0,057
8	0,042	0,044
9		0,038
10		0,037

Exploitation of an aquifer leads to modification of its hydrodynamic conditions. This may provoke an evolution of the fluoride concentrations particularly in confined aqüifers. Pumping in these aquifers creates or accelerates the drainage and the leaching through the top of the reservoir. For example this phenomenon may be found in France in the Bajocien nappe of the Lorrain basin (Maubeuge & Jecko, 1977). In order to predict the eventual increase in fluorine concentration it is necessary to understand the mineralisation mechanism. Two mineralisation processes are plausible ; lessivage of the roof zone of the confined aquifer or descending percolation originating from the discontinuous Eocene aquifer.

Percolation or lessivage ?

Different piezometric investigations, geochemical and isotopic data and F^- diffusion modelling have been used for groundwater migration evaluation.

Piezometric investigations ; to day, except in the unconfined and karstified part of the aquifer, water table evolution does not indicate that groundwater recharge occurs after the rainy season. However, piezometric heads measured in 1971, before the commissioning of the Dakar well field and the first intensive water supply schemes, showed a dome to the East within the confined part of the Paleocene aquifer (fig. 6). At this place, Maastrichtian aquifer is not actually implicated for

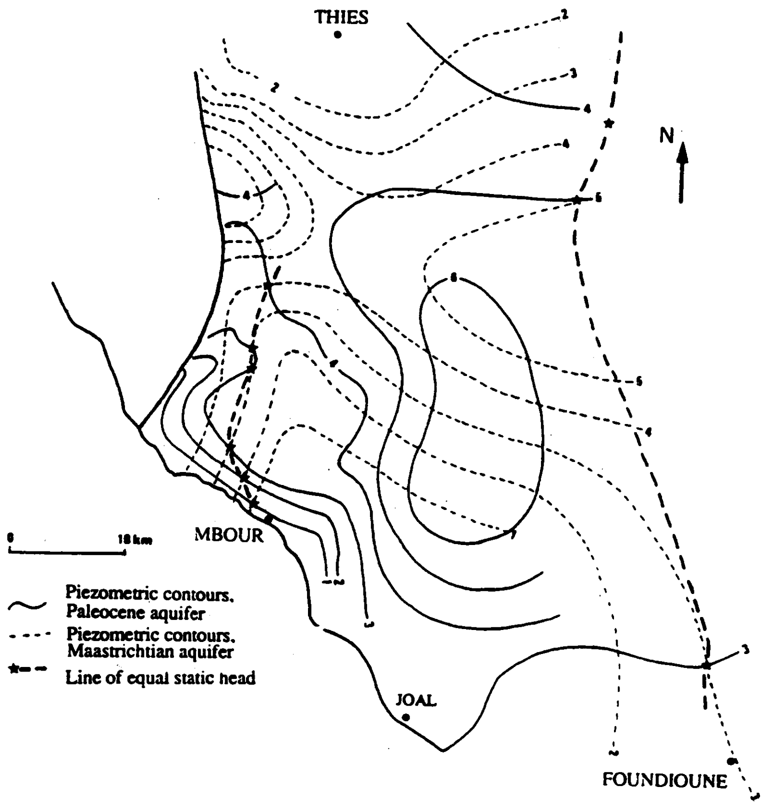


Figure 6: Piezometric map of the Paleocene and Maastrichtian aquifers in the region around Mbour, 1971 (O.M.S., 1972).

recharge (fig. 6). Besides, head differences between the Eocene and Paleocene aquifers allow drainance by "descensum" at different places.

Geochemical and isotopic studies of groundwaters ; taking into account the recent (10 Ky) sea level variations and consequently the possible reversal of ground water drainage, two sources of Paleocene aquifer recharges could be expected : from the surface or from the underlying Maastrichtian aquifer. Two observations indicate that "Paleocene" ground waters are marked by evaporation and mixing with brackish water infiltrated at the level of ancient "arms" of the Sine Saloum delta :

First, samples collected in the Paleocene aquifer present some $\delta^{18}O$ high values and, in a ^{18}O vs ^{2}H diagram all the points lie significantly under the present-day meteoric water line defining several evaporation lines (fig. 7).

Second, in the Cl^- *vs* Br^- diagram all the points show a good trend of values along the sea water dilution line (fig. 8).

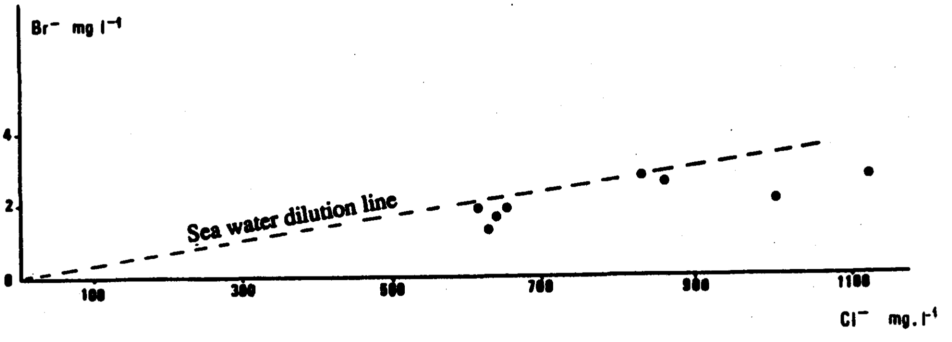


Figure 7 : Relationship of oxygen and hydrogen stable isotope composition in Paleocene aquifer.

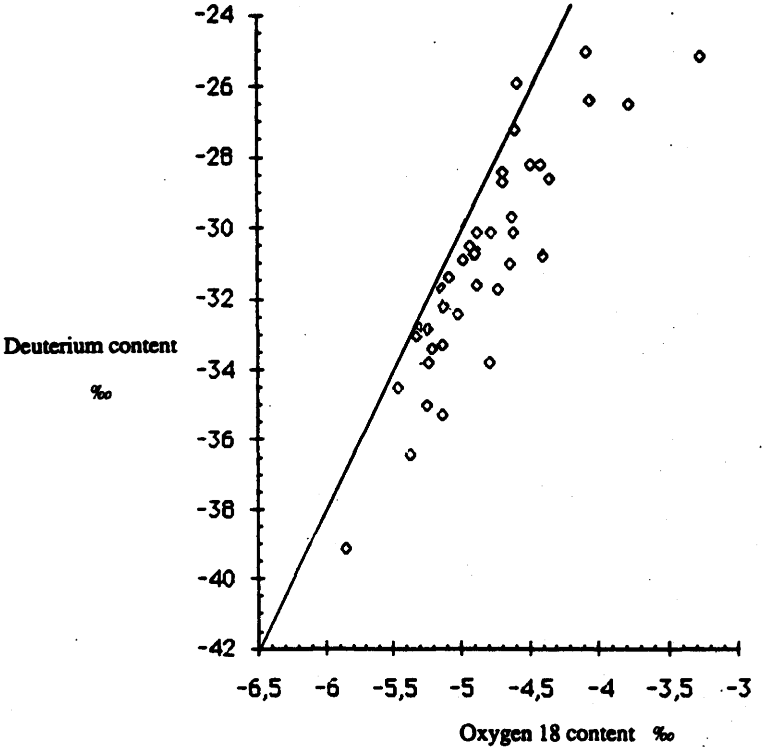


Figure 8 : Relationship of chloride and bromide contents in the Paleocene aquifer.

Besides, at this place groundwaters issuing from Maastrichtian aquifer show a boron enrichment of approximately 10 times relative to Paleocene aquifer (Travi & Faye, 1990).

Therefore, isotopic (natural stable isotopes) and geochemical interpretations indicate that recharge from the surface and transit through the Eocene aquifer has been possible. ^{14}C radiogenic ages (Faye, 1983 ; Travi, 1988) and our knowledge of paleohydrology in West Africa (Gasse *et al.,* 1990) has allowed us to suggest that this recharge took place mainly during the last humid period with a top sea level (3000 to 4000 years B.P.).

F^- diffusion ; in the case of lessivage of the roof zone, mineralisation first controlled by the diffusion phenomenon would be progressive. However, fluoride concentrations measured at different depths do not show any vertical gradient and are very often controlled by saturation processes. Further, an attempt at modelling using Fick's law shows that this phenomenon will be very slow; under the average physical and chemical conditions of the Paleocene aquifer (H = 100 m, T = 303°K, F = 5 mg l^{-1}) the resolution of the equation, $div\,(d_o\,grad\,C) = \frac{\partial C}{\partial t}$ *(with d_o = diffusion coefficient = constant)* indicate that it would take more than 2 million years .

For all these reasons fluoride mineralisation of the waters is therefore linked to a downward drainage.

Under these conditions an important decompression of the aquifer following excessive pumping would provoke an increase in contamination.

INFLUENCE OF OVEREXPLOITATION : OBSERVATIONS AND FORECAST

In order to verify this hypothesis, field hydrochemical measurements have been repeated three years after our earlier investigations. They clearly indicate :
- a slight increase in global mineralisation along the limits of the freshwater zone, characterised by modifications in Na^+, Cl^-, sometimes SO_4^{--} concentrations; it marks the beginning of lateral water displacement towards the central zone (Travi *et al.*, 1984) ;
- in the confined part of the aquifer, an appreciable F^- increase of the waters having the least fluoride content and little or no change in waters with high concentrations.

The groundwater chemistries were evaluated using the EQUILT speciation programme (Fritz, 1981). Measurements carried out in Senegal and Tunisia (Travi, 1988) as well as published data reveal in most cases the fundamental importance of fluorite saturation. When the water is saturated or supersaturated, the equilibrium relation, $[Ca^{++}]\,[F^-]^2 = K$ controls the fluoride concentration. All changes of Ca^{++} activity are liable to modify the amount of fluoride in solution. The latter depends indirectly on the equilibrium with calcium carbonate, gypsum or anhydrite as well as the formation of calcium complexes ($CaSO_4$, $CaHCO_3^+$, $CaCO_3$). Also, in Paleocene aquifer, high concentration of magnesium can significantly increase the quantity of fluoride carried in the form of MgF^+ (Travi, 1984). The understanding of these hydrochemical controls has permitted :

-First, to explain the different F^- variations. In the confined part of the aquifer, waters with high concentrations are saturated or supersaturated with respect to fluoride; in this case F^- content, in agreement with chemical control already evoked, fluctuates in sympathy with minor variations of Ca^{++} and Mg^{++} activities, as well as ionic strength. The greatest increase of fluoride content is localised near the confined-unconfined boundary where waters are undersaturated (fig. 9).

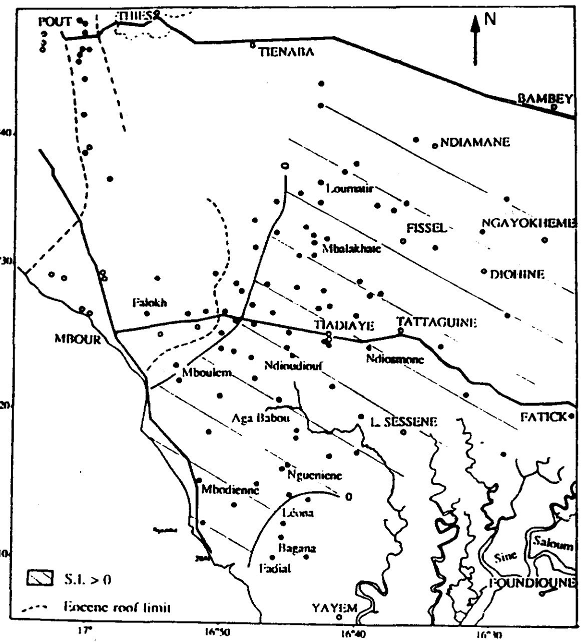


Figure 9: Map of fluorite Saturation Indices in the Paleocene aquifer.

- Second, to quantify the maximum possible increase in fluoride content, two cases could be envisaged:

Ca^{++} and Mg^{++} activities are not modified. In unsatured groundwaters fluoride contents could rise ; the upper limit will then be determined by the solubility product $(Ca^{++})(F^-)^2 = K$, and the dissociation constant $(Mg^{++})(F)^- = K$.

Ca^{++} and Mg^{++} activities are significantly modified: an estimation can be made on the basis of mixing models especially taking into account the carbonate equilibria.

In the Paleocene aquifer groundwaters are always saturated or oversaturated with respect to calcite and dolomite, and consequently Ca^{++} and Mg^{++} activities will not be very significantly modified. Taking into account the extreme values of ionic strength for calculating chemical equilibrium we obtained contents ranging between 3 and 4 mg/l fluoride.

In the Western part of the aquifer, fluoride contents may rapidly attain these values. In the unconfined zone the fluoride enrichment will probably be slower on accout of the influence of the rainy season dilution.

REFERENCES

Brouwer, I., De Bruin, A., Backer Dirks, O., Hautvast, J.G.A. 1988. Unsuitability of world Health organisation guidelines for fluoride concentrations in drinking water in Senegal. *The Lancet*, January 30, 1988; 223-225.

Faye, A. 1983. Contribution à l'étude géologique et hydrogéologique du horst de Ndiass et de ses environs (Sénégal). *Thèse 3e cycle*, Univ. Dakar.

Fritz, B. 1981. Etude thermodynamique et modélisation des réactions hydrothermales et diagénétiques. *Mém. Sc. Géol.*, 65.

Gasse, F., Téhet, R., Durand, A., Gibert, E., Fontes, J.C. 1990. The arid-humid transition in the Sahara and the Sahel during the last deglaciation. *Nature*, 346; 141-146.

Maubeuge, P.L., Jecko, G. 1977. Lixiviation expérimentale des marnes dans le bassin ferrifère lorrain : de l'origine du sulfate de calcium et du fluor dans les eaux de la nappe bajocienne. *C.R. Acad. Sc.*, Paris D, 285; 1291-1294.

O.M.S. 1972. Approvisionnement en eau et assainissement de Dakar et ses environs. Etude des eaux souterraines. Projet SEN 3201 (Ex 22), III.

Pitaud, G. 1980. Etude hydrogéologique des calcaires paléocènes de la région de Mbour. Evaluation des ressources en eau et des possibilités d'exploitation. Rapport de synthèse. Dir. Et. Hydraul. 01-80-HG-DEH, Dakar.

Travi, Y. 1984. Origine des fortes teneurs en fluor des eaux souterraines de la nappe paléocène de la région de Mbour (Sénégal) : le rôle de l'ion magnésium. *C.R. Acad. Sc. Paris*, 298, sér. 11, 7; 313-316.

Travi, Y. 1988. Hydrogéochimie et Hydrologie isotopique des aquifères fluorurés du bassin du Sénégal. Origine et conditions de transport du fluor dans les eaux souterraines. *Thèse Sciences*, Univ. Paris-Sud.

Travi, Y., Faye, A. 1990. Concentration en bore de la "nappe maestrichtienne" du Sénégal : leur influence sur l'aptitude des eaux à l'irrigation. *Journ. Afr. Earth Sci.* vol. 11, 4; 253-259.

Travi, Y., Lecoustour, E. 1982. Fluorose dentaire et eaux souterraines : l'exemple du Sénégal. Eau Québ., 15, 1; 9-11.

Travi, Y., Sarr, R., Faye, A., Gaye, C.B. 1984. Etude chimique de l'évolution du front salé de la nappe paléocène de la région de Mbour. *Rapport C.R.D.I.*, 3A - 82 - 4713, Dakar.

ENVIRONMENTAL EFFECTS RELATED TO AQUIFER OVEREXPLOITATION IN ARID AND SEMI-ARID AREAS OF CHINA

WANG ZHAOXIN
China Exploration Inst. of Hydrogeology and Engineering Geology
20 Dahuisi Street, Haidian District, Beijing, 100081, China

ABSTRACT. This paper describes a series of geo-environmental phenomena occurring under conditions of aquifer overexploitation in arid and semi-arid areas of China. These phenomena include groundwater table decline, land subsidence, attenuation and drying up of springs, seawater intrusion, collapse in karst areas, decrease in stream flow, some changes in ecological conditions, etc... The main positive and negative effects of aquifer overexploitation for several above-mentioned geo-environmental phenomena are analyzed respectively. Two basic approaches to deal with the problems related to aquifer overexploitation -the preventive approach and the remedial approach- are discussed.

INTRODUCTION

Since 1981 the Ministry of Geology and Mineral Resources of China has begun to implement a huge countrywide groundwater resources evaluation project, which consists of three components: (1) groundwater resources evaluation for 30 provinces independently, (2) groundwater resources evaluation for 26 natural regions, which comprise several provinces (of part of provinces), (3) summarized evaluation of groundwater for the whole country.

The basic data for this project are: (1) report of regional hydrogeological mapping at scale 1:200,000-1:500,000, which covers 2/3 of the whole country, (2) hydrogeological exploration for rural water supply and soil reclamation ($1.1x10^6$ km^2), (3) hydrogeological prospecting for urban water supply (more than 100 cities or industrial bases) and (4) long-term groundwater regime observation data.

The author of this paper worked as project coordinator and one of the designers of the project program. This paper is mainly based on the data collected during implementation of the above-mentioned project, and will discuss environmental effects related to aquifer overexploitation in arid and semi-arid areas of China, that is, the northern half part of China.

GEO-ENVIRONMENTAL PHENOMENA DUE TO AQUIFER OVEREXPLOITATION IN NORTHERN CHINA

The total inland territory of China accounts for 6.4% of that for the whole world. Annual precipitation is 648 mm. Natural resources of groundwater in China are estimated as 87×10^{10} m^3 per year. Mean annual groundwater recharge is 90 mm. The distribution of groundwater resources is quite uneven. Mountainous areas account for 2/3 of Chinese inland territory, while plains account for 1/3 and are mostly concentrated in the northern half of China. North China Plain and North-East China Plain and their surrounding mountainous areas are characterized by semi-humid or semi-arid climates with annual precipitation ranging from 400 mm to 800 mm. Annual runoff is 50-200 mm. Mean annual groundwater recharge is 80-120 mm per year. The North-West part of China is characterized by an arid climate with precipitation 200-400 mm, with in areas less than 100 mm. Annual runoff is 10-50 mm. Mean annual groundwater recharge is less than 30 mm.

The amount of natural groundwater resources in northern China, which is about 28×10^{10} m^3 per year, is one third of that in the whole country. The amount of exploitable groundwater resources for the northern plains of China is about 13×10^{10} m^3 per year, and more than 70% of that for plains of the whole country.

In northern China, especially in plain areas, groundwater is widely used for urban water supply and for irrigation. At the beginning of 1980s, the total groundwater withdrawal is estimated as 660×10^8 m^3 per year, which accounts for 85% of that for the whole country (Fig. 1). In some urban areas the extracted rate of groundwater may reach 300-500 mm per year. According to the statistics of 69 main cities of northern China, 70% of all cities are totally or mainly using groundwater for urban water supply, only 30% of all cities are mainly supplied by surface water. More than half of these cities have daily groundwater withdrawals of more than 10×10^4 m^3 per day.

Due to irrational development of groundwater, geo-environmental problems have been caused in some areas. These phenomena include groundwater table decline, land subsidence, attenuation and drying up of springs, seawater intrusion, collapse in karst areas, decrease in stream flow and some changes in ecological conditions (Fig. 2).

Groundwater table decline

In some parts of the North China Plain the rate of groundwater withdrawal exceeds recharge. Groundwater level is decreasing gradually. In the Beijing plain area the extent of 1-3 m groundwater depth declined from 2,634 km^2 in the year 1966 to 612 km^2 in the year 1984 (Hou Jingyan, 1987). In the western suburb of Beijing city, the unconfined groundwater table has declined 10-15 m between 1960 and 1984 (Fig. 3).

In the early 1980s, several depression cones of deep confined aquifers extended to 2,000-7,000 km^2 with 50-70 m water level depth in the plain areas of Hebei Province. Annual decline rate reached 2-3 m per year. As a consequence it has been necessary to replace types of pumps and to increase the water-lifting cost.

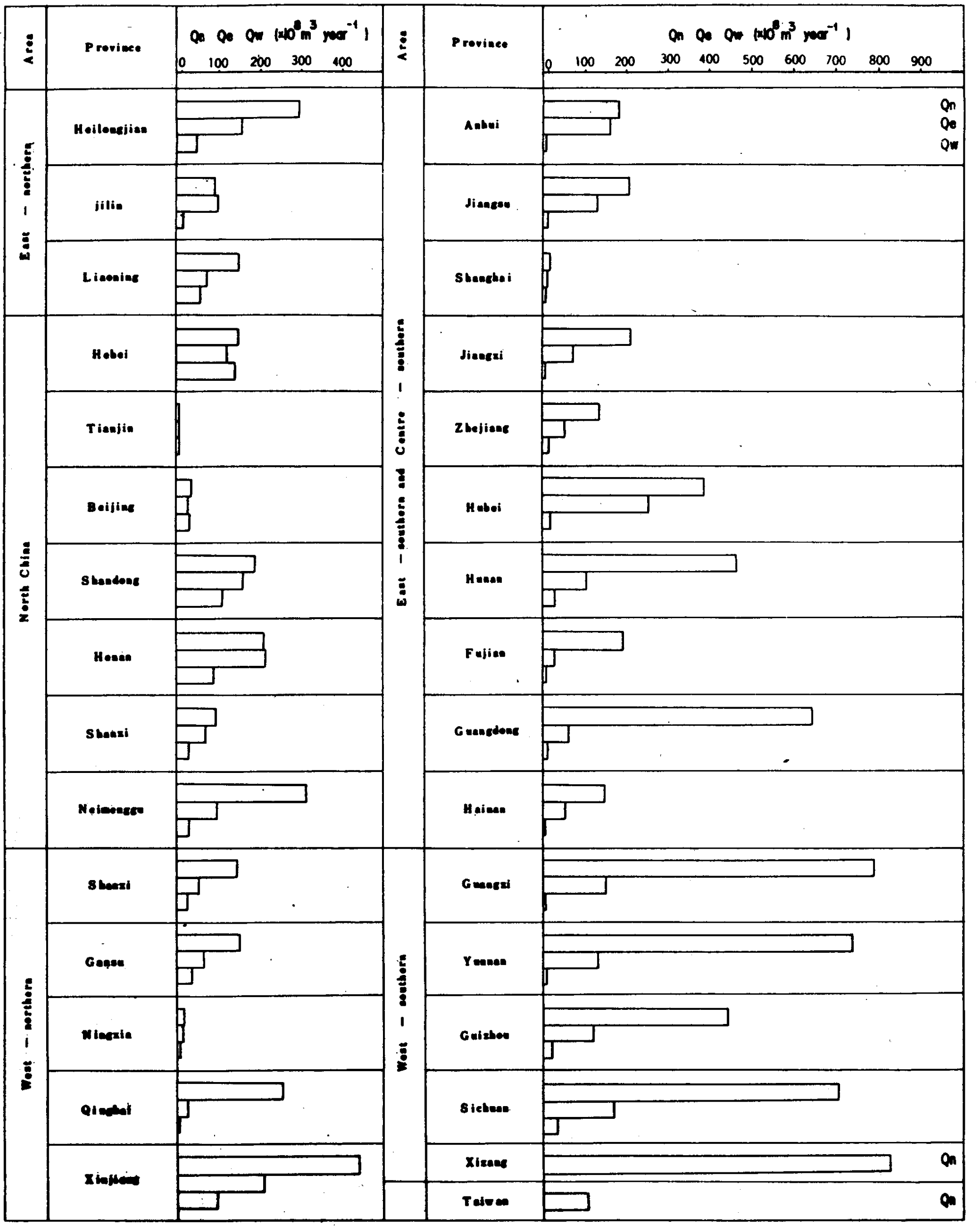


Figure 1: Groundwater natural resources (Q_n), exploitable resources (Q_e) and groundwater withdrawal (Q_w) (W. Zhaoxin, 1989; in press).

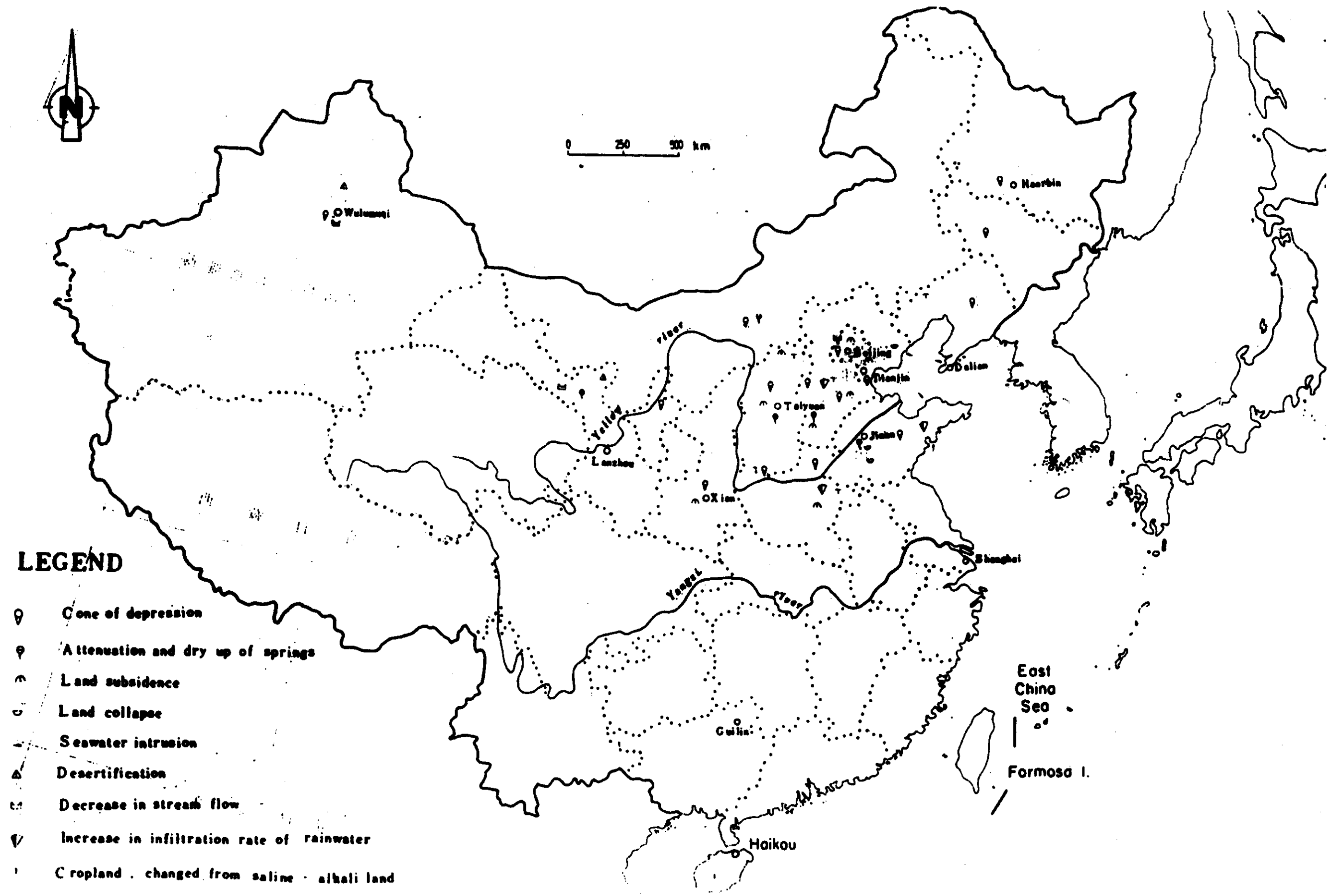


Figure 2: Environmental effects related to aquifer exploitation in the northern part of China.

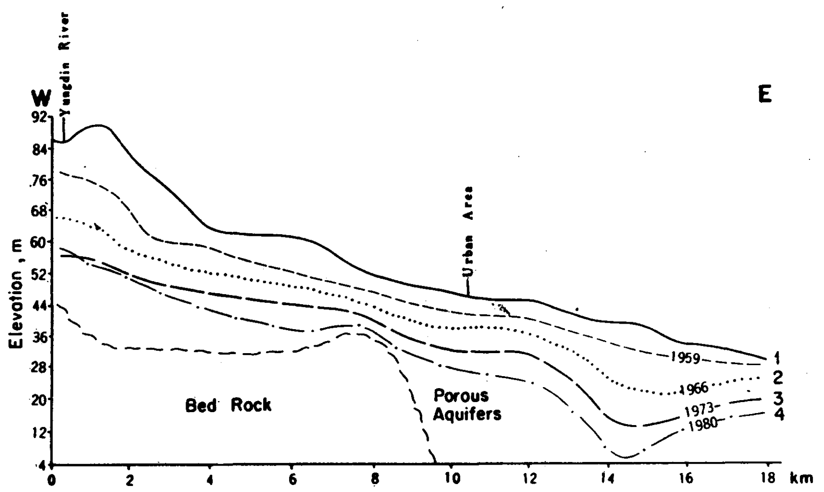


Figure 3: Groundwater level for different years in Beijing city (after Yang Beijing, 1986). 1- groundwater table level in 1959, 2- groundwater table level in 1966, 3- groundwater table level in 1973, 4- groundwater table level in 1980.

Land subsidence

Groundwater withdrawal in Tianjin city has increased six fold from the 1950s to 1980s. During 1959-1982 the maximum accumulated land subsidence reached 2.15 m. From 1983, when water was being transferred from the Luan River to the Tainjin urban area, groundwater withdrawal decreased sharply in the urban area. The land subsidence rate also obviously decreased. But in the Tanggu District, due to withdrawal, the accumulated subsidence is 2.6 m and the land surface has subsided 101 mm in 1986. Overexploitation of aquifers has caused significant water level decline in Tanggu District. In 1986 the groundwater level was 81 m below land surface, with a decline rate of 2.6 m per year (Fig. 4).

There are other cities with land subsidence due to overpumping, such as Cangzhou city (Hebei Prov.), Xian city (Shaanxi Prov.) and Taiyuan city (Shanxi Prov.).

Attenuation and drying up of springs

In Shanxi Province there are 20 big karst springs with individual discharge rates of more that 1 $m^3 s^{-1}$. Due to the construction of waterwells within the neighbouring area, discharge of the famous Jingci spring near Taiyuan city (a famous tourism site) has decreased from 1.96 $m^3 s^{-1}$ in 1950 to one sixth of the original discharge rate at the end of the 1980s (Fig. 5). Jinan city, Shandong Province has a beautiful name, the 'spring city'. There are more than 100 springs with a total discharge of 3.5-4 $m^3 s^{-1}$. Due to the pumping of karstic water from wells

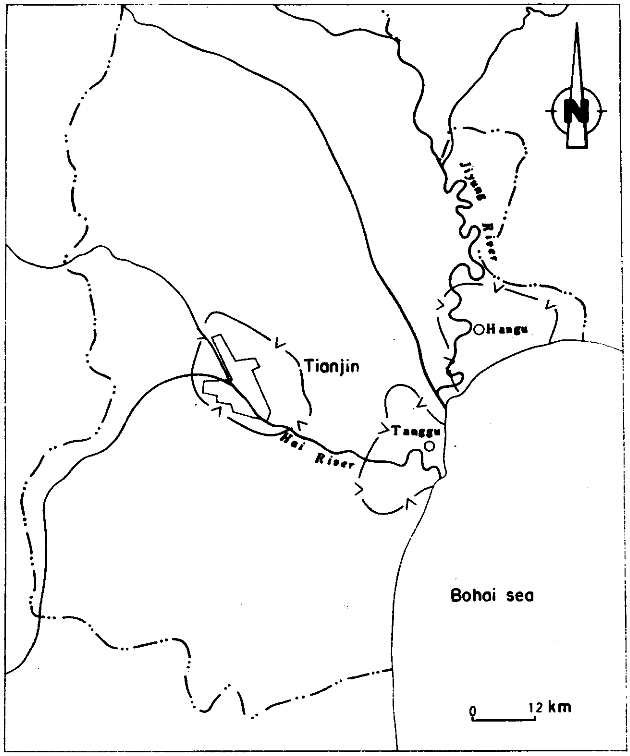


Figure 4: Lowering cones of groundwater level with land subsidence in Tainjin city (after Yang Benjin, 1986).

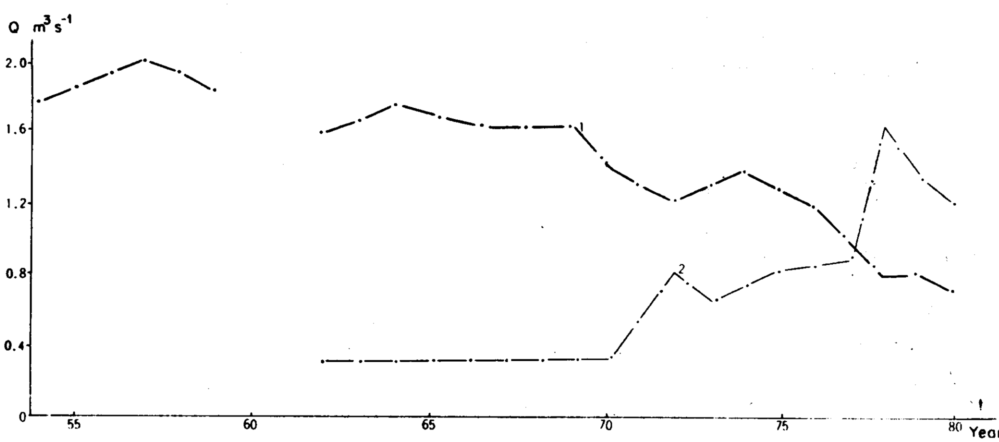


Figure 5: Curve of spring discharge (1) and curve of pumpage (2) (Jinsi Spring Basin, Shanxi Province) (after Zhao Jingfu, 1984).

in the city, the groundwater level is declining, which caused ceasing of flow of many springs in dry seasons of the 1980s. Based on detailed investigation the city government adopted the suggestion, given by hydrogeologists, for 'keeping the touristic scenery of spring city and providing sufficient water for urban water supply'. Positive results have already been achieved.

Seawater intrusion

In Dalian City, Liaodong Peninsula, overpumping of karst water has caused seawater intrusion. The content of chloride ions in groundwater increased due to overexploitation of karst water. The area of seawater intrusion reached 208 km^2 in 1986 (Fig. 6).

A similar situation occurred in Qinhuangdao city, Hebei Province (Han Zaisheng, 1990) and in the coastal plains of Shandong Peninsula (Gu Zhenfeng & Liu Yanbe, 1988).

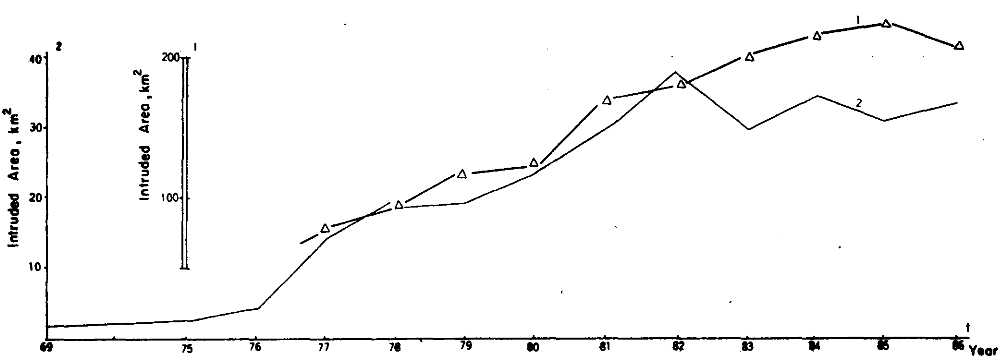


Figure 6: Extension of sea water intruded area (Dalian City, Liaoning Province) (after Wang ChengLin & Zhao Lianbin, 1987). 1- For whole city, 2- for Nanguanling District.

Collapse in karst areas

During exploitation of karstic water in areas with Quaternary cover, land collapse occurs quite often, which makes trouble for railway transport and other civil constructions.

In central and south of Shandong Province intensive pumping of karst water caused collapse (in Taian, Zaozhuang cities, etc.). According to statistical data, 143 collapse points appeared during 1970-1985, which spread over 11.9 km^2. The depth of collapse pits is 0.5-6 m (Gu Zhenfeng & Liu Yanbe, 1988).

Decrease of streamflow

In Shiyang inland river basin within the Hexi corridor, the streamflow fed by springs in the alluvial-proluvial plain has decreased to 50% in the last 30 years. Water sources for irrigation face shortages in the lower reaches of the inland river basin (Fan Xipeng, 1981; Wang Zhaoxin, 1985).

Changes in ecological conditions

In the lower reaches of above-mentioned Shiyang river, water shortage and irrigation by saline water caused desertion of some farmland. Given overexploitation of shallow groundwater withered trees were found and the desert area expanded. Drilling some deep wells for extracting artesian water is not a good solution due to lack of recharge of artesian aquifers.

OPTIMAL EXPLOITATION OF GROUNDWATER RESOURCES IN NORTHERN CHINA

In arid and semi-arid areas of China there are four main cases of groundwater occurrence and development:

(a) shallow groundwater in the plain areas with dominant vertical recharge by rainfall (most parts of North China Plain).
(b) shallow groundwater in piedmont proluvial plains in the north-west arid part of China with dominant recharge by rivers flowing from mountain areas. Here annual precipitation is usually less than 200 mm.
(c) deep confined aquifers usually at the depth of more than 200 m, with slight recharge at the present time.
(d) karst water in carbonate formations usually flows out in the form of large springs with discharge rates of more than 1 $m^3 s^{-1}$.

In the North China Plain the total extracted groundwater per year is more than $20x10^9$ m^3, which accounts for one third of that for the whole of China. Here groundwater exploitation gets positive results both for irrigation and for soil reclamation. Groundwater exploitation has increased water table fluctuation dramatically and accelerated the vertical water circulation. Large quantities of groundwater extraction during the irrigation period for March to June (which may reach 100-500 mm) may cause a conspicuous decline of the groundwater table. The results are, on one hand, that the soil is protected from salinization by declining water tables and minimizing groundwater evaporation in spring months, and on the other hand, greater space within the groundwater reservoir is provided to receive more rainwater infiltration during the next wet season (from July to September). Moreover, during a ten year cycle, dry year, normal year and wet years appear irregularly, but periodically. Some field experiences led to the conclusion that a perennial average groundwater table at the depth 3.5-4 m would be an optimal choice, and the water table would fluctuate higher and lower around the average water table (Ji Chuanmao, 1982). Overexploitation has occurred in mainly deep artesian aquifers and in urban areas. At the present time more emphasis is paid to extracting shallow groundwater for irrigation. Urban water supply experiences suggest that conjunctive use of surface water and groundwater may avoid aquifer overexploitation due to a greater water demand in a limited area (Wang Zhaoxin, 1990).

APPROACHES TO DEAL WITH AQUIFER OVEREXPLOITATION

There are two basic approaches to deal with the problems related to aquifer overexploitation, that is the preventive approach -planning of groundwater development according to results of groundwater resources evaluation, and the remedial approach- reduction of pumping rate from the overextracted deep confined aquifers, regulation of waterwell distribution, artificial recharge, etc.

The reason for the occurrence of so many negative effects of aquifer overexploitation is that people don't know the behavior and consequences of intensive exploitation, especially in the deep aquifers. So in newly developed areas, hydrogeologists should play a more important role in urban and rural groundwater development planning. The conclusion should be: the preventive approach should be used for newly developed areas, and the remedial approach should serve as a measure for areas with negative environmental effects due to aquifer overexploitation.

REFERENCES

Fan Xipeng. 1981. Reciprocal transformation of ground water and river water and rational utilization of water resources in the Gansu Corridor. *Hydrogeology and Engineering Geology*, 4; 1-6.

Hou Jingyan. 1987. Present situation of groundwater resources in Beijing city. *China Geology*, 7; 25-27.

Han Zaisheng. 1990. Seawater intrusion in coastal porous aquifer -a case study of the alluvial plain of Yang River and Dei River in Qinhuangdao city-. In: *The Hydrological Basis for Water Resources Management, IAHS Publication*, no. 167.

Gu Zhenfeng & Liu Yanbe. 1988. *Measures for mitigating water resources shortage in Shandong Province*. Jinan. Published by Bureau of Geology and Mineral Resources.

Ji Chuanmao. 1982. Variation of the groundwater regime under the effects of human activities and its artificial control. In: *Proc. of Exeter Symposium, IAHS Publication*, no. 13, Exeter.

Wang Chenglin & Zhao Lianbin. 1987. Study on seawater intrusion and mitigation measures in Dalian City. In: *Proc. of Workshop on urban geology of coastal areas in Asia and The Pacific*. Shangai, China.

Wang Zhaoxin. 1985. Genetic types and artificial control of groundwater regime in the northern part of China. In: *Selected papers of International Geological Exchange-Contributions to 27th International Geological Congress*, Ed. by Geological Society of China, Beijing, Geological Publishing House, vol. 6; 1-12.

Wang Zhaoxin. 1989. National summary of groundwater resources evaluation and development prospect. In: *Groundwater resources evaluation, artificial recharge and management in the typical areas of China*. Ed. by Department of Hydrogeology and Engineering Geology, Ministry of Geology and Mineral Resources, Beijing, Geological Publishing House.

Wang Zhaoxin. 1990. Reciprocal water transfer between groundwater and surface water under conditions of water resources development. In: *The Hydrological Basis for Water Resources Management, IAHS Publication*, no. 167; 103-108.

Wang Zhaoxin (Chief editor). 1992 (in press). *Groundwater resources development and utilization in China*. Huhehaot, China, Neimenggu Publishing House.

Yang Benjin (Chief editor). 1986. *Environment atlas for territory management in the region of Beijing, Tianjin, Tangshan*. Beijing, China Ocean Press.

Zhao Jingfu (Chief editor). 1984. *Big karst springs in Shanxi Province*. Taiyuan. Published by First team of Hydrogeology and Engineering Geology, Bureau of Geology and Mineral Resources of Shanxi Province.

Section 3:

PROTECTIVE AND CORRECTIVE MEASURES IN CASES OF AQUIFER OVEREXPLOITATION. LEGAL AND SOCIOECONOMIC ASPECTS

PROTECTIVE AND CORRECTIVE MEASURES WITH RESPECT TO THE OVER-EXPLOITATION OF GROUNDWATER

J.W. LLOYD
Hydrogeological Research Group
School of Earth Sciences
University of Birmingham
Edgbaston
Birmingham B15 2TT
U.K.

ABSTRACT. Protection from over-exploitation is advocated through proper but flexible management criteria combined with comprehensive hydraulic and hydrochemical modelling of aquifer responses to abstraction. Where corrective measures are required cost is one of the main considerations if alternative supplies or re-arrangement of abstraction are contemplated, however hydrogeologically attractive. If artifical recharge is used, basic recharge is probably most effective when properly maintained.

INTRODUCTION

Clearly the over-exploitation of groundwater resources is undesirable and it is necessary to manage the resources within the defined exploitation limits. As with any management this requires continual appraisal and re-definition as circumstances dictate.

For proper management, apart from a clear abstraction policy, there is the need for legislation and licensing, the will to adhere to the legislation and the will to enact the legislation.

Unfortunately the definition of over-exploitation is difficult and obviously varies with circumstances. While an abstraction and protection policy must be well defined it should also be flexible in order that other operations can co-exist without unreasonable impact on the groundwater resource. In terms of value to the community, abstraction and protection policies that are unnecessarily rigid, may be just as unacceptable as over-exploitation. Such policies unvariably arise from a lack of adequate resources appraisal or imaginative management.

In fairness to those that formulate exploitation policies adequate hydrogeological asessment is frequently difficult so that proper understanding, and indeed the formulation of proper management policies, can often only realistically be established when an aquifer has been stressed.

Much of the inadequacy in hydrogeological assessment stems from the lack of appreciation of the total system concept. Emphasis is properly placed upon understanding the hydraulic responses in the aquifer to be exploited (Gorelick, 1983) but insufficient appreciation may be obtained of juxtaposed minor aquifers with poor quality water, unsaturated zone impacts, irrigation/domestic water returns, etc.

Over the past two decades groundwater management has in many countries moved from the practice of safe yield to more imaginative practices (Fig. 1) such as conjunctive use, aquifer storage manipulation, artificial recharge and controlled groundwater mining (Lloyd, 1990). These types of management require extremely careful assessment, monitoring and operation

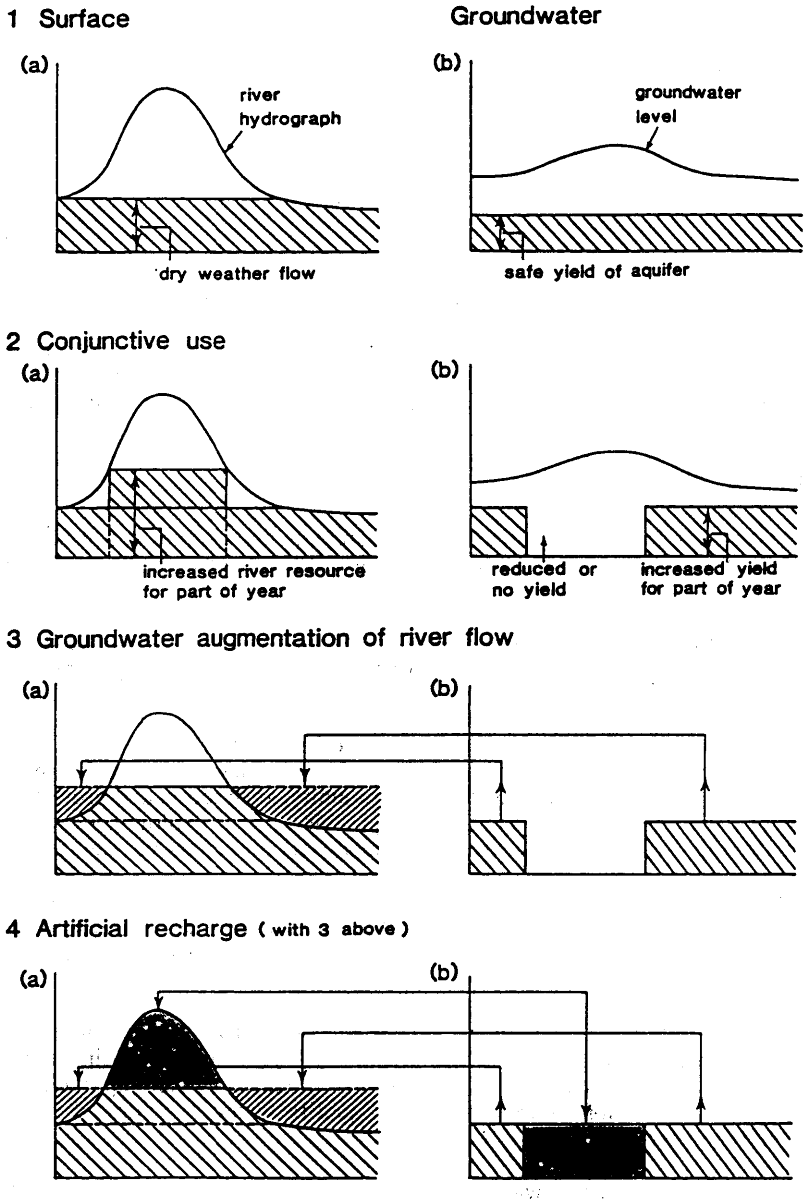


Figure 1: Combined surface and groundwater management options.

flexibility. Conjunctive use and storage manipulation schemes are unfortunately very susceptible to climatic conditions so may lose favour in the future with the possiblity of climatic change.

In the discussion below the need for resources monitoring is considered with various examples, and aspects and examples of corrective measures to combat over-exploitation are given.

PROTECTION THROUGH MONITORING

Irrespective of the competence of initial resources assessment the resources magagement depends upon a combination of monitoring and re-appraisal once abstraction has commenced. Monitoring related to strict management criteria is the best protection against over-exploitation and should be aquifer or situation specific in that it does not readily lend itself to statistical consideration for example with respect to point monitoring distribution.

The monitoring requirements can be divided as follows:

(a) In-aquifer system
 (i) Hydraulic
 (ii) Chemical

(b) Aquifer influencing
 (i) Surface waters
 (ii) Return flows
 (iii) Ecological factors
 (iv) Unsaturated profiles

In (b) both hydraulic and chemical factors are normally considered.

Clearly the continual monitoring of flows and heads is essential and standard practice on an aquifer or area wide management basis. The inclusion of such data periodically into a groundwater management model allows proper abstraction control and provides flexible options.

Methods of head data collection are well known and many sophisticated transducer-data logger techniques are available. Increasingly head profile data through the depth of an aquifer system are being collected to establish three dimensional flow conditions that are so important in leaky, layered or relatively low hydraulic conductivity ground. Such data can also provide management control for operations not necessarily directly associated with normal aquifer usage (Fig . 2).

In arid and some semi-arid areas long-term head response monitoring is vital particularly where specific yield dominates exploitation and the sensible determination of this parameter can only be established once the aquifer has been adequately stressed (Fig . 3). If specific yield is not a dominant parameter in these areas then long-term exploitation may in any case be suspect.

For any properly conceived monitoring programme, protection of the resource should also be instituted in terms of hydrochemical deterioration, in combination with hydraulic monitoring. In high permeability systems, even under major abstractions, heads may not noticeably decline as water is removed principally from storage. These circumstances are readily recognisable in fresh water lenses where the diminution of the total lens volume can be identified using hydrochemical monitoring criteria. In Figure 4 the result of over-exploitation in Qatar is clearly defined by long-term fresh water lens chemistry although in some of the central lenses of

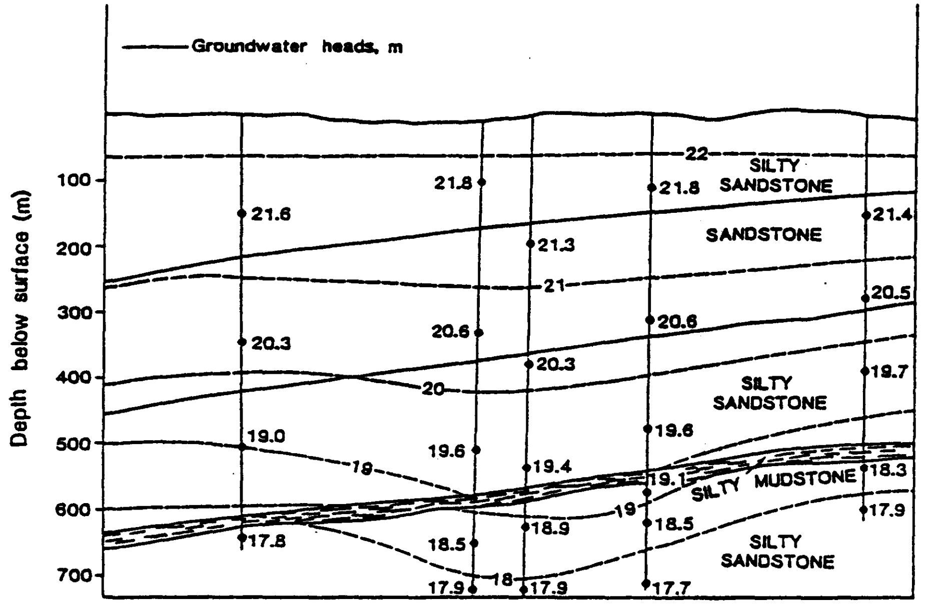


Figure 2: Example of detailed multi-port groundwater head monitoring of mine drainage effects on an aquifer used for public supply.

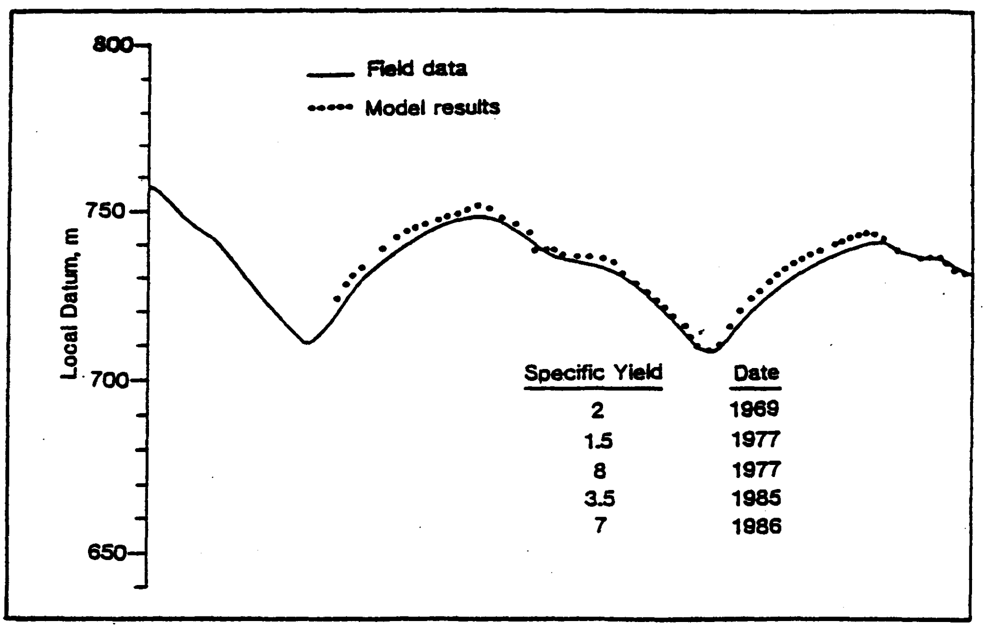


Figure 3: Time-variant groundwater head monitoring in a controlled unconfined groundwater mining project in order to determine specific yield, after Lloyd & Pim (1990).

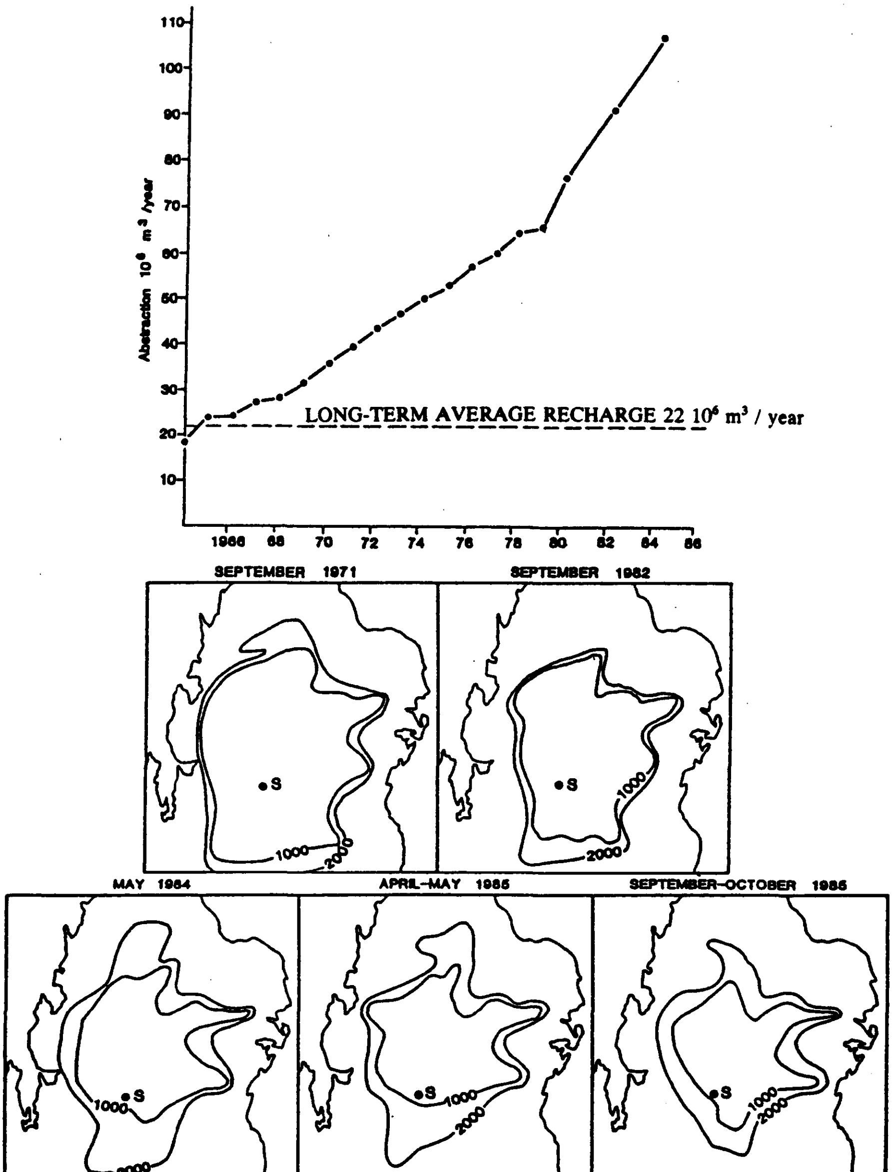


Figure 4: Over-exploitation and fresh water lens depletion in Qatar (salinity in μS/cm), after Lloyd *et al.* (1987).

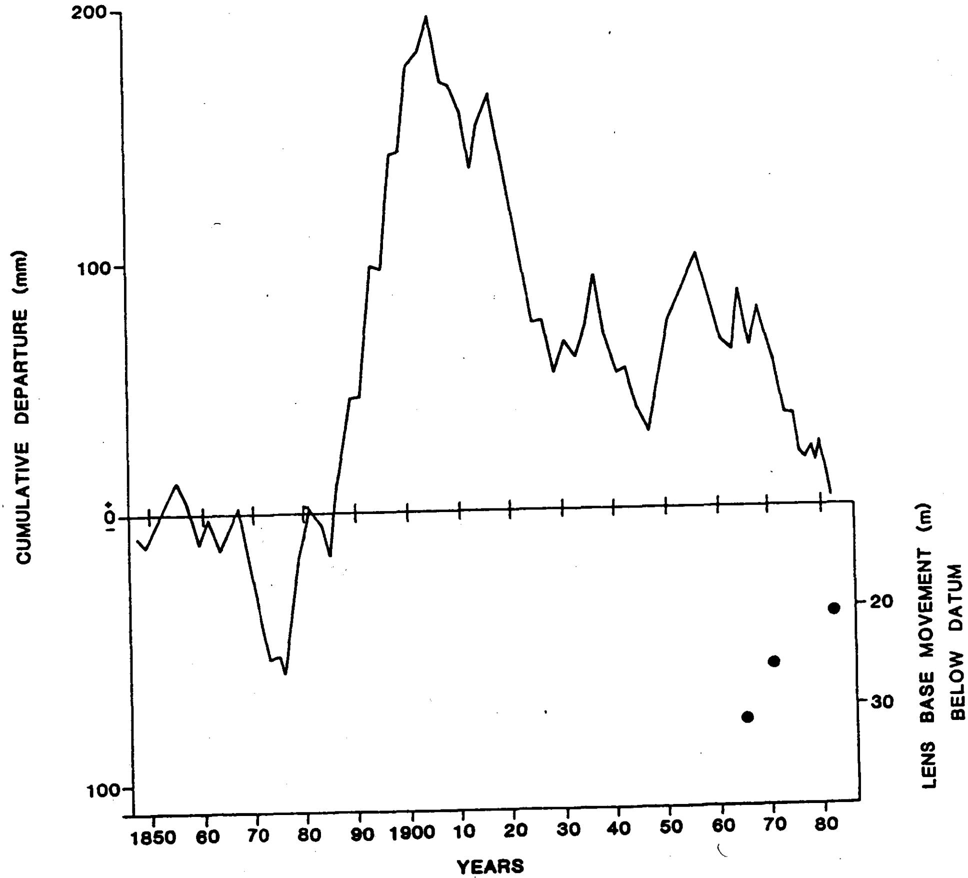


Figure 5: Depletion of fresh water lens resources identified by lens base hydrochemical monitoring in Barbados, after Lloyd (1985).

major well-fields water level decline has been small. In Figure 5 some limited data on the lens base in Barbados are given. A thinning of the lens based upon hydropchemical monitoring is apparent but as yet it is unclear whether this is due to over-exploitation or long-term rainfall/recharge decline.

Over recent years monitoring of hydraulically layered situations has benefited considerably from groundwater pollution studies so that a plethora of multiple-point monitoring configurations can be seen in the literature. The most desirable construction are those that provide both head and quality monitoring. Single string multi-post systems are suitable for some circumstances but are expensive and require careful installation. Experience shows that the multi-piezometer construction with slotted pipe properly located is still the best multiple monitoring procedure.

For salinity ingress monitoring, resistivity strings are commonly installed but can deteriorate with time. Conductivity cells provide more meaningful data but again are expensive and require larger diameter wells than the conventional resistivity strings (Lloyd & Walters, 1988).

Combined conductivity data and two-level pumping data are proving most valuable in understanding ingress distributions with depth (Van Wonderen & George, 1986; Tellam & Eyre, 1990).

Under natural hydrochemical conditions saline groundwater movement is not the only feature that requires monitoring. In many thick partially layered aquifers redox conditions and degassing effects can vary with depth and change significantly as a result of abstraction. Monitoring of any such changes maybe vitally important for the corrosion of wells and distribution installations, and also well yield performance. On Figure 6 an example of layered redox conditions is shown from Indonesia. Monitoring of both head and dissolved iron species is carried for both layers shown. During the wet season water is drawn preferentially from the top layer but as this layer is gradually depleted into the dry season water is progressively drawn from the lower layer. Eventually a critical balance is reached in the wells such that major ex-solution of iron in the pump rising mains from the lower layer water occurs because of oxygenation by the upper waters and the wells cease to function. Alternative supplies therefore have to be introduced if the heads cannot be adequately managed.

CORRECTIVE MEASURES

Despite good intentions on the part of hydrogeologists and water supply engineers over-exploitation is frequently a problem, particularly but by no means exclusively, in developing countries. The reasons for over-exploitation are manifold but may be summarised as:

(a) Lack of awareness for the need of management
(b) Lack of historical management
(c) Poor hydrogeological understanding
(d) Poor licencing policies and legislation
(e) Disregard for legislation and poor enactment

The Qatar situation shown on Figure 4 is the result of a combination of lack of awareness and licencing policies. In Figure 7 an example of bad historical management leading to localised over-exploitation is shown for the Great Artesian Basin of Australia. The example is typical of difficulties encountered in flowing artesian well areas and can also be seen in North Africa in the Chad Basin in the western desert of Egypt.

In the Great Artesian Basin apart from causing significant groundwater head decline centrally, the uncontrolled artesian flows have effected the unconfined-confined inteface so that more surface water recharge now enters the aquifer (Fig. 7) derogating local agricultural supplies that are provided by the surface flows.

Where over-exploitation exists management corrective options may be few and are often difficult to put into practice. Some of the available options are:

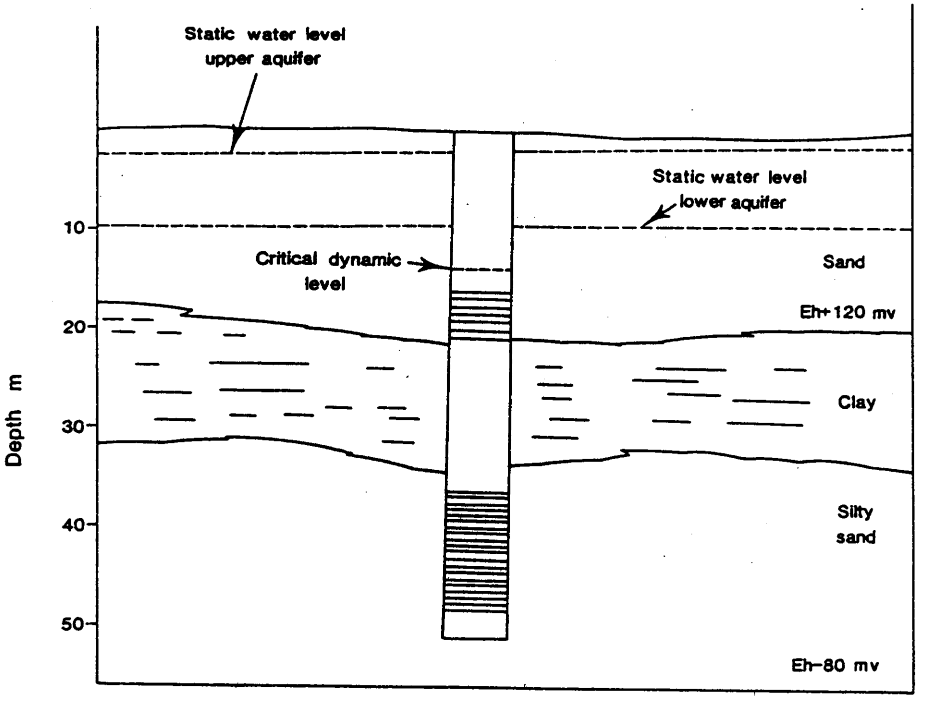


Figure 6: Hydrochemical monitoring of redox layered groundwaters in Indonesia.

(a) Reduction of pumping and alternative supply implementation
(b) Re-arrangement of pattern of abstraction
(c) Improvement in aquifer recharge
(d) Groundwater desalination
(e) Ground/aquifer sacrifice
(f) Scavenging

In many countries where over-exploitation has occurred, alternative supplies have been introduced to offset aquifer depletion. Such schemes can be expensive and obviously alternative water has to be available. Circumstances will be unique to the problem, but as an example, details are shown in Figure 8, of aquifer responses to abstraction reduction in the historically over-exploited Merseyside Triassic Sandstone aquifer in western England. Because of progressive groundwater head decline cessation of spring flow and increasing saline intrusion, abstraction was reduced as a matter of policy in the late 1960's resulting in a decline in storage release, cross boundary flows and saline intrusion. The overall aquifer response has proved beneficial; however, the replacement supply has had to be obtained from surface water resources.

In response to over-exploitation the re-arrangement of abstraction is always an attractive hydrogeological option. For example in Figure 9 a very advantageous storage situation is shown for a drought period in an English aquifer based upon a well distribution alternative to that actually existing. Unfortunately such re-arrangements can prove economically prohibitive in terms of surface abstraction and distribution networks.

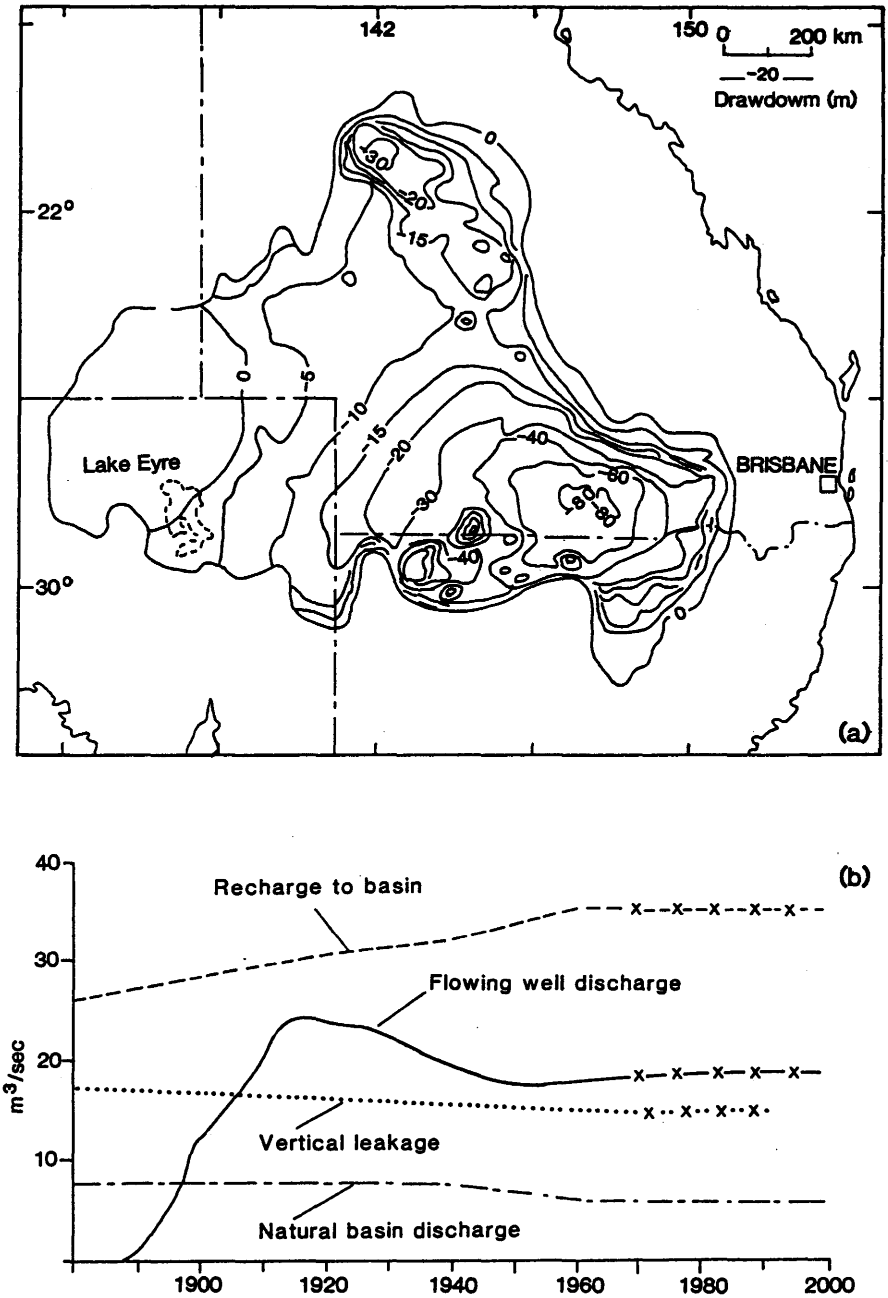


Figure 7: Uncontrolled artesian groundwater discharge effects in the Great Artesian Basin of Australia, after Habermehl (1980).

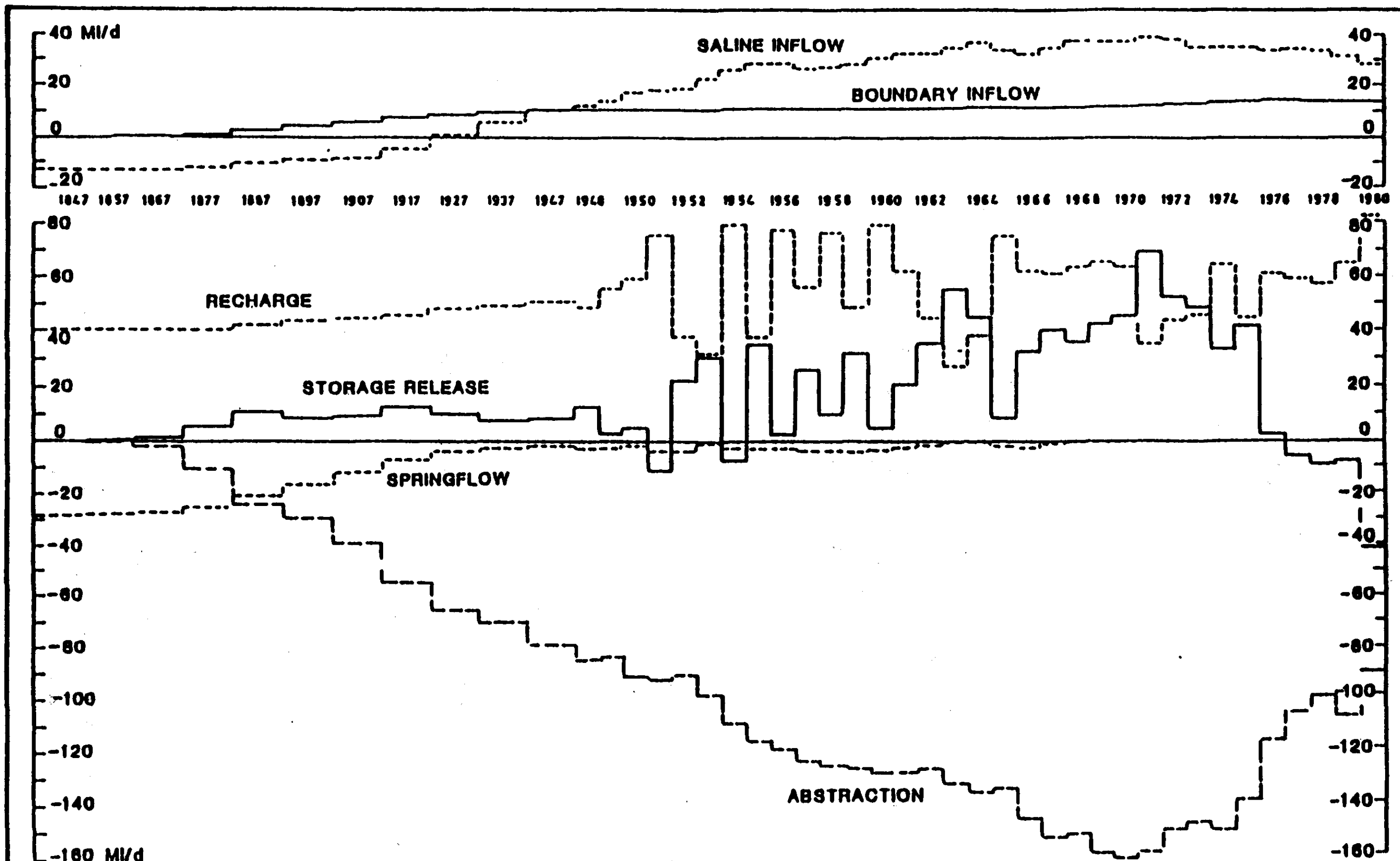


Figure 8: Groundwater head responses to abstraction decrease in the Triassic Sandstone aquifer of Merseyside, U.K.

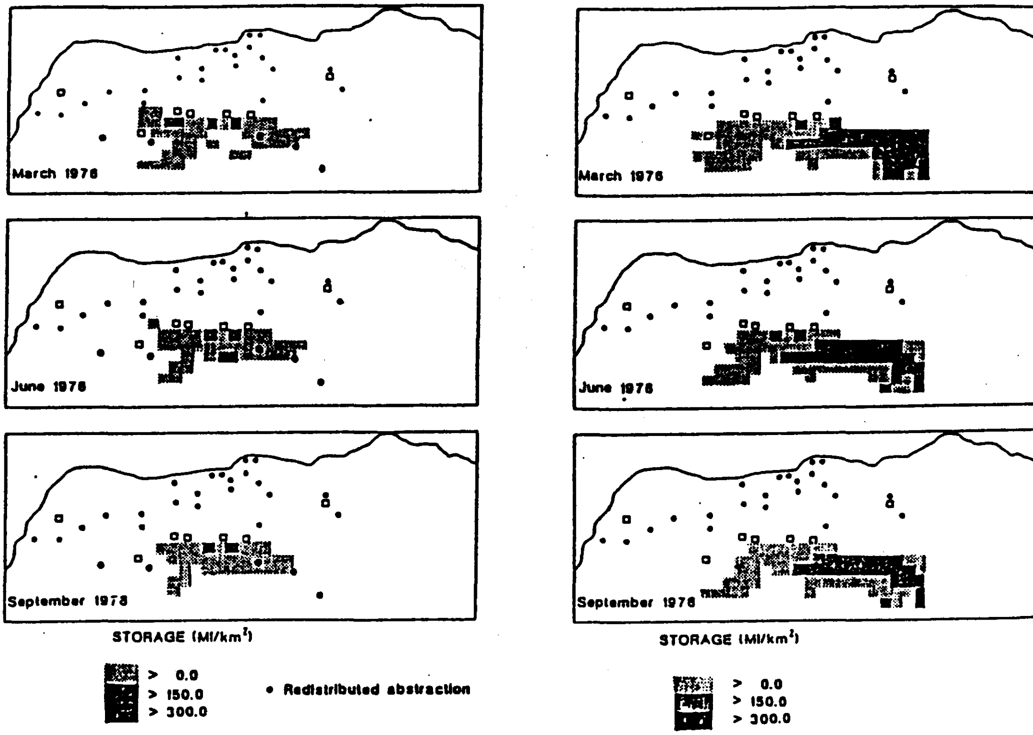


Figure 9: Advantageous groundwater storage manipulation resulting from alternative abstraction patterns. Modelled example after Spink & Wilson (1987).

Improving recharge to aquifers to counter over-exploitation is normally undertaken by the means of specific structures, although careful catchment management can help. Unfortunately in order to improve direct recharge from precipitation, deforestation, which is largely environmentally unacceptable, has to be invoked. When recharge occurs deforestation can dramatically increase input as witnessed in Australia where, however, it has unfortunately had disasterous results causing extensive salination (Fig. 10). In some arid countries particularly, the converse is important, in that forestation should be carefully controlled in relation to natural recharge areas.

Much has been written about artifical recharge structures but in fact the real experience is limited and contradictory (O'Hare *et al.*, 1986). The conventional methods include runoff spreading structures (Davis *et al.*, 1964), recharge basins or pits (Wilson *et al.*, 1976) and recharge wells (Chowdhury & Shakeja, 1978). The source waters are normally natural runoff, although waters used for industrial purposes, notably cooling and treated sewage effluent are also artifically recharged.

River spreading to promote artificial recharge has proved effective in various countries notably in the California central valley in the USA. Extensive irrigation in the valley has caused an annual over-exploitation of 1.85 km^3 of water so that in the southern arid area of the valley water banking of imported surface water is being implemented (Shelton, 1990). Spreading and

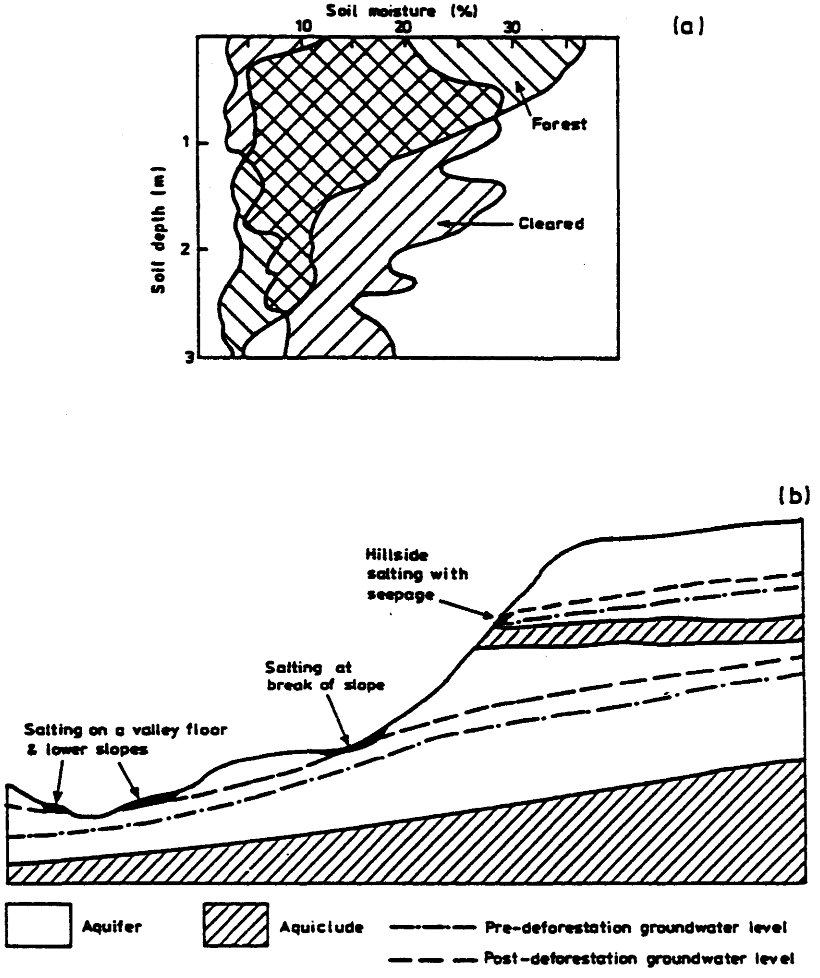


Figure 10: a) Soil moisture profiles from forested and deforested areas in Victoria, Australia; b) Concepts of sedimentation down the hydraulic gradient into progressively arid areas as a result of deforestation in the recharge area, after Jenkin (1981).

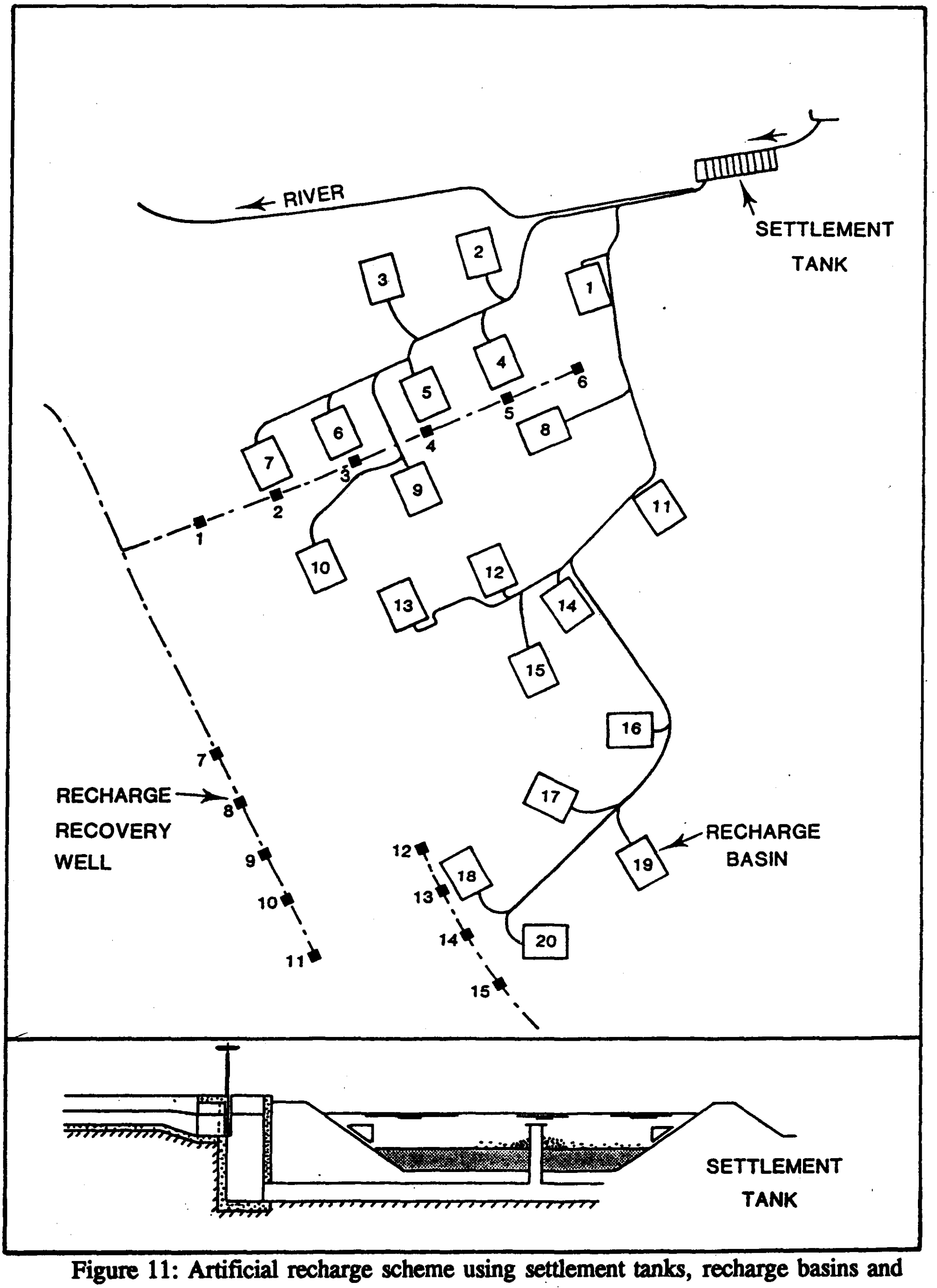


Figure 11: Artificial recharge scheme using settlement tanks, recharge basins and recharge recovery wells.

basin recharge structures are to be used to eventually bank 1.2 km^3 of water. Apart from the capital cost of such a scheme the over-riding factor is maintenance so that ground recharge capacity is not progressively reduced.

In most countries when artificial recharge is used or contemplated the surface water flows are highly variable and rivers frequently non-perennial. Flood waters are naturally silt laden so that settlement basins are required in addition to recharge basins. The type of scheme employed is shown in Figure 11 for artificial recharge via basins from non-perennial river flows in an arid part of South America. Pre-settlement tanks, recharge basins and recharge recovery wells are employed.

For the right ground conditions and with continual maintenance, recharge basins can prove extremely efficient and are probably preferable to recharge wells. Such well structures can be complicated because of the need to combat siltation remotely, and further such wells are susceptible to yield deteoriation if recharge water chemistry is incompatable with existing groundwater chemistry.

CONCLUSIONS

Over-exploitation is in most cases undesirable, although in arid areas can be a successful controlled groundwater management policy. The causes of over-exploitation are manifold and most frequently ensue from poor historical management and poor hydrogeological assessments. To be successful and protect resources any management policy must clearly operate a comprehensive groundwater head and hydrochemical monitoring programme. This should be geared not only to the resource needs but also to any associated environmental factors which may be effected by abstraction.

Within the local definition, over-exploitation can obviously be avoided by constraining operations in response to the monitoring information and mangement criteria. Where over-exploitation, however, has occurred, and corrective measures are necessary, options can prove very expensive. Alternative supplies, re-arrangement of abstraction or artificial recharge may theoretically appear attractive but all pose cost problems and in the case of artifical recharge are often seen to progressively fail because of lack of comprehensive maintenance. As with many other things it must be concluded that prevention is better than cure.

REFERENCES

Chowdhury, P.K. & Shakeja, S.K. 1978. Drainage by Recharge Wells in a Leaky Aquifer. *Jl. Hydrol.*, vol. 36, No. 1/2, Jan.; 87-93.

Davis, G.H., Lofgren, B.E. & Seymour, M., 1964. Use of groundwater reservoirs for storage of surface water in the San Joaquin Valley California. *U.S. Geological Survey Water Supply* Paper 1618.

Gorelick, S.M. 1983. A Review of Distributed Parameter Ground Water Management Modelling Methods. *Water Resources Research,* vol. 19, No. 2, Apr. pp. 305- 319.

Habermehl, M.A., 1980. The Great Artesian Basin, Australia. *Bur. Min. Res. J. Austr. Geol. Geophys.*, 5, 9-38.

Jenkin, J.J., 1981. *Dryland salting in Victoria.* Wat. Res. Foundation Sym., Soil Conservation Authority, Kew, Victoria Australia, 28.

Lloyd, J.W., 1985. *A review of some of the more important difficulties encountered in small island hydrogeological investigations.* British Commonwealth Science Council Workshop, Water Resources of Small Islands, Fiji. 180-210.

Lloyd, J.W. & Walters, M., 1985. *Sampling of groundwater with special reference to saline/freshwater conditions*. Final Report Phase I to U.K. Dept. Environment, London. 230.
Lloyd, J.W., Pike, J.G., Eccleston, B.L. & Chidley, T.R.E., 1987. The hydrogeology of complex lens conditions in Qatar. *Jl. Hydrol.* 89, 239-258.
Lloyd, J.W., 1990. Groundwater conditions and development in the Eastern Sahara. *Jl. Hydrol.* 119, 71-87.
Lloyd, J.W. & Pim, R.H., 1990. The hydrogeology and groundwater resources development of the Cambro-Ordovician sandstone aquifer in Saudi Arabia and Jordan. *Jl. Hydrol.* (in press).
O'Hare, M.P. *et al.*, 1986. *Artificial Recharge of Ground Water - Status and Potential in the Contiguous United States*. Lewis Publishers Inc., Chelsea, Michigan.
Shelton, M.L., 1990. *Water banking in the central valley of California, U.S.A.* Int. Conf. on Groundwater in Large Sedimentary Basins, Perth, Australia, 9.
Spink, A.E.F. & Wilson, E.E.M., 1987. *Computer aided management of groundwater resources*. Groundwater and the Environment (Eds. Awadalla and Noor), Kuala Lumpur, Malaysia, G16-27.
Tellam, J.H. & Eyre, S.F., 1990. *Estimating rates and electrical conductivities of boreholes inflows using a logging/two-level pumping technique*. In: Bell, F.G., Culshaw, M.G., Cripss, J.C. & Coffey, J.R. (eds.), Field testing in engineering geology. Geol. Soc. Engineering Group Special Publ. 6, 335-344.
Van Wonderen, J.J. & George, D., 1986. *Two level pumping to determine salinity and flow variation with depth.* In: Proc. 9th Salt Water Intrusion Meeting, Delft, The Netherlands, 563-574.
Wilson, L.G., Rasmussen, W.O. & O'Donnell, D.F. 1976. *Feasibility of Modelling the Influences of Pit Recharge on Ground Water Levels and Quality in Alluvial Basins*. Report No. OWRT-A-056-ARIZ(2), National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia.

GROUNDWATER OVERDRAFT IN NORTH WEST PARTS OF INDO-GANGETIC ALLUVIAL PLAINS, INDIA. FEASIBILITY OF ARTIFICIAL RECHARGE

K.P.SINGH
Punjab State Council for Science & Technology,
SCO No.2935-36, Sector 22-C,
(P.Box 958), Chandigarh-160022, India.

ABSTRACT. Punjab and Haryana States, and Union Territory of Chandigarh in north west parts of India, forming parts of Indo-Gangetic alluvial plains, suffer from the problem of depletion of water levels and groundwater overdraft. In Punjab, the problem is acute because 86 blocks out of 116 blocks in total are in a critical stage. In some of the areas like Malerkotla in the Sangrur District of Punjab, water table has gone down by 8 to 9 m. In other areas in Punjab, depletion of about 4 to 5 m has been observed. Similarly in Ambala, Karnal and Kurukshetra Districts of Haryana, depletion of water of about 1-4 m has been observed. In Union Territory of Chandigarh, where groundwater is the only source of water supply, depletion of water level at the rate of 1 m/year around well fields since the last decade has been observed. Constant depletion of water levels has affected the working of about 1200,000 shallow tubewells in the area studied. Many tubewells have reduced discharge or have failed. In the absence of groundwater legislation, groundwater is free to be exploited by anybody and by any mechanism. Some experiments have been done to examine the feasibility of artificial recharge and suitable sites have been identified. Solutions to arrest the depletion of water level by artificial recharge are discussed alongwith limitations/constraints.

INTRODUCTION

The studied area lies in the north west part of India (Fig.1). The area forms parts of Indus basin (Punjab and Union Territory of Chandigarh) or forms part of watershed between the Ganges and Indus River Basins (parts of Haryana State). Nearly the whole area of States of Punjab and Haryana lies in the Indo-Gangetic alluvial plain and is an important food grain producer of the country. In the north-western parts, rocks of Siwalik system are exposed. The rainfall varies from 1500 mm in the north-western parts to about 200 mm in semiarid/arid parts lying in the south-western parts of the studied area. The general slope is from north-east to north-west direction. During the last two decades, large scale development of groundwater has taken place, especially in areas where the quality of ground water is good. Surface irrigated area has remained more or less at the same level. Large scale installation of tubewells (shallow as well

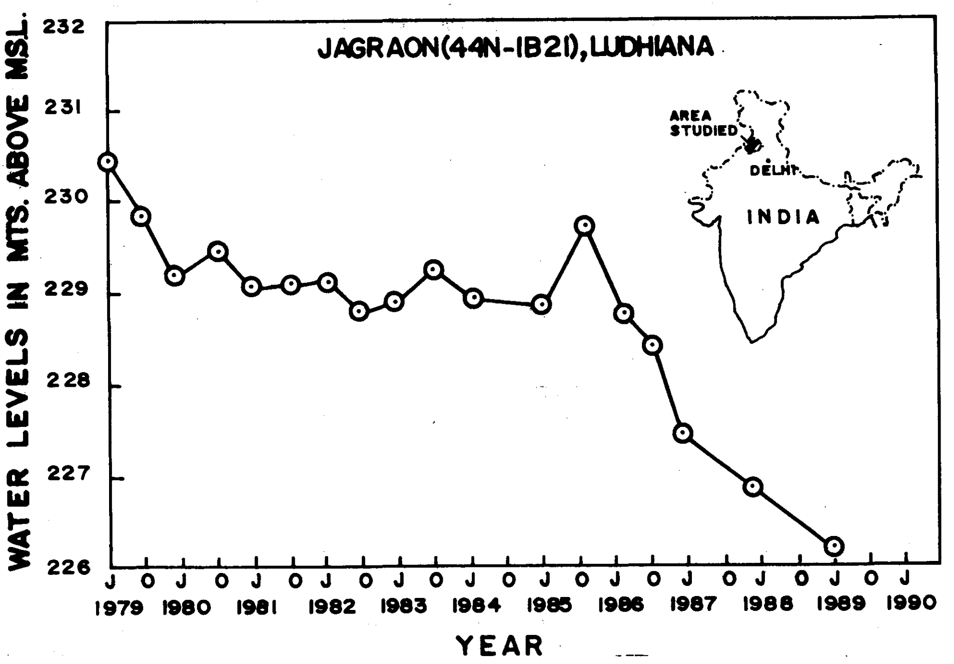


Figure 1: Location of the Area (inset) and representative Water Level Trends (J denotes June and O October).

as deep) has caused the depletion of water due to groundwater overdraft. The present paper is concerned with the problem of groundwater overdraft and remedial measures such as artificial recharge, conjunctive use of surface and groundwater, water conservation measures, changes in cropping patterns, etc. are proposed to control the problem.

HYDROGEOLOGY

Indo-Gangetic alluvial plains are predominated by Quaternary formations comprised of fluvial and aeolian deposits of considerable thickness except in the north-eastern parts where rocks of Siwalik system are exposed. In Haryana, rocks belonging to Delhi system are exposed in some areas and underlie the Quaternary deposits.

The unconsolidated sediments comprised of sand, clay, silt and calcareous concretions cover almost the whole area. In the north-eastern parts, at the base of Siwaliks, in Kandi belt, boulders, pebbles are also present. The bed rock topography over which the alluvium rests slopes towards northeast. The thickness of the unconsolidated sediments is considerable in north-eastern and central portion, which decreases in south-western and southern parts.

In most of the area, Quarternary deposits act as a single multiple aquifer system upto about 150 m depth. However, locally, upper aquifers are phreatic in nature while in the deeper ones (below 150 m) leaky confined conditions occur. Confined conditions have been encountered at the depth of 270 m as revealed by Central Ground Water Board's exploration in Upper Yamuna Basin in Haryana State. Water is deep in the submontaneous 'Kandi region' (30-50 m b.g.l.). In central parts, depth of water ranges between 5 and 30 m on the average. High water table zones (0-3 m) are common in saline and waterlogged areas which suffer from the problem of waterlogging and salinity. Around canals, rivers, shallow water table zones exist. Transmissibility values of aquifer ranges between 500-2500 m^2 day^{-1}, specific yield in unconfined top phreatic aquifer ranges between 8-15%. Groundwater flow is from north-east to south-west.

Chemical quality of groundwater is good with electrical conductivity values below 2,000 μs cm^{-1} at 25°C in areas where groundwater overdraft exists. However, in saline and waterlogged areas high salinity and alkalinity is encountered.

PROBLEM OF GROUNDWATER OVERDRAFT

Problem of groundwater overdraft normally occurs when annual draft exceeds annual recharge resulting in constant depletion of water levels which cause undesirable situations and disturb the ecology of the region. It has been observed that constant overdrafting has resulted in the problem of depletion of water levels in the following areas, which are shown in Table 1. Depletion of water levels has caused reduction of discharge of tubewells or drying up of wells. In fresh water lenses of saline areas upconing of saline water has been observed.

Table 1: Areas suffering from groundwater overdraft

State	Areas	Critical Areas	Remarks
Punjab	- Sangrur - Patiala - Jalandhar - Kapurthala - Ludhiana Districts	- Malerkotla area of Sangrur Distt. - Nakodar area of Jalandhar Distt.	Water table gone down by 8-9 m. Water table gone down by 6 m.
Haryana	- Ambala - Karnal - Kurukeshtra - Mohindergarh	- Thanesar & - Ladwa Blocks	Lowering of more than 2 m has been reported
Union Territory	- Chandigarh	- Chandigarh	Water table depletion at the rate of 1 m/year since last decade

The estimates of groundwater potential given by Pathak (1988) are summarised in Table 2, which indicate the seriousness of the problem.

Table 2: Groundwater Potential of Punjab & Haryana States

State	Utilizable resources *M ha m/year	Net Draft M ha m/year	Potential available for future M ha m	Stage of groundwater development (%)
Haryana	0.7248	0.5085	0.2163	70.16
Punjab	1.5276	1.5181	0.0095	99.38

*M ha m : Million Hectare Metre

SOLUTIONS TO THE PROBLEM

In order to control the depletion of water levels, the remedial measures can be broadly divided into two types i.e. (i) Artificial recharge and (ii) Other measures like change in cropping patterns, legislative measures, water conservation measures etc. These are briefly discussed below :-

Artificial Recharge

Artificial recharge of groundwater is the process of enhancing movement of water into underground formations by constructing infiltration facilities or by induced recharge from surface water bodies. The following methods are available :

Spreading Method: Artificial recharge by spreading method comprises increase in the surface area of infiltration, thereby allowing more surface for infiltrating waters. Infiltration facilities for groundwater recharge can be divided into in-channel and off-channel systems Bouwer (1989). In-channel systems consist of weirs, dams, and levees (T-dikes and L-dikes) to increase the wetted area and, hence, the infiltration in the stream bed of flood plain. Such systems can be constructed in Kandi area of Punjab and Haryana States at the base of Siwaliks Singh & Tewari (1978). Infiltration properties were determined and average permeability comes to be 21.85 m day^{-1}. If 1000 m is the length of river bed (improved by removing clay and silt particles) with 50 m width, with the infiltration rate of 2 m day^{-1}, it has been found that rate of recharge comes out to be 100,000 m^3 day^{-1} or 1.2 m^3 s^{-1} Sinha (1985).

Off-channel systems are basins in old gravel pits or especially constructed basins in areas of permeable soil. Design and management criteria to maximize the hydraulic capacity of infiltration basins depend on water quality, climate and soil Bouwer (1989). Thus the criteria are site-specific and they must often be evaluated by on-site experimentation. Factors to be studied are optimum schedules of flooding, drying and cleaning of the basins; optimum pretreatment of water; optimum water depth, and optimum velocity of the water (basins with stagnant water versus channels with flowing water). There are also environmental factors like algae, insects etc. to be considered. Sources of water are also to be kept in view. Such basins can be constructed in the area of old river courses, in wide channels in Chandigarh 'Sukhna Choe' to make artificial recharge. Clay layers in vadose zone may occur in some areas. In such cases perched groundwater storage may be favourable if the water table is deep and sufficient storage space is available over the clay band. Shallower or top clay band will have to be removed. Studies by Central Ground Water Board have shown that basins of 250 m x 60 m size and having depth of 2 m to 5 m can be constructed to carry artificial recharge in Chandigarh area. The distance between adjacent basins should be 10-15 m or less. The basins should have sand pillows (0.5-0.8 m) thickness and they should be scraped often to remove clay/ silt particles at the top. The basins should be cleaned when infiltration rate drops below 0.5 m day^{-1} i.e. every two or three months.

Where the water for recharge contains considerable suspended material, it can be more economical to remove this material in presedimentation or desilting basins with possible use of coagulants to enhance setting of the solids. Further if the water is having slight turbulance, it may keep the finer material in suspension. If the channel system with moving water is used, a few infiltration basins may have to be constructed at the end of the channels to catch any residual flow. This method can also be adopted in areas of old river courses which have been identified by LANDSAT data and where thick permeable deposits exist.

Injection Methods: Such methods are of particular interest where overdrafting occurs in confined aquifers and areas located close to major canals. As water is available during monsoons, injection methods are suitable on account of clean waters available close to sites. Such methods can be tried in Kurukeshtra district of Haryana and in other areas of Punjab. Experiments were made in Dabkheri in Haryana under United Nations Development Programme where the author also participated in the experiment.

The average hydrogeological parameters along the entire length of Narwana branch canal were: transmissibility 1936 m^2 day^{-1}; aquifer thickness 79.6 m; permeability 24.3 m day^{-1} and specific yield 19.4%. The experiment was conducted for about 415 minutes, including a non-injection period of about 45 minutes. The injection rate was 43.8 l s^{-1}, injection pressure was 1 atm. at the beginning of the experiment and rose to 1.6 atm. after 10 minutes, 1.98 atm. after 40 minutes and 2 atm. after 295 minutes, remaining 2 atm. until the end of the experiment. Rise of water levels was observed; maximum 0.42 m was observed in a well 30 m from the test well and a minimum of 0.15 m in a well which was 125 m from the test well. The experiment proved that it is possible to carry out artifivial recharge at a high rate (43.8 l s^{-1}) in confined aquifers in this area, and when canal water is suitable.

After the injection experiment, gravity recharge was also tried. The recharge rate by gravity lasted for 101 hours. The recharge rate was higher than 5.1 l s^{-1} at the begining and was decreased to 3.5 l s^{-1} by the end. A maximum rise of 0.14 m was observed in a well 30 m away from the test well.

From the results it can be seen that recharge obtainable with injection under pressure is about 10 times higher than the rates obtained by gravity flow.

In view of the results of injection experiments by the Central Ground Water Board, the author feels that around canals, it can be one of the methods to carry out artificial recharge, specially where confined aquifers are to be recharged. It may be mentioned here that the cost of making artificial recharge by injection method in alluvial areas is 10 times the cost of making artificial recharge by spreading methods Phadtare (1989).

Induced Recharge: Such methods are especially useful where overdraft areas are located close to rivers. This method was experimented at Tatiana site in Haryana by Central Ground Water Board where the author also worked. The main purpose of the investigations was to study the possibility of inducing recharge from the Ghaggar river into unconfined aquifers in order to increase groundwater extraction during dry season. The top aquifers of the area (Tatiana) are in hydraulic continuity with the river. The aquifer has transmissibility-400 m^2 day^{-1}, permeability-22.2 m day^{-1}, depth to groundwater is about 6 m bgl and hydraulic gradient is towards the river in the dry season and is reversed during the wet season and aquifer receives recharge from the river. The results of experiment showed that the most effective and economical measures will be to periodically scrape off the clay film and clogged upper part of the river bed, as well as widening and levelling of river bed. Adoption of this measure alone will make it unnecessary to use only clean water for recharge in this part of river, even during the rainy season. Scraping away the clogged portion of the aquifer beneath the river would considerably reduce the hydraulic resistance (L-94 m) offered by the river bed and, consequently the specific capacity of the individual wells would be increased.

In order to use this method, a well field has been suggested parallel to the river on each bank, at a distance of not less than 100 m from the river. The distance between the individual wells should be 200 m Sinha (1985).

Other Measures

The other measures aim at reducing the groundwater overdraft. It is suggested that in severely overdraft areas, new cropping patterns may be introduced. Crops which require less water than the existing crops will have to be promoted. Improvement of irrigation methods by adopting drip/sprinkler irrigation methods etc. are also suggested.

In critical areas, legislative measures can be introduced. Pumping patterns can be regulated keeping in view the available water supply in the canals.

It is necessary to educate the farmers regarding optimum water utilization aspects, irrigation planning etc. Public awareness regarding water conservation measures should be created through celebration of 'National Water Day' and with the help of awareness programmes through people's participation and voluntary organisations.

Recycling of water and re-use of water should be promoted especially in those areas where industrial units consume groundwater.

CONCLUSIONS

Large scale development of shallow and deep tubewells in Punjab and Haryana States and Chandigarh area has resulted in the problem of groundwater overdraft as a result of which constant depletion of water levels has been observed specially in districts of Ludhiana, Jalandhar, Amritsar, Sangrur and Patiala of Punjab State and Ambala, Karnal, Kurukshetra, Mohindergarh districts of Haryana State and Chandigarh area of Union Territory. The depletion of water levels has caused the reduction in discharge/drying of shallow tubewells, disturbance of aquatic eco-system of effluent rivers and upconing of saline water in saline zones where thick lenses of fresh water overlie the saline water. Artificial recharge can be carried out to control the depletion of water levels. Basin method is best suitable in areas where unconfined aquifers do not have clay bands in the zone of aeration. This basin method can also be tried in areas over old river courses which have been identified by LANDSAT data and aerial photography. In Kandi belt, check dams or embankments over the river beds in recharge zone seem to be feasible. It is also 10 times cheaper as compared to artificial recharge by injection methods.

Induced recharge is possible in areas close to rivers/streams where direct communication exists between groundwater and the rivers/streams.

Besides carrying out artificial recharge, appropriate legislative measures should be taken to regulate pumping patterns. There is a need to look for new cropping patterns to reduce irrigation water requirements. Recycling and re-use of water should be promoted in industrial units where the source of water is mainly tubewells. Water conservation measures should also be taken to save water from waste. Voluntary organisations can be of help in taking up educational programmes for various target groups.

REFERENCES

Bhatnagar, N.C. 1986. Waterlogging and Soil Salinity in Punjab and Haryana States. Pre-seminar volume of seminar on *Conjunctive Use of Surface and Ground Water Resources, New Delhi, India*; 5-1 - 5-28.

Bouwer,H. 1989. Systems for Artificial Recharge of Groundwater. Vol.2 *Proceedings of International Workshop on Appropriate Methodologies of Development and Management of Groundwater resources in Developing Countries organised by NGRI,India*; 315-324.

Pathak, B.D.1988. Groundwater, its Development Potential and Problems in Indo Gangetic Plain. Vol.3, No.3. *Bhujal News*. July-Sept;29-33.

Phadtare,P.D. 1989. Artificial Recharge to Groundwater State of Art and Limitations. Vol.2. *Proceedings of International Workshop on Appropriate Methodologies of Development and Management of Groundwater Resources in Developing Countries organised by NGRI,India*; 299-314.

Singh, K.P. & Tewari, B.S. 1978. Hydrogeological Investigations of Mahilpur Block, Punjab with special reference to artificial recharge. Vol.2. *Bulletin, Indian Geologists Association*; 73-78.

Sinha, B.P.C.1985. Artificial Recharge Studies in Ghagar River Basin, India. *Pre-seminar Volume of Seminar on Artificial Recharge of Groundwater, Ahmedabad, CGWB, Government of India*; 12B-1 - 12B-17.

ECONOMIC CRITERIA FOR THE CHARACTERIZATION OF OVEREXPLOITED AQUIFERS

A. SANCHEZ-GONZALEZ
Servicio Geológico, Dirección General de Obras Hidráulicas, MOPU
Avenida de Portugal, 81, 28011 Madrid, Spain

ABSTRACT. The mobilization of the water resources stored in an aquifer can constitute an important source of development to the region where they are located. But solid economic grounds can also be argued to support conservationist attitudes towards the resource: protecting the interests of future generations and preventing illusory developments which could give rise to dramatic social conditions. These undesirable results are likely to occur in the absence of regulations stopping them from arising.

This paper presents a simple analytical model which defines whether an aquifer is being exploited over its social optimum or not. It shows clearly that overexploitation appraisals must take into account the piezometric state of the aquifer, and not merely the amount of water abstracted. In conditions of high spatial homogeneity of the parameters involved, the model provides two significant boundaries within which the state of the aquifer should be kept in order to avoid overexploitation.

INTRODUCTION

Unlike mineral and fossil fuels, ground water is a renewable resource. As a consequence, the opportunity arises of profiting from it on a sustainable yield basis, its upper limit being the mean natural recharge of the aquifer. The amount of water abstracted can temporarily be larger than the natural recharge by consuming part of the stored resource. Under certain circumstances a policy of storage replacement will be the appropriate one, allowing the water levels to recover.

The problem of adopting aquifer exploitation policies by nature is public. Ground water rights should be acknowledged according to guidelines established by water authorities. Where water legislation does not specifically govern ground water, or where it permits access to the resource disregarding the existing level of exploitation, some aquifers will certainly be subject to excessive depletion from society's point of view. Since the resource is open to all and owned by none, no user will have an incentive to conserve it because refrainment from one individual simply enhances the neighbours opportunities.

This paper analyses the economic rationality of aquifer depletion, rehabilitation and conservation strategies. Simple analytical models are employed for this which do not contemplate water quality aspects. The approach to the problem follows a path parallel to the one used by Gordon & Scott (1985) in their works on fishery economics, a subject which bears many similarities to ground water resources management. The economic formulation of the dynamic model has been taken from Clark *et al.* (1979), a classic paper on fishery economics.

A STATIC APPROACH, NOT INVOLVING CAPITAL COSTS

Consider an aquifer as a single cell unit, of uniform horizontal water section, A, the product of the real section and its effective porosity. Natural recharge, *R*, is constant over time. The extraction, *Q*, takes place on the datum plane, and the depth of the water table is denoted by *h* (Fig. 1).

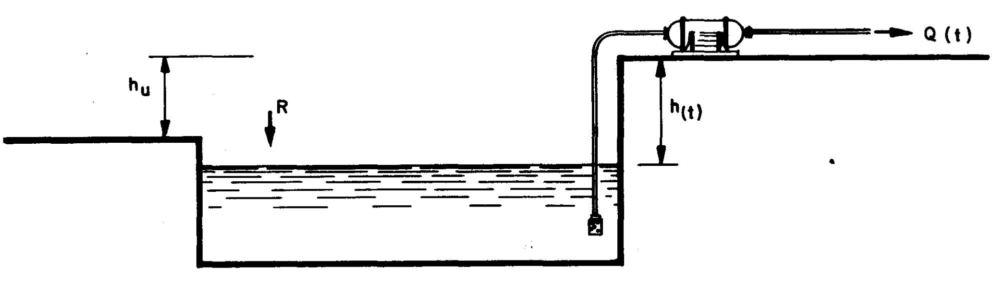


Figure 1: Simplified scheme of exploitation.

The economic parameters involved are the discount rate of money, *r*, the cost of lifting water per unit of volume and meter of elevation, *k*, and the unit value of the water, *p* on the datum plane and zero at all other positions. The latter means that there are no other beneficial uses than those related to the availability of the water on the datum plane; more specifically, the outflow from the aquifer to its natural stream has no economic value.

The available pumping capacity is first assumed to be unlimited. If capital costs are not considered, the problem of determining the optimal management of the system described, taking into account the interest of all future generations, can be stated as determining $h = h\ (t),\ Q = Q\ (t)$, which maximize the present value of net benefits, *B*.

$$\max B = \int_0^\infty e^{-rt} \cdot Q\ (p - kh)\ dt \qquad [1]$$

subject to the continuity equation dh/dt = $(Q-R)/A$, $\forall h \geq h_u$.

The solution encompasses two steps:

(a) an instantaneous extraction of the volume contained between the initial position of the water table and the optimal one:

$$h_{opt.} = p/k - R/Ar \text{ or} \qquad [2]$$

$$h_{opt.} = h_u, \qquad \text{if } [2] < h_u$$

All initial positions lower than $h_{opt.}$ can be considered as if they were economic overexploitation for which the best policy is to allow the water table to recover by not pumping any water until $h_{opt.}$ is reached.

(b) a constant pumping rate with $Q = R$ at $h = h_{opt.}$, if $h_{opt.} \geq h_u$; or $Q = 0$, if $h_{opt.} < h_u$.

It can be shown that if the pumping capacity is limited, the optimal operation rule consists of making $Q = Q_{max}$ until $h_{opt.}$ is reached, and then to continue extracting the discharge, R. Both imply a rapid mining process, known as the 'bang-bang' type solution, until a compromise is reached between the immediate and long-term benefits to be respectively enjoyed by present and future generations. Notice that the lower the specific recharge of the aquifer, or the higher its effective porosity and the discount rate, the higher is the initial mining. Thus, poorly recharged detritic aquifers appear particularly suited to heavy pumping at the initial stages of their development.

Under conditions of free access to the resource, equilibrium would be reached at position $h = p/k$, below $h_{opt.}$, at which the mean and marginal costs of production equal the price of the water, and the residual benefit is zero. The theory of perfect competition then leads to rent dissipation through an excessive depletion of the resource. This is so because an essential requirement of the free market theory is missing: the one that establishes the coincidence between private and social interests. This justifies a public intervention to restrict access to the resource and to regulate the exploitation rights.

THE COST OF CAPITAL EMPLOYMENT

The assumption that energy is the only component of production costs will progressively be dropped. First we shall consider that capital costs can be treated as pure variable costs, their value depending on the value of the pumping equipment involved. This means that the equipment is perfectly mobile, usable for other purposes, thus capital possession is acquired as on a letting contract basis in which the lessee pays according to the value of the facilities he uses.

For the sake of mathematical convenience, the value of the equipment is assumed to be

$$V = a\,h\,Q + bh; \quad V/hQ = a + b/Q \qquad [3]$$

The first term of [3] is proportional to the power installed. The second term is introduced to account for the fact that h has a larger effect on *V* than *Q*. In other words, there exists a certain economy of scale between the unit cost of the power installed and the pumping discharge.

Leaving aside the differences in amortizartion periods of the equipment parts, the cost of using these capital goods would be $(ahQ+bh)\ (\gamma+r)$ with γ being the capital depreciation rate. Our management problem can therefore be formulated as

$$\max B = \int_0^\infty e^{-rt}\ [pQ - KhQ - (ahQ + bh)\ (\gamma+r)]\ dt;\ dh/dt = (Q-R)/A \qquad [4]$$

and the solution, obtained through variational calculus, is

$$h^* = p/\alpha - R/Ar - b\ (\gamma + r)/A\alpha r;\ \alpha = k + a\gamma + ar \qquad [5]$$

The optimal policy is again of the 'bang-bang' type, whereas the water table position is now higher than in [2].

But the assumption of perfect capital mobility is far from reality. The rapid extraction of a substantial amount of the stored resource requires huge capital investments which are fixed, specific to the activity, and therefore have to be fully borne. The next section shows that this is central to the problem. Static approaches are easy to understand and provide a good insight into the social significance of storage depletion or restoration. Nevertheless, it is necesary to analyse the capital asset problem of the adjustment phase between the initial conditions of the system and its long-term state.

DYNAMIC ANALYSIS

In what follows it will be assumed that instead of the single installation depicted at Fig. 1, the aquifer can be exploited by a number of existing wells, *N*. The wells have a uniform construction cost, *c*, and their pumping discharge is $q\ (t),\ Q = Nq$.

The value of capital stock is formulated as

$$V = N\ (ahq + bh + c) \qquad [6]$$

and its evolution is governed by the equations

$$dV = I\ (t)\ dt - \gamma V dt;\ V(o) = V_0 = N\ (ah_o q_0 + bh_0 + c)$$

where $I\ (t)$ is the time rate of gross investment and $\gamma\ V$ represents the natural depreciation.

For the purpose of future decisions V_0 is a by gone, so the objective function is

$$\max.\ B\ (V_0, h_0) = \int_0^{\infty} e^{-rt}\ N\ (pq - khq - I)\ dt \tag{7}$$

The constraints are

$h\ (t) \geq h_u$; $V\ (t) \geq 0$; $0 \leq I\ (t) \leq \infty$; $q\ (t) \leq q_{max.}$ from [6]

$$dh/dt = (Nq - R)/A \tag{8}$$

$I = \infty$ allows for instantaneous discrete acquisitions of capital and its nonnegativeness implies that capital is specific to the industry, since it can not be sold.

The model has two state variables (h, V) and two decision variables (q,I), being analogous to other exhaustible resource models. Readers interested in the mathematical justification of the solution are referred to the literature (Clark *et al.*, 1979).

Fig. 2 and 3 synthesize the results in the h, V and h, Q planes. For each initial state of the system (h_0, V_0), the solution of [7], [8] determine the optimal trajectories until a unique final position.

The plane is divided into three regions, R_1-R_3, in which the following policies are to be applied

in R_1, $I = 0$; $Q = 0$
in R_2, $I = 0$; $Q = Nq_{max.}$
in R_3, $I = \infty$

Points A and B reflect the two states of the system at which the capital available is that necessary to pump the recharge R from the positions h^* and $h_{opt.}$ respectively. These water table positions are the optimal corresponding to 'perfect capital mobility' and 'no capital costs', as shown in before sections.

At initial states like D capital is abundant, the resource stored is above the optimal of no capital costs, consequently pumping proceeds at the maximum possible rate. Investment is nul since $h_{opt.}$ is not the long term target. When $h_{opt.}$ is reached some capital is abandoned, and from point C it continues to depreciate. Other trajectories can not reach $h_{opt.}$, but they all curve backwards when $Q = R$ (Fig. 3). At $h = h^*$ there is a sudden jump to point A, the final equilibrium position, where R can be abstracted on a sustained basis keeping V* as the permanent capital stock level.

In R_3 water table is higher than h^* and the optimal policy specifies a sudden capitalization up to the curve σ_1, the entrance to R_2. In R_1, a policy of recovery, consisting of a moratorium, is indicated. Pumping must not start until curve σ_2 is reached.

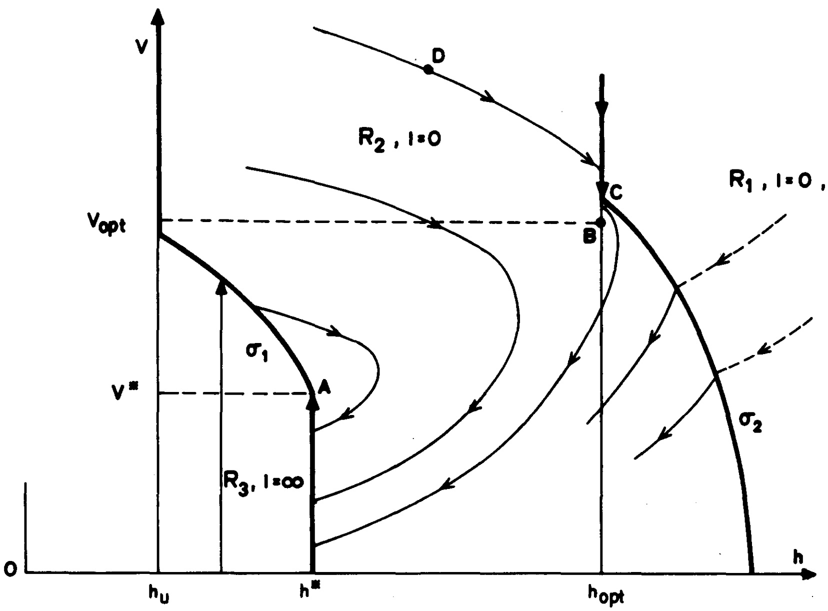


Figure 2: Optimal evolution of water table depth (h) and capital stock level (V).

For the mathematical formulation of the model h_{opt} is given by expression [2] an h* is obtained from [5], substituting b by Nb. Curve σ_1 is the set of all points h_0, in which the marginal benefit obtainable from increasing the initial equipment is equal to the required marginal investment. Hence it is determined from $\partial B(h_0, Q_0)/\partial Q_0 = Na\ h_0$.

The right boundary of region R_2 is curve σ_2, the set of points where $\partial B\ (h_0,Q_0)/\ ds = 0$, ds being the direction of the trajectory.

From the economic point of view, it is clear that the term 'overexploited' can be labelled upon aquifers whose mean piezometric state and installed capacity yield points within R_1, since zero pumping is indicated for them. Positions in R_2 above the trajectory ending at point C can be termed as of overcapitalization, for a sudden decrease in the production rate will be pertiment when $h = h_{opt}$.

On the left side of the figures, systems below σ_1 could be termed as underexploited and undercapitalized, including some whose rate of pumping is larger than the replenishment.

Curves σ_1, σ_2 are not readily obtainable since the determination of optimal trajectories poses many practical problems. But still it can be ensured that while the piezometric state of the aquifer lies within the interval h^*-h_{opt}, a policy of non investment is indicated, thus pumping discharge will be selfdiminished until one of the extremes of the interval is reached. If the right boundary is firstly attained, it then would be wise to adjust pumping to the recharge level as rapidly as possible, and then to continue the non investment policy.

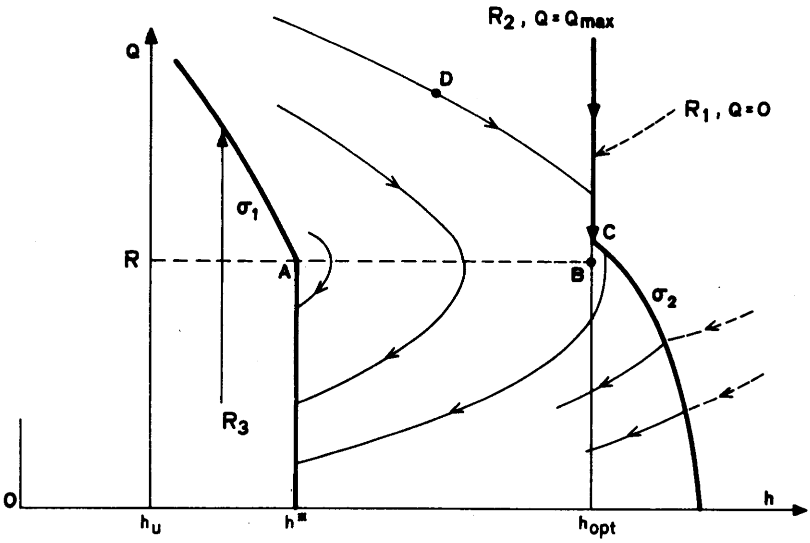


Figure 3: Optimal evolution of water table and pumping discharge.

Piezometric states on the left side of h^* should not worry public administrators unless the abstraction rate is well above R, whereas positions at the right of h_{opt} must be prevented. Drastic rehabilitation policies consisting of well shutting, theoretically optimal in R_1, can hardly be sustained unless the resource has become very severely depleted.

The physical model can be improved by setting

$$dh/dt = (Q - R)/A + \delta\ (hu - h),\ \forall h \leq h_u \qquad [9]$$

Expression [9] is the balance equation for a single cell aquifer with "positive storage" (mean water table elevation above h_u), admitting a linear relationship between the natural outflow discharge and the volume stored above h_u, the position of the outlet (streambed, spring, etc).

This refinement yields for the vertical boundaries of regions R_1-R_3:

$$h_{opt} = p\ (r + \delta)/k\ (r + 2\ \delta) + (A\ \delta\ h_u - R)/\ A\ (r + 2\ \delta),\ \text{ if } h_{opt} < h_u$$

$$h^* = p\ (r + \delta)/\alpha(r + 2\ \delta) + (A\ h_u\text{-}R)/A\ (r + 2\delta) - Nb\ (\gamma + r)/A\alpha(r + 2\delta),$$

and in both cases,

$$Q = R - A\delta(h_u - h).$$

CONCLUSION

The results of the model are conceptually clear and they provide some simple guidelines to deal with overexploitation problems. Quantitative applications for deciding the optimal equipment of underdeveloped aquifers or to determine rates of pumping decrease are rather limited due to the simplifications adopted.

Taking into account the different amortization periods of the capital components (well, power line, motorpump, etc.) would mean introducing additional state and decision variables which would augment the dimension of the problem. In fact, the assignment of a value to parameter p raises a problem of this sort, for water markets rarely exist. This obliges working with final product prices, i.e. crops, and their other related costs. Microeconomic analysis of the production processes can be performed to derive cost functions from which the water table interval $h_{opt.}$-h^* can still be deduced.

Problems of space heterogeneity of land elevation, recharge per unit area, porosity, and productivity of the wells, may be treated if the aquifer can reasonably be divided into a small number of homogeneous cells. The relevant h values can be obtained separately for each cell, and eventual adjustments would have to be made by trial and error to account for internal water transfers.

REFERENCES

Clark, C.W., Clarke, H. & Munro, G.R. 1979. The Optimal Exploitation of Renewable Resource Stocks: Problems of Irreversible Investment. *Econometrica*, 47; 25-47.

Munro, G.R. & Scott, A.D. 1985. The Economics of Fisheries Management. In: *Handbook of Natural Resource and Energy Economics*. A.V. Kneese & J.L. Sweeney (eds), North Holland, vol. II; 623-673.

MANAGING AQUIFER OVER-EXPLOITATION: ECONOMICS AND POLICIES

R.A. YOUNG
Department of Agricultural and Resource Economics
Colorado State University, Fort Collins, CO 80523 USA

ABSTRACT. Aquifer management, which deals with a complex interaction between human society and the physical environment, presents an extremely difficult problem of policy design. Aquifers are exploited by human decisions and over-exploitation is defined here, not in technical terms, but as a failure to achieve maximum economic returns to the resource. It can be best understood as a suboptimal policy regime. Aquifer over-exploitation may be caused by either, or both, of two classic types of social dilemma problems. First, aquifers are typically common pool resources, in which a migratory subtractible resource is exploited under an unrestrained rule of capture. Those using the resource are little motivated to preserve its value (since anyone conserving it for future use simply leaves it for others to capture), and the collective inefficiency of a pumping race is likely to result. Second, extensive exploitation of aquifers often imposes unwanted damages on third parties (external costs). Examples include: damage from subsidence of overlying lands, from intrusion of water of poor quality, or from interference with interrelated water supplies claimed by others in wetlands or streams. Two types of collective policy decisions must be addressed in the management or regulation of over-exploited aquifers. For one type, termed 'managing the water', decisions must be made on a) the appropriate annual rate of pumping, b) the geographic distribution of pumping, c) whether to augment water supplies and/or whether to artificially recharge the aquifer. Another important type of policy decision, which is the second major focus of this paper, can be called 'coordinating the people', determines a) the institutions and policies that divide the extraction rate among potential individual users and user classes and influence pumper behavior, and b) how rules for limiting pumping are monitored and enforced. Taxes, subsidies, pump permits, exchangeable pumping entitlements and education and research are among the people management options. Choosing an aquifer management policy must in the final analysis, be recognized as a political, rather than a technical decision, because social goals must be brought into play and making tradeoffs among goals is a policy decision.

INTRODUCTION

Reports of aquifer status from many parts of the world suggest that all is not well with our groundwater resources. Symptoms of management problems begin with extraction rates that exceed natural recharge. Primary symptoms of problems are: over-rapid exhaustion of stocks and the consequent increase in pumping costs. Further symptoms of less-than-optimal aquifer exploitation include intrusion of poor quality water; subsidence of overlying lands; interception of related flows in wetlands and streams; adverse effects on smallholders' wells from larger and deeper wells; and community economic decline as aquifers are too rapidly exhausted.

Aquifers are exploited by mankind. Adverse effects of over-exploitation are significant as they affect human activities. Hence, the study of humankind's role in aquifer exploitation can be claimed to be at least as important as is the study of the role of geohydrology. Underlying the subsequent analysis is the thesis that aquifer over-exploitation is basically a failure to design and implement adequate institutional arrangements to manage the people who exploit the groundwater resource.

From the broadest perspective, aquifer exploitation can bring about either or both of two types of social dilemma problems. First, overdraft is an example of a class of resource problems, usually called 'common pool' problems. A common pool resource can be defined by two characteristics. The first is subtractibility (meaning that a unit of resource withdrawn by one individual is not fully available to another individual user). The second is high costs of exclusion of potential beneficiaries from exploiting the resource. Fugitive or mobile resources, such as water, petroleum or migratory fish or wildlife are typical examples of high-exclusion cost resources (Gardner *et al.*, 1990).

Common pool problems or dilemmas arise when individually rational resource use decisions bring about a result that is not optimal when considered from the perspective of the exploiters as a group. Gardner *et al.*, (1990) specify the following additional conditions as necessary to produce a common pool resource dilemma. First, there are many appropriators or users withdrawing the resource. Second, the actions of the individual users, given the particular situation with respect to the resource itself, the characteristics of users, demand for the resource and extraction technology bring about suboptimal outcomes from the group's viewpoint. Finally, there must exist institutionally feasible strategies for collective management of the resource that are more efficient than the current situation (see also Ostrom, 1990). The roots of the problems associated with common pools are found in the inadequate economic and institutional framework within which the resource is exploited. Common pool resources have been typically utilized in an 'open access' framework, within which resource ownership is according to a rule of capture. When no one owns the resource, users have no incentive to conserve for the future, and the self interest of individual users lead them to over-rapid exploitation. The characteristics of the economic institutions governing their use is the fundamental issue in managing common pool resources.

The second type of social dilemma frequently associated with groundwater exploitation is the imposition of *external costs* or 'externalities'. External costs are unwanted and uncompensated costs imposed on third parties who do not themselves benefit from the exploitation activity. In the presence of significant externalities, the private calculations of the costs and benefits by exploiters in this case also do not yield a collectively optimal rate of exploitation. Two types of externalities can be identified for purposes here: *technological* and *pecuniary*. Technological externalities are those that are registered through technical or physical means, such as through the hydrogeologic system. Pecuniary externalities have their effect through the economic or market system, via their influence on supply, demand and/or prices and incomes. In the macroeconomic context, pecuniary externalities may be regarded as merely income transfers, not real welfare effects (in the local context, they are still important to agents in the local economy. See Howe, 1987). Technological externalities can be further subdivided into *reciprocal* and *unidirectional*. In the case of reciprocal externalities, each agent imposes costs on all others and each experiences costs imposed by others, while in the case of unidirectional externalities, an agent or set of agents impose an externality on another, or others, but not *vice versa* (Dasgupta, 1982, p. 31). Each of these types may be individually or jointly the source of an important suboptimality, or problem, in managing groundwater. An example of a reciprocal externality in groundwater exploitation is the jointly experienced pumping cost increases, as the water table declines when withdrawals exceed recharge. Unidirectional externalities can be exemplified by intrusion of poor quality water or by damages from subsidence of overlying lands. The case of pecuniary external costs can be illustrated as the reduction in business activity and income and loss of wealth in the regional economy via its linkage to an over-rapidly exploited aquifer.

The excellent papers collected in a previous conference volume (Custodio & Gurguí, 1989) provide heretofore unavailable detail on groundwater economics. Here I hope to go further into public policy aspects of groundwater management. My essay for this volume is designed to provide an introductory economic and policy analysis perspective for non-social scientists on the problem of aquifer management, and to show the potential contribution of the social sciences to this topic. The analysis is organized as follows. First, conditions for an optimal extraction rate are identified, and the economic definition of over-exploitation is presented. Economists and policy analysts can aid in proposing and evaluating alternative aquifer management policies. The remainder of the paper addresses policy options for managing aquifers, with emphasis on managing people. The existing literature on economics and policy relating to natural resources and the environment is drawn upon freely (see Dasgupta, 1982 and Pearce & Turner, 1990).

THE ECONOMIC CONDITIONS FOR OPTIMAL AQUIFER EXPLOITATION

Preliminaries

Managing an aquifer can be viewed as a special case—one of many—of allocating scarce resources among competing ends or uses and over time. The conditions under which resources are optimally allocated are the subject of microeconomics. Recent years have seen a large growth in the application of microeconomics to the study of natural resource and environmental policy (Dasgupta, 1982; Pearce & Turner, 1990).

The list of undesirable consequences frequently associated with groundwater exploitation, recounted in the Introduction, are seen by economists as 'resource allocation problems'. Optimal resource allocation determines how much of a resource should be devoted to each alternative production and consumption process, in combination with how much of other resources in each time period. The prescriptive application of the theory of resource allocation is termed welfare economics (Wolf, 1988). Welfare economics is based on the recognition that value judgements are necessary when policy decisions are to be made, and makes such judgments explicit. The value judgments underlying the application of welfare economics theory to resource allocation are: first, that individual preferences, expressed in market purchases and sales, are the appropriate basis for measuring welfare in resource allocation decisions, and second, the distribution of purchasing power in the community conforms to ethical standards. Under the proper condition, market allocation results in the maximum value of production. For short, economists usually speak of economic efficiency as the objective to be maximized in resource allocation problems.

Along with water resources in general, groundwater exploitation seems to present several conditions that violate the assumptions of the prescriptive model of resource allocation (Young, 1970). These conditions arise from the interdependency among users, which is characteristic of the water resource; because of the mobile, flowing nature of the resource, the actions of individual users affect the production and welfare possibilities available to other users. One violation arises from the absence of property rights and the consequent difficulty of excluding other exploiters from extracting each other's water. This is an example of the 'common pool' problem discussed above. The second violation is the 'externality', or 'spillover' problem. In the presence of substantial external effects, the calculations of costs and gains by individual users fail to reflect the total impact on society, and a suboptimal allocation of resources can result.

Optimal exploitation rates and definitions of 'over-exploitation'

A simplified graphical representation can help illustrate the essential elements of the groundwater management problem. The model incorporates the interaction of hydrogeologic and economic forces. We can develop the analysis to portray the prototypical case: extraction of water by numerous small agricultural enterprises. The following assumptions are made to facilitate the initial analysis:

- (a) the water is extracted by a variable number of pumpsets. The pumpsets, consisting of wells, pumps and water distribution equipment, are all identical in size. The land area irrigated from each pump and the potential list of crops grown on that land are the same, so each pump produces an identical amount of water each year. The number of pumpsets, the amount of land irrigated, the area of specific crops and the annual water pumped are all private decision variables.
- (b) the aquifer is homogeneous with respect to storage coefficient and depth to water throughout its region.
- (c) spatial distribution of pumping is uniform, and/or the lateral rate of water movement is rapid, such that the depth to water throughout the region remains uniform at any time during the planning period.
- (d) recharge (natural, artificial and that due to irrigation in excess of evapotranspiration needs) is instantly and uniformly available at the saturated zone.
- (e) decisions to invest in new extraction capacity are made on the criterion of long-term private profitability—pumps are installed only if the expected present discounted stream of annual revenues net of costs is positive.

(f) commodity prices, input costs and interest rates are constant over the planning period, and are unaffected by aggregate aquifer extraction rates.

Figure 1 can help us to understand the individual and collective economic impacts of alternative levels of pumping capacity. The horizontal axis measures the available alternative annual pumping rates. For simplicity, assume that the choice is among any of a range of constant annual pumping rates, to be determined for an entire prespecified planning period. The vertical axis represents the present discounted value of economic costs and benefits associated with alternative annual pumping rates.

The curve labelled B(E) represents the present value of revenues, or benefits, associated with alternative levels of extraction. Increased groundwater extraction capacity will at first yield a corresponding higher economic benefit. However, increased extraction eventually may bring other forces into play. It may cause commodity prices to fall and/or force the producers to seek crops of lower net return per unit of water extracted, and/or force production onto less-productive lands. Hence, the curve B(E) increases at a decreasing rate and eventually reaches a maximum and begins to fall.

The curve C(E) represents the present value of costs related to potential alternative extraction levels. *Costs are understood to include not only conventional direct operating and investment expenses, but also two additional special cost components.* One special cost component is termed 'user cost'. The term refers to the present value of foregone future benefits sacrificed by present extraction. The other special type of cost is a spillover, or external cost (a reciprocal externality), reflecting the added cost of pumping imposed on other users from the general water table decline stemming from any one pumper's extraction. With higher annual extraction rates, total pumping costs as portrayed by C(E) rise as depth to water increases.

The curve NB(E) in the lower part of Figure 1 reflects the present value of **net** benefits, the arithmetic difference between B(E) and C(E). This concept, the difference between total revenue and total cost, is sometimes termed the 'economic rent'.

The well-known conditions called the 'tragedy of the commons' can be identified in Figure 1. In the absence of controls on new extraction capacity, a rule of capture situation prevails; water users only have rights to water if they capture it and put it to use. This situation is sometimes called an 'open access' property regime. Individual farmers will continue to install pumpsets so long as prospective returns are positive. However, more pumps will increase costs for everyone more rapidly than revenues are rising. With sufficient additional pumps, **net** benefits are reduced to the point where no additional investment is attracted to exploit the aquifer. This equilibrium is reached at the level of pumping where total present value of costs are equated with total present value of benefits, or equivalently, where net present benefits, or rents, reach zero. On Figure 1, the open access equilibrium point is labelled $\hat{E}$. In these circumstances, the equilibrium level of extraction equates the total present value of revenues, with the total present value of costs. All economic rents or profits are dissipated.

Suppose, however, that the aquifer were managed according to the economist's preferred criterion of maximum net return (or maximum economic rent) to the entire aquifer. That

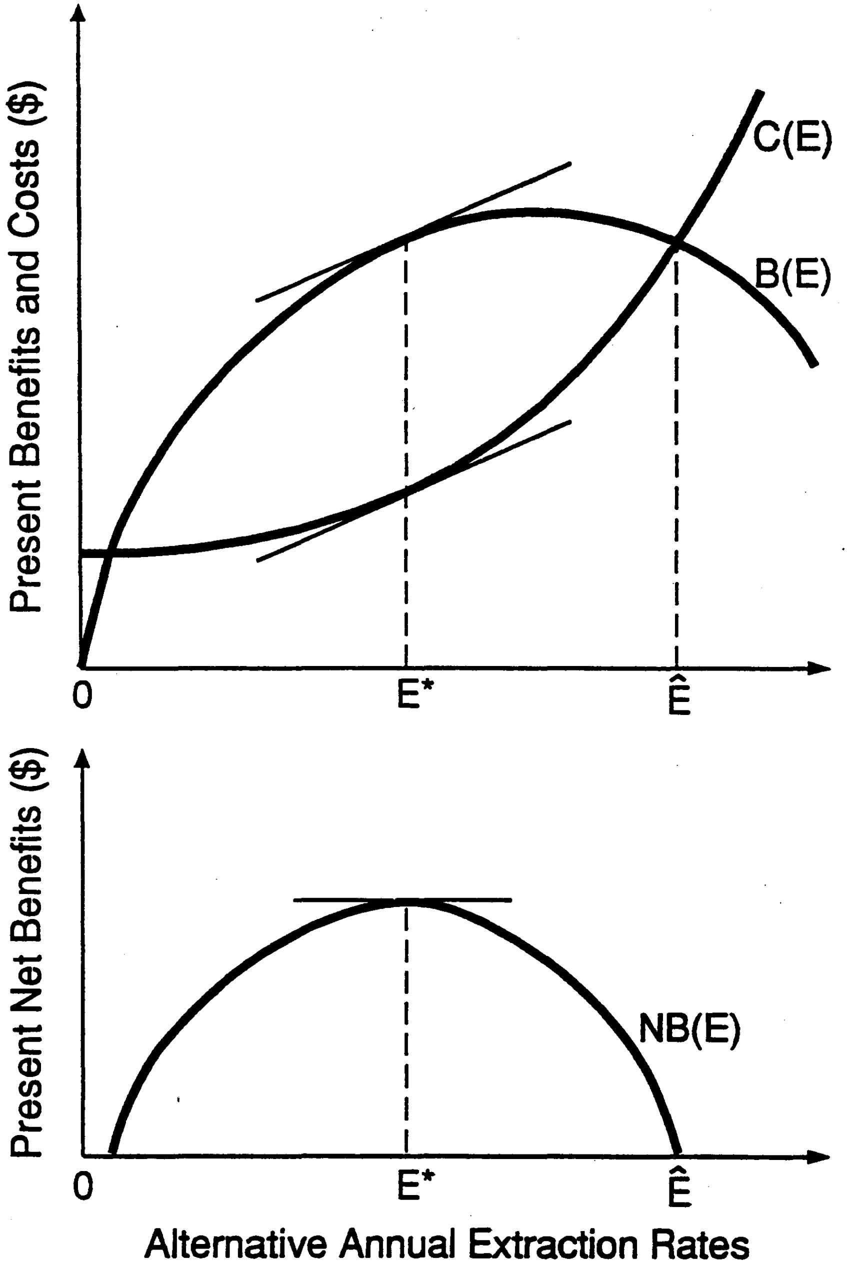


Figure 1: Present value net benefits for alternative extraction rates.

condition obtains where NB(E) is a maximum or equivalently, where the slopes of B(E) and C(E) are equal. This point is identified as E* on Figure 1, and represents the amount of extraction that would be chosen by a single monopolist owner of the resource. This rate of exploitation is, of course, much lower than obtains at the open access equilibrium, and will more effectively serve to preserve the aquifer on a sustainable basis, in addition to generating a much larger present value of economic return. ***Economists would then define 'over-exploitation', in the above formulation, as any pumping rate in excess of that which yields the maximum present value of net benefit.***

Dynamic modeling approaches: An aside is in order here regarding more sophisticated approaches to determining optimal extraction rates. For pedagogical simplicity, I have up to now assumed that the policy decision was only to choose an optimal annual pumping rate, a rate that once selected, would remain constant or fixed for the entire planning period. A more rigorous solution (developed first by Burt, 1964), incorporates dynamic optimization methods. The optimal annual pumping rate is, for any year, derived from a decision rule, which is defined as a function current aquifer stocks (the decision rule is further conditional, as was the simpler formulation, on demand, cost, interest rate, and aquifer parameters.) This approach requires pumping rates to vary between years; larger extraction being optimal in early stages of aquifer exploitation, but appropriate pumping rates declining to approach recharge rates when stocks have been severely depleted. The method captures the value of stocks to avoid higher pumping costs and as insurance against shortage. Application of this type of decision rule would yield a higher net present value than the simpler model maximizing present net benefits among fixed annual pumping rates. The dynamic optimization approach has been applied to several case studies (see Feinerman & Knapp, 1983). A notable example was the extension to a multiple aquifer, multiple demand source case by Noel *et al.* (1981).

Annual recharge does not define the economic optimum pumping rate: Some authorities assert that the appropriate level of pumping is just that which equals the annual average rate of recharge (the 'safe yield'), implying a policy that precludes any drawdown of aquifer stocks at all. The economic approaches just described clearly take a different tack, calling for some utilization of stocks if demand so requires, but scaling back extraction rates as the aquifer becomes depleted. This illustrates the important point that aquifer management should be recognized as a political, not a technical decision. Social values must come into play in making the collective aquifer optimization decision, and making tradeoffs among values is primarily a political matter.

The analysis developed above and the dynamic counterpart can be employed to assess the desirability of proposed alternative aquifer management policies. The economic approach to managing common pool resources adopts the criterion of maximizing present net returns. Effective policies must lower extraction rates to the optimal level, E*, or alternatively find substitute economical water supplies to replace the excess exploitation.

Optimal extraction rates with unidirectional externalities

A second type of externality is now incorporated into the analysis. In the previous section, reciprocal external costs were part of the source of inefficiencies from open access groundwater exploitation. Reciprocal externalities are those in which each agent inflicts costs on all others. In this case, they take the form of jointly experienced pumping cost increases, as each pumpers' influence on the stock of water adversely affects pumping costs of all. An alternative type, the unidirectional externality occurs where a particular agent (or agents) imposes an unwanted cost on others but the reverse is not the case (Dasgupta, 1982; p. 31). The future benefits to a receptor group are directly affected by the actions of source agents, actions over which the receptors have no control.

In the context of groundwater exploitation, examples of unidirectional externalities are readily found. The intrusion of poor quality water, such as sea waters encroaching as coastal aquifers are dewatered, is a principal case. Subsidence of overlying lands from extensive pumping may damage roads, railroads, buildings or other structures. In coastal areas, subsidence may subject low-lying areas to flooding during high tide and/or storm events. Groundwater exploitation may intercept flows in streams interrelated with the aquifer, adversely affecting those relying on streamflow for, say, irrigation of agricultural crops. A related case receiving increasing attention is the drainage, due to nearby groundwater exploitation, of wetlands that may serve as habitat for fish, waterfowl, or other forms of wildlife. Finally, exhaustion of groundwater supplies by farms may be linked to community economic and social decline, as farmer purchases in the regional economy and participation in the community decreases.

The optimal level of aquifer exploitation in the presence of unidirectional externalities can be illustrated by reference to Figure 2. We begin with the same basic framework as in Figure 1, but introduce the additional relation D(E) to represent economic costs of third-party damages. Expressions such as D(E) are called 'damage functions'. Direct plus reciprocal costs C(E) and damage costs D(E) are assumed to be added together to derive the full social costs of extraction, denoted SC(E) in Figure 2. The corresponding Social Net Benefits are shown in the lower part of the Figure.

Not surprisingly, incorporation of damage costs into the analysis yields a similar, but when compared to the analysis in Figure 1, an even more restricted solution to the question of the optimal level of extraction. The pumping rate yielding maximum net rents (shown by the equality of slopes of B(E) and SC(E) or by the maximum of the curve SNB(E) in the lower part of Figure 2) shifts to the left to the point labelled E**.

Aquifer over-exploitation is defined as non-optimal exploitation

We are now in a position to offer an economic definition of 'over-exploitation'. In terms of the above discussion and Figure 2, over-exploitation can be said to occur when the rate of extraction exceeds that represented by E**. Any rate in excess of E** will result in incremental extraction and external costs greater than the incremental value of production. Note here that E** allows for some 'mining' of the resource above levels of natural recharge. It also permits some imposition of unidirectional external costs.

An alternative perspective: Mention should be made here of an alternative perspective on determining the optimal level of exploitation, in the presence of unidirectional externalities. The mainstream economic model presented above is derived from a form of classical Utilitarianism (based on the criterion of 'greatest good for the greatest number'). However,

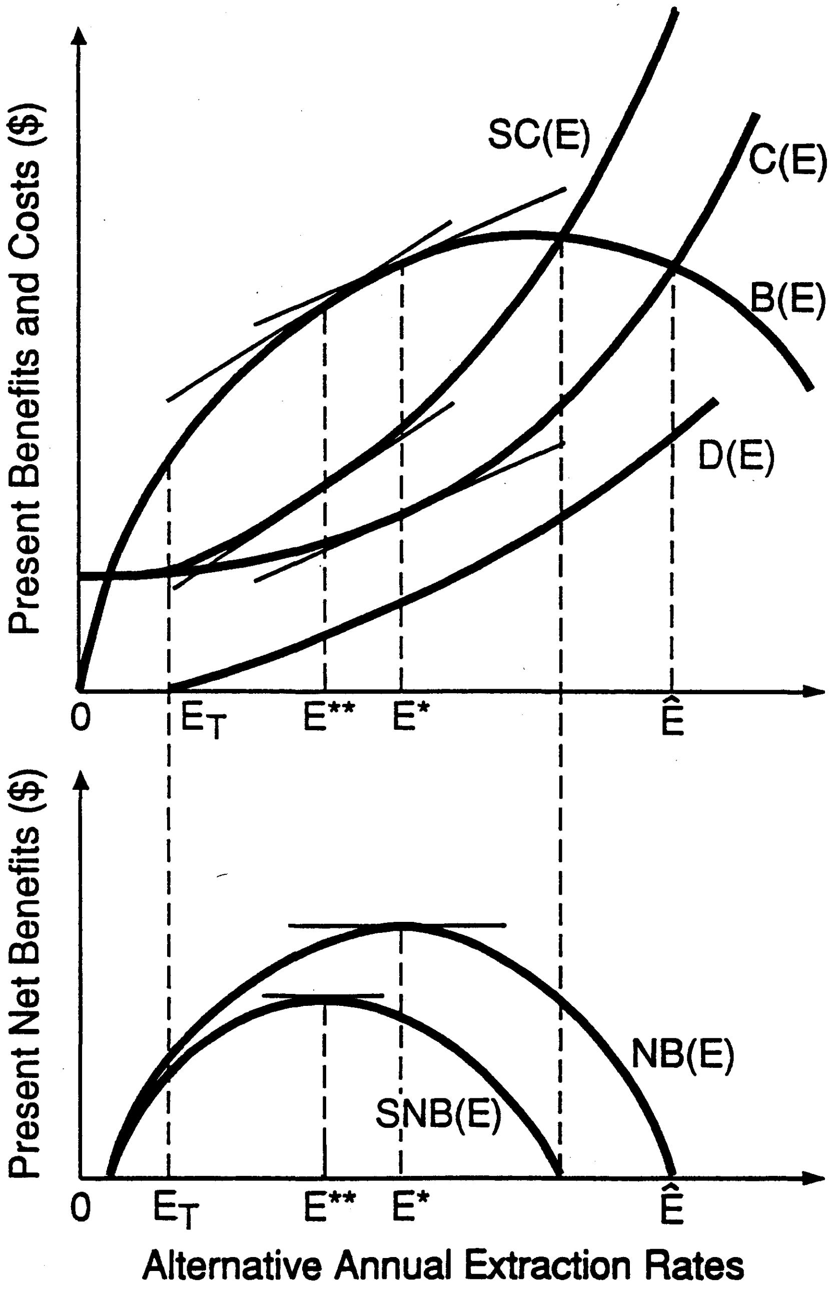


Figure 2: Present value net benefits for alternative extraction rates (with externalities).

it ignores distributional considerations (who gains versus who loses) as it urges maximum social net economic benefits. External costs imposed on unwilling recipients ('unwanted costs'), have in the mainstream model, the same status as do conventional direct investment and operating costs. Hence, the social optimum leaves receptors bearing some of the damage costs because they are the 'least-cost avoiders' when compared with the direct costs or benefits foregone incurred by the exploiters of the environment. An increasingly influential objection issues from certain environmental policy writers, e.g. Kelman (1981), Goodin (1983), Bromley (1989), who contend that receptors should be entitled to freedom from unwanted external costs. According to some versions of this view, all exploitation in excess of the threshold of damages should be proscribed, so the appropriate extraction level should be at or less than the damage threshold, the point labelled ET in Figure 2. Whichever philosophic position is adopted, the question still remains on how to choose policies so as to achieve the desired level of pumping. I now turn to that issue.

POLICIES FOR MANAGING OVER-EXPLOITATION: OVERVIEW AND CRITERIA

Numerous approaches are possible for ameliorating or solving overdraft problems, and economic analysis can contribute to choices among these. The general approaches can be conventionally grouped broadly into two classes. The first group includes supply-side or 'structural' techniques, which usually involve some form of water supply augmentation. The second class encompasses demand-side, user-targeted 'non-structural' methods (White, 1969). I shall emphasize the differences in these approaches by calling the first group of policies 'managing the water' and the second group "coordinating the people." Engineers and technical scientists often seem to be more comfortable with structural approaches, and prefer to avoid the messy arena of people management. Both approaches can make important contributions to needed solutions; indeed, the best approach is likely in incorporate a combination drawing from each.

Establishment of a groundwater management system is essentially a political, not a technical exercise. It involves selection among strategies which variously satisfy competing criteria or goals. Criteria in addition to economic efficiency are appropriate for assessing policies, and need to be made explicit.

Before elaborating on the topic of normative or value criteria, a digression is in order. Over sixty-years-ago, the Vienna Circle philosophers began development of an influential doctrine regarding the pursuit of knowledge. Logical positivism, as this approach came to be called, emphasized the pre-eminence of a combination of observation and logic to validate propositions. The positivist school tended to regard normative or value statements as non-factual and, therefore, ungrounded. Positivism has come under increasing challenge, including that aspect relegating value statements to the purely subjective realm. It is increasingly recognized that certain normative statements can be validated with methods similar to those employed in the sciences and that careful study of normative and ethical systems is necessary to fruitfully design public policy (see Johnson, 1986, for a persuasive review of these emerging views).

Several criteria are appropriate for assessing management strategies

Most of us would subscribe to such basic values as respect for the dignity of the individual, openness, and the rule of reason and broadly, improving quality of life. At an operational level, we find more tangible criteria. The list of criteria provided here draws from several sources, including Maass & Anderson (1978), Stone (1988), Bohm & Russell (1985; p. 399), and Goodin (1983), each of whom provide (frequently overlapping) lists of dimensions upon which policy instruments might be judged. Five major and six secondary criteria are identified.

We begin with the major criteria: efficiency, equity, security, liberty, and avoiding harm. Maass & Anderson (1987) list ***economic efficiency***, which refers to getting the most value of output from any given input. In the present context, efficiency means the ability to achieve the goal of maximizing net economic returns to the water resource. In a longer run, dynamic, economic context, efficiency can only be achieved if the system is flexible in the face of economic change, responsive to the emergence of alternative higher-valued water uses. Changing conditions may bring with it the need to shift water use to more productive activities-such as to areas with better soils within the farm sector or to more valuable industrial or other urban uses. ***Equity*** refers to the desirability of treating like persons in like fashion. From Stone, we adopt security and liberty: ***Security*** means satisfaction of minimum human needs. ***Liberty*** refers to the ability to do what one wishes so long as it doesn't interfere with others. ***Avoiding harm*** refers to the criterion found in the environmental philosophy literature (e.g. Goodin, 1983, p. 14-15) asserting that it is worse to create costs on others than to fail to produce equally large benefits.

Secondary criteria include five items. 1) ***Local control and popular participation*** have been shown by Maass & Anderson (1978) to be important in shaping workable and palatable water management strategies. 2) The same authors also emphasize ***orderly conflict resolution processes*** as a necessary component of an effective management strategy. 3) Bohm and Russell suggest ***information intensity***, which is concerned with how much data and what degree of modeling and predictive skills are required for implementation. 4) ***Ease of monitoring and enforcement***, also listed by Bohm & Russell (1985), involves the relative complexity of measuring (and interpreting the measurements of) extraction in order to enforce compliance. (5) What might be termed ***Social considerations*** can affect the choice of policy measure. An example is the view, apparently widely held, that for water, a substance essential to life and important to community stability, social control via an economic instruments such as pumping taxes, exchangeable property rights and pricing is inappropriate or at least should be carefully circumscribed.

Most of the criteria or goals listed below are usually non-compulsive, which means that when they are in conflict, some weight is typically assigned to each goal. No individual criterion 'trumps' or over-rides all others and tradeoffs are made in the political process. Different cultures are likely to assign different weights to the various goals, and thereby choose differing policies under similar physical circumstances.

MANAGING THE WATER: STRUCTURAL APPROACHES

Structural approaches to dealing with aquifer over-exploitation generally involve developing some alternative source of water supply. These solutions usually will draw on some distant surface water source, calling for conventional storage reservoir and conveyance facilities, and increasingly involve interbasin transfers. Of course, improving technical efficiency, such as by reducing conveyance and storage losses in the existing water supply system, requires early consideration. More technologically advanced proposals include desalination, although the high energy and capital costs of available desalination techniques has made it economically feasible only in special cases.

For the most part, economic analysis techniques associated with structural water supply options are well-developed, and need no elaboration here (see Howe, 1971; references cited in Young & Haveman, 1985).

One special form of technical solution calls for additional comment; groundwater recharge. When water is seasonally available in quantities exceeding immediate demands, using the excess to replenish the aquifer may be an economical policy. Storage in aquifers often has the advantages of plentiful capacity, low cost and no evaporation losses. Waste water is an important candidate for recharging aquifers. When groundwater is of good quality, waste water often can be 'treated' by recharging. However, technical problems with artificial recharge may include clogging, or siltation, of the soils in the recharge area or facility, inadequate depth to water table and water quality. Moreover, the costs of recharge must be balanced against the gains from using the water directly. Groundwater replenishment, in addition to the capital costs of recharge facilities, involves the additional energy expense of pumping the water back to the surface. The limited economic literature indicates that special conditions are necessary for economic feasibility. The value of storing water in the ground must exceed the cost of recharge plus the opportunity cost of water for recharge. Such cases arise when, for example, (a) water quality can be improved by recharge, (b) when water is seasonally available low opportunity cost, or c) recharged water will help prevent salt water encroachment (Brown & Deacon, 1974; Reichert & Bredehoeft, 1984).

COORDINATING THE PEOPLE: NONSTRUCTURAL APPROACHES

Nonstructural approaches are demandside policies, which involve coordinating the people. Most over-exploitation problems are inherently ones of unmanaged demand, so non-structural methods play a particularly important role in dealing with over-exploitation. Demand side methods can be fruitfully classified into 'institutional innovations' —which change the incentive structure facing pumpers— and 'cognitive' approaches —which attempt to change behavior by either education of persuasion-.

An essential characteristic of the common pool problem is that the actions of numerous individual and independent actors (including firms, households and even government agencies) affect the outcome. In the case of a potential overexploited aquifer, the pumping decisions of many types of pumpers can influence the stock of water, and hence, the future availability and cost of water and the degree to which side effects are registered. Pumpers will likely differ among themselves in production technologies and product mixes. Aquifers, in reality, are quite spatially heterogeneous in their characteristics, such as depth to water, saturated thickness, storage coefficient, and transmissivity.

Cognitive methods are inexpensive but of limited effectiveness

'Cognitive' approaches to modifying human behavior generally involve transmission of new information to the water user (Heberlein, 1974). Educational and informational programs employed to change beliefs or motivation are typical examples. The news media or formal group meetings of water users can be used to transmit knowledge. Both written and oral means can be utilized. An instance of modifying beliefs might be to provide individual pumpers with data on annual aggregate rates of pumping together with predictions of the corresponding changes in water table and pumping costs. Another example might be the publicizing of adverse third-party effects, such as salt-water intrusion or land subsidence. Appeals to the group to place collective interests above individual benefits is an example of attempts to change motivations.

Cognitive fixes are attractive in some respects but also have limitations. The avoidance of apparent or actual coercion is appealing in light of the value criterion of individual freedom. Cognitive approaches are likely to be much less costly than supply side or structural methods. The principal disadvantage with cognitive approaches is their limited effectiveness. Individual beliefs and attitudes are difficult to change and modified behavior is not likely to permanently follow (Heberlein, 1974). The fundamental problem of over-exploitation is not inadequate information, but an inappropriate incentive structure. Nevertheless, because of its low cost, the cognitive approach may be fruitfully applied in conjunction with structural and/or institutional methods. It may particularly be useful for increasing understanding and acceptability of the necessary costs of alternative approaches.

Institutional arrangements coordinate activities of individual water users

We can think of the activities of the people who produce and use groundwater as being coordinated by 'institutional arrangements'. As used by Fox (1976), this term refers to an interrelated set of *organizations and strategies* that serve to coordinate activities to achieve social goals. Organizations provide the necessary administrative mechanism in contact with the individual groundwater user to set the ground rules and administer the chosen policy strategy. Strategies -also called 'policy instruments'- serve to change individual behavior, to get people to do what they otherwise wouldn't do. They can take several forms (Stone, 1988, Part IV). One form consists of 'inducements', which include financial rewards and/or punishments. A second classification is that of 'rules' which determine permissions or entitlements to or limits on behavior.

Administrative organizations are a necessary element of institutional arrangements

Several alternative administrative organizational structures for controlling groundwater can be visualized. These include: a) granting a monopoly for the extraction of water to an organization or agency; b) national or state government oversight of water users;

c) management by the users themselves; or d) some combination of the latter two. These are briefly touched upon in turn.

Centralized or monopoly control of groundwater extraction by a government agency could be imposed to solve the overdraft problem. The organization could extract at the optimal rate and sell water to users at cost. I understand that in Israel a central water agency retains control of both surface and groundwater supplies, and sells to users within a combination quota and increasing block pricing system. I am not aware of any other examples where centralized control has been adopted. Centralized ownership and control may present an unacceptable conflict with the local control and individual liberty criteria. Further, government ownership of the means of production is seldom as economically efficient than are decentralized approaches.

Management of groundwater by the water users themselves is attractive option, based primarily on the criterion of local control. Solutions to commons problems by collective action by user-groups have been successful in some instances. Such management regimes have recently come to be termed *common* or preferably, *communal* property (Ostrom, 1990).

No instance of long-term success of strictly communal management of an aquifer system has come to my attention. My conjecture is that external legal authority is necessary to enable such organizations to function effectively. Hunt (1990) persuasively argues that water-user groups will effectively self-organize only if both internal and external jurality are present. External jurality refers to the case where the group and it regulatory strategies have legal standing from entities outside the user group, such as with the national, provincial, or state government. Internal jurality exists when members of the user-group are organized so that they can appoint the system's manager(s) and impose sanctions for inadequate performance, and when the users effectively participate in decisions regarding acquisition and distribution of the water.

The major obstacle to successful internal control is the unwillingness of members from within a community to sanction other members of the group for failure to follow rules. People do not, in general, enjoy causing difficulties for their neighbors or friends. Continuing good relations with co-members of the group is valuable asset. Externally sanctioned inspectors and inducements, limited as they are (Wolf, 1988), are more likely to succeed in preserving an aquifer than the actions of a group alone.

The local groundwater management district is the organizational arrangement that best combines these characteristics. Local districts are frequently employed (in the U.S., at least) to provide many types of limited and local collective goods and services. Education, sanitation, and health provision, in addition to water supply, are examples. The organization is largely governed and financed by its beneficiary group; however, a higher level legal entity, such as the state or national government, sets the basic ground rules, retains oversight responsibilities, and provides forums for dispute resolution. Examples of groundwater management districts that exhibit these characteristics are given by Ostrom (1990) and Whipple (1988).

Allocating shares of the aquifer

When regulation of an aquifer is undertaken, and a total annual water withdrawal is determined, a basic issue is how to divide the withdrawal rate among existing and perhaps potential pumpers. Several criteria come into play on this question. Frequently employed in agricultural water use, including irrigation with groundwater, are the doctrines of a) *prior appropriation*, and b) *proportionate equality*.

The criterion of prior appropriation holds that whoever is first to exploit a resource confirms an entitlement to continue that degree of exploitation. This concept is sometimes described by the phrase 'first in time, first in right'. Those first to bring a well into production come to believe that their customary patterns of use are a permanent right.

However, use-rights must be constrained to avoid conferring an inequitable degree of benefit on one or a few individuals. The criterion of proportionate equality can be applied so as to limit the amount of water withdrawn, for example, in proportion to surface area irrigated (Maass & Anderson, 1978, p. 41).

INCENTIVE AND SANCTION SYSTEMS CAN INFLUENCE INDIVIDUAL PUMPER BEHAVIOR

Two general types of incentive-based strategies can be employed to influence the behavior of pumpers in an over-exploitation situation. One type includes financial incentives, both positive and negative. The other consists of permits and entitlements. Consider first the financial inducements.

Pumping charges or taxes as policy instruments

A charge to pumpers appears at first glance to be a potentially suitable method of achieving an economically efficient rate of extraction (Cummings, 1971; Brown & Deacon, 1974). An appropriately scaled charge could serve to confront the pumper at once with both the foregone user cost and the external cost (from increased pumping costs) imposed on neighboring pumpers. However, in the case of aquifer management, this approach faces a difficulty in that the costs in question are registered on pumpers themselves (that is, they are reciprocal), and are not unidirectional spillovers upon parties outside the group enjoying benefits from the aquifer. A charge collected to internalize user costs and external costs by an outside government or management agency could, in principle, achieve an optimal extraction rate. However, the reduction in use would be at the expense of redistributing rents to the taxing authority. It would dissipate net income to the aquifer exploiters as quickly as would an open access regime, although the total net rents would be increased.

In an earlier study (Bredehoeft & Young, 1970), I was involved in analyzing the concept of a pumping charge as an instrument for aquifer management. We avoided the income redistribution effect by contriving a form of charge in which the revenues were assumed to be refunded to users in such a way as to be independent of pumping decisions. Although it worked quite nicely in a simulation model, subsequent reflection has convinced me that this concept is unworkable in the real world. A basic difficulty is finding a mechanism that the tax revenues would be refunded in a way that the charges are actually separated from the tax in the mind of the pumper. Another problem with a pumping tax arises from the short-run nature of the pumping decision. Pumpers likely optimize by equating marginal returns with short-run marginal costs. A relatively large tax is necessary to influence short-run pumper behavior, but such would be larger than the external costs a management authority would wish to internalize. A tax would have no advantage over a quota on informational or enforcement grounds, but a tax that could influence pumping would redistribute income from pumpers to the taxing entity. Finally, for agriculturalists, imposition of a large new tax would bring about severe capital losses on overlying landowners by reducing net returns to the farm, thereby deflating the market value of their property. I conclude that taxes are not preferred policy instruments. This conclusion is reinforced by the apparent absence throughout the world of any successful aquifer regulation system based on financial disincentives alone. This is not to argue that some limited tax to support the operation of the local regulatory organization would not be appropriate.

Subsidies: A financial incentive with similar potential effects on extraction rates as a tax or charge is a subsidy. Subsidies can be either direct or indirect. A direct subsidy could be paid by a government agency to individual users to encourage reductions in pumping. However, subsidies have opposite wealth-distribution effects. Probably because of the perceived undesirability of transferring wealth from the general treasury to a small group of water users, no example of this approach being actually implemented has come to my attention.

However, indirect subsidies to reduce over-exploitation have been adopted. An indirect approach could subsidize technologies that reduce water demands, such as sprinkler or pipe systems, which reduce irrigation losses. Such subsidies have been offered in the U.S. as part of general programs to encourage resource conservation. The U.S. Federal government also provided most of the funding for a major water supply project to replace groundwater overdraft in Arizona, under the condition that the state government implement a program to substantially reduce groundwater extraction rates.

I personally can generate little enthusiasm for subsidies of either form in the present context. In general, it would seem more appropriate that solutions to over-exploitation be primarily implemented at the local and regional level, and whatever costs are entailed should be borne by those who have and will receive benefits from aquifer exploitation.

Quantity-control approaches

We can conceive of several types of quantity-control mechanisms to help avoid over-exploitation. These can range from simple well permits to exchangeable pumping entitlements.

Permits: Well and pump permits, which grant the right to develop and operate a pumping system are one response to the need to regulate pumping. Such a permit might entitle a potential groundwater user to install and operate a well of a particular capacity at a specified location. The permit, in the case of irrigation withdrawals, could also identify the lands on which water pumped from the well could be put to use. It could forbid transport of water to other sites. A permit for a new well would be granted only if it would be located far enough from existing wells to avoid excessive damage to existing extractors. For example, the state of Colorado, USA, in non-renewing groundwater situations identifies designated groundwater basins, in which new well permits must meet criteria of not exhausting more than 40 percent of stocks located within a three-mile radius within a twenty-five year period. Other than being limited to irrigating specified lands, these particular permits, however, do not provide for any limits to the quantity of water pumped; the economic limitations imposed by pumping costs and crop demands are assumed to inhibit excessive withdrawals.

Permits represent a step toward the goal of avoiding the problems of over-exploitation. They can, with appropriate specification of size and spacing criteria, achieve a slowdown of extraction rates. They are relatively easy to monitor and where pumpers strongly reject more stringent regulatory devices, may be reasonably palatable to pumpers. However, permits are mainly applicable when problems are not yet severe or complex. Permits can be effective at early stages of over-exploitation, when preventing new pumps will suffice to solve the problem, or when pumped water is not exported away from the area overlying the aquifer. However, in more serious cases, where existing users must all reduce annual extractions, some form of regulation of actual rates of withdrawals must be given consideration.

Pumping quotas: A more precise quantity control mechanism might be a pumping quota, which would specify a fixed annual rate of extraction to each water user. The initial quantity might be assigned in proportion to use in a base period (which might, however, set off a pumping race to establish initial rights), or be based on proportion of land owned which overlies the aquifer. The technology for metering withdrawals is neither complex nor expensive, so if the pumpers are willing to be metered, regulatory monitoring and enforcement need not be difficult. In principle, pumping quotas are no different than conventional surface water rights, which entitle owners to fixed shares of each year's available flows (however, anecdotal evidence suggests that farmers who have previously exploited an unregulated aquifer come to believe they are entitled to unlimited withdrawals for use on lands overlying that aquifer. They may be reluctant to submit to metering and, once installed, meters are reportedly subject to high rates of unexplained 'breakdown').

Very small wells, for livestock or for individual households might be exempted from the permit and quota system. At moderate levels of overdraft, the cost of monitoring might outweigh gains from reduced pumping. For income distribution reasons, small holder units might not be restrained from exploitation.

Aquifers and their patterns of exploitation are frequently not homogeneous. Hydrogeologic characteristics, such as saturated thickness, storativity depth to water or water quality, frequently are quite variable across a particular groundwater deposit. Demand characteristics may also not be uniform. Soil productivity factors (texture, depth, fertility) influence agricultural demands, while proximity to urban centers and the availability of alternative surface water supplies can affect urban and industrial needs for groundwater. In recognition of these supply-side and demand-side variations, aquifers can be divided into zones and differing extraction policies applied to each zone.

Nunn (1985) insightfully recounts the evolution of management options to respond to over-exploitation of an artesian aquifer near Roswell, New Mexico, USA. New pumpers were prohibited beginning in 1931. At the same time a conservancy district was formed, one of whose major tasks was to plug abandoned artesian wells. In 1967, meters were required, and an annual water duty of three acre-feet per acre was imposed. Rights to use can apparently be transferred to other places and/or types of use in the immediate region, subject to the usual appropriative doctrine protections against adverse third party effects (Nunn, 1985, p. 884).

Transferable pumping entitlements: A fixed quota is likely to be too inflexible in the face of changing water stocks, demand conditions and changing value of alternative water uses. Transferable pumping entitlements have been proposed by economists as an instrument which can accommodate both of these concerns.

One version attributed to Smith (1977) is described by Anderson, Burt & Fractor (1983). Rights to groundwater would be fully privatized; a well-defined, enforced and transferable pumping entitlement would be established. The pumping right would be divided into two parts, one component providing a claim to the basic stock of water, and the other to the annual recharge. Both claims would be variable from year-to-year. The allotments would be set annually by the groundwater authority. Annual rights to the basic stock would vary according to current and anticipated economic and hydrologic conditions, including energy and commodity prices, interest rates and the remaining stock of groundwater. Rights to the recharge, including that from natural processes and return flows from human uses, could be set to reflect a moving average of estimated recharge in recent years. Transferability of entitlements would promote economic efficiency in the longer term, permitting reallocation to higher valued uses as economic conditions change. Such a system can be consistent with the local control criterion and requires minimum interference with individual freedom to operate the business enterprise Ostrom (1990), describes a system developed over two decades ago in the Los Angeles metropolitan area of southern California which appears to possess these attributes, and seems to be functioning effectively. Some recent approaches to allocating surface reservoir capacity (Dudley & Musgrave, 1988) appear to have application, but have not been exploited in aquifer management.

In the writer's opinion, the quantity-based approaches are preferable to the financial incentives discussed earlier. They can yield economically efficient solutions, with similar monitoring and enforcement burdens, while avoiding the redistributive implications of taxes or subsidies. While some new degree of outside controls on pumping will be required, these need not be any more repressive than property rights in other resources or commodities, and thus need not unduly infringe on individual liberties.

Use of water-rights markets to offset over-exploitation: The previous discussion has implicitly assumed an aquifer characterized by limited, or no connection, with a flowing stream or river. Aquifers interrelated with a flowing stream (called tributary aquifers) may present different problems. Brief mention is made here of a decentralized institutional approach to treating conflicts over the effects of pumping on a stream-aquifer system.

Pumping from a tributary aquifer reduces the flow of the stream that penetrates the aquifer. Pumped groundwater is replaced by streamflows directly or by reduced aquifer contribution to the stream. Such interrelated stream-aquifer situations are frequently encountered in the western U.S., and I expect, elsewhere. Open access to the groundwater may lead to enough pumping to noticeably reduce the available water for those holding rights to streamflows. In my own state of Colorado, this problem arose two decades ago for irrigators in the South Platte Basin. Groundwater exploitation, in the short-run, reduced streamflow, but by only a small fraction of the amount pumped. It was, therefore, clear that the most obvious option, putting pumpers into the existing system of appropriative surface water rights, while protecting those holding rights to surface water, would do so only at the sacrifice of most of the large economic benefits of exploiting the aquifer. After experimenting with several methods, a solution based on existing water rights markets for surface water was adopted and seems to be successful. Groundwater users must be prepared to replace, in the event of shortage, that fraction of streamflows which would be taken from the stream by pumping during the summer irrigation season. They may accomplish this replacement by purchasing, and delivering when needed, rights to reservoir water. Young *et al.* (1986) compared alternative policies with a hydrologic-economic systems model. They demonstrated that this augmentation plan solution to the stream depletion problem, for the specific hydrologic and institutional conditions that exist in this case, is quite economically superior to the alternative of forcing pumpers into the surface right system. However, the ready availability of substitute water supplies and the existence of flexible water transfer institutions is necessary to implement a solution of this type.

Monitoring and enforcing pumping controls

Regulation of rates of pumping will require pumpers to act in ways contrary to their perceived self-interest. In such cases, it becomes necessary to observe the actions of pumpers and thus to provide resources and authority to the water management agency for monitoring and enforcement. So far as the writer can determine, all models of optimal aquifer regulation in the literature now implicitly assume full compliance by pumpers and/or zero monitoring cost to the regulatory authority. In reality, implementation of groundwater regulations confronts a less-perfect world. The emerging literature on environmental management is suggestive of the issues that need to be faced. Russell *et al.* (1986) identify four sorts of assumptions open to environmental policy modelers. First, will the pumper cheat if it is in his self-interest? Can the pumper control their discharge levels exactly? Will the aquifer management authority monitor for compliance with its rules? Finally, what degree of error can be expected from the authority's chosen monitoring technique?

In the groundwater management case, the problem does not appear to be as difficult as it is in monitoring pollution discharges. Pump meter technology is well-developed and relatively inexpensive. The tendency for water meters to be damaged by their owners could be reduced by requiring the pumper to deposit a monetary bond sufficient to replace non-functioning meters and enforcing a prohibition on pumping from an unmetered well.

Another question is, once non-compliance is detected, what steps should the authority take to correct the situation. The practice of pollution control agencies (Russell *et al.*, 1986, Chap. 4) seems to be to assume good-faith by the pollution sources, and encourage voluntary compliance by avoiding severe penalties except when continued willful violations are observed. Space limits prevent a full development of this theme, but it is clearly an issue that warrants further analysis for the case of groundwater management.

CONCLUDING REMARKS

I hope the reader will take away from this discussion the following major points:

(a) First, the usual physical characteristics offered as definitions of over-exploitation (declining water tables, saltwater intrusion, subsidence, interfering with other water rights, etc.) are symptoms of an underlying socio-political problem. An appropriate definition of over-exploitation should refer to extraction rates that result in depletion of economic rents, or more generally, extraction of groundwater in excess of that rate which maximizes the long-run present value of net economic returns including external costs.

(b) Second, the real underlying problem can be characterized as a condition of economic scarcity of water combined with inadequate or nonexistent institutional arrangements for dealing with that scarcity. The problem, defined in political-economic terms, is one of a common pool resource managed without secure property rights to future pumping, and/or without consideration of external costs.

(c) Third, a number of solutions or policy instruments to deal with overdrafts are available. The appropriate policy mix will depend on the seriousness of the overdraft problem. It will be important that emerging problems, and those which will exert adverse impacts in the distant future, be anticipated by establishing the necessary organizational arrangements, setting in place legal mechanisms for controlling pumping and initiating an educational program to inform water users of the evolving situation and to try to persuade them to act in the collective interest with respect to the shared groundwater resource. The most suitable policy will not focus on only one single policy instrument, but will include a mix of structural, institutional and cognitive measures. A successful policy will likely require a combination of user-based local organization and a legal structure sanctioned and enforced by the relevant (national or state/provincial) government. The monitoring, enforcement and dispute resolution systems must balance the need to safeguard against infringements on individual liberty while pursuing the collective interest in avoiding problems associated with over-exploitation.

(d) Finally, for economically important and seriously threatened aquifers, the most suitable policy mix should be built around a system of limited but transferable property rights to pump from the aquifer. Pumping rights must be monitored, and infractions enforced, by a user-based organization which has support and backing of the state or national legal system. The most economically efficient system would permit rights to be exchangeable, so that water could move to the most productive uses.

The need for more interdisciplinary efforts: Permit me to close with a plea for more interdisciplinary efforts toward resolution and avoidance of aquifer over-exploitation problems. The behavior of an aquifer in response to pumping clearly requires the skills of the hydrogeologic sciences. Technical solutions demand the techniques of engineers. However, the reductionist, positivistic methods that have served so well in developing an understanding and predictive capability regarding aquifer behavior will not be fully effective for designing remedial policies. Aquifer exploitation is performed by humans, of course, and understanding how people respond to hydrologic facts, economic opportunities, and institutional constraints are important but frequently neglected considerations in designing appropriate groundwater management policies. 'If people are part of the problem, they must be part of the solution'. Diagnosis and successful resolution of existing and potential aquifer over-exploitation will be best achieved by a coordinated interdisciplinary approach.

ACKNOWLEDGEMENTS

This effort was supported by the Colorado Water Resources Research Institute, Project 'Economic Evaluation of Policy and Institutional Changes in Groundwater Management and by the Colorado State University Agricultural Experiment Station, Project no. 178, "Water Management and Conservation in Western Irrigated Agriculture'.

REFERENCES

Anderson, T.L., Burt, O.R. & Fractor, D.T. 1983. Privatizing groundwater basins: a model and its application. In: *Water Rights: Scarce Resource Allocation, Bureaucracy and the Environment*, T.L. Anderson (ed), Ballinger Publ. Co.; Cambridge, MA.

Bohm, P., & Russell, C.F. 1985. Comparative analysis of policy instruments. In: *Handbook of Natural Resource and Energy Economics*, vol. 1, A.V. Kneese & J.L. Sweeney (eds), Elsevier Science Publ., Amsterdam.

Bredehoeft, J.D. & Young, R.A. 1970. The temporal allocation of groundwater: a simulation approach. *Water Resources Research*, 6; 3-21.

Bromley, D.W. 1989. *Economic Interests and Institutions: the Conceptual Foundations of Public Policy*. Basil Blackwell Inc.; New York, NY.

Brown, G. Jr. & Deacon, R. 1974. Economic optimization of a single-cell aquifer. *Water Resources Research*, 8; 557-554.

Burt, O.R. 1964. Optimal resource over time with an application to groundwater. *Management Science*, vol. 11.

Cummings, R.G. 1971. Optimal exploitation of groundwater with saltwater intrusion. *Water Resources Research*, 7; 1415-1424.

Custodio, E. & Gurguí, A. (eds), 1989. *Groundwater economics: selected papers from a U.N. symposium in Barcelona, Spain*. Developments in Water Science, 39. Elsevier Science Publ., Amsterdam.

Dasgupta, P. 1982. *The control of resources*. Harvard University Press; Cambridge, MA.

Dudley, N.J. & Musgrave, W.F. 1988. Capacity sharing of water reservoirs. *Water Resources Research*, 24; 649-658.

Feinerman, E. & Knapp, K.C. 1983. Benefits from groundwater management: magnitude, sensitivity and distribution. *American Journal Agricultural Economics*, 65; 703-710.

Fox, I. 1976. Institutions for water management in a changing world. *Natural Resources Journal*, 16; 743-758.

Gardner, R., Ostrom, E. & Walker, J.M. 1990. The nature of common pool resources. *Rationality and Society*, 2; 335-358.

Goodin, R.E. 1983. Ethical principles for environmental protection. In: *Environmental Philosophy*, R. Elliot & A. Gare (eds), Pennsylvania State University Press; University Park, PA.

Heberlein, T.A. 1974. The three fixes: technological, cognitive and structural. In: *Water and Community Development: Social and Economic Perspectives*, D.R. Field, J.C. Barron & B.F. Long (eds), Ann Arbor Science Publ., Ann Arbor, MI.

Howe, C.W. 1971. *Benefit-cost Analysis for Water System Planning*. Water Resources Monograph no. 2, American Geophysical Union, Washington, D.C.

Howe, C.W. 1987. On the theory of optimal regional development based on an exhaustible resource. *Growth and Change*, 18; 53-68.

Hunt, R. 1990. Organizational control over water. In: *Social, Economic and Institutional Issues in Third World Irrigation Management*. R.K. Sampath & R.A. Young (eds),. Westview Press, Boulder, CO.

Johnson, G.L. 1986. *Research Methodology for Economists: Philosophy and Practice*. Macmillan, New York, NY.

Kelman, S. 1981. *What Price Incentives?: Economics and the Environment*. Auburn House Publishing Co., Boston, MA.

Maass, A. & Anderson, R.L. 1978. *. . . and the Desert Shall Rejoice: Conflict, Growth and Justice in Arid Environments*. MIT University Press, Cambridge, MA.

Noel, J., Gardner, B.D. & Moore, C.V. 1980. Optimal regional conjunctive water use management. *Am. J. Agric. Economics*, 62; 489-498.

Nunn, S.C. 1985. Political economy of institutional change: a distribution criterion for acceptance of groundwater rules. *Natural Resources Journal*. 25; 867-892.

Ostrom, E. 1990. *Governing the commons: Evolution of Institutions for Collective Action*. Cambridge University Press, Cambridge, UK.

Pearce, D.W. & Turner, R.K. 1990. *Economics of Natural Resources and the Environment*. Johns Hopkins University Press, Baltimore, MD.

Reichard, E.G. & Bredehoeft, J.D. 1984. An engineering economic analysis of a program for artificial groundwater recharge. *Water Resources Bulletin*, 20; 929-939.

Russell, C.S., Harrington, W. & Vaughan, W.J. 1986. *Enforcing Pollution Control laws*. Johns Hopkins Univ. Press for Resources for the Future, Baltimore, MD.

Smith, V.L. 1977. Water deeds; a proposed solution to the water valuation problem. *Arizona Law Review*, 26; 8-12.

Stone, D.A. 1988. *Policy Paradox and Political Reason*. Scott, Foresman and Co., Glenview, IL.

Whipple, W. 1988. Management of depleted coastal zone aquifers. In: *Coastal Water Resources: Symposium Proceedings*. American Water Resources Association, Bethesda, MD.

White, G.F. 1969. *Strategies for American water management*. University of Michigan Press, Ann Arbor.

Wolf, C. Jr. 1988. *Markets or Governments: Choosing Between Imperfect Alternatives.* MIT University Press, Cambridge, MA.

Young, R.A. 1970. Safe yield of aquifers: an economic reformulation. *J. Irrigation and Drainage Div.*, Proceeding. Am. Soc. Civil Engineers. 96, no. IR 4; 377-389.

Young, R.A. & Haveman, R.H. 1985. Economics of water resources: a survey. In: *Handbook of Natural Resources and Energy Economics*, vol. II, A.V. Kneese and J.L. Sweeney (eds), Elsevier Science Publ., Amsterdam.

Young, R. A., Daubert, J.T. & Morel-Seytoux, H.J. 1986. Evaluating institutional alternatives for managing an interrelated stream-aquifer system. *Am. J. Agric. Econ.*, 68; 787-791.

THE INCLUSION OF EXTERNAL EFFECTS IN THE PRICE OF AQUIFER WATER. A COMPARISON BETWEEN THREE DIFFERENT METHODOLOGIES

O. ALFRANCA & J. PASQUAL
Institut Universitari d'Estudis Europeus
Universitat Autònoma de Barcelona
08193 Bellaterra, Barcelona, Spain

ABSTRACT. In this paper some of the possible instruments available to a public institution wishing to establish an optimal price of water contained in an aquifer (from a social point of view) will be analysed. The main target is to obtain an exploitation coinciding with a maximal level of use. A proposal will be presented taking into account costs and benefits associated with the supply cycle of drinkable water.

INTRODUCTION

Before evaluating the model and some of the possible methods for regulating sale, some of its concepts will be introduced.

If water contained in an aquifer is distributed exclusively on the market, the resulting allocation will not be efficient, since private costs will be different from public costs. The overexploitation of the aquifer implies a series of negative effects with ramifications, not excluively for its direct exploiters, but for the whole community. The optimal allocation, hence, will not be found in the points of equity between price and marginal public cost, which includes the marginal private costs and its corresponding external effects. We speak of external effects, or externalities, when one can not avoid a variable whose decision corresponds to a consumer, or a production unit, entering directly into the utility function, or the production function of another consumer or another producing unit.

In the case of overexploitation of an aquifer, the result of including the external effects is a price rise and a drop in the quantity consumed (see Figure 1).

Externality associated with the overexploitation of an aquifer is negative; hence the equilibrium price and quantity of extracted water will be inefficient (the price will be smaller and the extracted water will be bigger than the optimal ones).

For aquifer water to be exploited optimally, it is necessary that the price goes from P_c to P_0.

It can be proved that if water prices remain constant in the long run they have no influence in the decision of overexploiting the aquifer. In this situation the problem is the choice between either a constant water flow *q*, or over exploiting the aquifer and sell a quantity *Q*.

Overexploitation will be preferred if, and only if, $pq/r < pQ$; that is, when $r > q/Q$, which is independent on the price on the water *p*.

It must be taken into account that water supply functions are usually very rigid, not mainly because of the costs, but due to administrative regulations and political restrictions.

Priority given to the supply of drinkable water in modern socities could force the producer to supply more water than the optimum from his point of view. Hence the importance of studying the effects on demand.

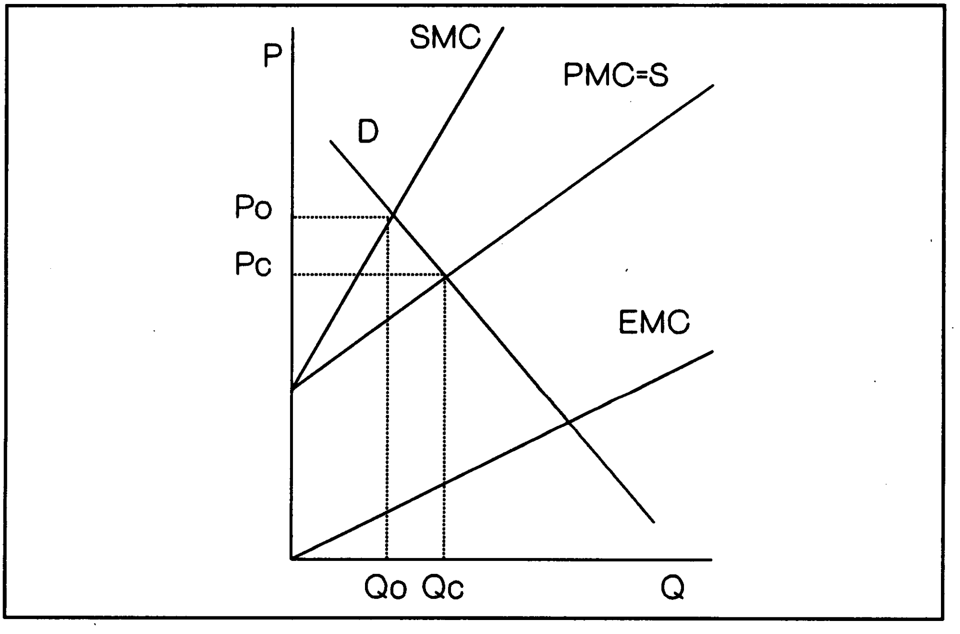


Figure 1: The inclusion of external effects.

THE PRICE OF THE WATER

The price of water in an aquifer can be formulated according to two basic criteria:

(a) The market. In the formulation of this price only private criteria are included. We do not include losses assumed by the community because of the overexploitation of the aquifer. From the viewpoint of the producers and consumers, the distribution of water is efficient since the water is destined for uses costing more than the water itself. However, this theory is incorrect, failing to take into account costs which do not fall exclusively upon those derived from the overexploitation and salination of the aquifer water, or the loss occasioned by later generations, who can no longer use the aquifer water. Since the costs which fall upon the consumers and producers in this generation are not all of those associated with production, the quantity consumed is above the optimal.

(b) Public Regulation. The price of the water could, in certain ways, include these factors pertaining to the price which are not present in other types of goods without external effects in their production or consumption. Water has private good and public good characteristics. Water can be used for private purposes, either in consumption or production, and can be exploited as well for the satisfaction of collective needs. Water is then a natural resource with a limited stock. Limited quantity of water could become an obstacle to development. All society is affected, and especially future generations.

The water contained in an aquifer exhibits the quality of rivalry, since two people can not consume the same unit of the goods, but it does not fulfill the condition of exclusion, as do goods which are strictly private. Accordingly, it is impossible to prevent a consumer or a producing unit from using the goods.

Given that increasing private water consumption implies a reduction in social consumption, regulating the market use will necessarily regulate the available water for public or social consumption.

Taking this into account, the price at which the water is commercialized should include:

(a) the actual cost of the the water, both for current and future generations. This reflects the money anybody is willing to pay to keep the water instead of letting the aquifer run out. In Pasqual (1991) it is proposed to use two rates of return to calculate the values of projects affecting the environment. One of the rates, r, is the ordinary one, and it is used to calculate the present values of costs and benefits of the project for one generation. The second rate, R, must be used to find the present value for aggregated generations;

(b) those social benefits and losses associated with the exploitation of the aquifer, which the owner is unable to internalize through the usual market mechanisms. If we suppose that the aquifer is likely to run out or salify as a result of continuous overexploitation, this can be justified only in the following cases:
    (i) when the interest rate yielded by the activity in which the water from the aquifer is used is greater than the social interest rate,
    (ii) when the actions of the society are ruled by selfish criteria. In exploiting the aquifer, no account is taken of the consequences for future generations; instead, only the present profits are considered.

These kinds of costs (or benefits), in which the individual value is different from the social one, should also be included in the selling price of the water;

(c) its transport and treatment cost.

REGULATION OF WATER CONSUMPTIONS IN CONDITIONS OF SCARCITY

In this section some possible methods of regulating water consumption will be described briefly, and a third examined in more detail. With this last method, the user receives a reduction on the total amount to be paid depending on the water which was not used from his assigned quota, and of the more or less difficulty to recycle the water consumed.

The methods can be divided according to a basic criterion: the presence or absence of external effects.

Pure Market

One possibility for the Public Sector is to refrain from intervening in the disribution of the aquifer water and let the market be the only criterion for the establishment of its consumption.

If there is a risk of overexploiting the acquifer, and we leave the choice just to private decisions, water use tends to exceed socially desirable levels. When social costs exceed private costs because of the external effects on others, some public action could adjust such differences.

Either if the quantity associated with the consumption in a market scenario can lead or not to overexploitation (in which the social loss is maximum), the users are consuming a scarce resource subject to a number of competing demands, and society is receiving a cost without receiving compensation for it. The only difference is that when overexploitation is achieved, the damage is more clear. There is always a cost and users should have to compensate for it to the rest of society.

We will not talk about different methods of tariffing in this article, nor about alternative forms of restricting consumption by way of supply cuts. On the contrary, we will focus on three different forms of regulating consumption, using classical methods of fiscal policy such as taxes and subsidies, and a third method that will try to bring together the establishment of quotas and subsidies.

Taxes

We will draw a distinction between a specific tax 'per unit' and an 'ad valorem' tax.

A tax on each unit of the output. If we use a Pigouvian tax (of quantity u), it will have to be equal to the external marginal cost. The tax now becomes a part the merchandise. It is converted into an element between the market price obtained by the sellers, and the net price it maintains. Since the sellers are interested in the net price, now they have to charge a higher market price in order to cover their costs. The market prices until OF and the next price for the sellers drops to OK (the variations in price and quantity will depend logically on the elasticity of supply and demand). The immediate effects are a price rise and a lessening of the quantity consumed (see Figure 2).

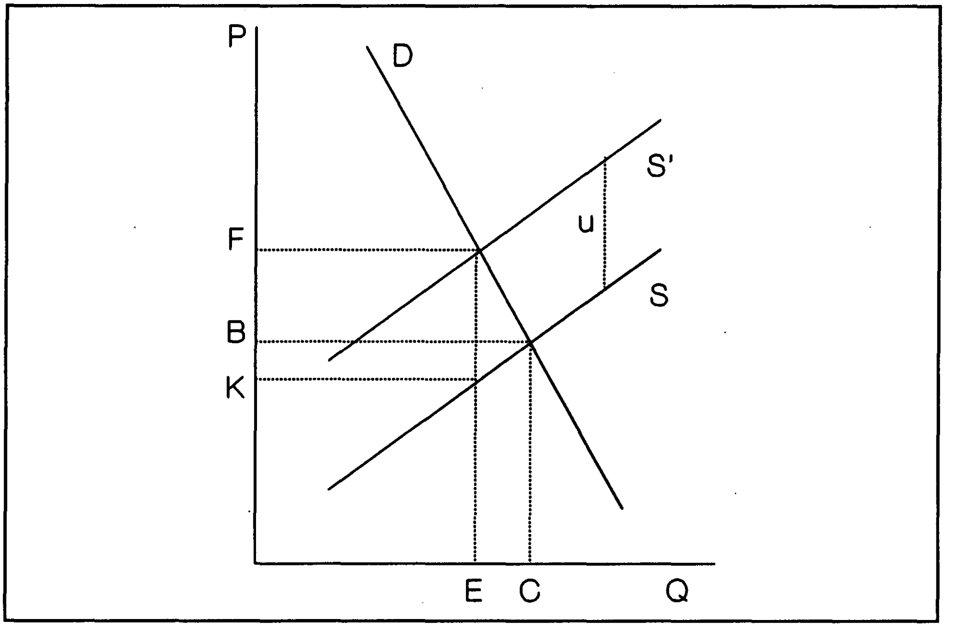


Figure 2: A tax 'per unit'.

'Ad valorem' tax. This tax is applied now as a percentage of the net price. Again the tax is included between the gross price or the market price which the buyer pays and the net price which the seller receives.

The effects will be very similar to those of a unique tax, and again the price variation and quantity depend on the elasticity of supply and demand.

If demand is very rigid, as in this case, when the supply curve moves up, the quantity consumed will not vary, but the price will raise in function with the quantity of the tax. The price rise will be greater when the demand is less elastic and the supply is more elastic (see Figure 3).

Subsidies. By subsidy we mean, simply put, a financial aid supplied by the Public Sector, to whichever agent, for the reasons of public well-being.

Apportionments will be made to each business according to lhe lowering of its output. In our case, for the reduction of volume of exploitation. The solution will depend upon the structure

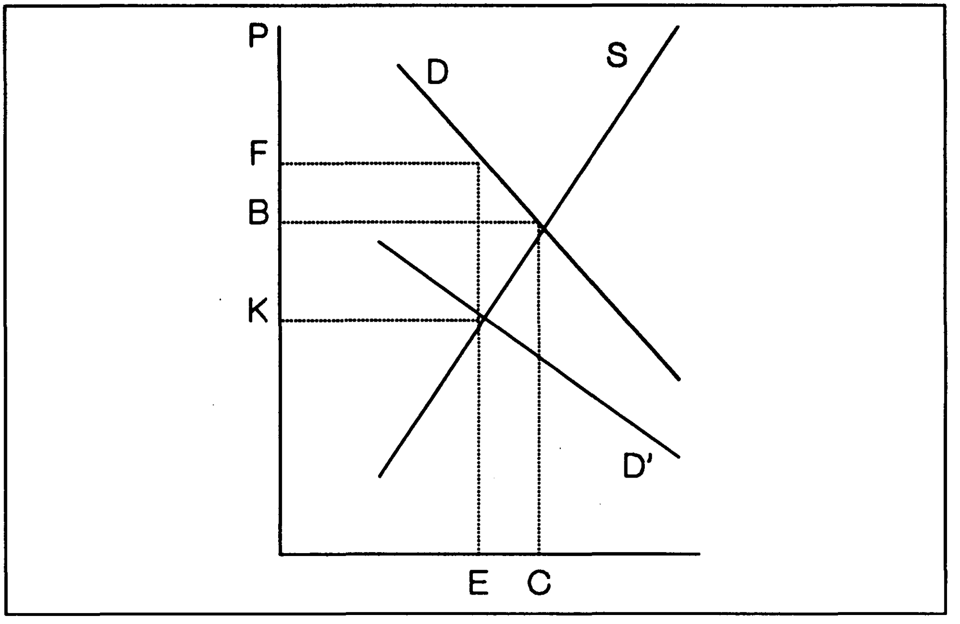


Figure 3: An 'ad valorem' tax.

of the market in which we find ourselves.

The immediate effect of a subsidy is the upward displacement of the curve of marginal cost (see Figure 4). If the subsidy has established at a quantity equal to the preceding tax, the curve will logically reach the same point. The explanation that the subsidy moves the marginal cost curve up, as if it were another cost, can be found, for example in Pearce & Turner (1990). According to these authors if a business increases its output it should renounce subsidies, this being a way of paying taxes. Due to the incurring opportunity cost, there is a loss in both cases. However, although the marginal cost may have increased, the average costs have dropped, since an income has been received for reducing the level of output.

Concerning all the above, the short-term equilibrium price and quantity will be the same as that obtained by the establishment of a tax.

The difference between the effects produced by a subsidy and those produced by a tax lies basically in long-term effects. In the case of a subsidy a displacement of the curve of average cost will move towards the axis of the abscissa. This implies that temporarily the price can be higher than the average cost, which implies an incentive for businesses who see in the sector the possibility of obtaining an extraordinary profit. That is, a rise in the number of businesses in the industry will take place. If the market structure was near perfectly competitive there would be no price modifications, since a very large number of extractors is needed to modify this variable.

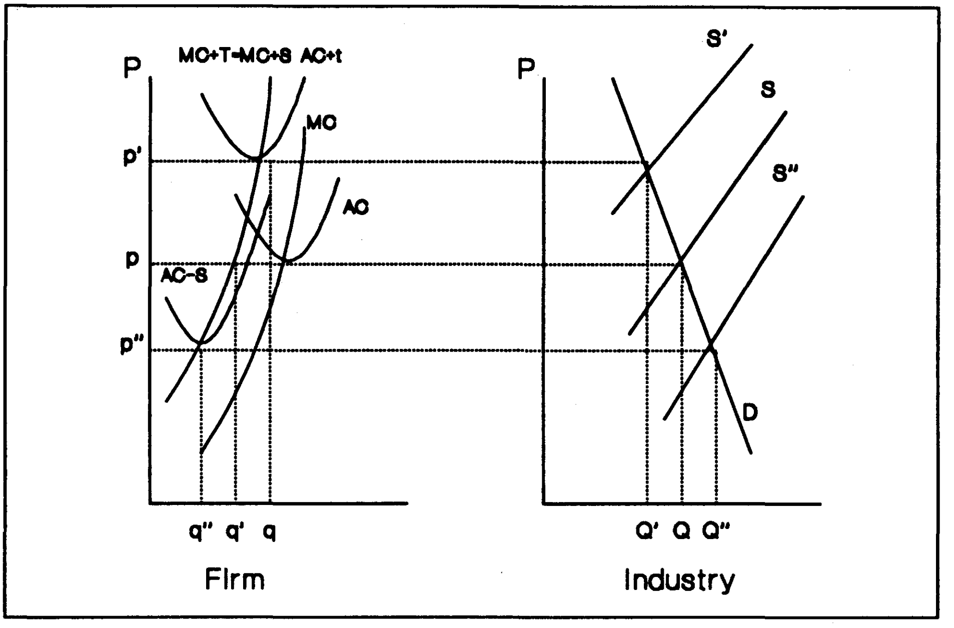


Figure 4: The effects of a subsidy.

In the case of an oligopolistic market, then the emergence of new producers would certainly produce a price decline. This decline will be more accentuated the more rigid the demand for the goods in question. The emergence of producers will continue while the attractiveness of an extraordinary profit continues to exist. These extraordinary profits will not disappear until the price is equal to the long-term average cost. In this connection, there do not exist incentives for the emergence of more business since the extra profits are non-existent.

In our case, since water is a commodity which has always been characterized by rigid demand, we will suppose small rises in the quantity produced, in reaction to large drops in price.

PROPOSED MODEL: INTEGRATED REGULATION

The proposed solution consists of a system, called in this paper Integrated Regulation, which acts both on water supply and demand disciplining the behaviour of producers and consumers, and taking into consideration costs and benefits related to the water cycle. The main features of the model are:

Agents

Producers: The Government owns the property rights on the drinkable water supply to households, and delegates the management to a firm. The firm must fix the water price for each kind of consumer, according to the established public rules. The firm acts as a public agency when managing the taxes and subsidies associated to the water cycle. The firm receives the profit from these actions and, in some cases, a determined fixed quantity, whether positive or negative, according to the concession agreement. With these mechanisms, the firm has an incentive to minimize the cost (the smaller they are, the bigger the profit), and technical efficiency will be reached. Economic efficiency will be reached acting on the consumer prices.

Households: On the demand side, the policy is centered in a reduction in the bill according to two variables:

(a) the difference between the water consumed and the optimum quantity. An incentive scheme will be established in order to adjust water demand for the social optimum. According to this scheme, households prices will be smaller if the quantity actually consumed maximizes the savings from the assigned quota, and vice versa. Once we know the optimal consumption quantity Q_O for each kind of consumer, the discount in the water bill for consuming Q will be $M(Q_O - Q)$, being M the external marginal cost, which is the value of water as a natural resource; that is, the cost the Society must pay in order to increase their drinkable water reserves in one unit;

(b) the amount of water which is likely to be reused. The reduction in the tariff will be higher, the easier recycling is. With these tools the conservation of water is favoured and recycling costs will decrease. Using a quantity of water Q, some percentage of it, σ, may be recycled, with a cost R. The rest of the water, $(1 - \sigma)$, is destroyed. If the cost of water as a natural resource is M, social savings from recovering a percentage σ will be equal to $\sigma(M - R) > 0$. Price M is the same for all the different consumers, whilst R depends on the different uses of water.

Hence, the water for urban consumption which can be re-used is a percentage σ_U, so that if the family consumption is Q_O, the Society will be able to reuse $\sigma_U Q_0$ (the water can be reutilized, but not necessarily for the same purpose). A similar kind of reduction σ_I, will be given to the industrial water consumer. For agrarian consumption, the reduction in the tariff associated with the water likely to be reused is σ_A. We can assume (albeit the model is valid in any case) that $\sigma_A < \sigma_I < \sigma_U$, because of the difficulties with recovering and re-utilizing the water.

The bill F for using Q, if σ can be recycled will be:

$$F = QP - Q(M - R)\sigma - (Q_O - Q)M \qquad [1]$$

where P = Private Marginal Cost in the market equilibrium.

QP is the amount of money to be paid if the price is formed in a competitive market; $Q(M - R)\sigma$ is the reduction in the bill once the deductions for saving and ease of recycling are included; $(Q_O - Q)M$ represents the discount in the water bill which is in function of the level of achievement of social objectives Q_O.
Equation [1] can be rewritten in the form

$$F = Q[P + M - \sigma(M - R)] - Q_O M \qquad [2]$$

The final price for the consumer σ will be, differentiating [2] with respect to Q:

$$\sigma = P + M - \sigma(M - R) \qquad [3]$$

Hence, the consumer pays a price which includes the private marginal cost P, the external marginal cost M and receives a price $(M - R)$ for the amount of water which is likely to be re-used σ. Social efficiency in consumption is reached, because all important concepts regarding costs and benefits are included into the price π.
It is interesting to note that the effective subsidy $Q_O M$ is always smaller than the Pigouvian tax QM. Therefore, the public budget will not present a deficit in any case with this regulation system. In the optimum the fiscal balance will be neither positive nor negative. If a positive balance is preferred for one or several groups of consumers, a change should be introduced in the consumer subsidy $Q_O M$ for a constant -S- positive or negative, depending on the preferred balance, as can be seen in [4]:

$$F = Q[P + M - (M - R)\sigma] - S \qquad [4]$$

SOME COMPARISONS AMONG MODELS

Using a Pigouvian tax, a rise in the sale price of aquifer water will be produced, and furthermore, the total average cost increases. Since this tax reduces the internal profitability which can be obtained from the exploitation of the aquifer, this will cause some businesses in the sector to abandon, which in the long run will produce a decline in supply and, consequently, a rise in the price of the water (without any public intervention).

If a subsidy is used, the price rise in the short run will be the same, but the effect on total average cost will be the opposite. When the average cost is reduced, and is hence less than the commercialized price of the water, extraordinary profits will be produced, and consequently there will be a rise in the incentive to exploit aquifers which will lead us to expect, in the long run, a price decline and an increase in the quantity of supply.

In a case where the market structure is perfectly competitive, the profits derived from the lowering of the total average cost probably would be maintained longer, facing the difficulty of modifying the price in a market with lots of producers and consumers. If we are faced with an imperfect market, the length of the period of time that businesses enjoy extraordinary profits will depend on the severity of the barriers for entering the market. In the long run a lowering of the market price will be produced, together with a supply rise.

Even accepting all the above, it can be suggested that supply of drinkable water to households presents, in general, some of the Natural Monopoly characteristics (decreasing average sale costs, for instance). If this is the case, then initial market conditions will not be relevant, because in the long run, the new market structure will be similar to the classical monopoly. As the demand for water is very rigid, the difference between price and marginal cost would be so important that social pressures for a public intervention would be decisive.

Considering these arguments, the theoretical frame which seems more appropiate to analyze real problems it is not the widely used Perfectly Competitive, but the one of the Monopoly under tariffs regulated by the Government, which is the one used in the third model.

In the third model shown, the reduction is granted taking into account two different criteria:

(a) the first regulation included in the model consists of allocating quotas, and of the lowering of the tax to be paid relative to the quantity saved. The price at which water has been sold in the form of quotas already contains the social costs derived from possible overexploitation. Whether or not there exists a market for the quotas, the extractor will consume all the water available. However low be the derived utility, all the quota will be used, either in their own projects or in sales.
With this regulation all conflicts between private and social optimality disappear; the best decision for every consumer is to adjust the consumption for the assigned quota;

(b) a subsidy will be granted taking into account the quantity of water which is likely to be recycled and the quality of the water. This scheme can be assimilated to a contract by which the Government buys any quantity of used water at a prefixed price. Incentives exist in the short run to pollute less water. In the long run, the incentives are mainly on the quality of the water. The higher the quality, the higher the price $(M - R)$ will be for the consumer when selling the water.

In this proposed system, producers are regulated by means of a voluntary administrative contract, so that, to maximize their welfare, consumers and producers must behave according to the rules of Perfectly Competitive markets. Consumers will face prices including both private and social costs and benefits, even those stemming from recycling water. It is, from a theoretical point of view, an optimum result. Although in practice it may be impossible to reach such an optimum, substantial improvements can be expected in the allocation of water.

CONCLUSIONS

To be concise (and concentrating on long term effects in Competitive Markets), with the use of a unitary tax, a price rise and a lowering in the quantity consumed will be produced; with the subsidy, the price will drop and the quantity exploited will rise; with the third method presented above, the quantity extracted can be reduced if the subsidy is sufficient, and furthermore the price will rise, as will the quality of water.

The choice of one method or another will depend on the objectives of each Government. While the third appears the most attractive (since quantity is maintained and includes other objectives such as the quality of the water), it is also more complex, and the possibility of maintaining a long term constant extraction is not clear. If keeping the water in the aquifer is the main objective, the unitary tax could be attractive. From the consumers' point of view, the use of subsidies would be the preferred instrument, since it is the only one which produces a lower price with a rise in the supplies quantity.

The proposed system includes a Pigouvian tax in order to adjust the consumption, and an automatic system to increase the value of residual water, in order to reduce the amount of water destroyed in the different uses and reduce the cost of reusing it.

Some of the main problems that can be found when trying to apply this system to actual market situations are:

(a) complexity in the estimation process of parameters in function [1];
(b) heterogeneity of the different groups of consumers would make advisable a recursive application of the method. In the first approach low values should be used both for external effects -*M*- and for the price of the recyclable water -*R*- taking care that $(M - R)$ is widely higher than zero. In further iterations the values of *M* and *R* will be fixed with values closer to the optimum, according to the results yielded by the first approach;
(c) the identification of the fluxes generated by each of the consumers must be done carefully. In the first stages the use of aggregate values seems wise and advisable.

Whichever the method used, external effects should be included (whether positive or negative), equally in the prices as well as in the IRR associated with the activities related to the aquifer. Only in this way will an efficient allocation of water resources be produced.

The problem does not have a simple solution, and is repeated in forests, rural zones, coasts, etc. What is hoped for in this paper is to propose some kind of solution to stop the disappearance of Nature's 'priceless treasures'. The solution perhaps is to put a price on these priceless treasures, and then to pay that price.

REFERENCES

Alfranca, O. (1991). Alternative uses of water and methods for pricing. In: *Aquifer Overexploitation*, Proc. XXIII International Congress I.A.H., Tenerife; 267-270.
Casahuga, A. (1985). *Fundamentos Normativos de la Acción y Organización Social.* Ed.

Ariel, Barcelona.
Frederick, K. (1988). Water policies and Institutions. In: *Perspectives on Water Uses and Abuses*, D.H. Speidel, L. Ruedisili & A.F. Agnew (eds), Washington.
Hansen, B. (1967). *The Economic Theory of Fiscal Policy.* Allen & Unwin. London.
Musgrave, R. & Musgrave, P. (1980). *Public Finance in Theory and Practice.* McGraw Hill Book Co., New York.
Pasqual, J. (1991). *Nuevos y viejos instrumentos de política ambiental.* Working Paper 91.02. Departament d'Economia Aplicada. Universitat Autònoma de Barcelona.
Pearce, D. & Turner, R. (1990). *Economics of Natural Resources and the Environment.* Harvester Wheatsheaf, London.

GROUNDWATER PROBLEMS IN SEGURA BASIN. ECONOMIC IMPACT OF OVEREXPLOITATION IN MAZARRON ZONE (MURCIA, SPAIN)

R. ARAGON
Instituto Tecnológico GeoMinero de España (ITGE)
Avda. Alfonso X el Sabio, 6 30008 Murcia, España
L. SOLIS; U. GARCIA-LAZARO
J. GRIS & T. RODRIGUEZ-ESTRELLA
Empresa Nacional ADARO, S.A.
Gran Vía, 42, 1º-e, 5º A. 30005 Murcia, España

ABSTRACT. The Segura basin presents a great water shortage (500 hm^3 $year^{-1}$) because of the imbalance between demand (2,000 hm^3 $year^{-1}$) and available resources (1,500 hm^3 yr^{-1}); partially alleviated by the overexploitation of aquifers (315hm^3 $year^{-1}$) from middle and lower basin zones. In this work the wealth created and sustained thanks to the exploitation of the Mazarron area aquifer reserves are shown. It is one of the most problematic zones whose only available resources are of groundwater origin. Use and water demands, average exploitation, groundwater cost and agrarian production are analysed. Finally, an estimation of the economic impact of aquifer overexploitation in this area and its possible evolution in the short-term are presented.

INTRODUCTION

The Segura basin shows a great difference between water demand (2,000 hm^3 $year^{-1}$) and available resources (1,100 hm^3 $year^{-1}$ adding groundwater and surface water), which is partially palliated by the Trasvase Tajo-Segura (variable annual volume not exceeding 400 hm^3 $year^{-1}$ at this moment).

In order to reduce these important differences in hydrologic conditions (aproximately 500 hm^3 $year^{-1}$), intensive groundwater overexploitation has taken place. However, this has not been planned and has produced reserve depletions of 315 hm^3 $year^{-1}$ which have caused alarming situations in some of the aquifers, as much from a hydrodynamic point of view as the associated problems that are endangering the existing actual exploitations for shorter or medium periods. The diverse geological, climatic and socioeconomic characteristics of the basin have produced a great inequality in the spatial distribution of overexploitation incidence. Problems are almost exclusively concentrated in low and middle basin zones, concretely in southern and eastern areas of Murcia and the western area of the Alicante province in the following aquifers: Jumilla-Villena, Ascoy-Sopalmo, Quibas, Sierra de Crevillente, Valle del Guadalentín, Cresta del Gallo, Mazarrón-Aguilas zone, Bosque and Santa Yéchar. In the first six, water authorities take administrative action according to the stated overexploitation verdicts.

The degree of knowledge about basin aquifers, their situation, evolution and problems is high because of the research done since 1969 by the Instituto Tecnológico GeoMinero de España (ITGE) and also because of other local studies made by institutions such as the Dirección General de Recursos Hidráulicos de la Comunidad Autónoma de Murcia and the Dirección General de Obras Hidráulicas del MOPU. The main hydrogeological characteristics of aquifers and defined basin units, historic evolution, overexploitation degree and the problems originated by this, have been the subject of a recent publication (Aragón *et al.*, 1989).

In this work, Mazarron zone is analyzed in detail because this is one of the most representative basin areas suffering overexploitation. It includes all the municipal district and parts from those of Lorca and Cartagena. Mazarron's economic boom began 30 years ago and is due to agrarian development, aided by ideal climatic conditions. It is important to emphasize the progressive expansion of tomato planting. Out of season crops and farming under plastic began. This practice is flourishing, but there is a special factor -the area is not within the zone that is irrigated by the Tajo-Segura Trasvase- so Mazarron can only use groundwater as a hydraulic resource because surface sources are insignificant. The present situation is that of an intensive horticultural producing centre with great limitations, both in present maintenance and future growth, due to the gradual exhaustion of existing aquifers in the Mazarron area. This situation poses a serious threat to the prosperity of the area. The investigation of this zone's problems has been studied by the Instituto Tecnológico GeoMinero de España, thus this work is fundamentally based on the studies of ITGE from 1989 and those which are being done at present.

HYDROGEOLOGY

Mazarron area is located in the hydrogeological unit 'Mazarrón-Aguilas'; it is separated from the adjacent ones by outcrops of Paleozoic rocks. There are no permanent river flows but only dry ravines, the most important ones being Ramonete and Moreras.

Aquifer formations have diverse lithology and strength: triasic marbles, limestones and dolomites; volcanic rocks, calcarenites and sands from Neogene and Quaternary sands and gravels. The stratigraphic and tectonic complexity has produced a great hydrogeological diversity which has caused a large number of aquifers; most of them are small and twelve of them have become individual ones. Together they have an extension of barely 200 km^2 (Fig. 1).

Annual average resources of this zone are between 2.5 hm^3 and 5 hm^3. Storage does not exceed 200 hm^3.

GROUNDWATER EXPLOITATION

Pumping volume in 1988 was 25.7 hm^3 with 199 wells belonging to 12 aquifers (ITGE, 1989). 61% of the pumping is done in the aquifers Molares-Lorente (8 hm^3 with 21 wells) and Vaqueros (7.7 hm^3 with 71 wells); the remaining 39% is distributed as follows: Gañuelas (3.4 hm^3), Las Moreras (2 hm^3) and others (4.6 hm^3).

Consequently there is a great difference between recharge and discharge evalued at 21 hm^3 for 1988; equivalent to 81% of the total zone exploitation. This has produced a continued piezometric level decline, progressive salinity of water (at this moment salinity ranges from 1,000 to 5,000 ppm) and in the case of coastal aquifers, some marine intrusion (Solís *et al.*, 1988). To this serious situation it is necessary to add the consumed groundwater reserves which, according to the four biggest evaluated aquifers (Gañuelas, Molares, Lorente, Moreras and Vaqueros), do not exceed 160 hm^3 with very high salinity in some cases that impedes direct water use without previous treatment. Besides that, 85% of pumping is restricted to Vaqueros aquifer, which causes some problems of a hydraulic structural nature in order to fulfil demands for the whole zone.

IRRIGATION ORGANIZATION

Farmers in this zone have established the Comunidad de Bienes Agricultores de Mazarrón. Due to the exploitation dispersion this Association has been subdivided into four smaller ones (Fig. 2): Balsicas (1,464 ha), Gañuelas-Mazarrón (1,253 ha), Ifre-Ramonete (1,080 ha) and Ugéjar-Morata (191 ha). The resource origin is only groundwater. Springwater owners use part of the pumped volume; frequently the rest is sold to other farmers who have not their own resources or with complementary water necessities. Pipe systems are very developed so there are no problems of distribution.

The number of owner's wells is 134, but only 19 receive 77% of the total collected volume.

USES AND DEMANDS

According to data from the most recent inventary (ITGE, 1989) the whole irrigable surface for 1989 was 3,988 ha with the following distribution:

1. <u>IN THE OPEN AIR</u>	<u>3,267 ha</u>
1.a) Herbaceous	2,407 ha
- vegetables (tomatoes)	2,125 ha
- vegetables (rest)	282 ha
1.b) Ligneous	860 ha
- Citrus	462 ha
- Fruit-trees (almond)	320 ha
- Fruit-trees (rest)	78 ha

2. FARMING UNDER PLASTIC		721 ha
	- vegetables (tomatoes)	689 ha
	- vegetables (rest)	32 ha
3. TOTAL		3.988 ha

Water is exclusively destined for agrarian use (Fig. 3).

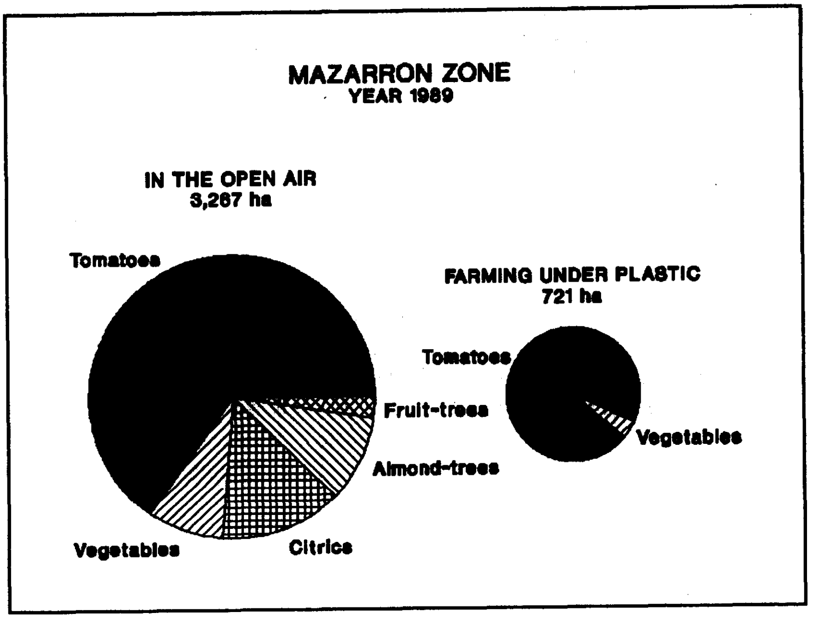


Figure 3: Irrigated crop distribution.

According to regional statistical data (Consejería de Agricultura, 1989), irrigation evolution during the 1976-1989 period showed the following characteristics (Table 1): In terms of superficial area, irrigation was reduced to 86% of that used in 1976. The reduction of open air crops is specially significant, and in contrast with the continued increase (since the 1983 drought) of farming under plastic. This method, besides using water more economically, produces greater profits (in the case of tomatoes the profits have increased by 85% from 1983 to 1989). Ligneous crops are represented specially by citrus (lemon-tree, orange-tree and mandarin-orange tree), fruit-trees (almond-tree) and vineyard (grape) and became relatively important from 1976 to 1982. Since 1983 they began a slight regressive phase with two exceptions: lemon and orange, whose future will possibly worsen rapidly because of the increasing difficulties with commercialization in international markets.

The intercensus evolution of agrarian exploitation decreased between 1962 and 1982 for cropping lands and also for the quantity of exploitations and plots. Private ownership dominates the land management system (almost 77%) followed by partnership (12%), farmership (11%) and other less important systems (0.2%).

Total water demand was 25.7 hm^3 for 1989, 80% of which was destined to open air crops and the rest for farming under plastic. The distribution was: Ugéjar-Morata 0.7 hm^3; Balsicas, 9.4 hm^3; Ifre-Ramonete, 9 hm^3 and Gañuelas-Mazarrón, 6.6 hm^3. With respect to demand distribution by months: those of greatest volume are January, February, March and December (43%) and the least are April, May and June (16%).

Table 1: Irrigated crop development in the Mazarron zone (1976-1989). Index number.

Year	1.In the open air	1.1 Herbaceous	1.2 Ligneous	2.Farming under plastic	3. Total
1976	100	100	100	-	100
1977	104	100	115	-	104
1978	100	98	105	-	100
1979	98	93	115	-	98
1980	86	75	121	-	86
1981	85	74	122	-	85
1982	83	71	121	-	83
1983	84	73	117	100	99
1984	83	72	118	101	98
1985	89	83	106	120	107
1986	86	79	107	124	105
1987	81	73	107	124	100
1988	72	74	66	133	93
1989	65	62	74	135	86

GROUNDWATER COST

In order to calculate the pumping cost the following exploitation well costs have been considered: energy cost for pumping water, equipment amortization, expenses for installations and pumps and overhead charges. The expenses generated by unprofitable or dry wells because of overexploitation and those costs originated by failed wells are considerated as amortised and added to the agrarian production costs in the referred years.

In order to calculate energy costs the new rate system for electric power is estimated according to that legislated by Royal Decree 2660/1983 from October 13th and Order from October 14th with complementary arrangements such as the Royal Decree 774/1984 from April 18th and Order from April 27th, which develops the former. To determine the power parameter, we have considered the various power blocks contracted for low and high voltage supply. Thus, the 199 wells of Mazarrón zone have a contracted power of 12,362 kw of which only 2.5% is for low tension and 97.5% for high tension. According to users' associations contracted power is: Ifre-Ramonete (36.3 per 100), Balsicas (35.0 per 100), Gañuelas-Mazarrón (23.0 per 100) and Ugéjar-Morata (5.7 per 100). In order to fix power parameters we consider the energy consumption of the pumping equipment, taking into account the existance, or not, of hourly or reactive energy discriminatory terms.

In 1989 the Mazarrón zone pumping equipment had an energy flow valued at 48.7 million kw, of which approximately 26% were supplied without any discriminatory terms and the rest, i.e. 74%, were supplied with hourly or reactive energy discriminatory terms with the idea of obtaining a discount in energy costs. According to users'associations consumed power is distributed in the following way: Ifre-Ramonete (42.8 per 100), Gañuelas-Mazarrón (28.0 per 100), Balsicas (25.8 per 100) y Ugéjar-Morata (3.4 per 100).

Another cost to be considered because of its importance is that derived from the amortisation of pumping installations. To calculate this, it is necessary to take the historic cost value of water-collecting works and raising equipment. The investment in this region by well owners until 1989 has been 16 million US dollars (made up to actual prices). The users' associations which have made the greatest investment are: Ifre-Ramonete (43.8 per 100), Balsicas (26.4 per 100), Gañuelas-Mazarrón (23.3 per 100) and Ugéjar-Morata (6.5 per 100). It is useful to point out that the greatest well investment was made for the period 1979 to 1984 (almost 60% of the total). We also must remark that in 1983 a long dry period began and was the moment when open air crops started their recessive phase that persisted until 1989. 1984 was the first year for farming under plastic. It is considered as a general criterion that pumping installations are amortized in 18 years. On the other hand, this is the longest period allowed by Ministerio de Hacienda, through its Order of February 23th of 1965, which regulates the annual amortisation coefficient table. Testing the related calculations, we have an annual amortisation value of 380,700 US dollars which is distributed among users' associations in the same way as for investments.

Maintainance expenses and overhead charges (bookkeeping, repairs, pump substitution, etc.) suppose, according to previous testing, an average of 10% of the actual market prices for installation. Concerning users' associations, those 1.6 million US dollars per year on account of maintenance expenses and overhead charges are distributed in the following way: Ifre-Ramonete (41.5 per 100), Balsicas (26.4 per 100), Gañuelas-Mazarrón (23.7 per 100) and Ugéjar-Morata (8.2 per 100).

According to all these factors or parameters and to the pumped volume, average price per 1 m^3 of groundwater is 0.248 US dollar. This price is very similar to that charged by the Comunidad de los Canales del Taibilla of 0.252 US dollar before it introduced the last rise to 0.273 US dollar per 1 m^3 in July 1990. For users' associations the unit costs are: Balsicas 0.172 US dollar m^{-3}, Gañuelas-Mazarrón 0.256 US dollar m^{-3}, Ifre-Ramonete 0.304 US dollar m^{-3} y Ugéjar-Morata 0.462 US dollar m^{-3} (Fig. 4 and Table 2).

These variations are due to the different influences that the various aquifers have on the supply to each association, because of the great difference in their hydrogeological characteristics (depth, geometry, overexploitation rate, etc). The cost per aquifer is specified in Table 3 and Fig. 6; the group named 'without designation' pertains to the group of small aquifers not catalogued because of their very reduced dimensions.

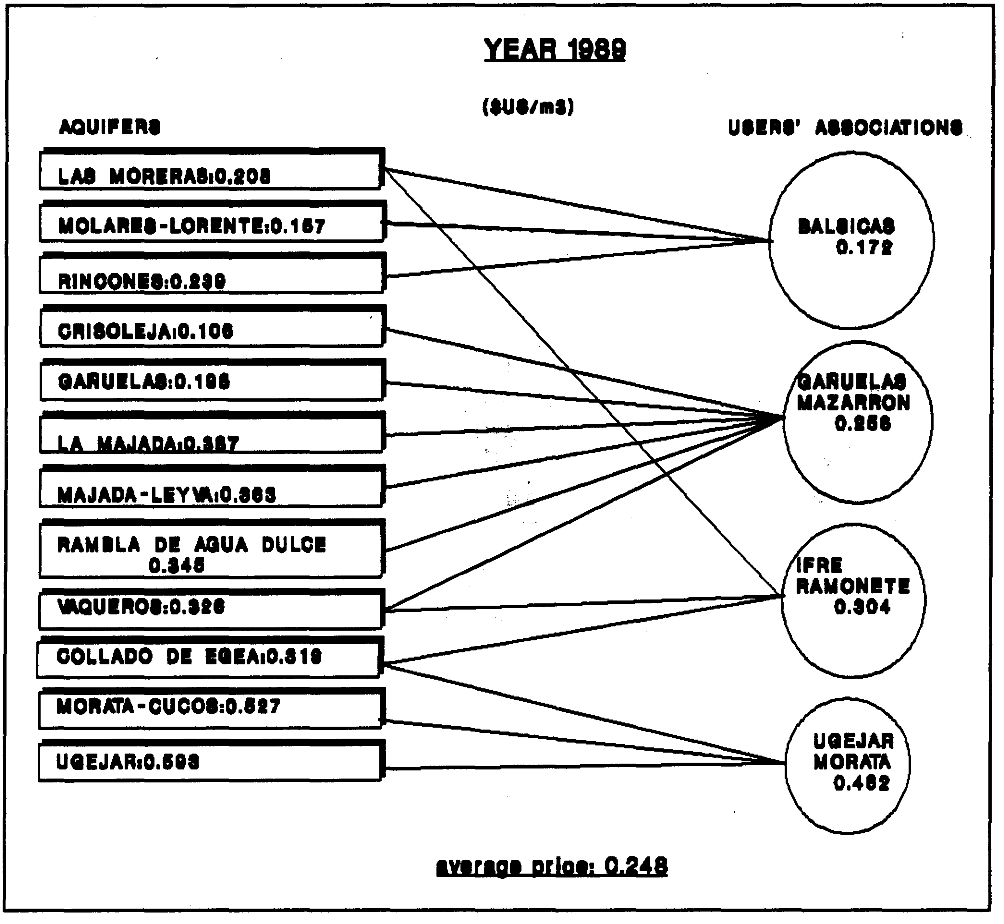


Figure 4: Groundwater cost.

Table 2: Mazarron zone. Groundwater cost for users' associations (US dollars).

Users' Associations	Vol. (m^3)	Power Cost	Amort. Cost	Overhead Cost	Total Cost	Unitary Cost
Balsicas	9,440,229	1,106,974	97,651	421,407	1,626,033	0.172
Gañuelas-Mazarrón	6,620,895	1,244,260	74,532	379,451	1,698,242	0.256
Ifre-Ramonete	9,003,783	1,928,325	151,727	662,862	2,742,914	0.305
Ugéjar-Morata	732,027	184,592	22,834	131,066	338,492	0.462
TOTAL	25,796,934	4,464,151	346,744	1,594,786	6,405,680	

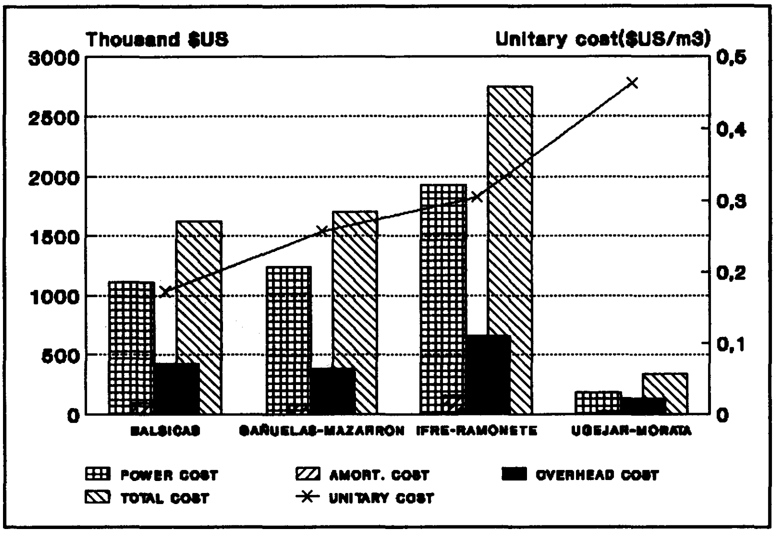


Figure 5: Schematic representation of table 2.

Table 3: Groundwater cost per aquifer (US dollars).

Aquifer	Vol. (m^3)	Power Cost	Amort. Cost	Overhead Cost	Total Cost	Unitary Cost
Collado de Egea	210,837	41,036	2,902	23,403	67,341	0.319
Crisoleja	95,323	5,808	1,439	2,898	10,146	0.106
Gañuelas	3,392,540	555,024	23,185	93,587	671,796	0.198
La Majada	44,970	9,777	1,251	6,377	17,404	0.387
La Majada-Leiva	1,739,843	400,617	33,108	198,633	632,357	0.363
Las Moreras	2,034,421	314,193	14,552	94,416	423,161	0.208
Molares-Lorente	7,950,927	912,869	69,602	271,207	1,253,678	0.158
Morata-Cucos	372,511	103,021	16,396	77,174	196,591	0.528
Rambla Agua-Dulce	31,295	3,211	1,565	6,023	10,799	0.345
Rincones	605,620	78,541	16,027	50,666	145,234	0.240
Without designation	1,505,265	254,445	22,350	119,372	396,167	0.263
Ugéjar	115,311	37,844	3,632	26,935	68,411	0.593
Vaqueros	7,698,071	1,747,766	140,830	624,095	2,512,691	0.326
TOTAL	25,796,934	4,464,151	346,840	1,594,786	6,405,777	

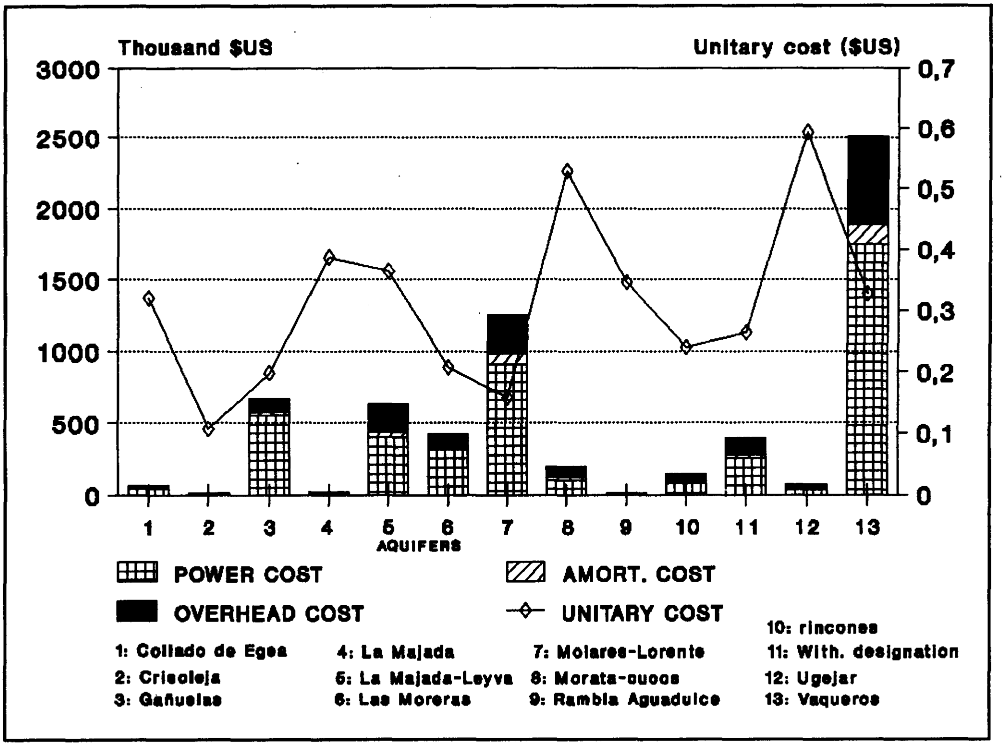


Figure 6: Schematic representation of table 3.

PRODUCTION AND AGRARIAN RENT

In 1989 the value of agrarian production for the Mazarrón zone reached 163 million US dollars (Table 4). Through a comparative analysis of what each crop contributes to the whole agrarian production (total quantity of products which are offered to the Market by the agrarian sector whatever their destination) and relating it to the cultivated surface, the economic importance of farming under plastic is clearly observed. The tendency to increase results from two necessities: on the one hand this is a water saving system in an agrarian zone where the sole available hydraulic resources are derived from overexploitated aquifers and, on the other hand, it furnishes greater profits per unit of cultivated surface; at the same time it supposes a high rentability for the producers. Thus crop farming under plastic, which represents about 18% of the surface area in Mazarrón, corresponds to 42.9% of the total value of the final agrarian production. Contrary to this, 82% of open air crops contribute 57.1% of the total value of the final agrarian production. This incongruity is more evident in the case of ligneous crops (21.6% of the cultivated surface area generates only 6.0% of the production value). The difference is minor for herbaceous crops (60% of the surface area produces 51.1% of the value).

Table 4: Mazarrón zone. Final irrigated agrarian production 1989.

CROPS	TRADED PRODUCTION (Thousand kg)	VALUE OF THE PRODUCTION ($US)
1.IN THE OPEN AIR	249,557,441	93,054,130
1.1.HERBACEOUS	231,950,831	8,328,390
- Forage (lucerne)	3,872,880	991,880
- vegetables	228,077,951	82,286,830
1.2. LIGNEOUS	17,606,610	9,770,230
- Citrus	16,306,080	5,824,400
- Fruit-trees (almond-trees)	1,250,550	3,870,550
- Vineyard (grape)	49,980	75,270
2. FARMING UNDER PLASTIC (Vegetables)	105,663,213	69,995,870
TOTAL:	355,220,654	163,050,000

Finally we must point out that the Mazarrón zone agrarian rent in 1989 (Table 5) is 100 million US dollars (including taxes and financial expenses), which is 61.1% of the agrarian production value.

Table 5: Mazarron zone. Added value to net cost of factors or agrarian rent of irrigated lands for 1989.

MACROMAGNITUDES	US DOLLARS	AVERAGE
1. Total agrarian production	163,050,000	100.0
2. Reemployment in the zone	68,480,900	4.2
3. Final agrarian production (1-2)	156,201,910	95.8
4. Costs out of the zone	53,531,060	32.8
5. GAV to market prices (3-4)	102,670,850	63.0
6. Subsidies for exploitation	4,076,250	2.5
7. GAV to factors cost (5+6)	106,747,110	66.5
8. Amortisations	7,174,190	4.4
9. NAV to factors cost or to agrarian rent (7-8)	99,572,900	61.1

ECONOMIC IMPACT OF OVEREXPLOITATION

Intensive overexploitation of aquifers in the Mazarrón zone for the last sixty years has allowed the depressed economic situation observed from 1900 to 1950 to be overcome. This overexploitation has been valued as at least 21 hm^3 for 1989 and represents 81% of the total zone exploitation (25.79 hm^3 for that year). Groundwater exploitation is at this moment destined to an exclusively agrarian use and made possible a total production of 163 million US dollars for 1989 and an agrarian rent of 100 million US dollars. According to generated richness criteria it can be affirmed that in this zone aquifer overexploitation has produced a beneficial effect during a fairly long period and has also initiated the parallel reactivation of other economic sectors. However, this overexploitation has not been carried out in a planned way. That is to say, different operating agents have not taken into account the available volume of groundwater reserves and therefore it is not possible to have a clear idea of the period for which the situation can be sustained. Thus, economic planning for the future has not been done. It is necessary to plan a progressive substitution of agrarian production for another activity which will be less exhausting for water resources or to obtain resources from outside the area. At this moment the actual situation is very alarming because of the gradual waste of groundwater reserves, the increase of pumping costs and water salinization. Total reserves evaluated by ITGE for 1989 do not exceed 200 hm^3, but their complete use can become progressively impracticable as much from a technical point of view as an economic one. According to 1989, prices total agrarian production is in a difficult sustainable situation in the short-term and reaches a value of 131.7 million US dollars.

In conclusion, because of this severe and problematical situation during the last few years in Mazarrón, related to the forementioned aspects of the wealth created with the help of groundwater overexploitation, it would be advisable to undertake energetic and determined public planning to enable a solution to be found as soon as possible.

REFERENCES

Aragón, R.; Solís, L & Rodríguez-Estrella, T., 1989. La sobreexplotación de acuíferos en la cuenca del Segura. In: *La Sobreexplotación de acuíferos*. AIH-AEHS (eds). Proc. Congr. Nac. Almería; 157-175.

Consejería de Agricultura, Ganadería y Pesca. 1976 a 1989. *Estadística Agraria Regional*. Comunidad Autónoma de Murcia.

Diputación Provincial de Murcia-IGME. 1981. *Los recursos hídricos subterráneos de la comarca de Mazarrón-Aguilas. Situación actual y perspectivas futuras*. Diputación de Murcia.

ITGE. 1989. *Explotación, usos, demandas y propuestas de normas de actuación en las aguas subterráneas de la comarca de Mazarrón-Aguilas (Murcia)*. Ed. ITGE. Madrid.

Solís, L; Mora, V; Rodríguez-Estrella, T. & Aragón, R. 1988. Situación de la intrusión salina en la cuenca del Segura. In: *TIAC'88*. Proc. Congr. Internac., vol. III; Almuñécar (Granada); 249-265.

Section 4:

OVER-EXPLOITED AQUIFERS IN WATER RESOURCES MANAGEMENT

EXPLOITATION OF THE TERTIARY-QUATERNARY OGALLALA AQUIFER IN THE HIGH PLAINS OF TEXAS, OKLAHOMA AND NEW MEXICO, SOUTHWESTERN U.S.A.

K.S. JOHNSON
Oklahoma Geological Survey, University of Oklahoma,
100 E. Boyd, Room N-131, Norman, Oklahoma 73019, U.S.A.

ABSTRACT. The Ogallala aquifer, of Tertiary and Quaternary age, is a major source of irrigation and municipal water that underlies about 135,000 km^2 of the semiarid High Plains region in Texas and adjacent parts of Oklahoma and New Mexico in the southwestern United States. The aquifer is a heterogeneous sequence of fluvial and windblown sands, silts, clays, and gravels deposited and reworked from streams that flowed eastward from the Rocky Mountains. In most of the 3-state study region the Ogallala aquifer is 60-180 m thick, and the saturated thickness of the aquifer is 30-120 m. The Ogallala is a water-table aquifer recharged almost entirely from precipitation that falls in its outcrop area. The average precipitation in the region is 40-60 cm year^{-1}; most estimates of recharge to the aquifer in the region are 0.5-1.3 cm year^{-1}.

Water in the Ogallala is used extensively for irrigation in the region. Total dissolved-solids concentrations are 200-400 mg l^{-1} in most areas, although in much of the south and scattered areas of the north they are 500-2,000 mg l^{-1}. Groundwater withdrawal was negligible until the drought in the southwestern United States during the 1930s. Ground-water irrigation then developed rapidly due to drought conditions, cheap energy, improved well-drilling and pumping systems, and profitable crop prices. By 1980, approximately 18,583 km^2 of land in the region were being irrigated, and annual water use was 7.679 km^3. This excessive pumpage, at annual rates many times greater than annual recharge rates, caused large water-level declines in most parts of the region. In nearly half of the region the water levels declined by 3-15 m from predevelopment days to 1980, and in another fifth of the region the decline was 15-30 m or more; in the remainder of the region water levels had fallen or risen less than 3 m through 1980.

Projections of several water-use strategies for the years 1980-2020 indicated that, without voluntary and/or mandatory reduction of water use, the drainable water remaining in the region would be only 49% of the water originally in storage. Water levels were projected to decline an additional 3-30 m by 2020, and the saturated thickness of the aquifer would be less than 30 m in most of the region.

Actual water use during 1980-1989 was less than predicted; thus water levels in about one-half of the region declined only slightly, and in the other half the water levels rose. Annual

precipitation in the study region during 1981-1987 was about 8.5-9.5 cm greater than normal, thus reducing the demand for irrigation water; in 1988 and 1989 precipitation was below normal. Other factors causing a reduction of pumpage are lesser amounts of land being irrigated, improved water-conservation methods, and increased costs of fuel, equipment, supplies, and loans. Increases in water levels in some areas probably result partially from recovery of local cones of depression caused by decreased pumping.

INTRODUCTION

The Ogallala aquifer, also referred to as the High Plains aquifer, underlies about 135,000 km^2 in the states of Texas, Oklahoma and New Mexico (Fig. 1). This aquifer is the principal source of water in the region, which is one of the major agricultural areas in the United States. Declining water levels and decreasing water supplies have caused major concerns about the future of crop production using Ogallala ground water for irrigation, and in many parts of the region there has been overexploitation of the aquifer.

To address the regional and national concerns about declining water supplies from the Ogallala aquifer, a multistate, interagency study was carried out between 1978 and the mid 1980s. Coordinated by the U.S. Geological Survey (USGS), this study was one of the first within its Regional Aquifer-System Analysis (RASA) program. The USGS High Plains RASA program was carried out to provide: (1) hydrologic information needed to evaluate the effects of continued ground-water development, and (2) computer models to predict aquifer response to changes in ground-water development (Weeks *et al.*, 1988).

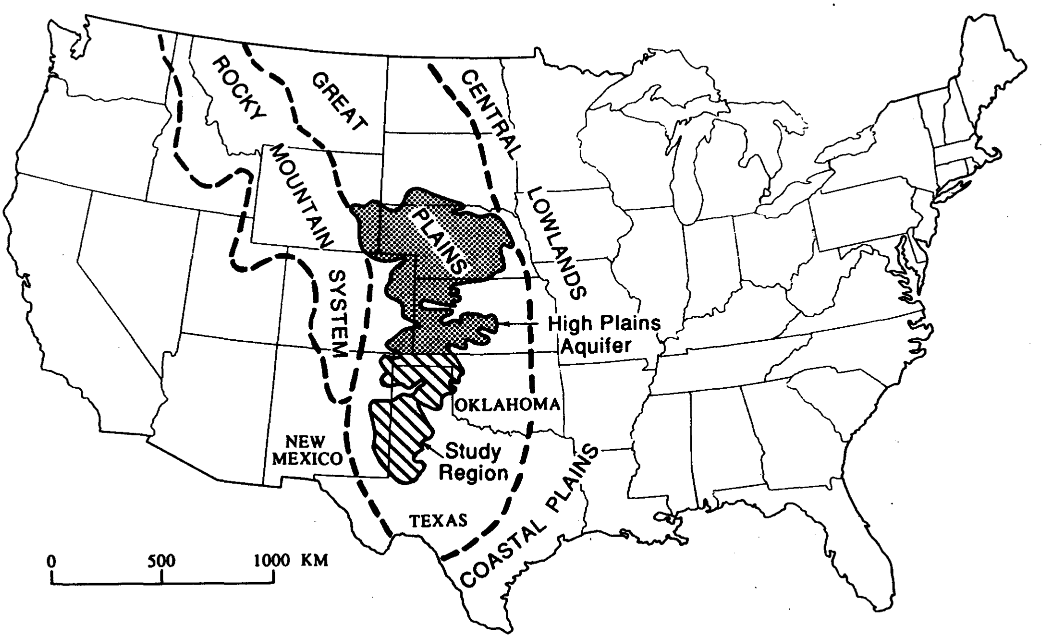


Figure 1: Location of the High Plains aquifer and the 3-state study region of Texas, Oklahoma and New Mexico.

The High Plains is part of the Great Plains physiographic province that lies between the Rocky Mountains on the west and the Central Lowlands and Coastal Plains on the east (Fig. 1). Although the original High Plains RASA study was carried out in parts of eight western states, the current study region deals only with the three southernmost states.

The current paper relies heavily upon the comprehensive High Plains RASA study by Gutentag *et al.* (1984), Weeks *et al.* (1988), Luckey *et al.* (1988), Weeks & Gutentag (1988) and Kastner *et al.* (1989), as well as other studies released by various state agencies, such as the work by Seni (1980), Knowles *et al.* (1984), Gustavson & Holliday (1985), Gustavson & Winkler (1988), Nativ (1988). The author expresses thanks for additional information provided through discussions with representatives of the USGS, Oklahoma Water Resources Board, Texas Bureau of Economic Geology (TBEG), Texas Water Development Board (TWDB), High Plains Underground Water Conservation District No. 1, Texas Tech. University Water Resources Center and New Mexico Bureau of Mines and Mineral Resources. Special thanks are extended to John B. Ashworth (TWDB), Thomas C. Gustavson (TBEG), and John S. Havens (USGS) for reviewing this manuscript and for their constructive comments. Appreciation also is expressed to Christie L. Cooper for editing the manuscript and to Charlotte C. Lloyd for drafting the illustrations; both work for the Oklahoma Geological Survey.

HYDROGEOLOGY

Physical setting

The High Plains forms a large, conspicuous, isolated plateau that slopes gently to the east-southeast (Fig. 2). It is a flat to gently rolling terrain consisting of eolian deposits and stream sediments laid down by ancient streams that flowed eastward from the Rocky Mountains. Subsequent erosion caused incision of streams into parts of the High Plains, as well as isolating the plains from the mountains on the west. Moderate to high escarpments typically mark the eastern and western boundaries of the plateau.

Eolian sand and silt, derived from earlier alluvial and windblown sediments, mantle much of the study region. Soil types in the region are mostly loams (including clay, silt, and sand loams), although sandy soils make up about 20% of the region (Gutentag *et al.*, 1984). Many intermittent lakes also occur across the 3-state region. They are shallow depressions, or playas, that typically collect water from local areas during periods of runoff.

The climate of most of the region is semi-arid, characterized by abundant sunshine, moderate precipitation, frequent and strong winds, low humidity, and a high rate of evaporation (Gutentag *et al.*, 1984); the eastern part of the region is subhumid. Average annual precipitation ranges from about 40 cm in the ranges to about 230 cm in the east, and average annual Class A pan evaporation ranges from about 230 cm in the north to about 275 cm in the south. Most precipitation falls between May and September, during the hot, summer months when evapotranspiration is greatest.

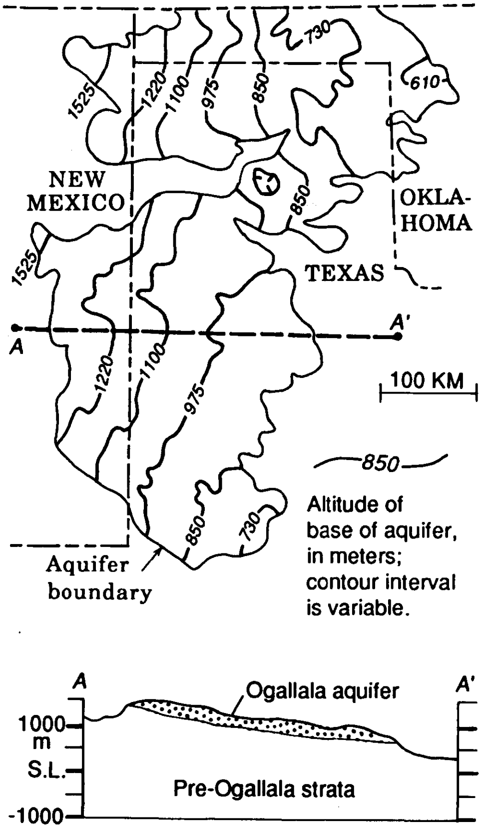


Figure 2: Structure at the base of the Ogallala aquifer (modified from Gutentag *et al.*, 1984).

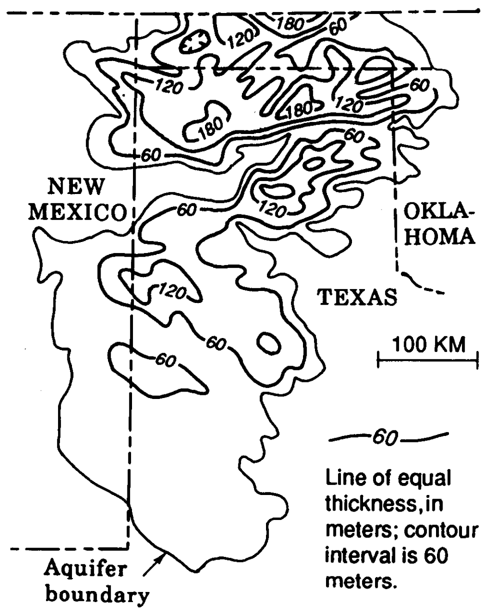


Figure 3: Thickness of the Ogallala aquifer (modified from Johnson *et al.*, 1988).

Geologic framework

The Ogallala aquifer consists of outcrops and near-surface deposits of Tertiary and Quaternary sands, silts, clays and gravels. The Ogallala Formation, of Miocene-Pliocene age, comprises the major part of the aquifer; it is overlain locally by the Pliocene Blanco Formation and by the Quaternary Blanckwater Draw and Tule Formations (Gustavson & Holliday, 1985). In many places, all these formations are overlain by Quaternary alluvial and dune-sand deposits. This entire package of largely unconsolidated Tertiary and Quaternary sediments is hydraulically interconnected, and they collectively comprise the Ogallala aquifer or High Plains aquifer. The Texas Department of Water Resources extends the concept of the Ogallala aquifer to also include underlying, hydraulically continuous units that contain potable water, according to Knowles *et al.* (1984), but that is not done in the USGS RASA study or in the current study. The thickest and most widespread units making up the Ogallala aquifer are the Ogallala and Blackwater Draw Formations.

The Ogallala Formation was deposited on an extensive erosional surface that was cut across Permian, Triassic, Jurassic and Cretaceous strata in the study region. Major paleotopographic features are preserved beneath the Ogallala, including large paleovalleys and intervening upland areas (Gustavson & Winkler, 1988). In addition, dissolution of underlying Permian salts has resulted in subsidence basins and other collapse features that deformed the basal Ogallala erosional surface near the eastern margin of the region. The base of the Ogallala Formation (and Ogallala aquifer) dips gently to the east-southeast at a rate of 2-4 m km^{-1} (0.1-0.2 degrees) (Fig. 2).

The lower part of the Ogallala Formation consists mainly of fluvial sediments laid down within the paleovalleys (Gustavson & Winkler, 1988). These fluvial deposits are laterally extensive, vertically stacked, channel-fill sands and gravels deposited by intermittent or perennial, high-energy braided streams. There are no significant fluvial deposits in the upper part of the Ogallala paleovalley fills or above the paleouplands. Termination of fluvial sedimentation across the region resulted from diversion of the streams that had flowed earlier to the east and southeast through the paleovalleys (Gustavson & Winkler, 1988).

Thick, wind-blown sands and silts of the Ogallala Formation overlie the paleovalley fluvial fill and paleouplands in most parts of the study region. These extensive sheets of sand and loess probably were derived by eolian processes acting on the floodplains of the fluvial deposits of the Ogallala Formation and the fluvial deposits of other streams and rivers in the vicinity of the study region (Gustavson & Winkler, 1988). The eolian sediments contain numerous pedogenic calcretes (buried calcic soil horizons), and the upper part of the Ogallala Formation commonly is marked by a caprock consisting of one or more pedogenic calcretes (calcite cement) or silcretes (silica cement), 3-15 m thick; these caprock units are locally known as 'caliche'. Fluvial sediments at the base of the Ogallala commonly contain ground-water calcretes (Gustavson & Winckler, 1988).

The Blackwater Draw Formation typically consists of about 10 m of loess with numerous paleosols (Holliday, 1989). The unit commonly is directly above the Ogallala Formation, and locally it is as much as 27 m thick. The eolian sediments generally are finer grained to the northeast, indicating that they were derived from the Pecos River valley area to the west and southwest of the study region.

The Ogallala aquifer (the Ogallala Formation and all overlying Tertiary and Quaternary sediments) is 60-180 m thick in most of the region, although it is 180-240 m thick at several places in northern Texas and in Oklahoma, where Permian-salt dissolution and collapse features are present (Fig. 3). Variation in thickness of the Ogallala aquifer results partly from the irregular paleotopography of its base and partly from modification of the upper surface by modern-day erosion.

The age of Ogallala-aquifer strata ranges from middle or early Miocene (about 10 million years b.p.) through Holocene (modern alluvial and eolian sediments). The Ogallala

Formation itself apparently is middle or late Miocene to early Pliocene (4.5 million years b.p.) in age (Winkler, 1985); the Blackwater Draw Formation is Quaternary (the last 1.4-plus million years) in age (Hollyday, 1989).

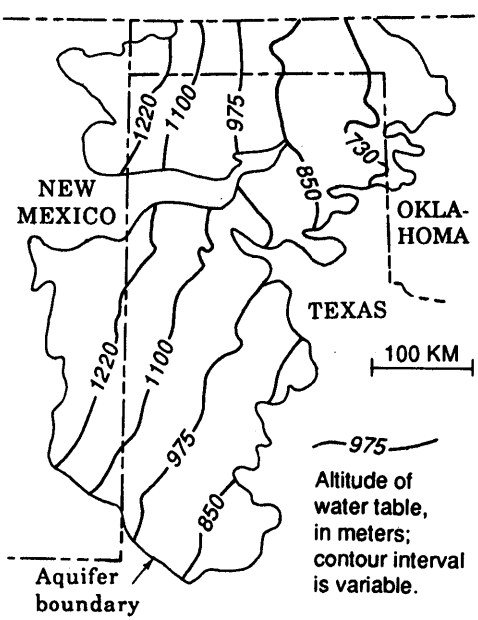


Figure 4: Altitude of water table in the Ogallala aquifer, 1980 (modified from Gutentag *et al.*, 1984).

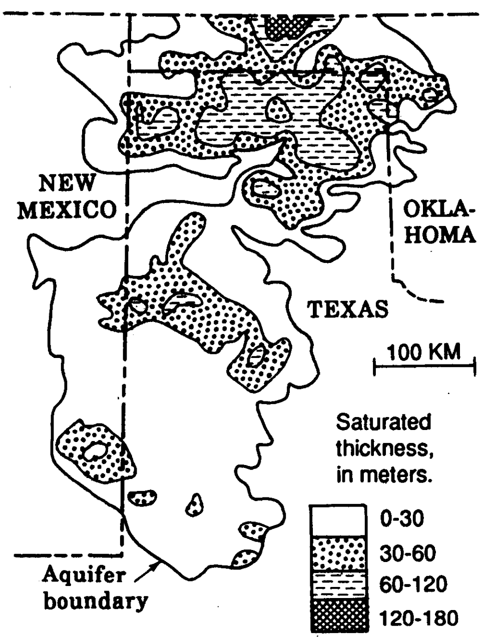


Figure 5: Saturated thickness of the Ogallala aquifer, 1980 (modified from Gutentag *et al.*, 1984).

Hydraulic characteristics

The Ogallala aquifer consists of several hydraulically connected geologic units of late Tertiary and Quaternary age that yield significant amounts of water to wells. The aquifer consists mainly of unconsolidated sediments, and water-table conditions prevail in most parts of the region. The water table slopes gently to the east-southeast (Fig. 4) at rates that range from 1-9 m km^{-1} and average about 3 m km^{-1} (Knowles *et al.*, 1984). Ground-water flow is to the east and east-southeast (the direction of the ground-water gradient), and the rate of movement is approximately 18 cm day^{-1}. Before irrigation wells were used to pump water from the aquifer, ground water flowed from the aquifer as springs scattered along the eastern edge of the study region, according to Brune (1981), and as base flow into some of the streams and rivers that crossed the eastern part of the High Plains. Because irrigation practices have lowered the water table in most areas, few springs of any size still exist, and base flow in most streams in negligible.

The saturated thickness of the Ogallala aquifer in the study region ranges from 0-30 m in most of New Mexico and Texas; locally it is 60-120 m in northern Texas, and is more than 120 m in Oklahoma (Fig. 5). Nativ (1988) points out that the areas of greater saturated thickness are along the major paleovalleys cut into pre-Ogallala strata, and the saturated thickness is less over the paleodivides. The saturated thickness of the aquifer in 1980 and today has decreased considerably since pre-irrigation days as a result of water withdrawal.

In most of the 3-state region the Ogallala aquifer has a hydraulic conductivity estimated at 8-30 m day^{-1}, although in some areas it is 30-60 m day^{-1} (Gutentag *et al.*, 1984); the average hydraulic conductivity for the region is estimated to be about 18-20 m day^{-1}. The higher hydraulic-conductivity values are mainly along the paleovalleys and fluvial systems (Nativ, 1988). However, Knowles *et al.* (1984) report that hydraulic conductivity does not vary obviously with depth, even though coarser sediments are present in the lower part of the aquifer.

The specific yield of the Ogallala aquifer in the region is estimated to be 5-25%, with most areas being 10-20% (Gutentag *et al.*, 1984). Cores from 41 test holes in the Texas Panhandle had specific yields of 7.2-19.5%, with and overall average of 16.1% (Ashworth, 1980).

Water quality of the aquifer in the study region is better in the north, with the concentration of both dissolved solids and chlorides increasing from north to south (Knowles *et al.*, 1984; Gutentag *et al.*, 1984). In the northern two-thirds of the region, dissolved-solids concentration commonly are 200-400 mg l^{-1}, and chloride concentration commonly are less than 50 mg l^{-1}. In the southern one-third, dissolved-solids concentration typically are 500-2,000 mg l^{-1}, and locally may result from: (1) alkali-lake basins at the surface; (2) declining water levels and saturated thickness of the aquifer; (3) industrial activities, such as petroleum productions and animal feed lots; and (4) dissolution of Permian salt beds that underlie the aquifer (Knowles *et al.*, 1984). Poorer quality water in the south typically is in areas underlain by Cretaceous strata, but the relationship (if any) is not understood.

Recharge

Inasmuch as the High Plains is an isolated plateau, the ultimate source of most recharge to the Ogallala aquifer is precipitation on the plateau. Precipitation in this semi-arid region is low, only 40-60 cm year^{-1}. Recharge rates in the study area are estimated at 0.25-2.5 cm year^{-1}, according to Gutentag *et al.* (1984), Knowles *et al.* (1984) and Nativ (1988), with most of the estimated being 0.5-1.3 cm year^{-1}. This estimated recharge rate typically is 1-3% of the mean annual precipitation (Gutentag *et al.*, 1984).

Recharge in any particular locality results from a combination of direct precipitation, playa-lake seepage, streamflow seepage, excess-irrigation seepage, and upward flow from underlying strata. Most precipitation in the region occurs mainly during the summer crop-growing season, and thus most moisture returns to the atmosphere by evapotranspiration.

Widespread loamy soils probably allow only minor recharge by direct precipitation, but sandy soils in the south are likely to be locally important for recharge.

Water collects in playa lakes after heavy rains, and part of this water infiltrates down to the water table (Kier *et al.*, 1984; Wood & Osterkamp, 1987). About 90% of the surface area in the study region drains internally to the playa lakes. The amount of playa-lake recharge is uncertain, inasmuch as some of the lake water is removed by evaporation. Streamflow, mainly runoff after heavy rains, does recharge the aquifer locally. Streams that carry water intermittently in the west and central parts of the region commonly are nearly dry when they reach the eastern edge of the region (Nativ, 1988).

Excess water applied to the land can and does seep down into the ground to help recharge the Ogallala aquifer. Fields irrigated for 25 years or more showed evidence of percolation to depths of 6-9 m (Knowles *et al.*, 1984). A substantial ground-water mound has been built up (locally by as much as 12 m) under the city of Lubbock, Texas, where much of the water is imported from other areas and is applied to the ground (watering lawns, etc.), and stormwater runoff from the metropolitan area is directed to nearby pits and playa lakes (Kastner *et al.*, 1989). Upward flow from underlying strata is possible in areas where pre-Ogallala strata meet the following conditions: (1) a hydraulic connection exists between underlying sandstones or limestones and the Ogallala, and (2) the potentiometric surface of water in the underlying strata is higher than water levels in the Ogallala aquifer.

GROUND-WATER USE

The Ogallala aquifer is the principal source of water for irrigation and for municipal, industrial, and domestic use in the 3-state region. Development of this resource for irrigation, mainly during the 1950s and 1960s, has made this one of the major agricultural regions in the United States; the region is noted for its productions of cotton, grain sorghums and wheat, as well as being a major center for raising beef cattle.

Discussion of ground-water use is herein divided into developments through 1980 and after 1980, mainly because the comprehensive High Plains RASA study used 1980 data as the basis for aquifer analyses. There was great concern about the excessive withdrawal of water up through 1980, and projections made at that time indicated the aquifer would be seriously drawn down in various areas within 10-40 years. However, above-normal precipitation and reduced irrigation during the 1980s have slowed the rate of lowering of the water table in most of the region.

State regulations concerning ground-water use

The three states in the region have different laws to regulate development of the Ogallala aquifer (Gutentag *et al.*, 1984). Texas and Oklahoma recognize private ownership of ground water, and also permit landowners to separately sell their rights to the ground water; New Mexico, on the other hand, regards ground water as being owned by the state. Permits for drilling and operating wells in the Ogallala aquifer are issued by the state in Oklahoma and New Mexico, and by local ground-water management districts in Texas.

In Texas, the Texas Water Development Board is the principal state agency responsible for water-resource planning (Gutentag *et al.*, 1984). However, the Board's activity is limited to fact finding, data collection and data analysis; it has no control over the drilling of wells or allocation of ground water. Management of ground water is in the hands of local people, who can vote to establish local ground-water management districts. Seven management districts, organized to cover nearly 70% of land underlain by the Ogallala, have the authority to require drilling permits, limit well spacing, restrict water allocations and prohibit waste of water. There are no restrictions on irrigation wells outside of the seven management districts.

Oklahoma ground water is owned by the landowners, but is administered by the Oklahoma Water Resources Board (Gutentag *et al.*, 1984). Oklahoma law allows formation of local ground-water management districts, but none has been created yet by landowner groups. The Board regulates the allocation of ground water; it also has the authority to require metering of wells (if the majority of landowners concur) and to determine minimum spacing of wells.

New Mexico ground water is owned by the state but only the water within declared ground-water basins is administered by the State Engineer; other ground water is not subject to regulations (Gutentag *et al.*, 1984). Two Ogallala ground-water basins have been declared in New Mexico, and these occupy about one-third of the area underlain by the Ogallala. Within the declared basins the State Engineer restricts drilling and limits allocation of water. Water-use permits are limited to 9,000 m^3 of water per hectare per year.

Factors affecting water-level changes

Changes in water level of the Ogallala aquifer are due to variations in the recharge to, and discharge from, the aquifer. Recharge results from downward percolation of precipitation or surface waters, whereas discharge results for evapotranspiration, seepage to streams and springs, and (mainly) pumpage from wells.

Recharge in the region is mainly from local precipitation, and this recharge is affected by climatic conditions, land use, vegetative cover and soil characteristics (Kastner *et al.*, 1989). Average annual precipitation is low, ranging from 40-60 cm, and during the high-precipitation period (May to September) the humidity generally is low, winds are persistent, temperatures are high and crop growth is greatest; thus most of the precipitation is used in evapotranspiration. Streamflow, fed by rainfall that is local or to the west of the region, also recharges the aquifer locally. Most estimated of recharge in the region are 0.5-1.3 cm $year^{-1}$, and, with an area of 135,000 km^2, the estimated total is 0.675-1.76 km^3 $year^{-1}$ of recharge water.

Discharge from the Ogallala aquifer is by natural or artificial methods. Where the water table is shallow, evapotranspiration of water from the saturated zone occurs naturally; and where the water table is intersected by the land surface, natural seepage of water to streams and springs occurs. Most natural discharge from the Ogallala occurs in the down-gradient, eastern part of the region.

Artificial discharge from the Ogallala is due to water being pumped from wells, with most of the water used for irrigation and other agricultural uses. Other uses of Ogallala ground water include domestic, municipal, industrial, livestock and petroleum-industry (drilling water and waterflood operation) supply.

Water-level changes reflect the amount of water that is pumped from the aquifer, which in turn is affected by precipitation, the cost of pumping (depth to water and energy costs), and conservation practices. If precipitation is not adequate for crops during the growing season, water is pumped for irrigation; conversely, abundant precipitation reduces the need for irrigation water. The cost of pumping and the financial return from crops are major factors controlling the amount of water pumped from the aquifer. Energy must be expended to pump the water, and the total cost for electricity or natural gas can rise sharply when their unit price goes up and/or the water table declines. Conservation and improved agricultural practices, such as better knowledge of soil-moisture conditions and plant requirements, reduce the amount of water needed for irrigation.

In 1969, 1974 and 1978, the amount of irrigation water pumped from the Ogallala aquifer in the 3-state region was estimated to be about 9.8-11.1 km^3 $year^{-1}$ (8-9 million acre-ft $year^{-1}$) (Gutentag *et al.*, 1984; its Fig. 22). This pumping rate is 5.6 to 16.4 times as much water as is estimated to be recharging the aquifer annually, and thus clearly there should be a marked decline in water levels under these conditions. Water-level fluctuations are not equal throughout the region, however; water levels decline most in areas with a high concentration of irrigated croplands, and show minor decline (or even a rise) in areas of little or no irrigation.

Water use through 1980

Ground water was first produced for irrigation in the study region in the late 1800s, when windmills were use to pump water to the surface. However, development of ground water was limited until the drought of 1933-1937. Ground-water irrigation developed rapidly after the 1930s drought, due to technical advances in well drilling and pumps, inexpensive energy, profitable crop prices and favorable financing (Gutentag *et al.*, 1984). The amount of land under irrigation, and the volume of water produced, rose sharply during the 1940s and 1950s; a drought during 1952-1956 helped spur irrigation in those years. Irrigation activity expanded only slightly during the 1960s and remained steady during the 1970s (Gutentag *et al.*, 1984). In 1980, about 7.7 km^3 of water was pumped to irrigate 18,583 km^2 of land in the 3-state region (Table 1).

As a result of ground-water withdrawal from the Ogallala aquifer, water levels have been lowered considerably in most parts of the region from predevelopment days to 1980 (Fig. 6). The water level was drawn down 3-15 m in about 46% of the region, 15-30 m in about 12% of the region, and more than 30 m in about 5% of the region. In about 35% of the region the water level remained constant, or fluctuated no more than 3 m up or down; this is almost entirely in the eastern and western parts of the region where the aquifer is thinner and where relatively few irrigation wells were drilled. The areas where water-level declines were greatest are in the central and northern parts of the region, where irrigation was first developed and was most intense.

Table 1: Estimates of irrigated land and irrigation water pumped from Ogallala aquifer, 1980 (Weeks *et al.*, 1988).

State	Area underlain by Ogallala aquifer (km^2)	Irrigated land, 1980 (km^2)	Water pumped during 1980 (km^3)
Texas	91,816	15,694	6.373
Oklahoma	19,037	1,574	0.666
New Mexico	24,476	1,315	0.640
Totals	135,329	18,583	7.679

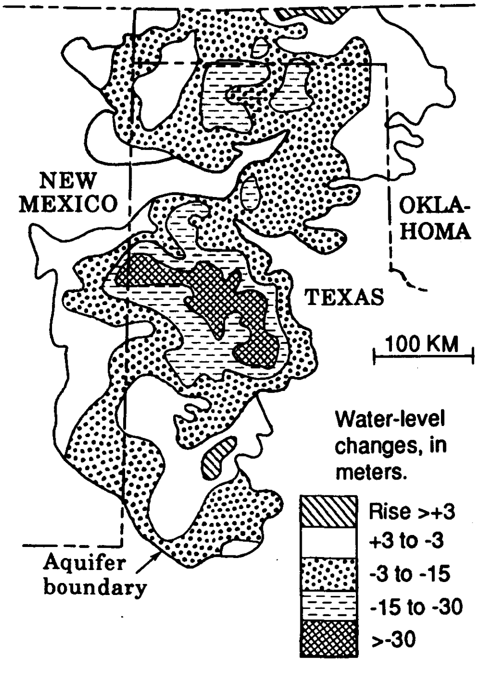


Figure 6: Water-level changes in the Ogallala aquifer, predevelopment to 1980 (modified from Gutentag *et al.*, 1984).

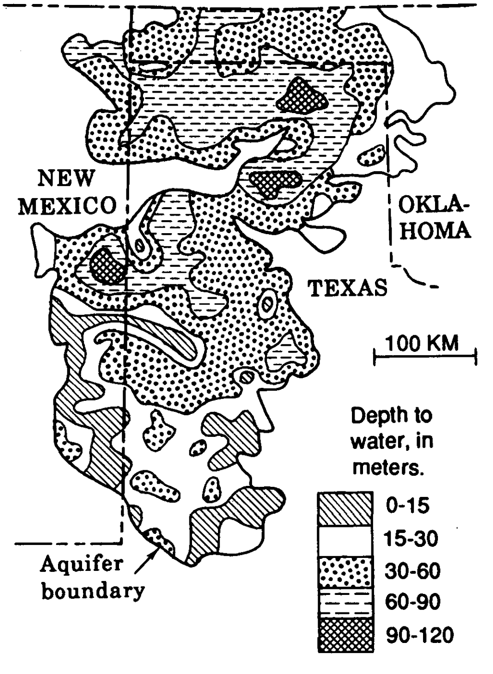


Figure 7: Generalized depth to water in the Ogallala aquifer, 1980 (modified from Gutentag *et al.*, 1984).

Through 1980, about 162 km^3 of water have been withdrawn from the Ogallala in the region (Table 2), representing about 19% of the drainable water that was in storage originally. Texas had the largest percentage of its original water withdrawn (23%), whereas New Mexico was second (15%) and Oklahoma was third (7%). Texas, however, still have the largest amount of drainable water remaining in 1980, followed by Oklahoma and then New Mexico.

The depth of the water table in the Ogallala aquifer in 1980 was 0-30 m in much of the eastern, western and southern parts of the study region, but was 30-120 m in most of the central and northern parts of the region (Fig. 7). The great depths of water in the central and northern areas resulted partly from the greater thickness of the aquifer in these areas and partly from the higher amounts of ground-water withdrawal through 1980 (compare with Fig. 6).

Projected water use from 1980-2020

Owing to the high rates of ground-water withdrawal in most of the High Plains (for withdrawal in this study region, see Fig. 6), and public concern that the Ogallala aquifer might be seriously depleted, in some areas, within several decades, computer models were developed to project future water levels and saturated thicknesses, based upon several water-use strategies (Luckey *et al.*, 1988). Three projections were made for the period 1980-2020, based upon a baseline strategy (continuation of current economic trends and government policies) and upon two alternative strategies, involving a voluntary reductions in water use (management strategy 1) and a mandatory reduction in water use (management strategy 2).

Within the 3-state study region, the total simulated pumping of Ogallala ground water for the period 1980-2020 would be 263 km^3 under the baseline strategy, 247 km^3 for management strategy 1, and 196 km^3 for management strategy 2 (Luckey *et al.*, 1988; its Tables 1 and 2).

Table 2: Water in storage and water removed, Ogallala aquifer, 1980; data from Gutentag *et al.* (1984), tables 8 and 11.

State	Predevelopment drainable water (km^3)	Water removed by 1980 (km^3)	Drainable water remaining 1980 (km^3)
Texas	226	140.6	481
Oklahoma	146	9.9	136
New Mexico	73	11.1	62
Totals	841	161.6	679

Based upon these three projections, the drainable water remaining in the region in 2020 would be, respectively, 416, 432 or 483 km^3, or about 49-57% of the water that was in storage originally.

Assuming the baseline strategy, water levels are projected to decline more than 3 m by 2020 in most parts of the study region, and more than 30 m in several large areas (Fig. 8). As a result of these projected declines, the saturate thickness of the aquifer in 2020 will be less than 30 m in most parts of the region (Fig. 9). The dramatic result of the projected declines is best seen by noting the sharp reduction in saturated thickness in 2020 (Fig. 9) compared to 1980 (Fig. 5). Under management strategy 1, water-level declines by 2020 would be nearly as much as in the baseline strategy. Under management strategy 2, the water levels would also decline by 2020, but not as severely; in all parts of the region the water consumption would be less than under the baseline strategy, (Luckey *et al.*, 1988).

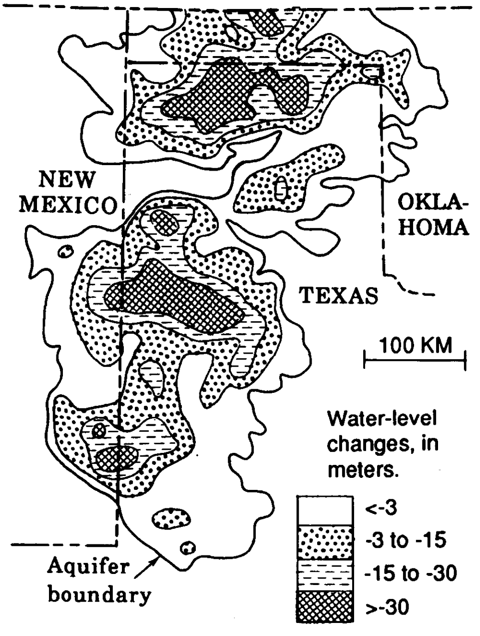


Figure 8: Projected water-level changes, 1980-2020, in the Ogallala aquifer resulting from pumpage in the baseline strategy (modified from Weeks *et al.*, 1988).

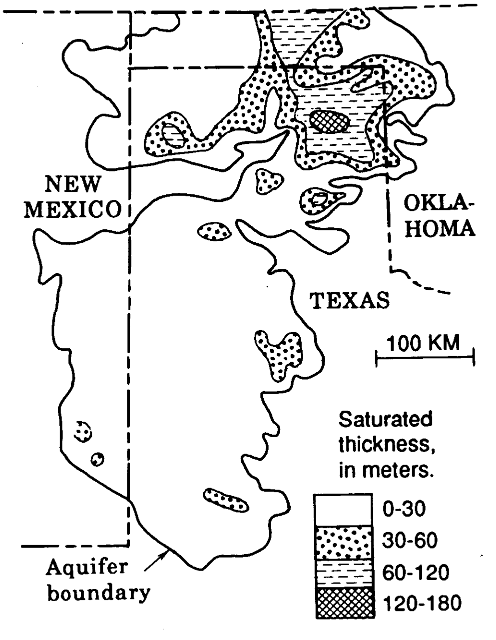


Figure 9: Projected saturated thickness of the Ogallala aquifer, 2020, resulting from pumpage in the baseline strategy (modified from Weeks *et al.*, 1988).

Actual water use during 1980-1989

The large water use and water-level declines that occurred in the Ogallala aquifer prior to 1980 did not continue during the 1980s (Kastner *et al.*, 1989). In about 45% of the study region the water level did decline, but not as rapidly as predicted, whereas in the other 55% of the region the water levels actually rose during 1981-1986, before declining again slightly. In some areas the water level rose by more than 3 m during 1981-1987 (Kastner *et al.*, 1989). Principal causes for these trends include above-normal precipitation, economic and conservation factors that reduced demand for irrigation water, and recovery of local cones of depression due to decreased pumpage.

Precipitation in the 3-state region during 1981-1987 was greater than normal (Kastner *et al.*, 1989). Annual precipitation, on an area-weighted basis, was about 8.6 cm above normal in Oklahoma, 9.5 cm in New Mexico, and an estimated 8.5-9.5 cm in Texas. Precipitation then dropped below normal during 1988 and 1989.

Above-normal precipitation in 1981-1987 helped cause a reduction in irrigation demands. There was a reduction in the rate of water-level declines, or a rise in water levels, during 1981-1985, and a general rise in water levels in most areas during 1986 and 1987. Water levels, weighted by area, rose in 1987 (between January 1987 and January 1988) by an average of 25.3 cm in Texas, 24.4 cm in Oklahoma and 4.6 cm in New Mexico (Kastner *et al.*, 1989). Water-level fluctuations during 1981-1987 were not uniform throughout the region; some wells had a water-level rise of as much as 5 m, while other wells in areas of continually increasing irrigation activity had declines of more than 3 m. However, on average, the steady rate of water-level decline prior to 1980 was reduced through 1985 and was actually reversed during 1986 and 1987. Water pumped in the 3-state region during 1985 was about 6.967 km^3, or about 10% less than was pumped in 1980 (compare with Table 1); individual state pumpage, in km^3, for 1985 was 5.819 for Texas, 0.343 for Oklahoma, and 0.805 for New Mexico (Kastner *et al.*, 1989).

Precipitation in 1988 and 1989 was below normal, and this resulted in resumption of high rates of irrigation. In one large ground-water management district in Texas, water levels that rose an average of 15 cm in 1986 and 27 cm in 1987, then declined by 16 cm in 1988 and 25 cm in 1989 (Anonymous, 1990): this district comprises about 22,250 km^2 (about 16% of the region) in the central part of the study region, and may be considered representative of the entire region.

Another factor important in reducing pumpage from the Ogallala aquifer during the 1980s is a reduction in the amount of land being irrigated. Some of the marginal croplands were taken out of production, and some lands were not planted because of government programs (i.e. Conservation Reserve Program and Payment in Kind Program) that offer incentives to decrease crop acreage. Some lands were taken from production due to increasing depths to the water table and increasing of fuel needed to pump the water and to operate farming equipment. Other financial problems that have beset agriculture in the region are decreased prices for crops and increased costs for equipment, supplies and loans.

Conservation efforts, also, are causing a reduction in water use in the region. More-efficient irrigation equipment and management include use of center-pivot sprinklers, furrow dikes and surge valves.

The dramatic rise of water levels in some areas during 1986 and 1987 probably resulted from recovery of local cones of depression caused by decreased pumping. Observation wells in the region include irrigation wells, domestic wells and abandoned wells, and the water level in these wells may rebound and rise sharply if they, or nearby irrigation wells, are taken out of production.

Resumption of water-level declines in 1988 and 1989 show that, on a long-term basis, water is still being withdrawn at a rate that exceeds recharge. The temporary reversal of the decline in 1981-1987 indicates the major importance of above-normal precipitation on farming and irrigation practices. However, the reduction in irrigated acreage and the improvements in water conservation should help reduce the long-term rates of water pumpage and water-level decline.

REFERENCES

Anonymous. 1990. District observation wells show one-foot average decline. *The Cross Section, 36* (5); 1-8. High Plains Underground Conservation District no. 1, Lubbock, Texas.

Ashworth, J.B. 1980. *Evaluating the ground-water resources of the High Plains of Texas*, results of test hole drilling. Texas Department of Water Resources. LP-129.

Brune, G. 1981. *The springs of Texas*. Fort Worth, Texas, Branchsmith.

Gustavson, T.C. & Finley, R.J. 1985. *Late Cenozoic geomorphic evolution of the Texas Panhandle and northeastern New Mexico: case studies of structural controls on regional drainage development*. Texas Bureau of Economic Geology. Report of Invest., 148.

Gustavson, T.C. & Holliday, V.T. 1985. *Depositional architecture of the Quaternary Blackwater Draw and Tertiary Ogallala Formations, Texas Panhandle and eastern New Mexico*. Texas Bureau of Economic Geology. Open-File Report OF-WTWI-1985-23.

Gustavson, T.C. & Winkler, D.A. 1988. Depositional facies of the Miocene-Pliocene Ogallala Formation, northwestern Texas and eastern New Mexico. *Geology*, 16 (3); 203-206.

Gutentag, E.D., Heimes, F.J., Krothe, N.C., Luckey, R.R. & Weeks, J.B. 1984. *Geology of the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming*. U.S. Geological Survey Professional Paper 1400-B.

Holliday, V.T. 1989. The Blackwater Draw Formation (Quaternary): a 1.4-plus-m.y. record of eolian sedimentation and soil formation on the Southern High Plains. *Geological Society of America Bulletin*, 101; 1598-1607.

Johnson, K.S., Amsden, T.W., Denison, R.E., Dutton, S.P., Goldstein, A.G., Rascoe, B., Sutherland, P.K. & Thompson, D.M. 1988. Southern Midcontinent region. In: *Sedimentary cover: North American craton*, Sloss, L.L., (ed.), Geological Society of America, The Geology of North America, vol. D-2; 307-359.

Kastner, W.M., Schild, D.E. & Spahr, D.S. 1989. *Water-level changes in the High Plains aquifer underlying parts of South Dakota, Wyoming, Nebraska, Colorado, Kansas, New Mexico, Oklahoma and Texas: predevelopment through nonirrigation season 1987-88.* U.S. Geological Survey, Water-Resources Investigations Report 89-4073.

Kier, R.S., Stecher, S. & Brandes, R.J. 1984. Rising ground water levels. In: *Proc., Ogallala aquifer Symposium II.* Texas Tech. Univ., Water Resources Center, 416-439.

Knowles, T., Nordstrom, P. & Klemt, W.B. 1984. *Evaluating the ground-water resources of the High Plains of Texas.* Texas Dpt. of Water Resources Report 288, vol. 1.

Luckey, R.R., Gutentag, E.D., Heimes, F.J. & Weeks, J.B. 1988. *Effects of future ground-water pumpage on the High Plains aquifer in parts of Colorado, Kansas, Nebraska, New Mexico, Oklahoma, South Dakota, Texas and Wyoming.* U.S. Geological Survey Professional Paper 1400-E.

Nativ, R. 1988. *Hydrogeology and hydrochemistry of the Ogallala aquifer, Southern High Plains, Texas Panhandle and eastern New Mexico.* Texas Bureau of Economic Geology Report of Investigations, 177.

Seni, S.J. 1980. *Sand-body geometry and depositional systems, Ogallala Formation, Texas.* Texas Bureau of Economic Geology Report of Investigations, 105.

Weeks, J.B. & Gutentag, E.D. 1988. Region 17, High Plains. In: *Hydrogeology,* W. Back, J.S., Rosenshein & P.R. Seaber, (eds), Geological Society of America, The Geology of North America, vol. 0-2; 157-164.

Winkler, D.A. 1985. *Stratigraphy, vertebrate paleontology and depositional history of the Ogallala Group in Blanco and Yellowhouse Canyons, north-western Texas.* Univ. of Texas, Austin, unpublished Ph.D. Thesis.

Wood, W.W. & Osterkamp, W.R. 1987. Playa-lake basins on the Southern High Plains of Texas and New Mexico: part II. A hydrologic model and mass-balance arguments form their development. *Geological Society of America Bulletin,* 99; 224-230.

MATHEMATICAL MODELS TO ANALYZE GROUNDWATER RECHARGE AND OVEREXPLOITATION FOR THE GUADALENTIN VALLEY AQUIFER, IN SPAIN

F. FRANCES, J. ANDREU, J. CAPILLA & A. SAHUQUILLO
Escuela de Caminos, Universidad Politécnica
Apdo. 22012, 46080-Valencia, Spain

ABSTRACT. The Guadalentín Valley aquifer is a highly overexploited aquifer in southeastern Spain. A recovery plan is currently under study. In order to check the feasibility of the corrective measures several mathematical models have modelling been applied. For the groundwater flow the well known finite difference MODFLOW model is used. In order to assess the aquifer recharge a rainfall-runoff model and an infiltration-percolation model are used. The recharge model is an extension of the model developed by Milly. It is used in order to explain the low values of the specific yield obtained in the calibration of the flow model. Even though more research is needed, it seems that the fast drawdown of the piezometric surface of up to 5 m year^{-1} experienced in the aquifer, together with the existence of less pervious layers can explain a lower value for the effective porosity. Finally, the corrective measures considered for recovery of the aquifer are discussed.

INTRODUCTION

In this paper an applied study of an overexploited aquifer in Spain is presented. A short description of the aquifer will be given, followed by a model of the flow from the ground surface to the piezometric level, through the unsaturated zone, and a description of the modelling of the flow in the saturated aquifer. Even though most of the identification and modelling of the aquifer have been performed, the plan for recovery is still under study.

THE GUADALENTIN VALLEY AQUIFER

As seen in Fig. 1, the Guadalentin Valley is located in the south east of Spain, in the region of Murcia. The aquifer is one of the three aquifer units located in a tectonic depression which trends northeastward and is filled by detritic permeable materials.

The aquifer has an area of about 740 km^2. The Guadalentín river flows through most of the length of the aquifer and contributes to its recharge. There are also ephemeral streams that are tributaries to the Guadalentín river along the valley which contribute to the recharge of

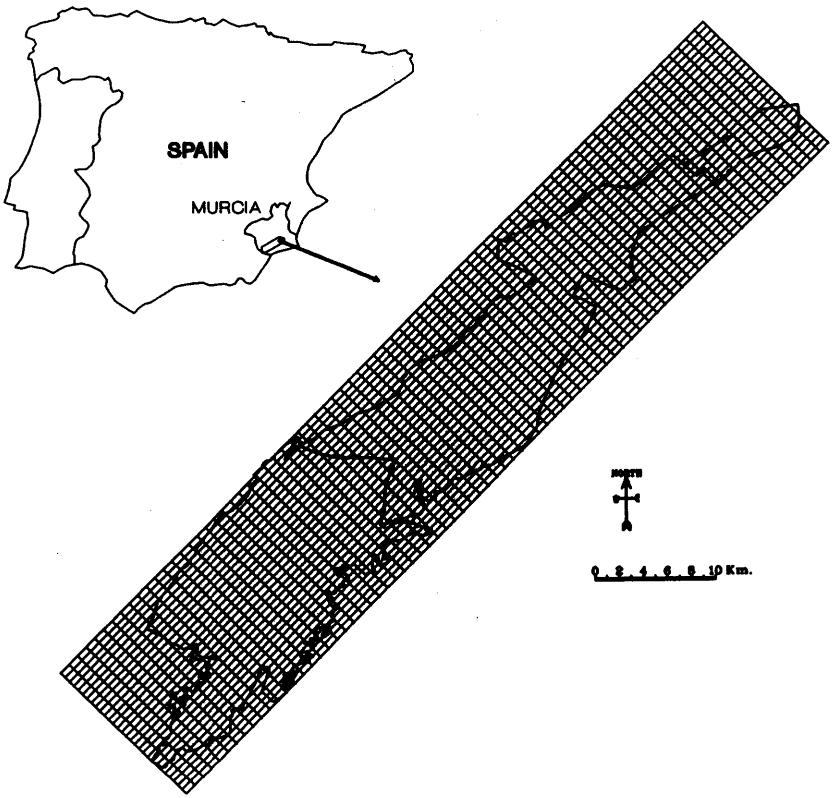


Figure 1: Geographic location of the Guadalentín valley aquifer and Finite Difference Mesh adopted.

the aquifer during flood periods. In the valley there are about 33,000 ha. of irrigated land. Most of the water for irrigation comes from pumping the aquifer. The average pumping has been about 100 hm^3 $year^{-1}$ for the past 20 years. The recharge due to infiltration of rainfall and irrigation return flows is about 20 hm^3 $year^{-1}$. Therefore there is an overexploitation of about 80 hm^3 $year^{-1}$. This is producing the lowering of the piezometric heads at a rate of up to 5 m/year and more, depending on the location, and eventually will lead to the exhaustion of the aquifer if no corrective measures are taken.

In order to predict the impact of changes in the exploitation on the aquifer state and life, several mathematical models have been used. On the one hand, in order to estimate the recharge, a model of rainfall runoff for the ephemeral streams and a model for simulation of the recharge through the unsaturated zone have been used. The later was done in order to verify the possibility of the infiltrated water not reaching the water table due to faster lowering of the piezometric surface than travelling from the recharge front and/or the possibility of an effective reduction in the porosity due to slower dewatering of the previously saturated zone. This last point was raised because the porosity values, estimated from the volume of dewatered aquifer, were in the order of 0.08 which is much lower than expected normal values given the lithology of the aquifer. On the other hand, a finite difference model for simulation of the flow in the aquifer has been calibrated.

THE RAINFALL RUNOFF MODEL FOR EPHEMERAL STREAMS

The surface aquifer is crossed by the last stages of several channels which join the Guadalentín river. To compute the recharge from these ephemeral streams a daily rainfall runoff model has been used, thus obtaining the volume of water arriving at the border of the aquifer.

The model was based on the well known U.S. Soil Conservation Service infiltration equation (see for example Viessman *et al.*, 1989), but using a daily time interval. The reason was that only data of 24 hour precipitation for the rain gauge stations were available.

Fortunately, the daily stream flow record of one of the watersheds, for the period 1946 to 1949, was available. The single parameter of the model was calibrated using this period. The result was a mean runoff of 0.027 $hm^3\ year^{-1}\ km^{-2}$.

THE INFILTRATION-PERCOLATION MODEL

The effective porosity will be defined as:

$$\phi_e = \frac{B-R}{\Delta H} \qquad [1]$$

where: B = pumping during period Δt, R = surface recharge or net infiltration during the same period Δt, and ΔH = water table drop.

One of the effects in an overexploited aquifer is the high dropping velocity of the water table. Intuitively, one can expect this descent to produce a longer water path through the unsaturated zone, a higher water retention enhanced by the existence in the vadose zone of less pervious layers, and a modification of the stable moisture content profile of the unsaturated zone. For these three reasons one can expect a decrease of the effective porosity defined by equation 1. Or, in other words, if pumping rate is higher than surface recharge rate, the water table will descend with higher velocity than that obtained from the study of a more stable water table in the past.

In order to confirm this idea an infiltration-percolation model has been developed. The model is quite simple for speed in long runs, due to the scarce information we have about the case study.

The model is divided into the three submodels described below.

Movement in the unsaturated zone

For this submodel the simplifications developed by Milly (1986), have been used. He assumes the profile of moisture content to be a succession of rectangles defined by their moisture content, θ_j, and the depth of the bottom of the rectangle, z_j. The flow $q(z,t)$ at each rectangle j is linear, and defined as:

$$q(Z,t) = q_j(t) + \Delta q_j(t) \frac{Z-Z_{j-1}(t)}{Z_j(t)-Z_{j-1}(t)} \quad Z_{j-1}<Z<Z_j \qquad [2]$$

The unknowns for the n rectangles are q_j, Δq_j, θ_j y z_j. The application of the continuity equation in the interior of each rectangle, the mass conservation between the wetting fronts, the Buckingham-Darcy equation and the assumption of gravitational flow in the top of each rectangle, reduces to $4(n-1)$ partial differential equations. For more details Milly's paper should be consulted.

The only modification made (in order to decrease the required data) is to use the relationship between the matric head and the relative moisture content given by Brooks and Corey (1966), and Eagleson (1978). With this modification, the set of resulting equations is:

$$\frac{\partial\theta_j}{dt} = -\frac{\Delta q_j}{Z_j-Z_{j-1}} \qquad j=1,2,\ldots,n \qquad [3]$$

$$\frac{dZ_j}{dt} = \frac{q_{j+1}-q_j-\Delta q_j}{\theta_{j+1}-\theta_j} \qquad j=1,2,\ldots,n-1 \qquad [4]$$

$$\Delta q_j = = -2q_j + 2\tilde{K}\theta_j^{*n} + \frac{2\tilde{K}\psi_{ce}}{1+3m} \frac{\theta_{j+1}^{*\frac{1}{m}+3} - \theta_j^{*\frac{1}{m}+3}}{Z_j Z_{j-1}} \qquad j=1,\ldots,n \qquad [5]$$

$$\left.\begin{array}{ll} q_j=K_j & j=2,3,\ldots,n \\ q_1=0 & \end{array}\right\} \qquad [6]$$

where: K = permeability, $\tilde{K}$ = saturated permeability, θ^* = relative moisture content, Ψ = matric head (negative), Ψ_{ce} = matric head at saturation, m =pore size distribution index, and n = porosity.

Connection with the aquifer

A last rectangle, equivalent to the capilliary zone, with moisture content equal to saturation and constant flow is considered. The two equations for this are:

$$\frac{dZ_n}{dt} = V \qquad [7]$$

$$q_n = \tilde{K}\left(1+\frac{\psi_{ce}}{Z_n - Z_{n-1}}\right) \qquad [8]$$

where: V = drop velocity of water table, Z_n = water table depth, and q_n = flow through capilliary zone.

With equation 7 the resulting drop velocity is introduced as external excitation instead of the pumping rate.

The resolution of the 4n partial differential equations given by equations 3 to 8 was made by the Runge-Kutta method (see for instance Carnahan *et al.*, 1979) with variable time interval. The new moisture profile at the end of the day is obtained in less than 10 steps, for a precision of three digits.

Surface balance

This submodel simulates the infiltration and evapotranspiration processes in the root zone. For the infiltration the rainfall runoff model described above was used. The actual evapotranspiration is proportional to the water in the root zone and the potential evapotranspiration. These two processes are simulated at the beginning of the day.

EFFECTIVE POROSITY VARIATION AS A FUNCTION OF THE WATER TABLE DROP VELOCITY

In order to isolate the drop velocity factor, simulations considering a wide range of constant surface recharges concentrated at the beginning of the first day of each year were first performed. The initial profile of moisture content is obtained from the stable case with an initial water table depth of 100 m. The types of soil considered are shown in table 1. For the four soils, the difference between saturated and residual moisture content, $\Delta\theta$, is 20%.

As can be seen in Fig. 2, with the same $\Delta\theta$ and V, the pumping rate (or the effective porosity given by the equation 1) increases with the permeability of the unsaturated zone, I. e., in coarse sand we can pump more water from the aquifer with the same effect on the water table than in silty sand. The main factor for this phenomenon is the mean moisture content in the unsaturated zone. For the scenario given in Fig. 3 and soil 1 it is equal to 0.548, and for soil 4 is 0.636.

Table 1: Soil characteristics used in the simulations.

Parameter	Soil 1	Soil 2	Soil 3	Soil 4
$\tilde{K}$ (m s^{-1})	10^{-5}	10^{-6}	10^{-7}	10^{-8}
m	1	0.5	0.4	1
Ψ_{ce} (m)	-0.5	-1	-1.5	-0.5

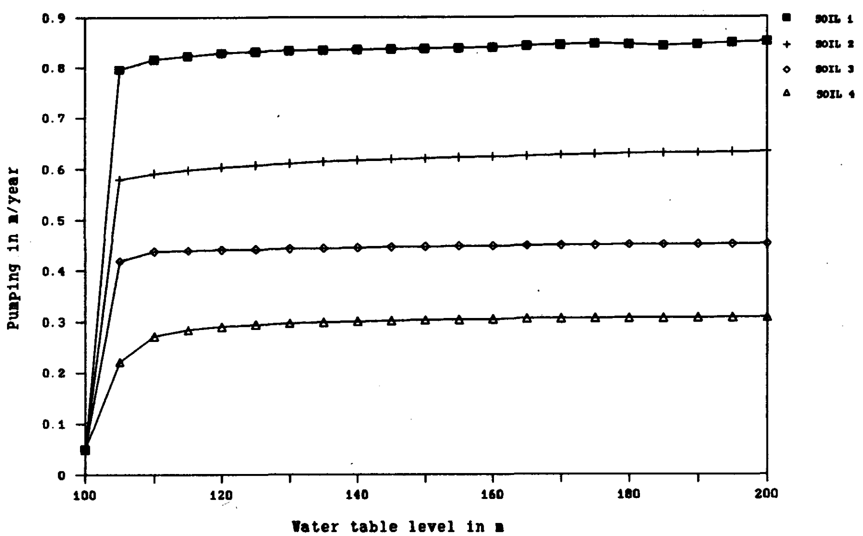


Figure 2: Pumping variation as a function of the soil type, for a surface recharge of 50 mm $year^{-1}$ and a dropping velocity of 5 m $year^{-1}$.

In Fig. 3 the results are presented for soil 1 (representative of sandy soils) in terms of ϕ_e. In the long term, the effective porosity increases with the drop velocity, but with small differences. With high drop velocity, the moisture content close to the capilliary zone is smaller and there is more space for water.

However, for clay soils another situation is found: the effective porosity decreases with the drop velocity of the water table (Fig. 4). In these soils the effect described above is balanced by the impossibility of important flows in the unsaturated zone, which is reflected by the increase in thickness of the capilliary zone.

For the Guadalentín aquifer just two runs of one representative soil column were made. During the 17 years of historic data, the mean rainfall is only 231 mm $year^{-1}$, and the

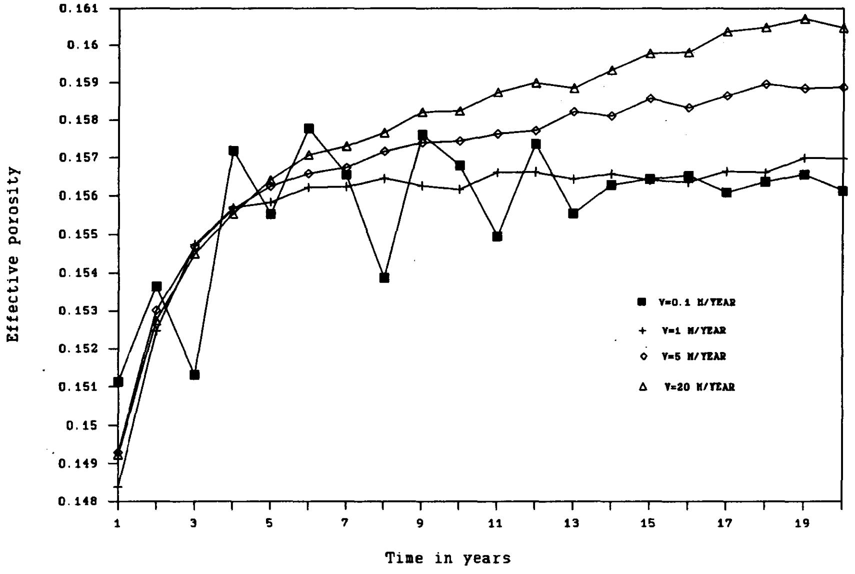


Figure 3: Variation in time of the effective porosity, with a surface recharge of 50 mm year^{-1}, soil type 1 and different drop velocity of the water table.

potential evapotranspiration is about 854 mm year^{-1}. The water table was 100 m deep in 1970 (first year of the runs), and the drop velocity is 5 m year^{-1}. The initial profile of moisture content is the profile obtained after 24 years of stable water table. The soil column has the features of soil type 2.

The first run corresponds to an irrigated area. It has 5 irrigations of 110 mm ha^{-1} each during the year. The second run is for a non-irrigated area.

The results are given in table 2 and the main conclusions are:

(a) the surface recharge of this aquifer is insignificant compared with the resulting pumping rate for the considered drop velocity. The effective porosity is similar in both cases and equal to 75% of $\Delta\theta$. As was analyzed before, if the drop velocity increases in the future the effective porosity will become smaller.

(b) the increase of the water volume in the unsaturated zone is due to the flow from the aquifer, not due to the small surface recharge.

(c) in the run corresponding to irrigated cases, the moisture content is slightly higher and, as a result of this, the pumping rate and the effective porosity are slightly smaller.

(d) as it can be seen in Fig. 5, the abstraction and the variation of the surface recharge are independent for a constant water table fall.

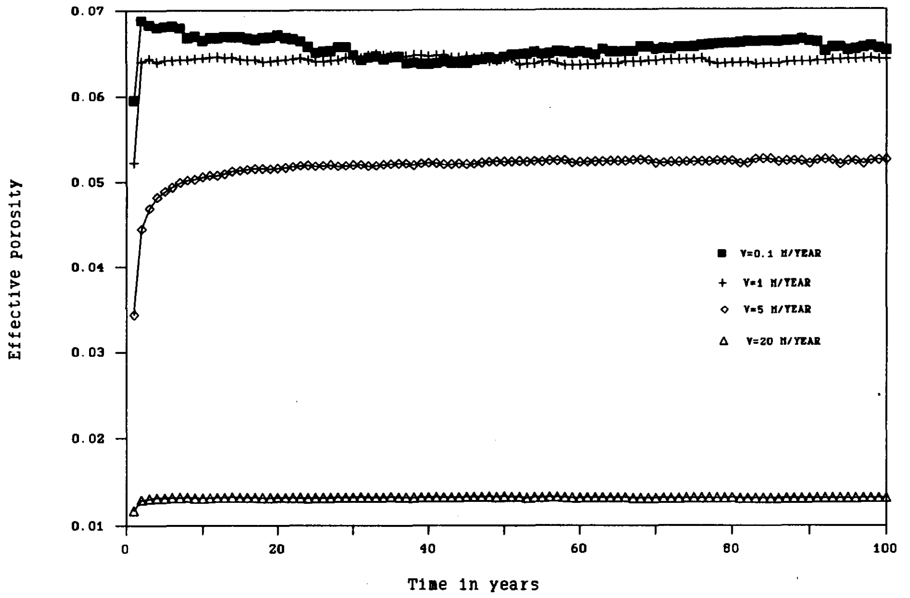


Figure 4: Time variation of the effective porosity, with a surface recharge of 50 mm year^{-1}, soil type 4 and different water table drop velocities.

Table 2: Results for the 2 runs in the Guadalentín aquifer.

	Irrigated	Non irrigated
Mean initial moisture content	0.552	0.540
Mean moisture content after 17 years	0.554	0.544
Mean infiltration, in mm year^{-1}	782	231
Mean actual evapotranspiration, in mm year^{-1}	759	231
Mean surface recharge, in mm year^{-1}	23	0
Mean pumping rate, in mm year^{-1}	745	759
Mean effective porosity	0.144	0.152

One of the assumptions of this model is the consideration of an homogeneous soil column. Usually, the aquifer will have soil characteristics similar to the soil type 1. However, it is possible to find less permeable layers in the unsaturated and saturated zone. For a stable

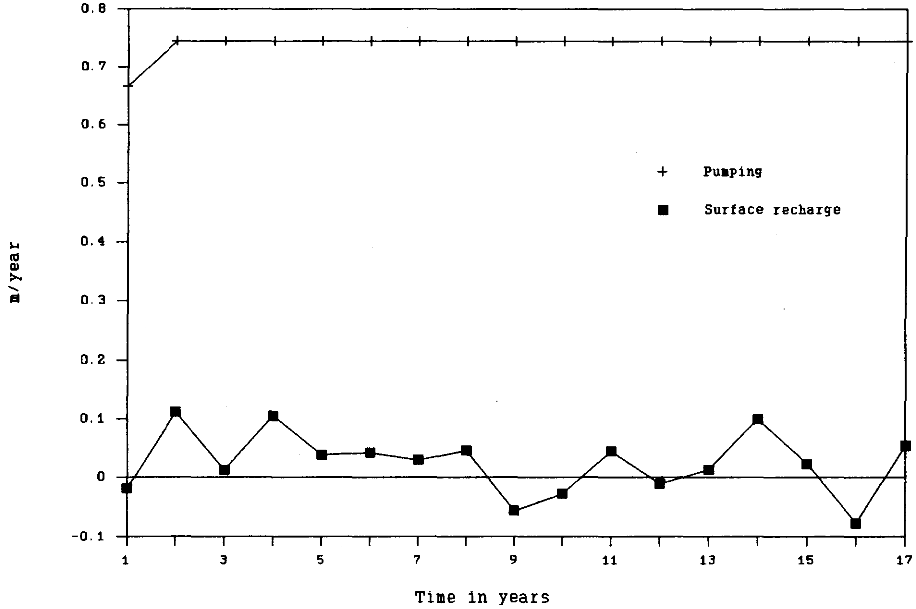


Figure 5: Surface recharge and pumping evolution in the irrigated case.

aquifer there is no difference. For an overexploited aquifer, if there are no clay layers the effective porosity probably will change very little. But the existence of clay layers will produce large moisture retention in the unsaturated zone (McWorter, 1985). This retention will decrease the effective porosity, as was shown in the simulations with soils type 3 and 4.

More research must be done to consider a multilayer column soil. For this reason the results of this study can only be considered as indicative.

THE GROUNDWATER FLOW MODEL

Aquifer Features and Model Adopted

Previous hydrogeologic studies of the Guadalentín valley aquifer lead to the conclusion that it may be considered as made up by two layers of different hydraulic characteristics. Both of them show highly heterogeneous materials with intercalation of pervious and impervious levels. The upper layer is made up by clays, limes, sands and conglomerates which are dated as belonging to the Pliocene. Its thickness varies from a few tens of meters to nearly 200 m. It extends only to part of the Southwest of the aquifer whose limits are shown in Fig. 1. The layer below is made up of clays, sands, sandstones, conglomerates and marls, dated in the Tortonian and the Andalucian. Its thickness varies from 30 m to 500 m and it extends over the whole aquifer except part of the Southwestern zone. Its hydraulic conductivity and specific yield are expected to be lower than those for the upper layer.

The layer below works as a leaky aquifer where there is s saturated upper layer, but when the latter becomes dry it works as an unconfined aquifer.

Field measures are scarce and sparse. Apart of some not too bad piezometric 'photos', evolution of heads is known only at twelve points in the calibration period.

The tectonics of the region are quite complex and the aquifer is fractured by many faults that cross it and could create barriers to the flow. Unfortunately, the quality and quantity of field data do not provide proof of their existence, location and influence on the flow. These faults could divide parts of the aquifer in blocks with a poor hydraulic connection between them and this could explain some anomalies that can be inferred from available data.

Given the features described above, the groundwater flow model of McDonald & Harbaugh (1984) was considered flexible enough for the case. The finite difference mesh adopted, shown in figure 1, has 76 rows by 29 columns in two layers. The cells are of 1000 x 500 m. The total number of active cells is 1446, 614 in the upper layer and 832 below. Boundary conditions where set to zero flow, except for the northeastern border, where a constant head has been imposed. Here the head values were obtained through the calibration.

Model Results

The calibration period, from 1982 until 1989, has been limited by the availability of spatial and temporal distribution of pumping. The piezometric level data were, as indicated above, scarce and sparse. In fact, initial heads had to be calibrated for some areas in the aquifer. Due to this additional data to verify the calibrated model were not available. Nevertheless, average results agree reasonably with those expected and are well fitted to field measures in the period.

The average hydraulic conductivity for the upper layer has been evaluated to be in the range of 10 to 13 m day^{-1}, but locally it decreases to very low values that cause the flow pathlines to be strongly modified. For the layer below the hydraulic conductivity is quite low and its mean is estimated to be about 0.5 m day^{-1}.

The specific yield of the upper layer has been evaluated to be 0.10, greater than that for the layer below. The latter is estimated to be in the range of 0.07 to 0.08, although this value implicitly takes into account the fact that when water table drops, a fraction of stored water is caught over lenses of impervious materials, so the levels decrease at a rate greater than expected. The storage coefficient of the lower layer has been estimated to be in the range of $1.5x10^{-4}$ to $2.5x10^{-4}$.

Fig. 6 shows how the results of the model fit with data in two of the most representative points of measure. It would be impossible to fit the cluster of points in months 55 to 70 for piezometer 11 since the real values of the pumping are unknown and they have been interpolated for that period. Besides, many wells have been abandoned and replaced by new ones in other areas.

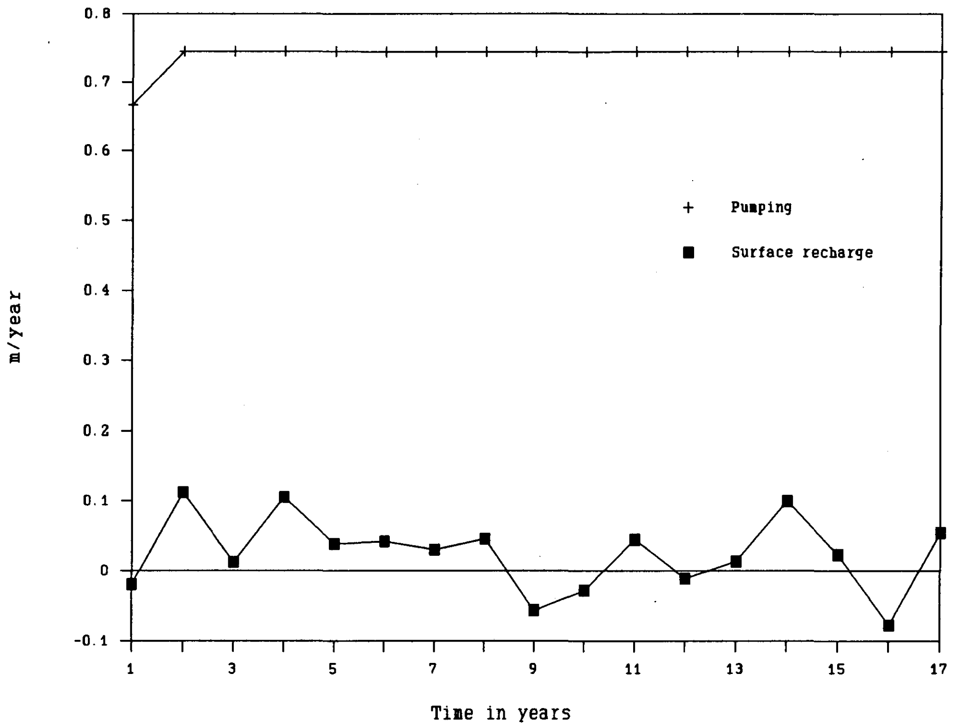


Figure 6. Example of fitting obtained for the calibrated model

CORRECTIVE MEASURES PROPOSED

As seen in the introduction, we are faced to a hyperexploited aquifer rather than to an overexploited one. The withdrawals are about 500 % of the recharge. In order to bring the figures for recharge and extractions closer and, hence, to reduce the deficit, some technical measures are available. Among them we can list the following:

(a) increasing the recharge to the aquifer. By means of land terracing and the construction of small dams across the ephemeral streams the surface runoff will be reduced, contributing to a higher amount of recharge. Also artificial recharge by means of recharge ponds and wells will be considered.

(b) reuse of water from municipalities and industries. In fact most of the potential reuse is already being practiced, but there is still some amount left.

(c) secondary recovery. A study will be performed in order to check the economic feasibility of recovering water from the unsaturated zone, since the results of the unsaturated zone model give some hope about significant amounts of water available. The methods to recover such water could be air injection and/or the use of substances that reduce the capillary tension of the water. It is quite clear that the secondary recovery should be performed only in the case that an exhaustive mining of the aquifer is decided; see for instance Sweazy (1984) and Redell *et al* (1985).

(d) optimizing the conjunctive management of the surface and groundwater resources of the valley. A more efficient use of the resources than that currently done will increase the effective resources.

(e) improving the efficiency of the irrigation methods. Even though the methods used in the zone are already quite efficient, some improvements could still be made.

(f) importing water from outside areas. The Guadalentín Valley belongs to the Segura River Basin, which is under a single Water Authority. Resources from the basin are completely allocated. An interbasin water transfer from the Tagus River Basin is completed and theoretically all the water is also already allocated. But, some rearrangements could be made taking into account that it may be preferable to help maintaining currently irrigated zones than developing the new ones that would receive the water from the transfer. Also, additional water could be obtained from the benefits of managing conjunctively all the resources of the Segura Basin system, including other aquifers with low exploitation.

In conjunction with the above mentioned technical measures some political, legal and socio-economic measures will be required. Some of them should be applied independently of the success of the technical measures to balance the resources and the consumptions in the long-term. Others will be needed in the case that such a balance be technically impossible. The measures that will be studied are:

(a) measurement devices should be installed in order to effectively control the amounts of water taken by the users. Wells and diversion canals and ditches should be gauged.

(b) an efficient network of monitoring wells should be designed in order to control the evolution of the piezometric heads and of the water quality.

(c) priorities for the use of water should be clearly stated, as well as the activities consuming water which will be allowed in the valley.

(d) pricing of the surface water according to its market value. Currently the surface water used has very low price. In scarcity situations such a low price does not stimulate conservation.

(e) subsidizing the change from irrigated farming to non irrigated farming, or to less water consuming crops.

(f) in case it is decided to mine the aquifer, the existing reserves should be allocated. This is necessary in order to avoid a race by the individual users in order to maximize their individual profits.

CONCLUSIONS

The Guadalentín Valley aquifer has been presented as a highly overexploited aquifer in which the abstraction is 5 times the recharge. A study to plan the future management of the aquifer to achieve a balance in the long-term is under way. In order to gain insight into the behavior of the aquifer some mathematical models are used. Among them, a rainfall-runoff model for the unsatured zone and a model for groundwater flow have been described in this paper. It is quite clear from the amount of the imbalance that technical measures within the valley alone will not solve the problem. Some socio-economic and legal measures are needed. Which ones will be applied will depend very much on the ability of the Water Authorities to create a framework in order to effectively manage the Segura River basin, to which the Guadalentín valley belongs, as a single system. This could accrue benefits from a more efficient management leading to more water resource availability. Also the irrigated land development in the whole basin should be reorganized in order to ensure water for already developed irrigated lands.

ACKNOWLEDGEMENTS

The work presented is part of a study being performed by the Hydraulic and Environmental Engineering Department of the Universidad Politécnica de Valencia in collaboration with ENADIMSA consulting firm for the Confederación Hidrográfica del Segura.

Thanks are due to Dr. Lopez and to Dr. Giraldez of the Universidad de Córdoba for their comments and discussions on Milly's model.

REFERENCES

Brooks, R.H., & Corey, A.T. 1966. Properties of Porous Media Affecting Fluid Flow. *Journal of Irrigation and Drainage*. Div. of ASCE. IRZ: 61-88.

Carnahan, B., Luther, H.A. & Wilkes, S.O. 1979. *Cálculo Numérico, Métodos, Aplicaciones*. Ed. Rueda. Madrid.

Eagleson, P. S. 1978. Climate, Soil and Vegetation 3: A simplied Model of Soil Moisture Movement in the Liquid Phase. *Water Resources Research*, vol. 14.

McDonald, M.G. & Harbaugh, A.W., 1984. *A Modular Three-Dimensional Finite-Difference Ground-Water Flow Model*. U. S. Geological Survey, Open-File Report; 83-875.

McWorter, D. B. 1985. Seepage in the Unsaturated Zone: A Review. *Seepage and Leakage from Dams and Impoundments*. Proc. of ASCE Symp.

Milly, P. C. D. 1986. An event-Based Simulation Model of Moisture and Energy Fluxes at a Bare Soil Surface. *Water Resources Research*, vol. 22.

Redell, D., Wyatt, A. & Claborn, B. 1985. Enhanced recovery of groundwater from unsaturated zone: the Ogallala case. *Water Res. Symp.* Twelve. Univ. of Texas.

Sweazy, R. 1984. *Scientific and economic research in support of the investigation of secondary recovery of groundwater.* Proc. of the Ogallala Aquifer Symp. II. Lubbock, Texas.

Viessman, W., Lewis, G.L. & Knapp, J.W. 1989. *Introduction to Hydrology*. Harper & Row Publishers, 3rd edn. New York.

GROUNDWATER MANAGEMENT MODEL OF THE DENDRON AQUIFER, REPUBLIC OF SOUTH AFRICA

W.R.G. ORPEN & W.E. BERTRAM
Directorate: Geohydrology
Dept. of Water Affaires and Forestry
Private Bag X313, Pretoria, RSA 0001

ABSTRACT. Overabstraction of groundwater resources for irrigation purposes from a discrete catchment area in the Northern Transvaal has resulted in the progressive lowering of groundwater levels over the past decade. This phenomenon has been exacerbated by the recent provision of electricity supplies in rural areas and the resulting proliferation of centre pivot irrigation systems. To promote the optimum utilization of the limited groundwater resources in the area, a management model has been designed and calibrated, based on the aquifer saturated volume fluctuation (SVF) method and using historic groundwater levels and groundwater abstraction volumes derived from records of electricity consumption at each irrigation setup in the area. Water balance modelling using a network of triangular elements enabled aquifer storativity and groundwater recharge to be estimated. This involved determining changes in saturated aquifer volumes and solving the overall water balance equation on a monthly basis. The calibrated model was then used to simulate responses of groundwater levels to various scenarios of annual rainfall and groundwater abstraction regimes. The model clearly shows that continuation of groundwater abstractions at the present rate will deplete the limited groundwater resources still further. Various remedial measures are suggested for conserving the available groundwater resources while still maintaining irrigation viability.

BACKGROUND

The village of Dendron, located about 60 km northwest of Pietersburg in the Northern Transvaal (Fig. 1), is the centre of an extensively irrigated area using groundwater. The study area (567 km^2) is drained towards the northeast by a network of poorly-defined 'laagtes' with an average gradient of about 0.003. Surface water flow occurs only after heavy or prolonged summer rains. The mean annual rainfall of the area is of the order of 450 mm and is highly variable. About 80% of the annual rainfall occurs during the summer months October to March. Figures 2, 3 and 4 portray, respectively, the annual march of mean monthly rainfall and evaporation, monthly and annual rainfall as recorded in the catchment since 1977.

The study area is underlain by granite and gneisses of Archean age which have been subjected to various phases of folding and metamorphism of the highest regional grade. Apart from occasional metaquartzites, outcrops are sparse and the area is largely covered by redbrown sandy soils, with minor calcrete horizons. Intruding into the basement rocks are numerous east-northeast trending dolerite dykes which have been identified aeromagnetically. Any influence that these dykes may have on the regional geohydrology is not readily apparent. From limited exploratory drilling and some geophysical borehole logging it would appear that weathering and decomposition of the bedrock occurs to an average depth of 35 to 40 m below the surface, and that this zone constitutes the major aquifer of the area. Below this zone groundwater occurs within a network of fractures in the bedrock, which have a matrix permeability and storativity about an order of magnitude higher and lower respectively than the upper weathered zone.

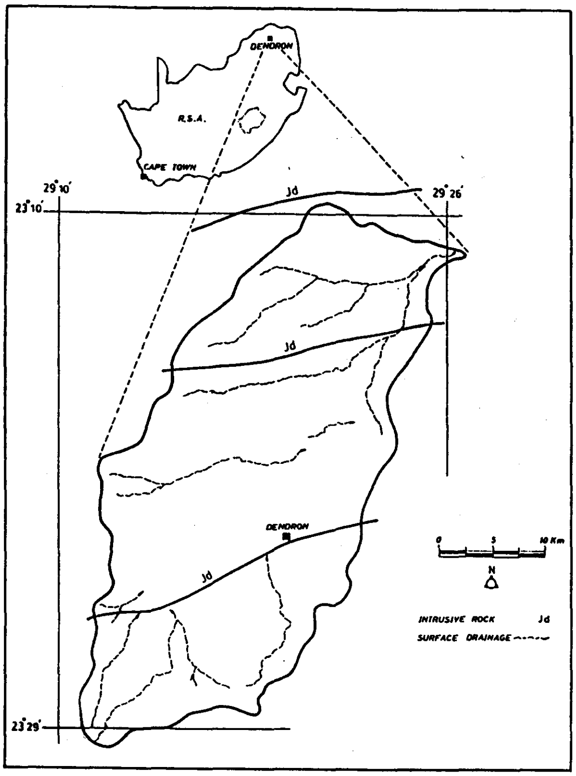


Figure 1: Locality map of study area.

From field surveys it was reported that of the 800 known boreholes in the area 36% have yields in excess of 20 l s^{-1}. Any borehole with a yield greater than about 10 l s^{-1} is considered suitable for equipping for irrigation purposes. Potatoes and maize are the main crops grown on 60% of the irrigated lands in winter and summer respectively. From satellite

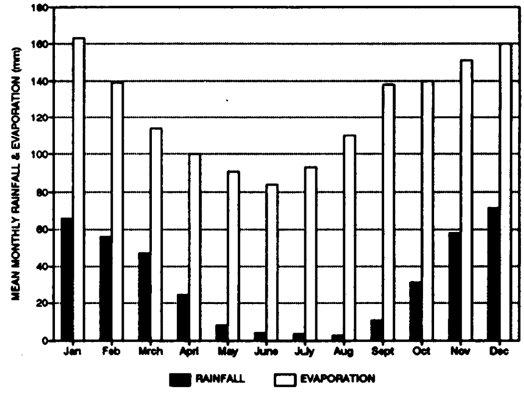


Figure 2: Annual march of rainfall and evaporation.

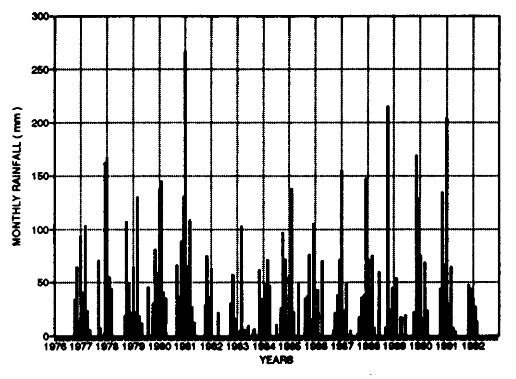


Figure 3: Monthly rainfalls.

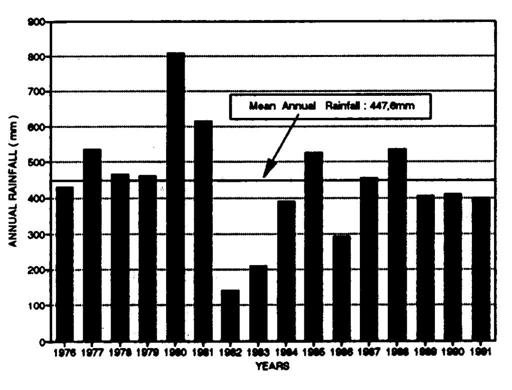


Figure 4: Annual rainfalls.

images of 1987 and 1988 it was estimated that about 1,000 ha of farmland was being irrigated in the area, both in summer and winter.

Borehole and irrigation surveys date back to 1968. Trends which have developed over the past decade or more include:

(a) an increase in the areas being irrigated,
(b) an increase in quantities of groundwater being abstracted,
(c) additional boreholes being drilled to exploit the groundwater resources in the deeper fractured zone,
(d) a steady decline in groundwater levels up to 50 m.

These trends can be attributed to overabstraction of the groundwater resulting from:

(a) electrification of rural areas,
(b) introduction of labour-saving centre pivot irrigation systems,
(c) attempts by local irrigators to increase crop yields by increasing field water applications,
(d) long periods of subnormal rainfall.

It is of great concern to the local irrigators that the groundwater resources of the area are gradually being depleted as large financial investments have been made in irrigation land and equipment and in market-related infrastructure. For this reason an attempt has been made to model the aquifer system so that the groundwater resources can be quantified and management strategies can be formulated. In this way the available groundwater resources can be optimally utilized by the whole community of irrigators whose very livelihoods depend on this resource.

MODEL INPUTS

Groundwater levels have been measured on a fairly regular basis at 58 private boreholes distributed widely over the study area since July 1976. Although the placing and distribution of monitoring boreholes and the frequency of measurements are not ideal, the records of groundwater levels have been usefully applied in the model. Records indicate that groundwater levels have declined on the average by at least 10 m since mid-1981, which marks the end of a relatively wet period during which in excess of 600 mm of rain was recorded in each of two consecutive years. In areas of particularly heavy irrigation groundwater levels have been lowered by more than 20 m. Figure 5 illustrates three typical groundwater level hydrographs synthesized from measurements made in the south, centre and north of the study area.

No records are available on groundwater abstraction at each of the 72 known irrigation setups in the area. However records are available of electricity consumed at each of the setups either on a quarterly or monthly basis from the beginning of 1978, the year electric power was first introduced to the area. In order to make use of these records field measurements were undertaken at all irrigation setups to establish the relation between electric power consumed by each motor and the delivery rate of each associated pump. Four categories of pumping setup were observed from which conversion factors could be determined, namely:

(a) groundwater pumped from one borehole to a reservoir and then pumped to the irrigated field using a booster pump,
(b) groundwater pumped from two boreholes simultaneously to a reservoir and then pumped to the irrigated field using a booster pump,
(c) groundwater pumped directly from a borehole to the irrigated field,
(d) groundwater pumped from a reservoir using a booster pump.

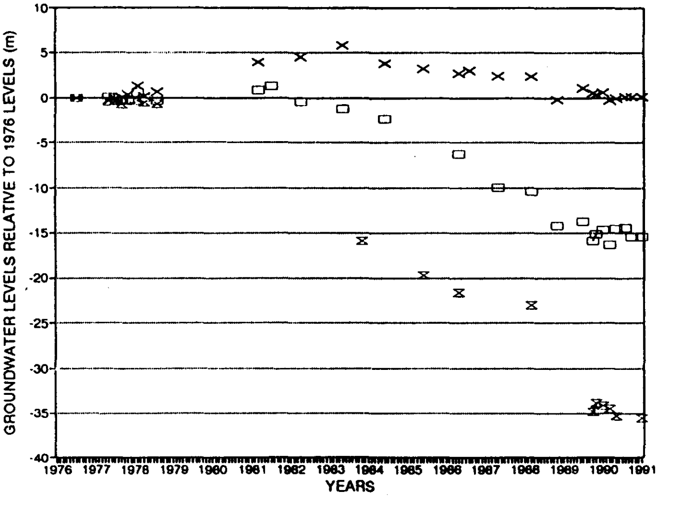


Figure 5: Typical groundwater level hydrographs.

Figure 6 shows the range of conversion factors obtained for each of the four categories of pumping setup. A record was then created of quantities of groundwater abstracted at each irrigation setup from the beginning of 1978. The realibility of this record depends on a number of unknown factors which include:

(a) changing head conditions in each borehole at each irrigation setup,
(b) changing motor and pump efficiencies,
(c) changing pumping configurations.

An allowance had to be made in the early part of the record for the gradual replacement of former diesel-driven pumps used before the introduction of electricity. The record was then used as input to the model. Figures 7 and 8 portray respectively the monthly and annual quantities of groundwater abstracted since 1977 in the study area.

Records of monthly rainfall are available for a number of rainfall stations in the study area

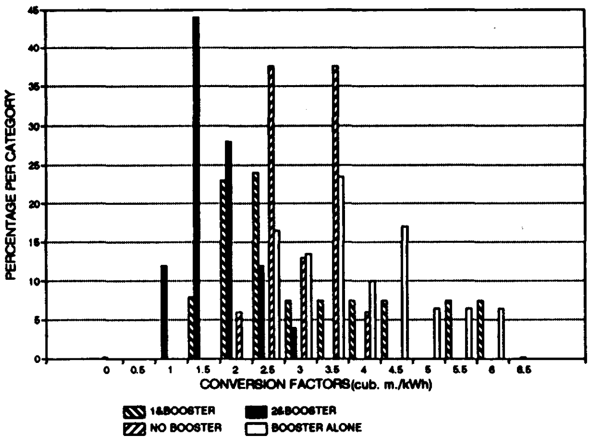


Figure 6: Distribution of conversion factors.

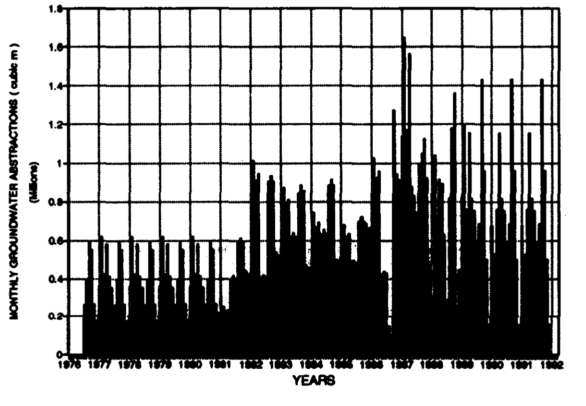


Figure 7: Monthly groundwater abstractions.

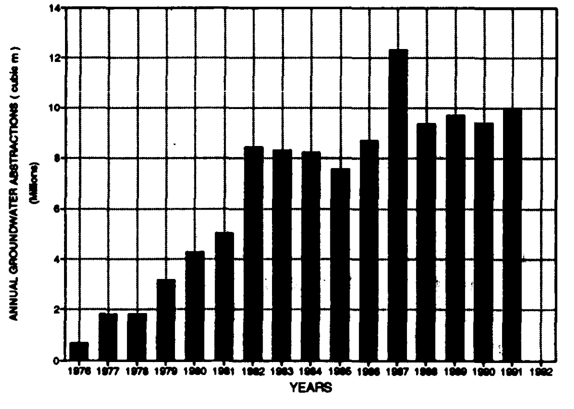


Figure 8: Annual groundwater abstractions.

and were used to synthesize a representative monthly rainfall record for the area.

Aquifer storativity and recharge remain however largely unknown. It is recognized that the latter will depend on the intensity and duration of rainfall events, and on soil and overburden conditions that have a bearing on infiltration rates. Although reliable quantitative estimation of groundwater recharge is therefore seemingly indeterminable, an innovative application of the groundwater balance equation has allowed not only groundwater recharge but also aquifer storativity to be estimated.

APPLICATION OF THE GROUNDWATER BALANCE EQUATION

The SVF method effectively makes use of the water balance method. The method essentially entails that the groundwater level fluctuations within the aquifer are converted to the integrated state of the volume of the groundwater stored in the aquifer, and the examination of its variation in time. The advantage of the SVF methods is that the changes in groundwater storage can be estimated more reliably using an integration technique, rather than simply using average groundwater levels. Any changes in the groundwater levels are of course dependent on the effective porosity of the aquifer. In the case of the Dendron aquifer it is assumed that there is a decrease in the effective porosity with depth. In order to make better use of the available groundwater data, runs of 12-months shifted one month at a time are accommodated in the analysis.

The groundwater balance equation appropriate to an unconfined aquifer with an impermeable base forms the basis of the groundwater model. Expansion of the equation making use of the Darcy formula for lateral inflows and outflows (signified by $A1$ and $A2$), and after simplification, results in the generalized groundwater balance equation

$$GR + A1.TI - A2.TO - A3.S = Q,$$

where GR is the effective groundwater recharge, Q is the groundwater abstractions, S is the aquifer storativity and $A3 = dV/dt$. If the aquifer is bounded by groundwater divides $A1$ and $A2$ can be assumed to be zero and the equation further simplifies to

$$GR - A3.S = Q$$

The dilemma of having two unknowns i.e. groundwater recharge and aquifer storativity is circumvented by solving for aquifer storativity ignoring groundwater recharge. This implies that the calculated storativity S^* would include a recharge component (Bredenkamp *et al.*, 1989). By solving S^* over periods of 12-months shifted one month at a time the S^* values can be related to the corresponding 12-months rainfalls. This allows for an S-value pertaining to a zero 12-month rainfall to be obtained which represents the mean storativity of the aquifer. Van Tonder (1989) has compiled a PC computer program DELV to analyse the saturated volume fluctuations for an aquifer on this basis. By substitution of the mean storativity of the aquifer into the water balance equation a rainfall-recharge relationship can be determined. The saturated volumes of the aquifer can now be simulated by varying the mean storativity value to obtain the best match with the observed saturated volumes. In this way the most probable mean storativity value for the aquifer can be estimated whereupon the annual recharge values can be determined and related to annual rainfall.

GROUNDWATER BALANCE MODEL

Using the positions of the groundwater level monitoring boreholes and centres of groundwater abstractions as element nodes (Fig. 9), a network of triangular elements was constructed as shown in Fig. 10. Nodes representing the positions of the major intrusive dykes and the boundary conditions were also incorporated into the network. The groundwater levels as observed from July 1976 were used to infer groundwater levels at all the other element nodes within the network for which no data on groundwater levels were available. All the groundwater levels were then used to synthesize the monthly saturated volume fluctuations of the aquifer on a monthly basis from 1976 (Fig. 11).

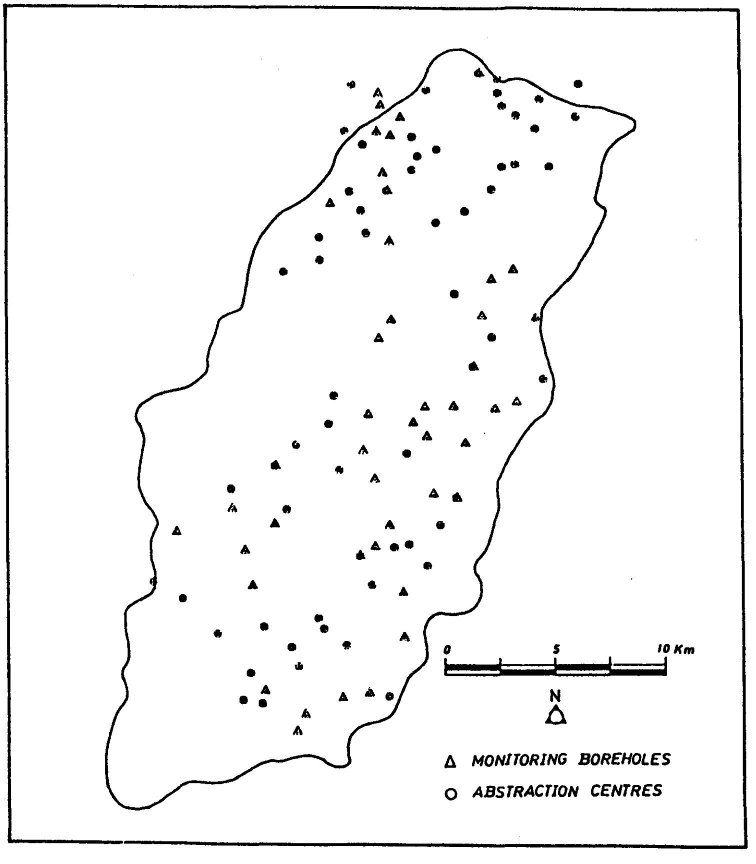


Figure 9: Positions of the nodes.

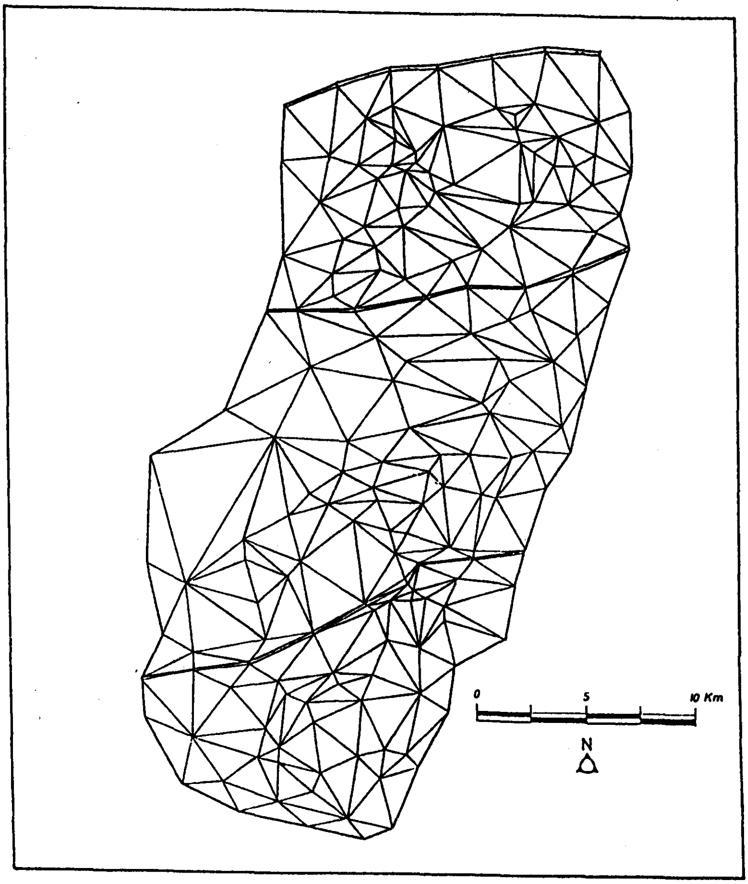


Figure 10: Position of the elements.

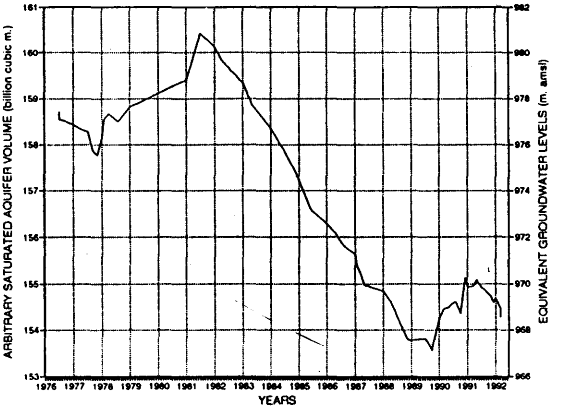


Figure 11: Monthly saturated aquifer volume fluctuations.

The reliability of the SVF method will depend on the accuracy of the groundwater abstraction data and on the validity of the assumption that subsurface inflows and outflows balance. The calculated storativity values for each 12-month period are shown in Fig. 12. It will be noted that the values lie on either side of the zero calculated storativity. The positive values indicate that the largest component of the calculated storativity is recharge. The inability to calculate from Fig. 12 the aquifer storativity at zero 12-month rainfall is probably due to inadequacies of the groundwater hydraulics prevailing within the aquifer. For the purpose of the model, however, the mean storativity of the aquifer was assumed to be 0.01 for the upper weathered and decomposed zone decreasing to 0.005 for the lower fractured zone. These values were confirmed as reasonable by aquifer pumping tests undertaken in similar areas.

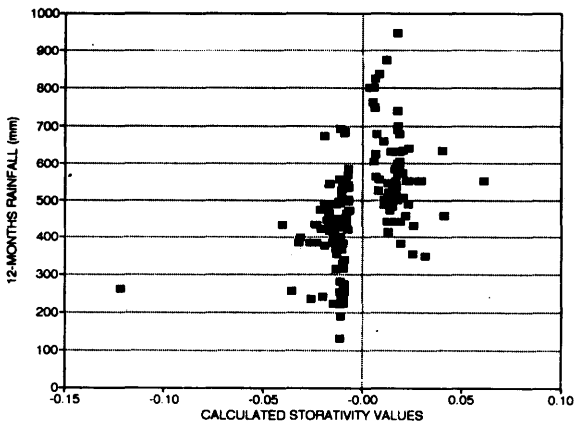


Figure 12: Calculated aquifer storativity values.

Simulation of the saturated aquifer volume fluctuations from the beginning of the record on an annual basis (Fig. 13) enabled a rainfall-recharge relationship to be determined as shown in Fig. 14 and expressed as:

Annual recharge (mm) = 0.08 (Annual rainfall (mm) - 342).

This implies that no groundwater is recharged to the aquifer for an annual rainfall less than or equal to 342 mm, which is somewhat less than the mean annual rainfall for the area.

Various scenarios were then simulated using the calibrated model and by replicating the previous annual rainfall record, as shown in Fig. 15. The results confirmed that continuation of groundwater abstractions at the present rate of about 10 million m^3 $year^{-1}$ would further deplete the available groundwater resources in the area to such an extent that after a further 14 years groundwater levels would be lowered to an average depth 40 m below the average mid-1981 levels, subject to the aquifer being that deep. This is obviously an undesirable situation. Reduction of groundwater abstractions to half this rate would result in a situation

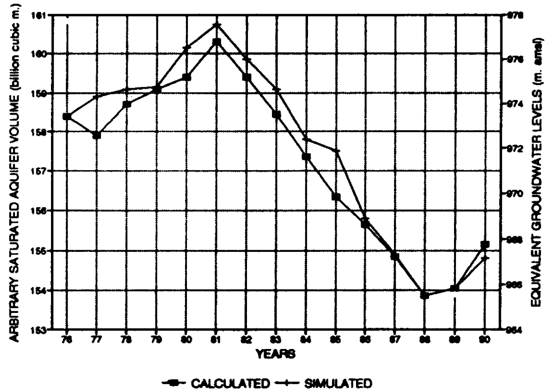


Figure 13: Model simulation.

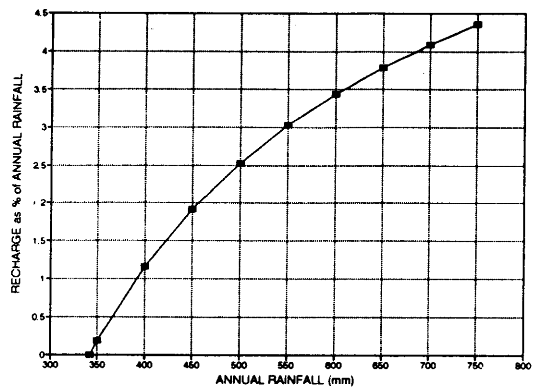


Figure 14: Rainfall-recharge relationship.

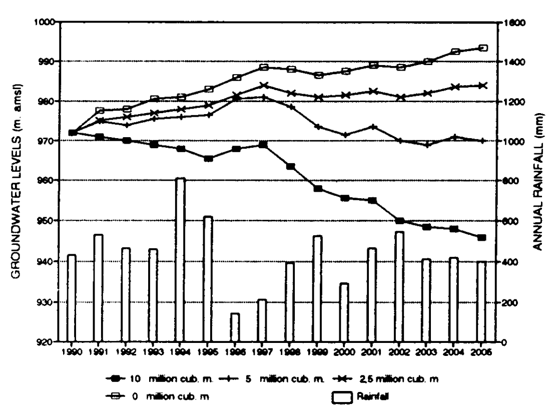


Figure 15: Simulated groundwater levels.

where groundwater levels only remained at about their present levels. Only for groundwater abstractions of less than about 5 million m^3 $year^{-1}$ would there be any significant recovery of groundwater levels as compared to present levels. For an annual groundwater abstraction rate of 5 million m^3 $year^{-1}$ and for field irrigation applications of 10,000 m^3 ha^{-1} $year^{-1}$ a total of only about 500 ha of farmland can be irrigated, an area about one-half of that presently being irrigated.

REMEDIAL MEASURES

The exercise of rights to the use of water in the RSA is still subject to the principle of South African law in which a distinction is made between public and private water. Groundwater by tradition is private water and the law permits its full and exclusive use by the owner of the land on which it occurs to the exclusion of any other person. The Minister for Water Affairs and Forestry has the authority to proclaim a subterranean water control area if in his opinion the groundwater resources of that area are in danger of being overexploited. Proclamation however only constrains further development of the groundwater resources. Alternative mechanisms exist, though, that provide the local groundwater user-group with the authority to impose some degree of self-control over the management of the groundwater resources contained in its area of jurisdiction for the mutual benefits of its individuals. The State then acts only in an advisory capacity. This is the case of the present study where the user-group is being provided with a PC incorporating an updated local data base and a calibrated groundwater computer model. Guidelines on how the available groundwater resources can be equitably allocated is also being provided.

Various practical remedial measures can be implemented in an attempt to adjust the imbalance prevailing in the aquifer, namely:

(a) the construction of a number of small inexpensive earth dams at suitable sites in drainage courses to retain some of the surface water runoff in order to augment the recharge of the groundwater,
(b) the introduction of more efficient irrigation systems to reduce evaporative losses, for instance drip irrigation,
(c) the cultivation of crops with reduced water demands,
(d) the irrigation of crops only at night and during only one season, preferably the winter.

Further refinement of the groundwater model using additional data will necessitate:

(a) regular monitoring of groundwater levels at dedicated monitoring boreholes optimally sited in the area,
(b) maintenance of adequate records of groundwater abstractions facilitated by the installation of water meters or hour meters on each pump or motor.

Clearly the groundwater model can be very usefully applied as an ongoing management tool in preventing overabstraction of the limited groundwater in the area and in prolonging the viability of some limited irrigation.

ACKNOWLEDGEMENT

Permission of the Department of Water Affairs and Forestry, RSA, to publish this paper is hereby acknowledged.

REFERENCES

Bredenkamp, D.B., Van Rensburg, H.J., Van Tonder, G.J. & Cogho, V.E. 1989. Quantitative estimation of aquifer storativity and recharge by means of a water balance and incorporating a finite element network. In: *Groundwater Management: Quantity and Quality*. A. Sahuquillo *et al.* (eds), IAHS Publication no. 188, vol. late papers; 160-175.

Van Tonder, G.J. 1989. *PC-program DELV to calculate the saturated volume and recharge of an aquifer on a monthly basis.* Unpublished computer program. Institute for Groundwater Studies, University of the Orange Free State, Bloemfontein, RSA.

SOCIAL-ENVIRONMENTAL IMPACT OF THE EXTRACTION POLICY OF THE GUAYMAS VALLEY AQUIFER, SONORA, MEXICO.

R. RODRIGUEZ-CASTILLO
Natural Resources Dept. Institute of Geophysics.
UNAM, Cd. Universitaria, 04510 México City, México.

ABSTRACT. The extraction policy of the Guaymas Valley aquifer in the north-western portion of Mexico has social-environmental repercussions. The annual extraction is 180 x 10^6 m^3 $year^{-1}$. The extraction over the recharge caused aquifer overexploitation and provoked seawater intrusion. The lands with mineralized wells are abandoned reducing the agriculture area. Every year 3 wells are closed. There is a drawdown cone, 40 km^2 area and 90m depth in Maytorena, the principal extraction zone. Shallow and deep wells must be relocated to the north. Some economic strategies are applied. The change in extraction policy and water uses will have repercussions on the regional economy.

INTRODUCTION

The Guaymas valley is one of the more important agriculture zones of the Mexican west coast. It is located in the oriental coast of the Gulf of California, in the Sonora Basin, in the state of Sonora (fig 1). Its development began in 1940. The only water supply is groundwater. In the valley there is only one important superficial drainage, flowing only in rainy seasons. The valley topography does not permit the construction of dams. Groundwater is used for agriculture and urban supply; there is not an extensive industrial development. In this area there are 2 cities, Guaymas, Empalme and the touristic development San Carlos.

The extraction regime has provoked seawater intrusion. Every year 3 wells are abandoned due to groundwater mineralization (more that 2,000 ppm is considered the critical concentration of TDS). These wells are relocated from the coastal area to the northern part of the valley. Until the late seventies nearly eight thousand cultivated hectares were damaged and more than 50 deep wells (more than 60m in depth) were abandoned because of degradation in water quality, as a consequence of the rate of water extraction at 180 x 10^6 m^3 $year^{-1}$.

This situation did not change in the eighties. The extraction regime was quite similar. One hundred cultivated hectares were abandoned. Some wells were closed and not relocated, due to the absence of water pipes and electrical lines in the north of the valley. The volume for urban supply is only 5 % of the total extraction, the rest is used for agriculture. Farmers have not an adequate agricultural policy. They do not look for high income products because water has a very low cost.

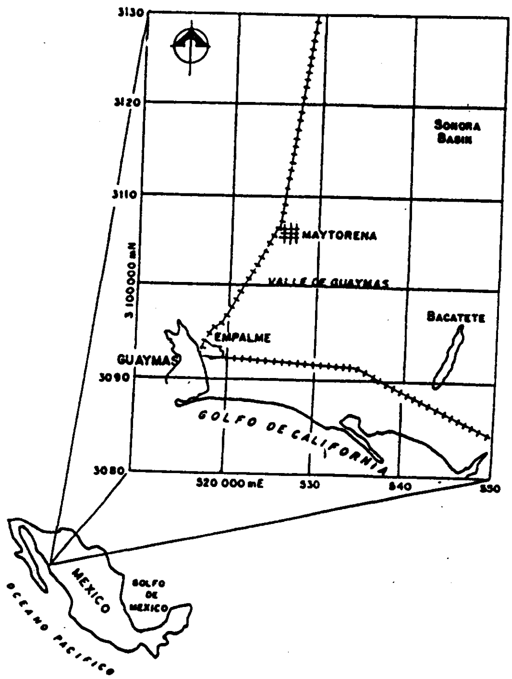


Figure 1: The Guaymas Valley.

The regional economy is mainly based on agriculture. The reduction of productive lands causes migration from Empalme to Guaymas. The population of Guaymas is increasing, while that in Empalme is decreasing. This migration process affects the local production system. The employment rate is altered.

GENERAL GEOLOGY

The Guaymas valley is located in the Sonora basin in the south of Sonora state (fig. 1). It is limited by the Sierra Madre Occidental to the east and by the Gulf of California to the west. Its dimensions are about 15 x 45 km. This basin was affected by tectonic tension with an east-west preferential orientation since the Mesozoic. These stresses caused a system of normal faults and perpendicular fractures cutting granitic basement. The result was a series of horsts and grabens that controlled the later geomorphologic evolution. Afterwards andesitic and basaltic flows covered the basement during the Quaternary. Great volumes of fluvial and aeolian sediments were also deposited in this zone. The first geological models of the valley included a clay layer (Arcilla Azul, *Blue Clay*) like a confining layer of a supposed deeper aquifer. This geological model was maintained for 20 years.

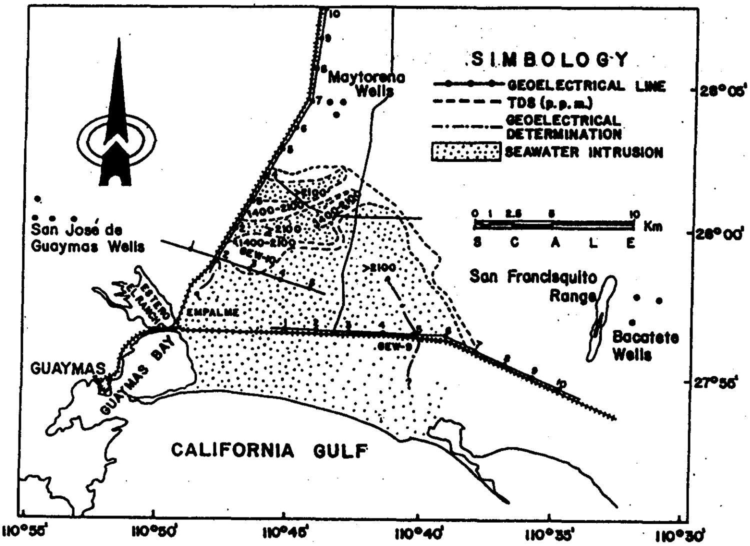


Figure 2: Geoelectrical and chemical determination of seawater intrusion.

Most of the prevailing physiographic features consist of valleys delimited by sierras varying in height from 500 to 1000 m. The main local sierras are: Santa Ursula, Bàcatete and San Francisquito. The oldest rocks in the valley are Cretaceous and are represented by andesitic and some granitic flows. Intrusive igneous rocks belong to late Cretaceous or early Tertiary. These rocks are represented by granitic masses and in less proportion by granodiorites and diorites. Overlying the Cretaceous rócks, Tertiary volcanic rocks are found and also sandstones and conglomerates from the Bacauri Formation. The younger formations are represented by Quaternary sediments.

The aquifer system.

The aquifer system is defined by permeable formations with a high content of fine grain material. This explains the variation of the aquifer parameters. The storage coefficient, S, varies between 0.10 and 0.20 and the specific storage has a mean value of $0.02 m^{-1}$. The transmissibility, T, has a range of 5 to 15×10^{-3} $m^2 s^{-1}$. The mean permeability, k, is estimated as 10^{-5} $m s^{-1}$ The hydraulic behavior, reflected in the piezometric levels, described a multi-aquifer with local confined and semiconfined units. The thickness is quite variable, about 50-150m in the coastal area and 200-400m to the north. For an unconfined aquifer thickness of 200m an effective porosity of 0.10 is estimated.

Groundwater quality has been degraded by natural and anthropogenic processes. In this region, chemical data are available since 1973. Seawater intrusion is identified by 2,000 $mg\ l^{-1}$ TDS. The isoline 2,000 advanced 2 km in the period 1973-1983 in the east and 5 km in the west of the valley. The seawater configuration was obtained from chemical analysis and geoelectrical results (fig. 2). In 1990 the saline front was found 12 km from the coastal line and has advanced to the Maytorena area. In the central area, chloride is not of marine origin, but is associated with connate waters.

Some wells in the west of the Maytorena area are characterised by relatively high temperatures. These wells show a good correlation with the tectonic framework which could explain the presence of chromium and barium above the drinking water standards. The presence of thermal water in the western border implies the incorporation of some chemical elements like arsenic and boron. On the basin borders it is common to find water at 50° C or more at 200 m depth.

THE URBAN WATER SUPPLY SYSTEMS.

Guaymas and Empalme have 3 well systems for water supply. One in San Jose de Guaymas Valley, the most important one in the western zone of Guaymas valley, named Maytorena and the last one in Bacatete valley (fig 2). These wells supply 635 $l\ s^{-1}$. For 1988 the urban demand was 743 $l\ s^{-1}$, for 2010 it will be 1554 $l\ s^{-1}$. That means a deficit of 100 $l\ s^{-1}$ for 1988 and 900 for 2010.

Water supply is affected by water quality degradation as a consequence of seawater intrusion provoked by the aquifer overexploitation. For these reasons federal water authorities (National Comission of Water CNA from the Agriculture and Hydraulic Resources Ministry SARH) carried out research projects to clarify the aquifer potential and to propose alternatives for water supply. The geometry and spatial distribution of the aquifer system was determined by a geophysical study carried out by the Institute of Geophysics, IGF, from the National University of Mexico UNAM. This involved not only vertical electrical soundings but also magnetometric, gravimetric and telluric profiles as well as chemical analyses and geothermometry (Rodríguez *et al.* 1984, Rodríguez *et al.* 1985).

Before the IGF investigations, the general conception of the aquifer system was quite simple: after some general studies carried out during the seventies, the aquifer was conceived as a water table aquifer, hydrodynamically separated from a deeper aquifer. The impermeable barrier was the Blue Clay. Its thickness decreases from S to N. This theory was supported by some exploration wells which detected this clay unit, but without other indirect evidence such as potentiometric or chemical differences.

Such a geological model justified the water extraction policy (based only in the supposed shallow aquifer) because it considered the deeper aquifer as a potential reserve for future demands. In this model, the seawater intrusion affected only the shallow aquifer. This geological conception was valid for more than 20 years. The new geological model, derived from IGF studies, consists of an aquifer system integrated by granular layers, clayey units and clay lenses with partial hydraulic communication. The sedimentation was affected by tectonic processes. The impermeable basement is defined by grabens and horsts. The seawater intrusion is pushing forward through a graben. It is possible to define two groundwater basins in the valley, Guaymas and Bacatete. Both of them are separated to the south by the Sierra de San Francisquito, but to the north are hydraulicly connected.

The aquifer overexploitation was established after the results of three mathematical models; Gidrotec (1981), Herrera *et al* (1985) and Herrera *et al* (1990). The vertical recharge due to precipitation on northern ranges was estimated at 20 x 10^6 m^3 $year^{-1}$ and the extraction at 180 x 10^6 m^3 $year^{-1}$. The hydrologic balance included irrigation seepage calculated at 40 x 10^6 m^3 $year^{-1}$ (twice the vertical recharge). Local precipitation is not an important recharge resource. The relatively high temperatures from some wells, near to Santa Ursula range, permitted an inferred local contribution from regional flow. This final water balance indicated that 120 x 10^6 m^3 $year^{-1}$ are extracted from the aquifer storage. This aquifer is **overexploited** as a consequence of the policy extraction over the natural recharge. The overexploitation as been reported since 1967.

MANAGEMENT ALTERNATIVES.

Some aquifer management alternatives were analyzed, taking into consideration the CNA opinion, through a mathematical model of flow and solute transport (Herrera *et al,* 1990). The modelling process starts in 1990 and considers predictions for 40 years until 2030. The calibration included the aquifer evolution over 10 years. Six options were considered for their possible implementation : 1) to maintain the actual extraction regime ; 2) to suspend urban supply wells ; 3) to suspend all the wells ; 4) to stop wells when they show mineralization ; 5) to suspend wells 5 years before their mineralization - after modeling results ; and 6) to stop selected wells in the central zone.

In the first option the evolution of the piezometric depression is 50m in 40 years (60 to 110m below sea level). The Maytorena wells will be affected by the seawater intrusion by 2010. In 2030, 50 % of the valley will present mineralization (fig 3); in the second option - suspension of 4 wells from Maytorena, 215 l s^{-1} or 6.8 x 10^6 m^3 $year^{-1}$ - the results are similar , the only difference is the position of the piezometric depression which has a SE displacement ; in the third, the more drastic, the drawdown cone shows some recuperation, at 2030 the deepest area will be 30m below sea level occupying 10 % of the valley, but the seawater intrusion is not stopped. For 2030 the isoline 2000 mg l^{-1} will be located only 1 or 2 km to the south with respect to the former options ; the fourth alternative considers a variable reduction of extraction. In 2020 there will be 95 abandoned wells from a total of 189. After 2000 a partial recuperation will begin until 2030 the evolution of the piezometric levels will show 60m below sea level in the critical area of Maytorena. This recuperation is not reflected in the groundwater mineralization. In 2030 70 % of the valley will have TDS concentrations of 2000 mg l^{-1}; the last analyzed alternative considers 3 options; suspension of 14, 32 and 54 wells in the central zone of the valley. To stop 14 wells, 26.3 x 10^6 m^3 $year^{-1}$, will provoke in 2030 a maximum depression of 90m and an advance of the seawater intrusion in that half of the valley affecting the Maytorena area. To suspend 32 wells, 48.3 x 10^6 m^3 $year^{-1}$, will generate in 2030 a depression of 80m, the intrusion will not reach Maytorena. With the suspension of 54 wells, 102.2 x 10^6 m^3

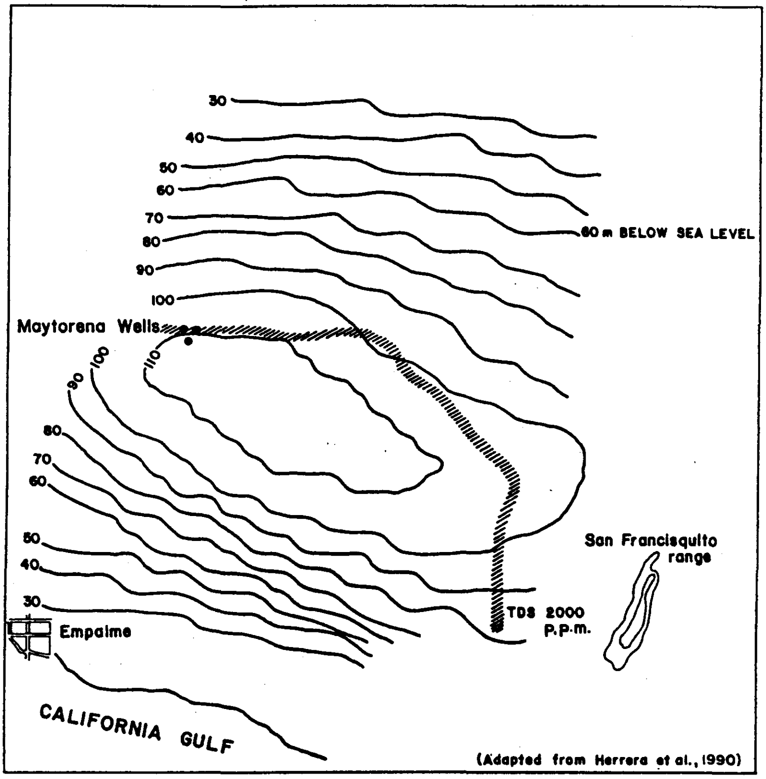


Figure 3: 2030 Predictions. Piezometry and saline front.

year^{-1}, the depression obtained is 70m below sea level affecting 8 % of the total area. In 2030 the curve of 2000 mg l^{-1} will not include Maytorena .

The extraction policy over the natural recharge provoked a drawdown cone of relatively big dimensions, more that 40 km^2 and 60m below sea level in 1990 (fig. 2). This can not be stopped with any of the analyzed management alternatives (fig 4). The inertia of this mineralized water body is so strong that its movement will continue even without extraction. The "total recuperation" of the piezometric levels requires additional recharge either vertical or lateral. Precipitation is variable. In rainy seasons irrigation is stopped, affecting the induced recharge by irrigation seepage.

SOCIAL-ENVIRONMENTAL IMPACT. WATER SUPPLY PRIORITIES

Regional development is based on agriculture, the first crop is wheat and the second is corn. Its expansion and diversification is now limited by water supply. Until 1970 water extraction satisfied the urban and agriculture requirements, but since the early seventies nearly 3 coastal wells per year are abandoned and relocalized inland. The most affected

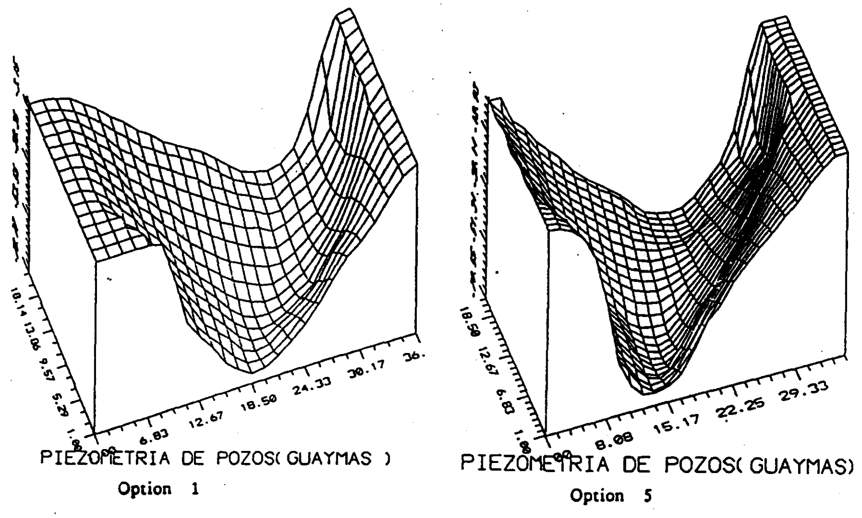


Figure 4: 2000 piezometric predictions. Option 1 and option 5 (55 suspended wells, extractioin reduced to 102 M m^3 year^{-1}) (Adapted from Herrera *et al.*, 1990).

crops by water mineralization are citrus, the third cash crop of the region. This complicates the development of new agricultural lands to the north of the valley. These lands have neither an agricultural infrastructure nor services such as electrification, roads or water pipes. The cost of new wells is higher than in the coastal area.

It is not possible to realize prospecting activities in the eastern border of the valley because this area is a yaqui reservation. The indian community does not permit drillings for urban wells, limiting future exploiting areas.

The abandoned lands, more than 200 km^2 in 20 years, are not used now. Soils have been gradually mineralized. Soil salt enrichment is due to irrigation with saline water, high evapotranspiration and the intense use of fertilizers. The local vegetation was partially changed with the introduction of agriculture. Nowadays some grasses and cacti grow in this land. The intensive agricultural development also affected local fauna. Some chicken farms are established along the coastal zone. They have shallow wells exploiting the scant layer of fresh water flowing to the sea.

Mexican, maybe international, water supply priorities put in first place the urban supply, in the second industry and in the third agriculture. Farmers must look for other activities. To change farmers to workers requires special considerations. Guaymas and Empalme have a limited touristic development; only San Carlos offers job possibilities in this area. Some social organizations obtained federal economic assistance to establish shrimp farms in abandoned lands using mineralized water from coastal wells. This activity is not so strange for local people. Guaymas is one of the most important fishing ports on the Gulf of California.

The Water Authorities (CNA) intend to change water use by transferring well rights. Farmers use good quality groundwater, CNA offers treated waste water for irrigation. CNA most pay for the well rights to manage them. Groundwater is a national property but wells could be private. This economic policy could explain the well relocalization. One degraded coastal well could be changed by other inland, because the CNA restrictions limit the increment of wells (Guaymas is a forbidden zone for new wells) not new drillings.

FUTURE ALTERNATIVES. MANAGEMENT, COST, SOCIAL ADAPTATION.

Seawater intrusion can not be stopped with any of the analyzed alternatives for aquifer management. The piezometric depression will act on the seawater intrusion by pushing it to the central zone. The recuperation of piezometric levels over the sea level will be very long . The total of piezometric levels to above sea level will be very long. The total closure of agricultural wells looks like too drastic a solution, but it may not be so.

Artificial recharge was analyzed as an alternative solution to stop the seawater intrusion. The required flow could be taken from a treatment plant for urban waste water generated in Guaymas and Empalme. The technical problems and high costs for this program disabled it because such action required a new drainage system for waste water. The percentage of houses connected to the drainage was 37 % for Guaymas and 41 % for Empalme in 1960; in 1980 the tendency was inverse, 41 % for Guaymas and 38 % for Empalme. Both cities are separated by a shallow bay. Most of the waste water is conducted to Guaymas bay. The ocean pollution is not known, but fishing is a local activity. At least tertiary treatment is required for waste waters. The original idea was based on a shallow clay barrier along the coastal line detected by geoelectrical soundings, Rodríguez *et al* (1984). This geological structure controls the advance of seawater intrusion (González & Rodríguez, 1989). The operation of a hydraulic barrier through relatively shallow injection wells, not more than 50 m deep, over the barrier could create a "ground dam".

Desalinization of ocean water is the most expensive solution. The generated volumes could not satisfy urban demand. Water consumption must be reduced. The actual rate is about 300 $l\ person^{-1}\ day^{-1}$. A reduction to 250 or 200 $l\ person^{-1}\ day^{-1}$ could be significant, but the volume for 450,000 inhabitants in 2010 will be twice the present water rate (230, 000 inhabitants in 1990). Urban water supply can not be suspended. One of the solutions is to take water from other basins. The nearest one is the Yaqui Basin. A system of 10 wells close to the Alvaro Obregon dam will supply 700 $l\ s^{-1}$ instead of the Guaymas Valley extraction. The water pipe, 50 km, is now being built and will be operating in 1992. The extracted water does not affect the water consumption of the Yaqui Valley. It is a surplus going to the ocean.

In Mexico, water cost is very low. Real cost is not calculated. Urban supply is well-known through the flow coming in the local distribution system, but the home consumption measurements are deficient. Well extraction most be paid too. Flow control is obtained from energy consumption but well pumping efficiency most be estimated for each well. Not all wells have electrical pumps. When they have gas pumps, the consumption is calculated after the reported time of operation and the irrigation volume required. These situations result in an unreal cost for water supply and limit the implementation of other water supply alternatives.

The extraction evaluation has a bearing on mathematical modelling. This important parameter has only been estimated. Recharge was calculated from piezometric evaluation. At this moment it is not possible to apply other methods for recharge estimation.

DISCUSSION

The Guaymas valley aquifer has been overexploited because the extraction is greater than recharge. The implemented exploitation policy has socioeconomic effects. Local and federal water authorities looked for adequate solutions. All the groundwater management alternatives analysed require cessation of irrigation . Irrigation with waste waters looks like a feasible alternative, but as in many other coastal cities there is not a treatment plant. Waste waters are conducted to the ocean near local beaches. The environmental impact has not been evaluated. Agriculture expansion is limited by water quality. Ranching is poorly developed. The introduction of salt resistant grasses must be studied in these lands. These socio-economic changes must be studied by economists and politicians.

To stop seawater intrusion or at least to control its advance is now the principal worry of the water authorities. They look for new urban water supplies. Local aquifer extraction will be exchanged by groundwater from other basins. This strategy is usual. Agriculture is not a priority. Industrial processes like fish or shrimp processing plants give higher value to water. People are not thinking in water cost, federal and local authorities most provide it. This social comprehension about water supply complicates any modification related to water management.

In order to obtain more representative modelling results it is necessary to continue with data acquisition programs, piezometry and vertical water sampling for chemical analysis. Some hydraulic parameters most be obtained with field activities. Aquifer evolution must be researched. Modeling predictions must be corroborated; if observational data are different from the calculated values, the mathematical model should be re-calibrated. The abandoned wells could be converted to observational points or adapted to multi-piezometers. The role of the clayey units is not clearly known. The model did not consider flow coming from clay units. Subsidence is not reported in this region nor has it been measured. It is necessary to obtain clay cores for lab determinations of elastic parameters.

REFERENCES

GIDROTEC, 1981. Modelo matemático sobre el comportamiento del sistema de acuíferos del Valle de Guaymas, Son., *Rep. Tec.* il. IGF-UNAM, SARH. México.

Gonzalez M.T. & Rodríguez R. C., 1989. Control geológico estructural del frente de intrusión salina en el Valle de Guaymas, Son., *Topografia y Cartografia*, Num 35 Nov-Dic. España.

Herrera I., Cruickshank C. V., Yates R. & Munch D.E., 1985 . Ampliación a la modelación matemática de las fuentes de abastecimiento para el suministro de agua en bloque a las ciudades de Guaymas, Empalme y San Carlos, Son. *Rep. Tec.* il. IGF-UNAM, SARH. México.

Herrera I., Rodriguez C. R., Medina B. R. & Hernández G., 1990. Simulación de alternativas de explotación del acuífero del Valle de Guaymas, Son. IGF-UNAM, CNA-SARH, *Rep. Tec.* il. México

Rodríguez C. R., Lima E., González M.T., Alvarez R. & Del Río L. 1984. Ampliación del estudio geofísico de Guaymas Son. IGF-UNAM, SARH. *Rep Tec.* il. México.

Rodríguez C. R., Campos G. & Medina B. R., 1985. Ampliación del estudio geofísico de Guaymas Son. (Anexo). IGF-UNAM, SARH. *Rep. Tec.* il. México.

PREDICTING THE LONG-TERM IMPACTS OF GROUNDWATER ABSTRACTION FROM AN INTENSIVELY EXPLOITED COASTAL AQUIFER

J.A.M. VAN DER GUN & W.I.M. ELDERHORST
TNO Institute of Applied Geoscience, P.O.Box 6012,
2600 JA Delft, The Netherlands
G.P. KRUSEMAN
TNO Institute of Applied Geoscience, P.O.Box 6012,
2600 JA Delft, The Netherlands
and ITC, P.O.Box 6, 7500 AA Enschede, The Netherlands

ABSTRACT. Intensive exploitation of groundwater from a coastal aquifer may result not only in increased salinity of groundwater near the coast, but sometimes also in significant declines of the groundwater level. These responses of the aquifer system to pumping threaten the sustainability of the exploitable groundwater resources. Hence, it is very useful to be able to predict these impacts reliably, and to investigate to what extent they can be controlled by an appropriate groundwater management strategy.

To this end, model simulations were carried out for the coastal aquifer of Wadi Surdud in the Republic of Yemen, where at present groundwater is abstracted in excess of the average rate of recharge. A simulation model for simultaneous flow of fresh and saline groundwater separated by a sharp interface was used to study the long-term regional impacts, for a time horizon of two hundred years. The simulations showed that without controlling the groundwater abstraction rate and pattern only a modest inland incursion of the saline groundwater is expected within the time horizon considered, but the declines of the water table will be dramatic, especially in the eastern part of the aquifer. Relocating the abstractions may mitigate this problem to some extent, but the simulations clearly demonstrate that the total rate of abstraction needs to be reduced considerably, sooner or later, if sustainable use of groundwater is aimed for. In this case practical constraints to the acceptable depth-to-groundwater dictate a maximum abstraction rate far below the average rate of groundwater recharge.

INTRODUCTION

The Quaternary aquifer system in the Tihama

The Red Sea graben, formed mainly during the Tertiary, is filled with fluvial, marine and coastal sediments to a total thickness of several thousand metres. The arid Tihama zone in the Republic of Yemen is in the eastern part of this graben system. Most of its Cenozoic graben fill consists of Tertiary sediments, generally poorly permeable and containing saline formation water. However, these are overlain by Quaternary deposits containing predominantly fresh groundwater. They constitute the most productive aquifer system of the Republic of Yemen, extending over more than 400 km along the coast over a width of 30 to 60 km between the escarpment of the Yemen Highlands and the Red Sea. This aquifer system is recharged by the streams descending from the mountains.

The Tihama Quaternary aquifer system is not a single, laterally homogeneous aquifer. As was demonstrated by Ritsema (1986) and Van der Gun (1986), observed patterns of hydraulic conductivity, piezometric level and groundwater mineralisation suggest that it is composed of a number of semi-independent 'groundwater flow domains'. These domains are more or less fan-shaped and are considered to act as preferential zones for groundwater flow (see Figure 1). A groundwater flow domain includes a recharge zone, one or more corresponding discharge zones, and the aquifer part connecting them. Recharge zones are associated with streams and can be found in the eastern part of the Tihama, while natural discharge of groundwater occurs at the western side, by evaporation on the coastal salt flats (sebkhas) or by submarine groundwater outflow. Outside the groundwater flow domains, groundwater is almost stagnant. Such 'stagnation zones' produce a certain hydraulic isolation between the groundwater flow domains.

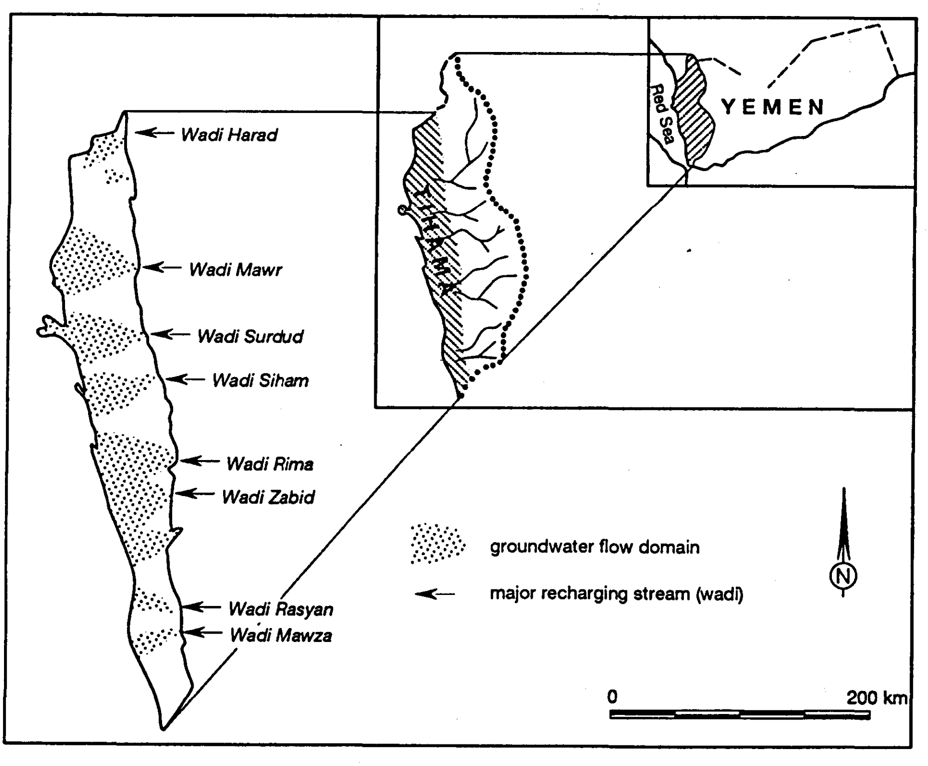


Figure 1: Groundwater flow domains in the Tihama.

This interpretation of lateral zoning within the Tihama aquifer system is consistent with current views on Quaternary sedimentation and on groundwater flow between natural recharge and discharge zones. The predominant role of the major streams (wadis) and their topographic position in relation to the aquifer system and to the natural drainage base (Red Sea) explain the observed patterns. These factors account for the observed distribution of coarser and finer sediments, the diverging groundwater flow pattern from recharge zones of limited areal extent to a virtually continuous discharge zone at the Red Sea coast, and the presence of certain zones where groundwater is relatively stagnant.

Groundwater development and its impacts

Until recently, groundwater in the Tihama was abstracted in small quantities only, lifted by rope-and-bucket from shallow dug wells. The water was used mainly for domestic water supply. Since the late 1960s, however, when power-driven pumps were introduced, groundwater abstraction has increased as never before. At present, approximately 10,000 pumped wells are supporting an area of groundwater-based irrigation much larger than the area irrigated by surface water in the traditional 'spate irrigation zones'. Consequently, use of groundwater has enabled an enormous increase of the agricultural production in the Tihama, and thus has significantly contributed to the economic development of the region. However, this growth in groundwater abstraction has negative impacts too. To date, they include upconing of saline or brackish water in a few wells, the need to deepen some wells that have become dry, and slight increases in the cost of pumping groundwater resulting from declining groundwater levels. The situation is expected to worsen significantly in the future if the rates of groundwater abstraction are not regulated. Without regulation the sustainability of groundwater exploitation will be threatened by: (a) steadily declining groundwater levels, particularly in the eastern part of the Tihama; (b) progressive intrusion of saline water into the aquifer system, primarily affecting the western part of the Tihama.

Model simulations of the Wadi Surdud aquifer system

One of the mentioned 'groundwater flow domains' in Tihama is associated with Wadi Surdud (see Figure 1). Van der Gun (1986) describes the water resources of the Wadi Surdud area that were assessed and analysed in some detail by the Yemeni-Dutch project 'Water Resources Assessment Yemen'. Some of the findings relating to the aquifer system are given below. Among the activities following the inventory and assessment of the water resources, a numerical simulation model was used to study the long-term response of the Wadi Surdud aquifer system to groundwater abstraction. Several alternative pumping regimes were assumed, in order to compare the options for relocating and/or reducing the groundwater abstraction with 'uncontrolled' groundwater abstraction. The information thus obtained was input into a more comprehensive water resources management study for the Wadi Surdud area; Van der Gun & Wesseling (1991) report on that study.

Below, we will demonstrate how groundwater modelling may contribute to the development of a sensible approach to groundwater management in an intensively exploited coastal aquifer system like that of Wadi Surdud.

THE QUATERNARY AQUIFER SYSTEM OF WADI SURDUD

General setting

Wadi Surdud is one of the major streams descending from the semi-arid to arid mountain belt of western Yemen. Its catchment area has a rough and dissected topography, with elevations up to 3,700 m above sea level. At approximately 50 km from the Red Sea, however, the wadi debouches into the rather flat Tihama zone and degenerates before reaching the sea. The Wadi Surdud area, consisting of a mountainous catchment area and of an adjoining zone downstream in Tihama, which 'absorbs' Wadi Surdud's waters, is approximately 4,000 km^2 in area.

Average annual rainfall is between 300 and 600 mm in the catchment area, but significantly less in the Tihama zone. In many parts of the area, water is diverted from stream channels or from springs, or pumped from aquifers. Under present conditions, most of it is used for irrigation, and no more than a few percent for domestic purposes. Soon after Wadi Surdud enters the flat Tihama plain, its base flow disappears entirely and recharges the underlying Quaternary aquifer. Part of the direct runoff produced by the 'spates' or flash floods percolates through the stream bed to the aquifer too, but a substantial part is diverted for irrigation in the traditional spate command zone. The Quaternary aquifer in the Tihama zone of Wadi Surdud is currently exploited by almost 1,000 pumped wells, mainly for irrigation.

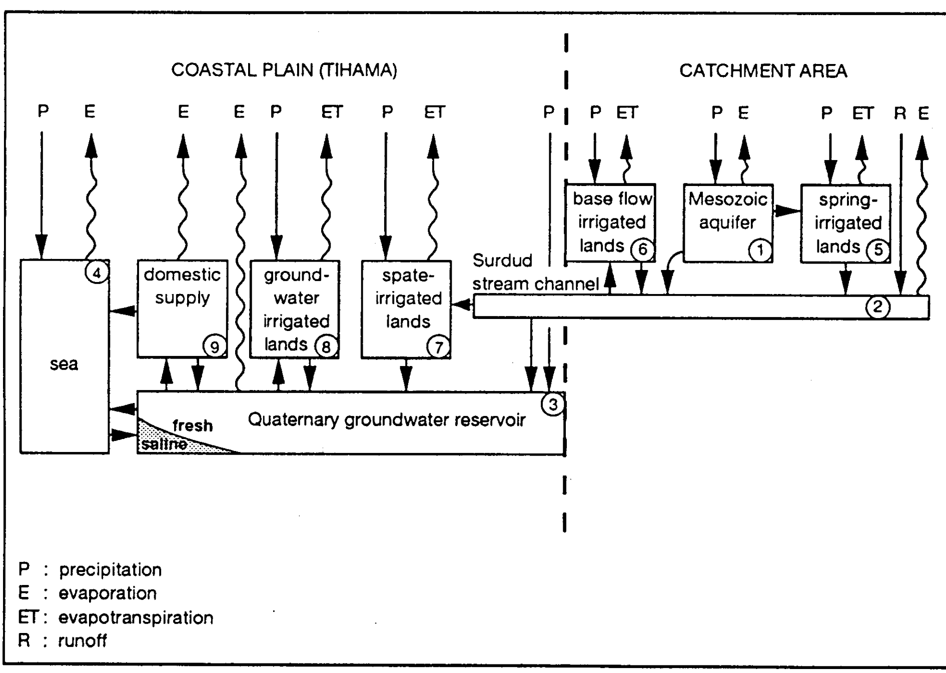


Figure 2: Schematic representation of the Wadi Surdud water resources system.

The water resources system of Wadi Surdud, with emphasis on the 'manageable' elements, is presented in Figure 2. It can be seen that the recharge to the Quaternary aquifer depends on water use in the area, not only in the Tihama zone but also upstream. Furthermore, it highlights the interaction between the Quaternary aquifer and the Red Sea, in terms of discharge of fresh groundwater and potential intrusion of sea water into the aquifer system.

Hydrogeological framework

Figure 3 presents a greatly simplified picture of the aquifer system considered. Fresh groundwater is contained in the Quaternary sedimentary complex. This complex is some 200 to 300 m thick in most of the area, but thins out towards the foothills bordering the Tihama. At or near the surface, the Quaternary is mainly present as alluvial fan and alluvial plain sediments in the eastern half of the plain; in the western half it is present as aeolian deposits, with locally -in the sebkhas- slightly evaporitic characteristics. Further west -under the Red Sea shelf- an evaporite facies (coral reefs and sandy limestones) becomes dominant.

The alluvial sediments are poorly sorted and vary in grain size from blocks and boulders to sands, silts and clays. The aeolian deposits, on the other hand, are well-sorted fine- to medium-grained sands and form a generally homogeneous formation.

The Quaternary deposits are underlain by very thick strata of unconsolidated Tertiary sediments. Only in the easternmost, tectonically uplifted part of the area do Quaternary deposits directly overlie consolidated rocks, mostly of volcanic and plutonic origin. Local anomalies occur, like a diapir composed of Tertiary rock salt penetrating the Quaternary cover not far from the coast (Jabal Quma).

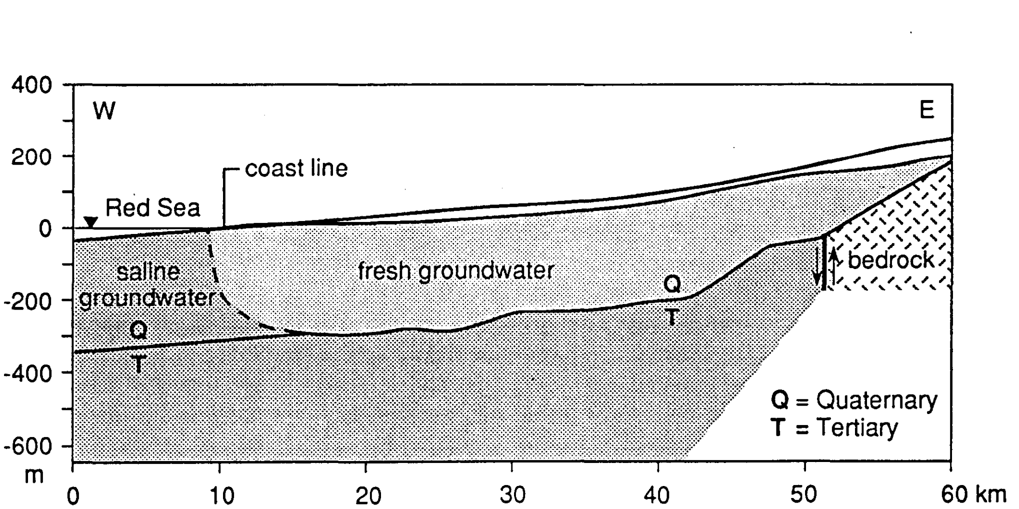


Figure 3: Simplified cross-section showing the Quaternary aquifer system in the Tihama zone of Wadi Surdud.

The piezometric surface observed (Figure 4) is consistent with the hypothesized groundwater flow domains presented above. Taking into account the information shown in Figure 5, the geometry of this piezometric surface suggests that the aquifer's transmissivity increases appreciably west of, approximately, the piezometric isoline of 30 m + mean sea level. Van Overmeeren (1989) shows on the basis of field observations that this increase can be largely attributed to the sedimentary facies changing from predominantly alluvial to aeolian in the western part of the aquifer. Transmissivity is low to very low (<200 m^2 day^{-1}) at the northeast and southeast edges of the area; but inside Wadi Surdud's 'groundwater flow domain' it ranges from 500-1,000 m^2 day^{-1} in the eastern part of the zone to some 4,000-5,000 m^2 day^{-1} near the coast. The aquifer is phreatic.

Fresh and saline groundwater

Groundwater in the Quaternary sediments is predominantly fresh, but the mineral content shows a general trend from as little as some 400 mgl^{-1} in the eastern recharge zone to more than 2000 mgl^{-1} in the western part of the area. It is underlain by brackish or saline groundwater. Near the coast this is more or less in the form of a 'sea water intrusion wedge'; further east, however, the transition from fresh to saline appears to be linked to the contact between the Quaternary and Tertiary sedimentary strata (see Figure 3). It is believed that the very poor permeability of the latter has prevented the saline or brackish water in the Tertiary sediments from being effectively flushed by fresh water, as would be expected to happen if fresh and saline groundwater were in equilibrium.

In the sebkha area near the coast (see Figure 5), saline or brackish water overlying relatively fresh water is observed. This can be explained by occasional inundation with sea water and evaporation of the groundwater near the surface.

The groundwater budget under steadily increasing groundwater abstraction

Water infiltrating and percolating through Wadi Surdud's bed and irrigation water losses are the main components of groundwater recharge. Annual rainfall increases from less than 100 mm on the coast to approximately 300 mm near the foothills; but direct recharge by local rainfall is considered insignificant even in the eastern part of the area. Discharge occurs by groundwater outflow into the Red Sea, by evaporation in the sebkha zone and by groundwater pumping.

Table 1 summarizes estimates of the main groundwater recharge and discharge components; Figure 5 shows where the related processes are taking place. In Table 1 note that the estimates for the rates of groundwater abstraction and losses from groundwater used for irrigation refer to 1989, but the values for all other components are medium- to long-term averages.

Groundwater abstraction is expanding rapidly: in 1989 it was most probably more than 100 times the rate of 25 years earlier, when groundwater was not yet pumped but was still withdrawn by hand or by animal traction. The 'natural' discharge components, however, adjust only very slowly to the changing abstraction rates: hydraulic gradients show that they are still very similar to what they were before pumps were introduced. Hence, a significant

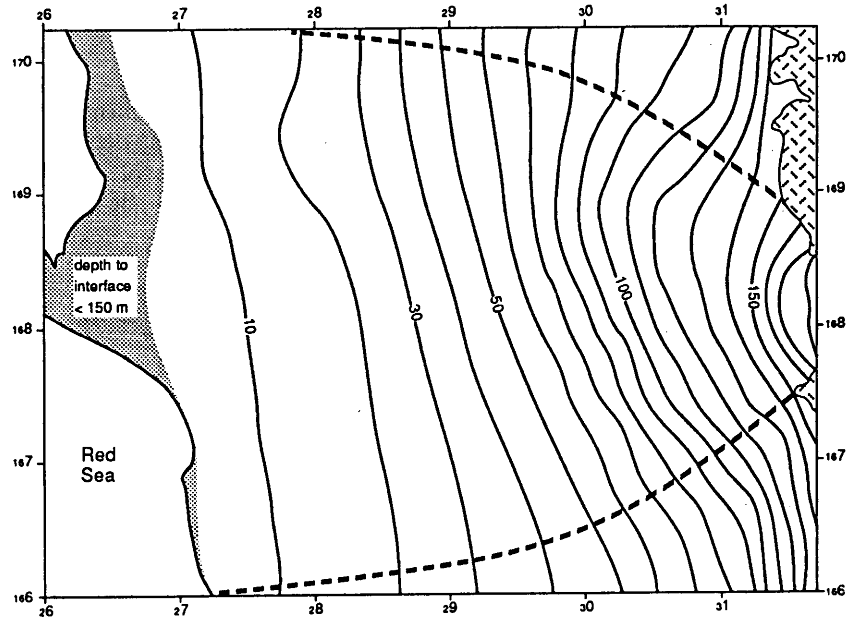


Figure 4: Groundwater levels and depth to the fresh-saline interface (1989 conditions, groundwater levels in m + m.s.l.).

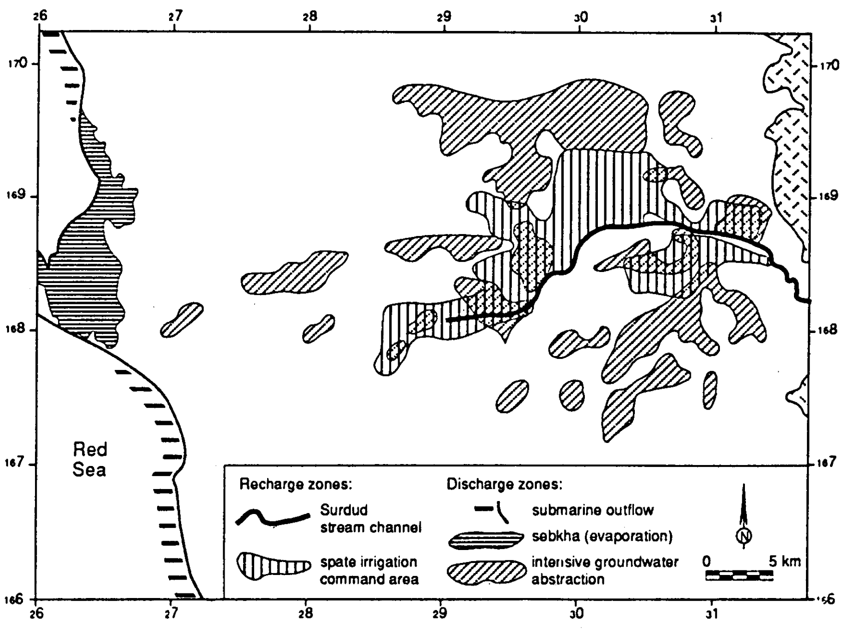


Figure 5: Main recharge and discharge zones.

discrepancy has developed between groundwater recharge and discharge, which is balanced by depletion of stored groundwater.

The nature of the groundwater system studied suggests that significant adjustment of 'natural' discharge will develop only in the long run; consequently, for a long time depletion of the reserves will be the dominant response of the aquifer system to overexploitation. If the impacts of such a depletion are considered unacceptable, control of the groundwater abstractions in time and/or in space becomes unavoidable.

Table 1: Estimates of groundwater balance components (in $Mm^3\ year^{-1}$).

COMPONENTS	VALUE	REMARKS
Recharge :		
Wadi bed infiltration	46	medium-/long-term average (includes subsurface component)
Losses from surface water irrigation	14	medium-/long-term average
Losses from groundwater irrigation	40	for 1989 abstraction rate
Discharge :		
Submarine outflow	35	long-term average
Sebkha evaporation	25	long-term average
Groundwater abstraction	133	1989 rate

MODEL SIMULATIONS

Approach

Groundwater model simulations were carried out to predict the long-term evolution of the aquifer conditions for alternative groundwater pumping regimes (cases). Because it was considered crucial to investigate the sustainability of the aquifer for the provision of water, a simulation period of 200 years was chosen, starting in 1989. The model developed is a regional numerical model that entails a certain degree of simplification, both because of the model code and because of the uncertainty in the data used. Nevertheless, the simulations are believed to reasonably reflect the regional behaviour of the groundwater system. Groundwater levels and the position of the interface are calculated to characterize the aquifer's state at any desired moment in time. By comparing the values for these variables obtained for alternative pumping regimes we were able to judge the merits of different degrees of controlling groundwater pumping.

The model

Model code. The groundwater model was based on the model code BADON-3. This is an extension of the BADON-2 code previously developed and described by Verruijt (1987). The modifications that distinguish BADON-3 from its predecessor suit the requirements of modelling the Surdud aquifer and comprise: (a) the introduction of a phreatic storage coefficient and (b) adjustment for a horizontally layered aquifer (two layers of different hydraulic conductivity). Details are given by Elderhorst (1991) and by Van der Gun & Wesseling (1991).

BADON-3 simulates the flow of fresh and saline groundwater in an aquifer where fresh and saline groundwater are assumed to be separated by a sharp interface. For given initial and boundary conditions it predicts how the piezometric levels in the fresh part of the aquifer and the interface between fresh and saline groundwater will change over time.

In the BADON-3 numerical model code the equation of motion and the continuity equation are formulated separately for the fresh part and for the saline part of the aquifer. Groundwater flow is assumed to be predominantly horizontal in both the fresh and the saline aquifer parts; this justifies the Dupuit assumption which states that the pressure distribution in the vertical direction is hydrostatic everywhere. The equations are coupled by defining the piezometric head in the saline aquifer part as a function of the phreatic groundwater level and the depth to the interface. Applying these principles leads to the following system of simultaneous differential equations:

fresh:

$$S\frac{\partial(h+\varphi)}{\partial t} = I_f + \nabla\{k(h+\varphi)\nabla\varphi\}$$

saline:

$$-S\frac{\partial h}{\partial t} = I_s + \nabla\{k(H_1-h)\nabla\varphi\} - \nabla\{\alpha k(H_1-h)\nabla h\}$$

in which:

- h = depth to fresh-saline interface (increasing in downward direction)
- ϕ = phreatic groundwater level (increasing in upward direction)
- S = storage coefficient (used for both the phreatic storage coefficient and the effective porosity near the fresh-saline interface)
- I_f = source/sink term for fresh groundwater
- I_s = source/sink term for saline groundwater
- k = hydraulic conductivity
- α = relative density difference = $(\rho_s - \rho_f)/\rho_f$
- ρ_f = density of fresh water
- ρ_s = density of saline water
- H_l = depth to the aquifer base (increasing in downward direction)
- t = time

Mean sea level is chosen as the common zero level for the variables h, H_l and ϕ.

This system of non-linear equations is solved by a finite element method.

Schematization, discretization and calibration. The lateral and vertical boundaries of the Quaternary aquifer system are modelled as indicated in the Figures 3 and 4. The aquifer is underlain mainly by Tertiary sediments that are considered to be impervious. Shallow saline and brackish groundwater related to processes other than sea water intrusion was ignored; only a relatively small zone near the coast is subject to such processes and ignoring it in the model was assumed to have no significant influence on the regional behaviour of the groundwater system. The densities of fresh and saline groundwater were assumed to be 1,000 and 1,025 kg m^{-3}, respectively.

For the horizontal discretization a rectangular grid of 2.5 × 2.5 km cells was defined, yielding a total of 432 nodes and 391 elements. To ensure stability of the numerical computations, time steps are initially kept small (50 days), but increase progressively (e.g. to a time step of 5,000 days after some 170 years from the start).

Steady-state calibration was carried out by trial and error on estimated 'pre-pumping conditions' of the groundwater system. Because groundwater pumping was started only recently in the Wadi Surdud area, the 1984 piezometric surface was assumed to be a reasonable estimate of the average 'undisturbed' piezometric surface prior to pumping. The calibration was done for a phreatic storage coefficient (specific yield) of 0.15; the same value was adopted for the effective porosity of the aquifer eds near the interface. Elderhorst (1991) shows that during the calibration a hydraulic conductivity pattern of the layers was obtained consistent with the information available on the aquifer's transmissivity.

Initial and boundary conditions. The initial conditions adopted for the simulations are the piezometric surface and the position of the interface at the beginning of 1989 (see Figure 4). External and internal boundary conditions can be described as follows:

(a) fixed head at the boundary between the aquifer and the Red Sea (to account for density effects, an equivalent fresh-water piezometric level of 0.5 m + mean sea level was assumed);
(b) no-flow conditions at the northern, eastern and southern lateral boundaries;
(c) prescribed discharge in 12 elements near the sea to represent a constant 'fresh groundwater' discharge by groundwater evaporation in the sebkha zone;
(d) prescribed recharge in a number of nodes to represent aquifer recharge by water infiltrating through the bed of Wadi Surdud and by percolation losses of surface irrigation water;
(e) prescribed discharge and recharge in a number of model nodes to represent groundwater abstraction and recharge by percolation losses of pumped irrigation water.

The numerical values of the items under (c) and (d) correspond to the values mentioned in Table 1. Values related to (e) vary according to the cases simulated; below, they are specified for the cases considered in this paper. For all cases it was assumed that 30 % of pumped groundwater returns to the aquifer as infiltration losses.

Note that the northern and southern boundaries to the area are in principle 'dynamic' boundaries. The current piezometric surface and the hypothesized groundwater flow systems presented above, however, make significant transboundary flow unlikely, especially when groundwater development in the adjacent flow domains is similar to that in Wadi Surdud. This justifies the model assumption of 'no-flow' boundaries.

The aquifer's behaviour under an uncontrolled abstraction regime

Until 1989, groundwater abstraction in the area increased steadily. It is reasonable to assume that this will continue for some time, if no restrictive measures are imposed. In the longer run, however, it is likely that groundwater pumping will stop expanding. This abstraction regime may be tentatively represented by a gradual increase of the abstraction from 133 Mm^3 $year^{-1}$ in 1989 to 166 Mm^3 $year^{-1}$ in 2014 and a constant abstraction (166 Mm^3 $year^{-1}$) thereafter.

Model simulations were carried out to predict the aquifer's behaviour under this abstraction regime. The total simulation period of 200 years (starting in 1989) was divided into two stress periods: the period of the first 25 years is characterized by an average groundwater abstraction rate of 159 Mm^3 $year^{-1}$, while an average abstraction rate of 166 Mm^3 $year^{-1}$ was taken for the second period. The spatial distribution of the abstraction was assumed to be identical to that of 1989.

The results of the simulations were converted to variables that are important for groundwater exploitation: depth-to-groundwater (in m below surface) and extent of the zone where the fresh-saline interface is within 150 m of the ground surface. To appreciate the first variable it should be mentioned that -under present conditions- traditional groundwater-irrigated agriculture in the Tihama ceases to be viable if depth-to-groundwater is more than approximately 40 m ('break-even' depth). For greater depths the cost of groundwater becomes prohibitive.

The simulation results are presented graphically in Figure 6 (for the same area as shown in the Figures 4 and 5). Regarding groundwater salination, the situation at the end of the time horizon (after 200 years) seems only slightly less favourable than in the base year 1989. But inspection of the simulated piezometric levels indicates that the fresh-saline interface is still moving towards an equilibrium position where finally the toe of the saline water wedge reaches into the eastern half of the aquifer zone.

The predicted evolution of the groundwater levels is extremely dramatic. Depth-to-groundwater increases quickly in the eastern half of the area, where groundwater plays a key role in irrigated agriculture. Bearing in mind the current 'break-even' depth for economically justified groundwater-irrigation in this area, a development of the groundwater levels as predicted is likely to put an end to most of the groundwater-irrigated agriculture in the area within a time span of only one or two generations. In spite of the many numerical uncertainties involved in this analysis, it is clear that the assumed abstraction rate is not sustainable and that the impacts of depletion of groundwater reserves will have severe

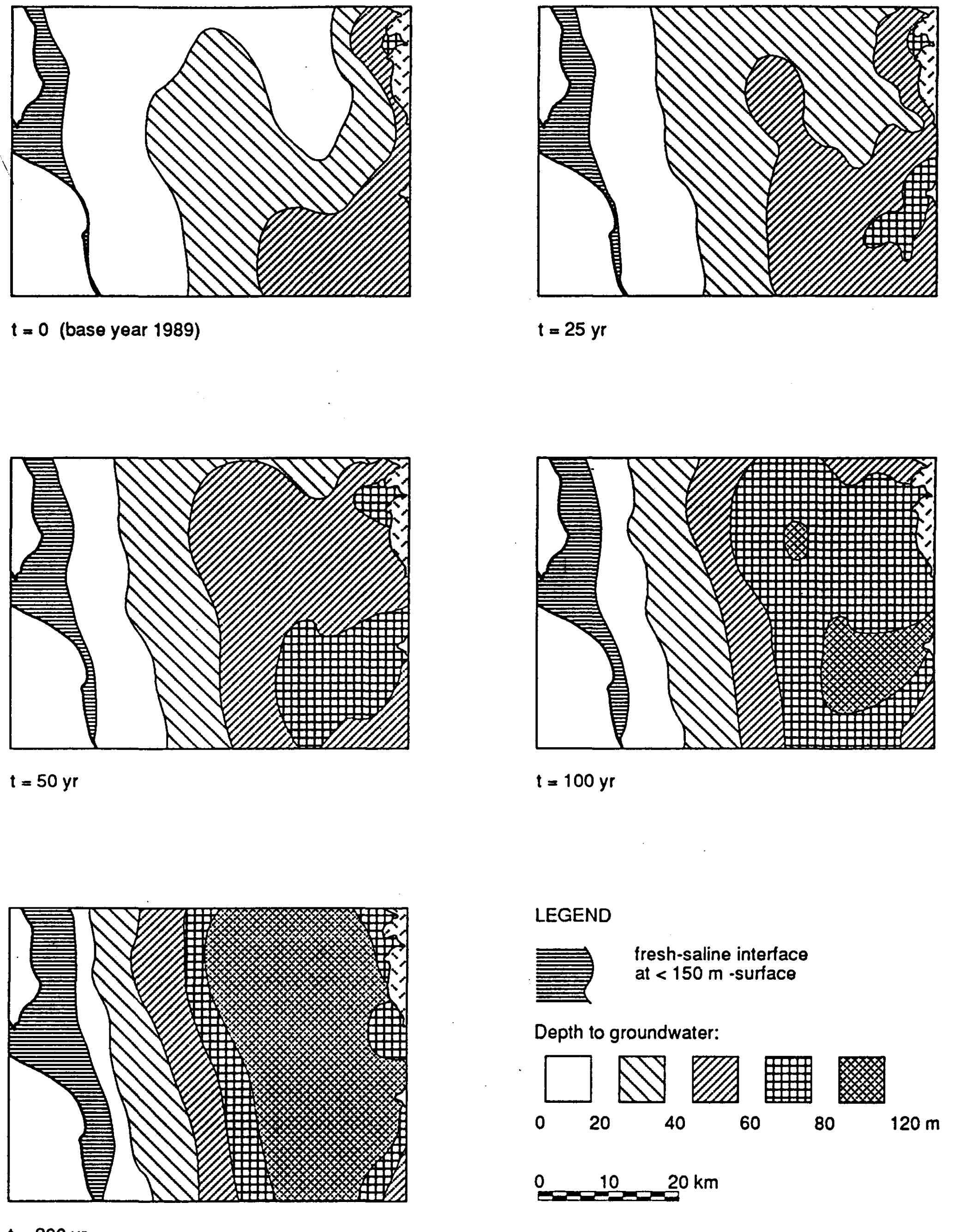


Figure 6: Simulation results for 'uncontrolled' groundwater abstraction.

practical consequences.

Relocating and reducing groundwater abstractions

The aquifer's state will develop differently if the total abstraction as a function of time or the spatial pattern of the groundwater abstractions will be modified. Such modifications can be imposed by proper groundwater resources management measures.

A number of alternative groundwater abstraction regimes were defined to analyse the effects of such interventions (see Table 2). Compared with the reference situation described above (case A) they assume from case B to case F an increasingly slower rate of groundwater pumping. As far as the spatial pattern is concerned, two patterns are considered: in pattern 1, local pumping rates are in the same proportion to the total pumping rate as observed in 1989; in pattern 2 a certain relocation has taken place, resulting in a relative shift to the west. The boundary between 'West' and 'East' is the UTM meridian of 29 (see Figure 5). Note that the spatial relocation is only modest; this is because the western part of the area offers only limited possibilities for irrigated agriculture.

Table 2: Definition of analysed alternative groundwater abstraction regimes.

	Average rate of groundwater abstraction (in Mm^3 $year^{-1}$)		Spatial pattern pattern	(% of abstraction)	
	year 1-25	25-200	no.	West	East
Case A	159	166	1	19	81
Case B	133	133	1	19	81
Case C	133	133	2	33	67
Case D	96	61	1	19	81
Case E	96	61	2	33	67
Case F	79	31	1	19	81

The expected intrusion zone and depth-to-groundwater at the end of the 200-year simulation period are shown graphically in Figure 7. These graphs confirm that extended exploitation of the aquifer at rates above the average rate of recharge lead to large declines of the groundwater levels. But even in the cases D and E, where the average groundwater abstraction is less than the average recharge, groundwater levels are still declining at the end of the 200-year simulation period. To ensure that in the long run groundwater levels remain largely within 40 m below ground surface -also in the eastern half of the area- there must be an even more drastic reduction of groundwater abstraction. This is because the natural discharge of the aquifer system is decreasing only very slowly for the pumping configurations considered.

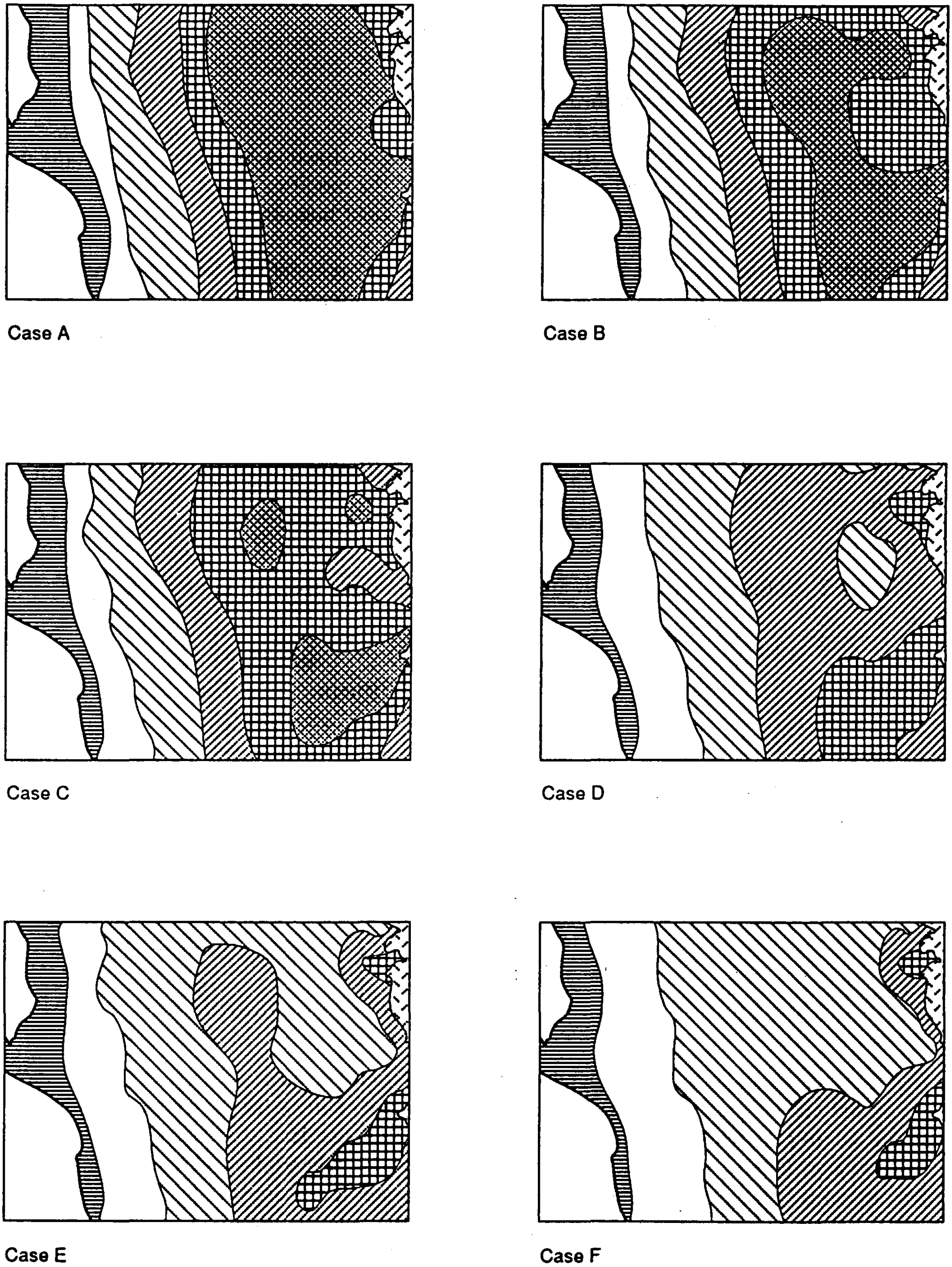


Figure 7: Comparative simulations of the aquifer's state at the end of the 200-year time horizon (for legend see Figure 6).

Relocation in the sense of changing from pattern 1 to pattern 2 has a slightly positive effect, as comparing cases B and C, and D and E, shows. If the western part of the area were more suitable for profitable irrigated agriculture, relocation could have been applied more effectively.

CONCLUSIONS

Although the model simulations discussed involve some uncertainty, because of simplifications adopted in the model and inaccuracy of data, they give a plausible prognosis of the long-term impacts of intensive groundwater exploitation in the Wadi Surdud area, and -in particular- they provide indications on the merits of different options for controlling groundwater abstraction.

The simulations have shown that among the main impacts of intensive groundwater exploitation in the Wadi Surdud area the increasing depth-to-groundwater is even more severe than the intrusion of saline water. Declining groundwater levels raise the cost of groundwater and thus may have extremely adverse effects on the profitability and sustainability of irrigated agriculture. Excessive declines in groundwater level can be delayed by proper relocation: reducing abstraction in the eastern part of the aquifer and pumping further west instead. Nevertheless, sustainable groundwater exploitation is only possible in this area if the current rates of groundwater pumping are reduced very significantly.

The system investigated is a coastal aquifer in hydraulic contact with the sea but without other recharging boundaries that locally maintain the groundwater levels at a fixed elevation. In such a system, economically sustainable exploitation of groundwater tends to require the long-term rate of groundwater abstraction to be considerably less than the average rate of groundwater recharge. This is not only in order to control the encroachment of saline water, but also to prevent groundwater levels falling to depths below which groundwater pumping is no longer economic.

ACKNOWLEDGEMENTS

The analysis presented in this paper would not have been possible without detailed information on Wadi Surdud and its water resources. Many of our Yemeni and Dutch colleagues in the successive phases of the WRAY programme have contributed to this information. Their efforts spent on field work, data processing and careful interpretation and analysis are gratefully acknowledged.

REFERENCES

Elderhorst, W.I.M., 1991. *Numerical simulation of salt water upconing and salt water intrusion in the Wadi Surdud area.* General Department of Water Resources Studies, Republic of Yemen, and TNO Institute of Applied Geoscience, The Netherlands, Report WRAY-21.

Ritsema, I.L., 1986. *Tihama basin water resources study, Geo-electrical survey report.* TNO Institute of Applied Geoscience, The Netherlands, Report IS-86-01.

Van der Gun, J.A.M., 1986. *Water resources of the Wadi Surdud area. Main report.* YO-MINCO, Department of Hydrology, Yemen Arab Republic and TNO Institute of Applied Geoscience, The Netherlands, Report WRAY-4.

Van der Gun, J.A.M., & Wesseling, H., 1991. *Pilot study on water resources management Wadi Surdud.* General Department of Water Resources Studies, The Republic of Yemen, and TNO Institute of Applied Geoscience, The Netherlands, Report WRAY-22.

Van Overmeeren, R.A., 1989. Aquifer boundaries explored by geo-electrical measurements in the coastal plain of Yemen: a case of equivalence. *Geophysics,* 54 (1); 38-48.

Verruijt, A. 1987. A finite element method for interface problems in groundwater flow. In: *Microcomputers in Engineering Applications,* B.A. Schrefler & R.W.Lewis. (eds), John Wiley & Sons, Ltd. New York.

Section 5:

CASE HISTORIES

UNSUSTAINABLE DEVELOPMENT AND IRRATIONAL EXPLOITATION OF GROUNDWATER RESOURCES IN DEVELOPING NATIONS - AN OVERVIEW

S.S.D. FOSTER
Chairman - IAH Burdon Commission on
Hydrogeology for Developing Nations
Assistant Director, British Geological Survey
Keyworth, Nottingham NG12 5GG, UK

ABSTRACT. Both physically-unsustainable development and sustainable but irrational exploitation of aquifers, resulting in inefficient utilisation of their groundwater resources, have become rather widespread phenomena in developing nations. In the more arid regions especially, water sector administrators are having to confront the reality and consequences of serious overexploitation of many aquifers. This is illustrated by selected examples from Latin America. These examples relate to essentially-unrestricted groundwater exploitation and this situation is contrasted with the controlled-development scenario. The conditions and problems complicating groundwater management in developing nations and a strategy for the priorisation and promotion of selective controls on abstraction are both briefly discussed.

> 'an underground reservoir that is almost always full is almost as badly utilised as one which is almost always empty' (Burdon, 1971).

> 'the problem of overextraction is essentially an economic one, in the long run a balance will somehow or other be reached, but meanwhile a major investment in money, in effort and in hope will be lost' (Burdon, 1973).

> 'the role of groundwater in socioeconomic development means that the hydrogeologist often has to become deeply involved in matters outside his scientific field' (Burdon, 1977).

INTRODUCTION

Definition of Concepts

Overexploitation is an emotive expression without (and perhaps incapable of) adequate definition.

All groundwater exploitation by wells results in some decline in aquifer piezometric level over a certain area. Some reduction is even necessary to maximise aquifer recharge rates. The fall in piezometric levels, however, can have consequences which become more pronounced as the number of wells and the volume of groundwater pumped increase. These consequences (or externalities) include interference with other wells and springs, and can also include near-irreversible aquifer deterioration due to ingress of saline or polluted water. Unplanned and unexpected aquifer overexploitation almost always brings negative impacts for groundwater users.

Overexploitation is often interpreted in the narrowest sense to describe situations where the rate of groundwater abstraction exceeds the average rate of aquifer recharge - here termed unsustainable development. This leads to a reduction of groundwater in permanent storage, effectively a consumption of reserves, and is thus sometimes known as groundwater mining or storage overdraft (Custodio, 1989).

Certain questions, however, immediately arise (Foster, 1988):

(a) for what area should the groundwater balance be evaluated, especially in situations where pumping is very unevenly distributed,
(b) over what period should this balance be established, especially in the more arid climates where major recharge episodes occur only once a decade or even less frequently.

The way in which these two factors are interpreted in practice can vary considerably with the exploitable storage volume of the aquifer system and the periodicity of recharge episodes involved. Localised aquifers with low storage coefficient and small sustainable yield will be more immediately susceptible to the side effects of overexploitation.

There are also circumstances in which development although sustainable must still be regarded as irrational, and by some definitions would be considered another case of overexploitation. These include situations where inefficient and uneconomic groundwater exploitation results from competitive development with indiscriminate drilling of excessive numbers of water-supply boreholes in relation to their potential total yield or in disregard of potentially-excessive interference with already-captured springs. Another example is the frequent construction of large numbers of shallow wells in aquifer discharge areas, without clear definition of individual abstraction rights, which subsequently prove an obstacle to the full exploitation of groundwater storage.

Economic Considerations

In economic terms, groundwaters (like fish) are a resource for which property rights are not capable of clear legal definition. Groundwater would thus be termed a common-property resource (Dasgupta & Heal, 1979), which is to a significant degree local in distribution. Its exploitation generates economic benefit to the individual user, but is also subject to externalities.

In an uncontrolled situation, the exploiter in effect receives all the benefits of groundwater development but pays only part of the costs -that is the capital investment in well construction plus the recurrent cost of pumping-, and not that of the externalities.

It must be recognised that unrestricted groundwater development can lead to serious problems of social inequity (Shah, 1989), associated with the competition for scarce resources, some exploiters benefitting at the expense of others. This externality could potentially frustrate public policy goals. Such a situation can occur where many domestic and small-scale agricultural users only have ready access to traditional water- lifting techniques, subject to absolute limitation in terms of operating head.

Exploitation of common-property resources is notoriously difficult to control and they may even be subject to accelerated depletion (Hardin, 1988), when individual users become aware of trends towards overexploitation and attempt to recover their investment while resources still remain.

It is important to mention that not all aquifer overexploitation is a dramatic or negative issue that needs to be considered an irrational use of groundwater resources. If planned with specific aims, and as long as the negative consequences have been technically evaluated and are economically acceptable, it may represent logical resource exploitation policy. This would be the case where groundwater mining enabled a cycle of economic development to occur, which will give way to substitution of more expensive water at a later date or to new technology improving the efficiency of water use.

Even so, the issue of intergenerational equity can arise and there is an argument to treat a natural resource as comparable to any asset worth holding in the present since it could become more scarce in the future (Barbier, 1990).

Controlled Development or Unrestricted Exploitation?

There are those who advocate that economic constraints, imposed by free market competition for groundwater resources, are the only effective control over aquifer exploitation. The larger capital cost of completing wells of increasing depth for decreasing yield and escalating recurrent costs associated with pumping from ever greater depths will, it is argued, rapidly result in achieving a high and sustainable level of resource exploitation and the most effective use of the groundwater produced.

A typical evolutionary trend for unrestricted groundwater exploitation, compared to the controlled-development case, is illustrated in Fig. 1 -although it should be recognised that neither utopian government control nor a perfect groundwater market will ever be found in practice-.

Where the only externalities of groundwater exploitation are hydraulic interference with other water users, then the unrestricted case is likely to achieve a higher level of resource exploitation more quickly (Fig. 1(b)), although at the possible price of drilling a disproportionately large number of wells to greater than optimum depth; that is of overcapitalisation in aquifer development.

The trend (Fig. 1(a)) is, however, likely to be very different for the scenario in which

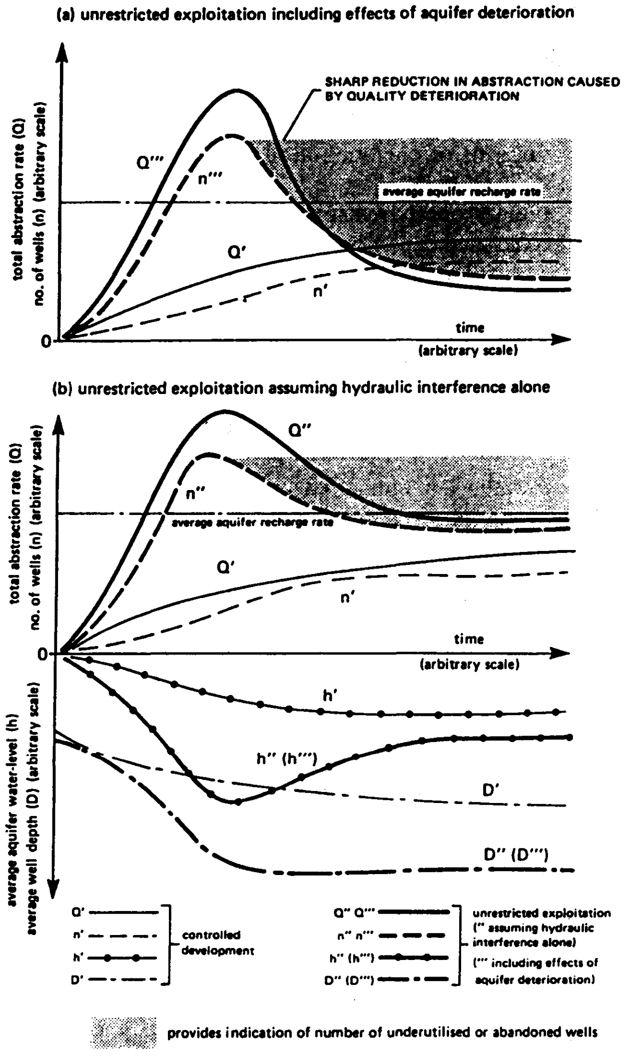


Figure 1: Evolutionary trends for unrestricted exploitation and controllea development of groundwater resources, after Custodio (1989).

unrestricted exploitation causes significant aquifer deterioration (Custodio, 1989). To reduce risk of deterioration, increasing caution in resource exploitation is required at the irreversibility margin, but this is unlikely to be taken into account by unrestricted private exploiters, and the reverse may even occur. The potentially sharp reduction in abstraction, as a result of the ingress of poor quality water soon after peak levels of exploitation are reached, can result in major losses of capital investment in groundwater development and utilisation. All three scenarios are expressed in relative cost terms in Fig. 2.

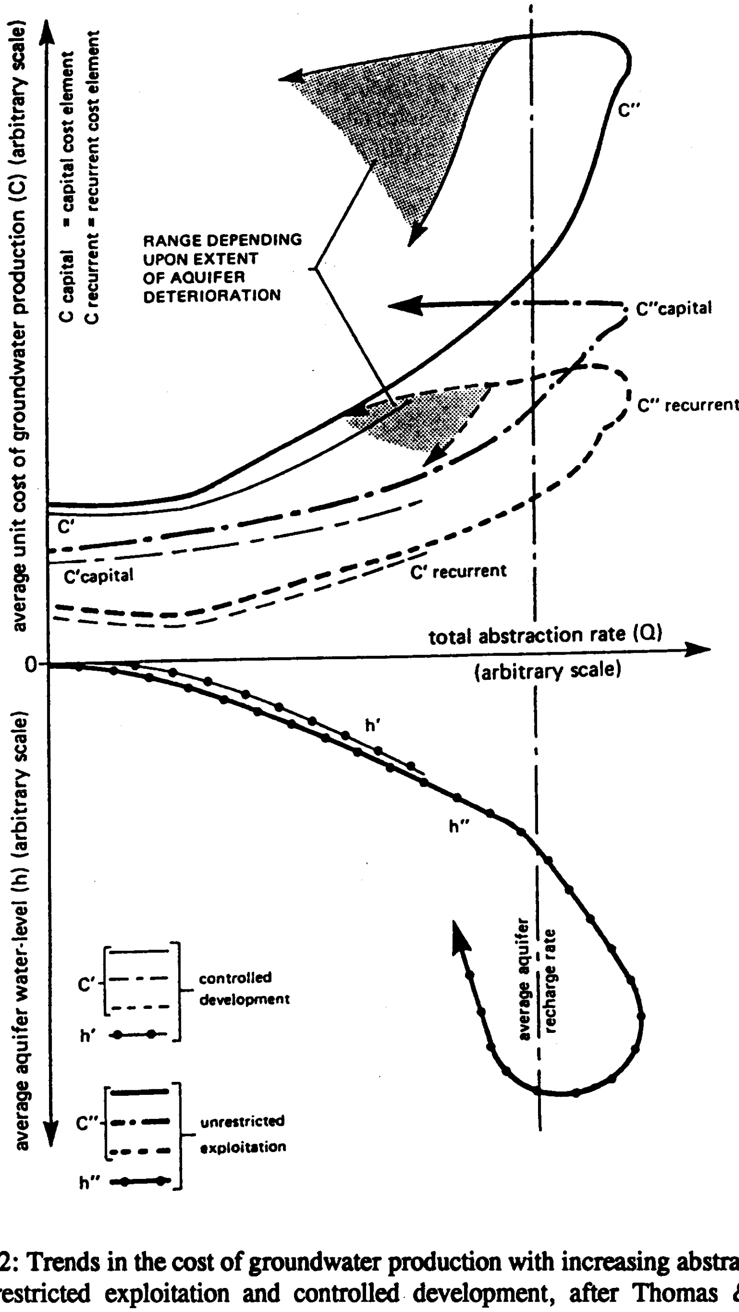


Figure 2: Trends in the cost of groundwater production with increasing abstraction rate for unrestricted exploitation and controlled development, after Thomas & Martin (1989).

The optimally-controlled development scenario, which eventually produces maximum resource utility for minimum number of production wells and lowest level of recurrent costs (Figs. 1 and 2), while taking all externalities into account, is obviously utopian in concept and unachievable in practice.

A common approach is to begin to exert an element of control over groundwater exploitation once substantial abstraction has already developed. This is normally achieved by prohibiting or limiting the construction of new boreholes and/or restricting abstraction rates from existing boreholes, with the aim of protecting existing users against subsequent developers.

Such a policy also has its limitations. In many cases the early exploiters may be the most irrational in terms of large numbers of small shallow boreholes, which will be susceptible to interference. This can become a severe obstacle to subsequent development of the storage capacity of deep aquifers during drought, thus sterilising a valuable element of groundwater resources against exploitation when most needed.

A more logical approach would be to submit all groundwater development to a compensation criterion, such that it would only be permitted if those who benefit can afford to fully compensate those they derogate and still be better off. In practice the evaluation of appropriate compensation is problematical and the criterion cannot be very widely adopted.

CONDITIONS AND PROBLEMS PARTICULAR TO DEVELOPING NATIONS

Sociopolitical and Institutional Issues

While there is wide variation between the so-called developing nations, there are a number of conditions that appear to be common to many such countries which are relevant to the multifaceted problem of controlling groundwater exploitation and correcting aquifer overexploitation. The following factors have to be borne in mind when discussing groundwater resources management issues in developing nations.

First, the pressing need to expand food production and to provide for rapid urban growth continues to place groundwater resources under strong development pressure. This is especially the case in the more arid regions where water rather than land is often the factor limiting development. This situation can be further complicated where there is reluctance by government to allow a realistic price to be levied for urban water-supply or there exists a policy decision to subsidise agricultural irrigation from groundwater to beyond realistic limits. There is also often a lack of political will to enforce controls upon economically-powerful lobbies.

Second, the traditional pattern of groundwater exploitation in some developing nations has led to very large numbers of small abstractors, many of which are highly vulnerable to interference effects (Shah, 1989). Such patterns have tended to favour the initial exploitation of shallower groundwater, such as that found in major aquifer discharge areas or in perched aquifers. This has been due to technological limitations on well construction and pumping plant.

Third, the implementation of controls on groundwater resource exploitation make considerable organisational and technical demands on central or local government, especially if these controls pretend to be comprehensive in their application. The institutional capacity of regulatory departments or agencies is commonly insufficient to cope with such demands and the legal provision by which they are backed is often insufficient to control abstraction.

Fourth, control of abstraction to reduce the risk of aquifer overexploitation presupposes that groundwater resources have been reliably evaluated. In many developing nations there is simply inadequate information to make such evaluations and major uncertainties remain over the size of the groundwater resource, in terms of both replenishment and storage (Foster, 1988), and about the potential side effects of overexploitation. The inadequacy of information results from the generally meagre nature of many hydrogeological databases, the fact that very limited research on hydrogeological processes has been undertaken and the lack of historic operational data on aquifer abstraction rates and water-levels (Foster, 1989). It may even be difficult to diagnose incipient signs of overexploitation because of the lack of time-series piezometric data from monitoring boreholes.

Consequences of Uncontrolled Aquifer Overexploitation

Serious overexploitation of numerous aquifers is a reality in many developing nations and the consequences are now having to be addressed.

While any groundwater development must have some negative externalities, the principal concern is with those side-effects which have significant or serious consequences (Foster, 1989; Custodio, 1989), such as:

- (a) increase in pumping costs and/or reduction in yield of neighbouring wells,
- (b) reduction in springflow and other groundwater discharge to surface watercourses,
- (c) ingress of saline water into coastal aquifers, through lateral intrusion or up-coning,
- (d) inducing infiltration of poor quality water from overlying (polluted) perched aquifers and on occasions surface watercourses,
- (e) consolidation of aquitards leading to land subsidence and resulting in problems with building stability, land drainage and sewer flows.

While the first two of these externalities are temporary effects, which can be reduced or reversed if abstraction is controlled, the latter three cause long term, and in some cases irreversible, consequences affecting large numbers of groundwater users and other interests. In common with the industrialised countries, instances of unsustainable development of groundwater resources in developing nations are most frequently the result of excessive exploitation for agricultural irrigation. They are most significant and widespread in arid and semi-arid regions -notably parts of Mexico, North Africa, the Middle East and parts of Pakistan and India- and affect a range of aquifer types.

Significant problems also occur in the vicinity of many major conurbations as a result of rapid growth of urban population and unrestrained demand for water supply. This has had especially dramatic effects in cities such as Mexico City, Bangkok and Jakarta where the principal aquifer is associated with highly-compressible aquitards and overexploitation has led to serious land subsidence. In many coastal towns excessive penetration of saline water has occurred, leading to the abandonment of hundreds of production boreholes.

Specific Example: (a) Lima-Peru. The alluvial fan aquifer of Lima and its port, Callao, is exploited by more than 320 municipal production boreholes, which provide a supply of up to 0.65 m^3 day^{-1}, and by many other private industrial abstractors. This is an extremely arid area and diffuse recharge from excess rainfall is virtually negligible. Total abstraction since the mid 1970s has considerably exceeded the (other forms of) aquifer recharge and, over a substantial area, the water-table has been falling by rates of more than 2 m $year^{-1}$, and in extreme cases by more than 5 m $year^{-1}$. The consequences have been to reduce dramatically the yield of production boreholes, especially in areas where the most permeable horizons of the alluvial aquifer occur relatively close to the groundwater table (Fig. 3). In other areas borehole yields have been less affected. The overall effect on the municipal water-supply situation is that the number of operational boreholes has had to be steadily augmented since 1980 to maintain groundwater abstraction at the same level and the unit energy costs of water production have increased by 25% during 1975-85 (Table 1). The average depth of new production boreholes has also increased very significantly.

Table 1: Operational history of municipal groundwater abstraction from the overexploited Lima alluvial-fan aquifer.

YEAR	1975	1980	1985	
production boreholes (number in operation)	151	219	264	
total groundwater abstraction (Mm^3 $year^{-1}$)	155	199	208	
average borehole yield (l s^{-1})	32	29	25	
unit energy consumption	0.70	0.82	0.88	(kWh m^{-3})

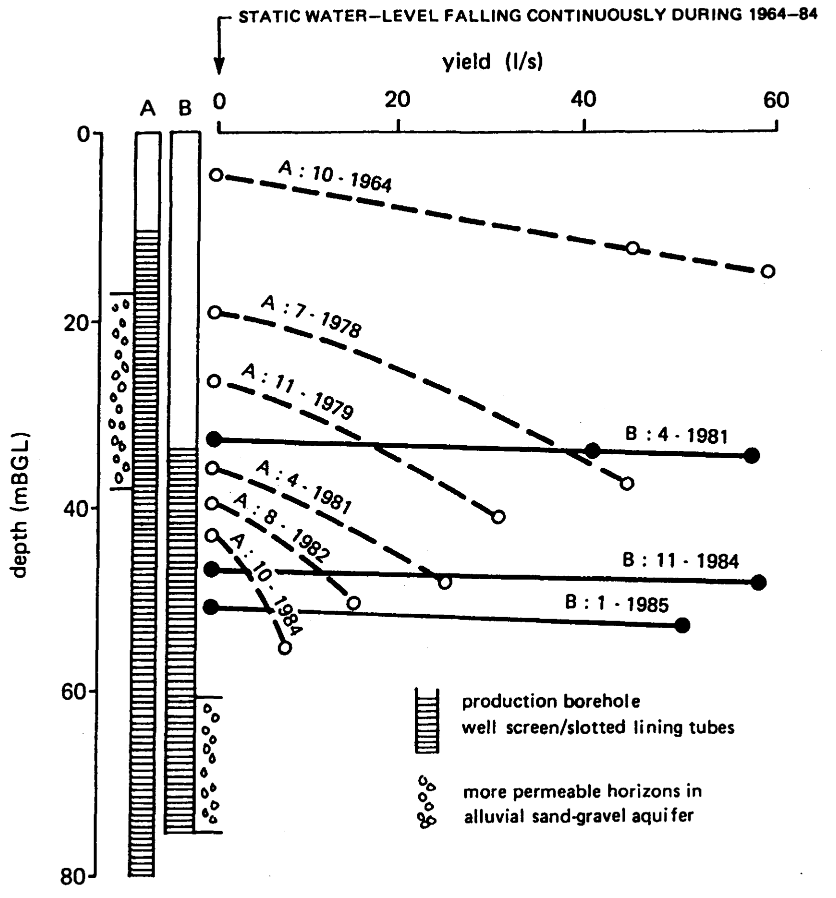


Figure 3: Historical evolution of operational performance of selected production boreholes in overexploited Lima alluvial-fan aquifer, after Foster (1988).

Specific Example: (b) Hermosillo-Mexico. Another example of gross aquifer over-exploitation and unsustainable groundwater development is found on the Hermosillo coast of northern Mexico (Fig. 4), where highly-productive irrigation of wheat and maize from both surface water and groundwater has been practised since the 1960s. This is also an arid region in which groundwater recharge is largely derived from excess irrigation and (very infrequent episodes of) excess rainfall associated with summer storms. Groundwater abstraction by some 500 production wells with an average capacity of 80 l s^{-1} has led to depletion of storage reserves in the 60-200 m thick alluvial aquifer, at rates of 400-750 Mm^3 $year^{-1}$ (Tinajero, 1989). Invasion of saline water for distances of up to 25 km from the coast has resulted, despite the fact that finer-grained sediments close to the coastline in places form a partial hydraulic barrier. This saline intrusion has led to the abandonment of many production wells and of much agricultural land.

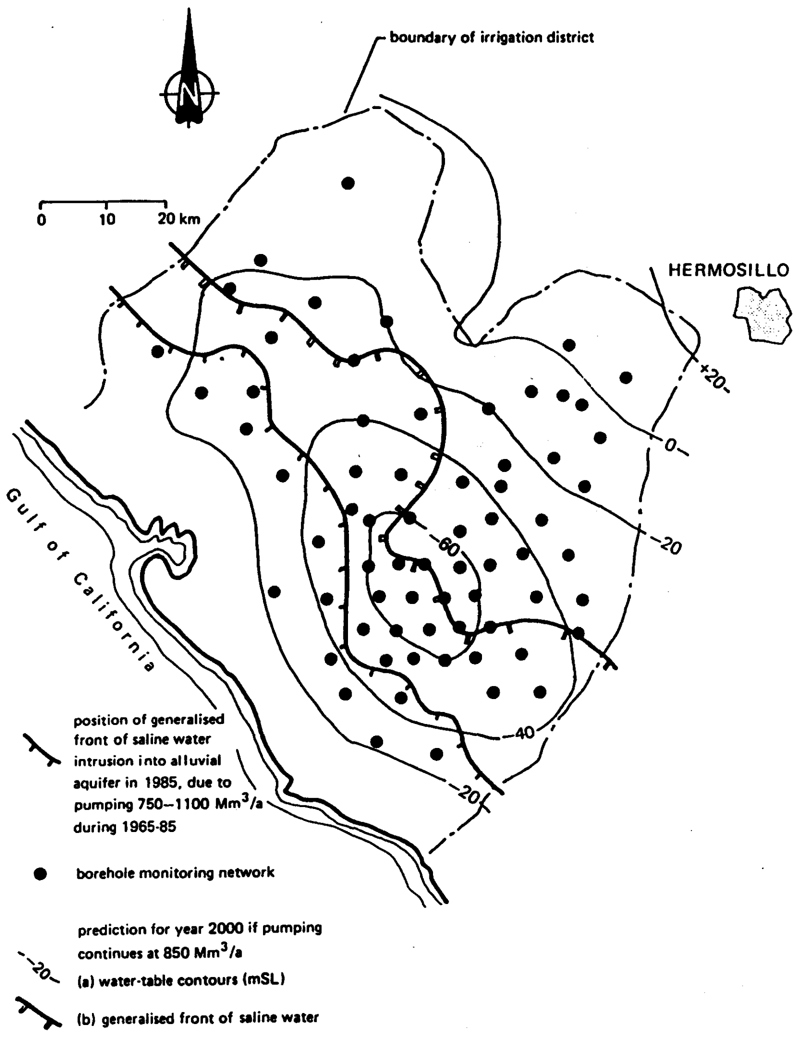


Figure 4: Current and probable future intrusion of saline water front into the overexploited alluvial aquifer of the Hermosillo coast-Mexico, after Tinajero (1989).

Specific Example: (c) Chihuahua-Mexico. The larger towns of the interior of northern and central Mexico are also highly dependent upon groundwater for municipal water-supply and for agricultural irrigation. In many cases this has led to continuously falling groundwater levels at rates similar to those observed in Lima, with fierce competition between municipal, industrial and agricultural water-supply interests (Fig. 5). In some cases this overexploitation is inducing infiltration and deep penetration of polluted water. In the alluvial aquifers of the Chihuahua area, for example, deterioration in groundwater quality has resulted from infiltration from unsewered sanitation in parts of the city itself and of urban sewage effluent downstream, either directly through the riverbed or following overirrigation of agricultural land.

	SACRAMENTO VALLEY		CHUVISCAR–TABALAOPA VALLEY			
	formerly zone of groundwater discharge upstream of impermeable barrier; condition reversed due to aquifer overexploitation with infiltration of urban effluents		riverflow (mainly urban wastewater) infiltrating and creating perched water-table	localised aquifer overexploitation with falling groundwater table	groundwater discharge to river and via vegetation upstream of barrier	
shallow groundwater quality Cl	5–15	30–80	40–100	5–15	>50	(mg/l)
shallow groundwater quality NO_3	<25	50–100	30–150	<25	<25	(mg/l)

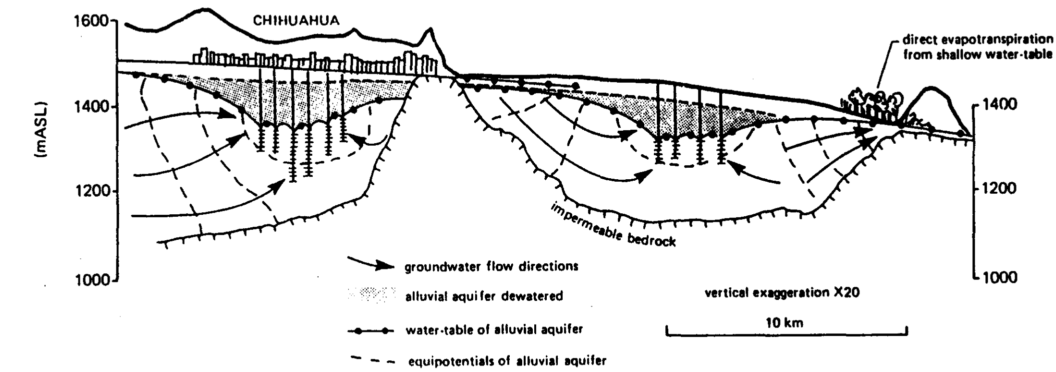


Figure 5: Schematic hydrogeological section to illustrate overexploitation of alluvial aquifers in the vicinity of Chihuahua-Mexico.

Problem of Irrational Exploitation

Examples of physically-sustainable but irrational exploitation of groundwater resources are found very widely. Common occurrences include the competitive drilling of increasingly deeper production boreholes, which obtain almost all of their yield from induced vertical seepage and simply dewater shallower aquifer levels, which were fully exploited by earlier production boreholes. There are also frequent instances of borehole drilling to capture groundwater that was largely being discharged immediately downstream as (geological contact) springflow, already captured for public water-supply.

The reverse type of situation also occurs quite widely as is the case in the Cochabamba valley of Bolivia (Fig. 6). Here natural groundwater discharge has been very inefficiently developed by a large number of individually small abstractors, dependent upon artesian pressures for well or spring discharge. In such situations major loss of water occurs due to under

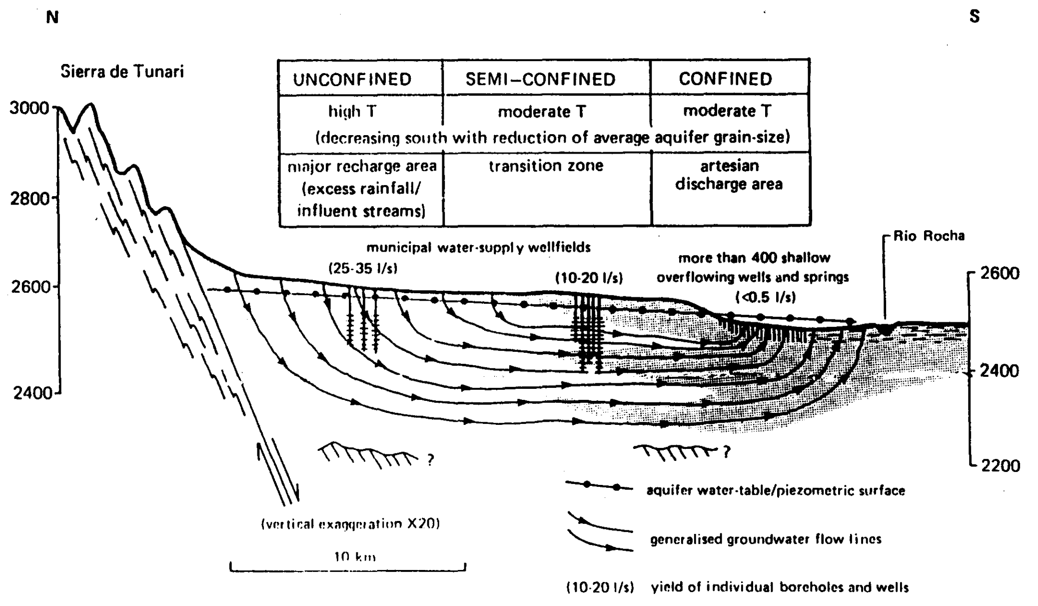


Figure 6: Schematic hydrogeological section of Rocha valley downstream of Cochabamba-Bolivia illustrating irrational pattern of groundwater exploitation.

utilisation and wastage. Such installations also have no capacity to exploit groundwater storage in drought years. Community pressure exerted by their users, however, can be a formidable obstacle to subsequent more efficient exploitation of groundwater storage up hydraulic gradient in the same aquifer system by municipal wellfields.

STRATEGY FOR CONTROL OF GROUNDWATER ABSTRACTION

Assigning Priorities

The question of where and how to attempt the control of groundwater exploitation arises. If the limited institutional capacity of regulatory departments of agencies (where these exist) is to be effectively deployed, realistic priorities for the implementation of control measures have to be established.

It is considered that priorities should be assigned by consideration of:

(a) the strategic importance of individual aquifers in the overall water-supply situation and the level of exploitation to which they are (or may be) subjected.
(b) the susceptibility of each aquifer system to adverse side-effects as a result of excessive or irrational exploitation.

In relation to the latter, Table 2 identifies the important factors and provides a technical basis for decision making.

Control Measures

Experience from the developing nations suggests that attempts to control groundwater development have been more successful where a regional or catchment regulatory agency has built good relations with those drilling waterwells, through, for example, providing hydrogeological advice. Exercising control over the construction of wells themselves -their numbers, depths and diameters- is the most direct and effective route to controlling groundwater abstraction.

If the control of drilling activities, through some form of simple gratuitous permit to both well driller and owner, is reasonably effective, the issuing of abstraction licences can be limited to larger users, greatly reducing the administrative burden. Charging for abstraction licences may be necessary to raise revenue for the regulatory agency, but such agencies should not have to be highly dependent upon resource exploitation for their financial solvency.

In the case of already overexploited aquifers, the introduction of control measures, which may include reducing abstraction by restricting pumping periods, is more likely to be successful when implemented through some form of water-user group organised within a community or municipal framework.

For any policy to be effective some form of sanction against those who construct waterwells without permit or exceed their licensed abstraction is required. Possible penalties include temporary (or even permanent) prohibition on the use of the well, depending on the scale of the offence and its effect on third parties or on the aquifer resource itself. Monetary fines may be considered but these are not normally appropriate.

The existence of adequate legislation might appear to be a prerequisite for the control of groundwater abstraction. While highly desirable, it can often in practice be substituted by provincial or municipal decree, declaring that a given aquifer must be protected against the negative impacts of overexploitation in the interests of all water-users and the community as a whole.

It must also be more widely recognised that careful monitoring of aquifer response to abstraction provides reliable data with which to improve the evaluation of groundwater resources in a cost-effective way (Foster, 1988), as well as being an integral part of the abstraction control process.

CONCLUSIONS

(a) The unrestricted exploitation of groundwater resources, free from all government control has already caused serious depletion and/or irreversible deterioration of important aquifers in some developing nations. It can only be considered a

Table 2: Factors affecting the susceptibility of aquifers to adverse side-effects from irrational exploitation.

FACTOR	SYMBOL	DIMENSION	ADVERSE SIDE-EFFECTS SUSCEPTIBILITY TYPE high ---→ moderate ---→ low						
aquifer response characteristic	T/S	$m^2\ day^{-1}$	100,000		1,000		100		10
aquifer storage characteristic*	S'/R	-	1	2	5	10	20	50	100
available drawdown to productive aquifer horizon	S	m	10		20		50		100
depth to groundwater table	h	m	2	5	10	20	50	100	200
proximity of saline-water interface*	L	km	0.1		1		10		100
vertical compressibility of associated aquitards		m^2N^{-1}	10^{-6}		10^{-7}		10^{-8}		10^{-9}

T = transmissivity ($m^2\ day^{-1}$)   S (S') = storativity ($mm\ m^{-1}$)

R = average annual recharge rate ($mm\ year^{-1}$)

* amongst the most readily estimated, these factors are also generally the most critical

tolerable option for:

(i) extensive aquifers with large storage reserves, very many times greater than their average annual replenishment, in situations where,

(ii) the consequences of temporary overdevelopment are not irreversible,

(iii) no account needs to be taken of reductions in spring discharge and river baseflow, and

(iv) it will not cause further social inequity between water-users.

(b) The risks of near-irreversible deterioration of aquifers and premature loss of capital investment associated with unrestricted groundwater exploitation are such as to urge all developing nations to place some controls on aquifer exploitation as a first step in positive (as opposed to passive) groundwater resources management.

(c) The difficulty that arises is drawing-up realistic control policy, given the limitations of institutional capacity and other factors in developing nations. Control strategies need to be based on economic criteria but not dependent directly on market forces as such. The questions of where control most needs to be exercised and of how most effectively to implement control measures have to be addressed pragmatically and priorities assigned.

ACKNOWLEDGEMENTS

This paper is published by permission of the Director of the NERC-British Geological Survey. The illustrative examples were collected as part of the WHO-PAHO Groundwater Protection Program for the Latin American-Caribbean Region, of which the author has had the pleasure to act as either coordinator or adviser since 1985, under the direction of Alberto Flores (PAHO-CEPIS).

The author is indebted to the following Latin American groundwater specialists for excellent discussion of groundwater exploitation problems and the provision of related data: Rubén Chávez (CNA), Pedro Martínez (CNA), Armando Canales (ITSON) and Adolfo Chávez (UACH) of Mexico, Juan-Carlos Ruiz (SEDAPAL) and Carlos Valenzuela (SEDAPAL) of Peru, and Víctor Ricaldi (CORDECO) and Orlando Villaroel (SEMAPA) of Bolivia. He is also grateful to his daughter, Vivien, for critical review of the original manuscript from an economist's viewpoint.

REFERENCES

Barbier, E.B. 1990. Alternative approaches to economic-environmental interactions. *Ecol. Econ.* 2; 7-26.

Burdon, D.J. 1971. Exploitation of groundwater resources for agricultural production in arid zones. *Food, Fiber & Arid Lands* 9 (III); 289-300.

Burdon, D.J. 1973. Challenge of groundwater development for agriculture. In: *Development of Groundwater Resources*. CSIR-New Delhi (ed). Proc. Intl. Symp., 3 (VI); 109-127.

Burdon, D.J. 1977. The role of the hydrogeologist. *IAH Congress Memoirs,* 13 (vol. 2); 89-104.

Custodio, E. 1989. Strict aquifer control rules versus unrestricted groundwater exploitation: comments of economic consequences. *Developments in Water Science*, 39; 53-65.

Dasgupta, P. & Heal, G. 1979. *Economic theory and exhaustible resources*. Cambridge University Press Cambridge.

Foster, S.S.D. 1988. *Quantification of groundwater recharge in arid regions - a practical view for resource development and management.* NATO-ASI Series C 222 (Reidel-Dordecht); 323-338.

Foster, S.S.D. 1989. Economic consideration in groundwater resource evaluation. *Developments in Water Science*, 39; 53-65.

Hardin, G. 1988. The tragedy of the commons. *Science,* 162; 1243-1248.

Shah, T. 1989. Externality and equity implications of private exploitation of groundwater resources. *Developments in Water Science*, 39; 459-482.

Thomas, J.F. & Martin, W.E. 1989. Mining of aquifers near metropolitan areas: towards a general framework for policy analysis. *Developments in Water Science*, 39; 397-408.

Tinajero, J.A. 1989. Economic assessment of the consequences of groundwater use. *Developments in Water Science*, 39; 133-152.

GROUNDWATER MINING AND DEVELOPMENT IN THE SOUSS VALLEY (MOROCCO)

M. JELLALI, M. GEANAH & S. BICHARA
Direction de la Recherche et de la Planification de l'Eau,
Administration de l'Hydraulique
Rue Hassan Benchekroun, Agdal, Rabat, Morocco

ABSTRACT. The intensification of water resources utilization in the Souss valley has become more threatening to the hydraulic potentialities and indirectly to the social and economical activities of the region.

The need of strict water utilization planning has become necessary to remedy this problematic situation.

The present paper presents the problems related to groundwater mining, the different results of the simulation models and the proposed water resources planning and management scenarios.

THE NATURAL FRAMEWORK OF THE SOUSS VALLEY

The Souss Valley is bounded by the High-Atlas mountains to the North, the Anti-Atlas to the South and South-West, the narrowing of the two mountains ranges to the East and the Atlantic Ocean to the West.

The area of the Souss valley represents only 4,150 km^2 over an area of the Souss river basin which drains about 16,000 km^2. The Souss river flows through this valley from East to West. Besides the flows of the Souss river itself, the valley receives flows from several tributaries which drain the South slopes of the High-Atlas and the North-South slopes of the Anti-Atlas (Fig. 1).

Generally speaking, the surface flows of the Souss river average 430 m^3 $year^{-1}$ distributed between the Souss river itself and the tributaries of the High-Atlas mountains.

The majority of the groundwater resources of the Souss emanate from the generalized aquifer which covers an area as large as the Souss valley. This aquifer resides in the heterogeneous Quaternary formations. The thickness of the aquifer varies from 200 m in the East to around 1,000 m in the Agadir zone.

The average yearly precipitation over the valley is about 240 mm and can reach 350 to 800 mm in the High-Atlas and 250 to 350 in the Anti-Atlas. The average temperature in the middle of the valley varies from a minimum of 13,6 °C in January to a maximum of 26,4 °C in August. The Souss has an agricultural basis. The irrigated area covers about 86,000 ha, whereas some 39,000 ha are precipitation dependent.

CHARACTERISTICS OF THE SOUSS AQUIFER

The hydraulic characteristic of Souss aquifer are synthesized from a network of 400 wells and boreholes.

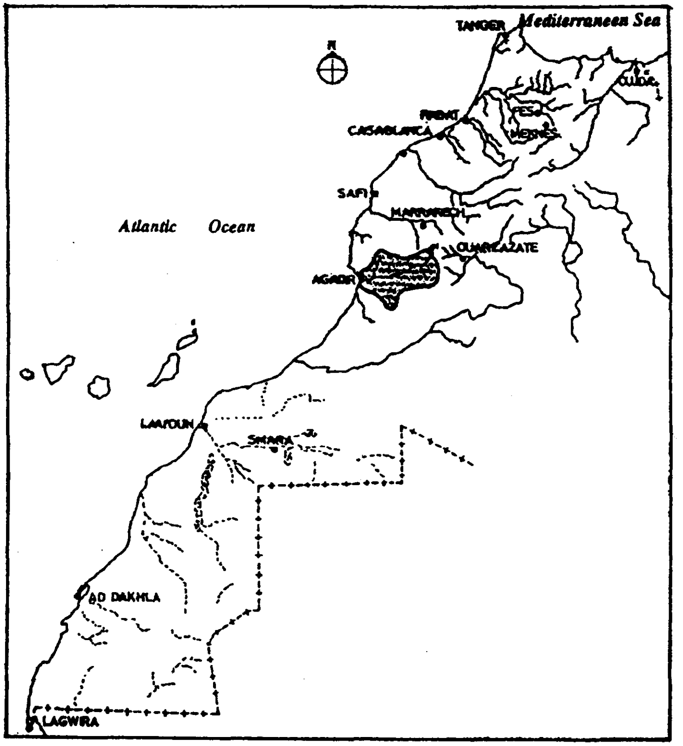


Figure 1: Location of the Souss valley.

The formations of the fossil bed of the Souss show some characteristics relatively resembling old alluvial deposits with an average thickness of 20 m and a length of 2 to 3 km around the Souss river.

The Souss formations have also some comparable hydraulic characteristics (Table 1):

Table 1: Hydraulic characteristics of Souss aquifer, after Motor Columbus *et al.* (1989).

	Transmissivity (m^2 s^{-1})	Permeability m s^{-1}	Storage Coefficient
Possible bedrock of Souss	$2x10^{-1}$ to $6x10^{-1}$	$8x10^{-4}$	$3x10^{-2}$ to 10^{-1}
Limestones of the Souss down stream	$0.2x10^{-3}$ to $6x10^{-3}$	-	$4x10^{-2}$
Old formations of the valley	$2x10^{-2}$ to $20x10^{-2}$	$4x10^{-4}$ to $40x10^{-4}$	$3x10^{-2}$
Souss formation	10^{-2} to 10^{-1}	10^{-4} to $15x10^{-4}$	10^{-2} to $5x10^{-2}$
Recent quaternary deposits	10^{-2} to 10^{-1}	10^{-4} to 10^{-3}	10^{-2} to 10^{-1}

THE HYDRAULIC REGIME OF THE AQUIFER

Aquifer recharge is achieved by (Motor Columbus *et al.*, 1987):

(a) rainfall infiltration (6 to 8% of the precipitation),
(b) infiltration along the Souss river,
(c) communication with other groundwater reservoirs at the edges of the High and Anti-Atlas mountains,
(d) infiltration from the surface water irrigation surplus, and
(e) probably by ascendent drainage in some locations from deep aquifers.

Aquifer discharge occurs:

(a) via deep water movement towards the Atlantic Ocean,
(b) via drainage by the downstream Souss channel when the piezometric levels approach the surface level, and
(c) via pumping, draining and resurgences.

The aquifer flows from East to West, with a gradient steeper in the recharge zones upstream than in the valley, and flows into the Atlantic Ocean. The depth of the aquifer varies between 10 and 20 m inside the fossil bed sectors and can reach 100 m to 130 m downhill from the Atlas mountains. The comparison of piezometric data and the reference situation of 1968 shows some drawdown ranging from 10 to 20 m (with some maximum values of 30 m) in the fossil bed sectors and to the East of the valley.

The Guerdane zone, in the middle of the valley, shows severe drawdown reaching 40 m with a yearly average drawdown rhythm of 2 m.

Drawdowns lower than 10 m have been observed at the edges of the valley to the North, at the origin of the Souss river at Aoulouz, upstream of Taroudant and in the coastal zone of Agadir (Fig. 2).

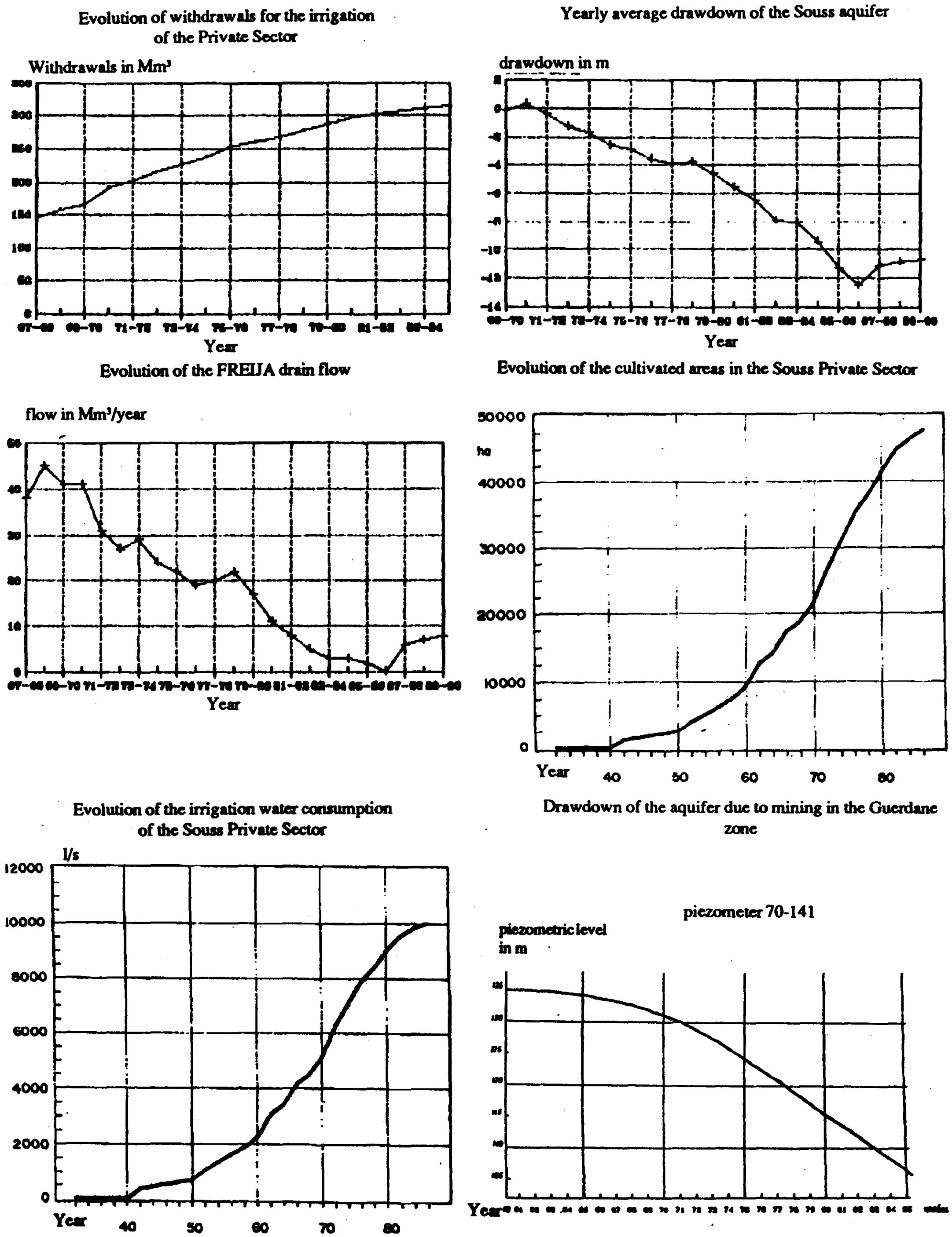


Figure 2: Evolution of groundwater supply and impact on the Souss aquifer.

THE HYDRAULIC BALANCE

The balance of inputs to the Souss aquifer can be summarized as follows: the average aquifer recharge is about 220 Mm^3 $year^{-1}$. If infiltration from irrigation waters is considered, the recharge can be increased to 240 Mm^3 $year^{-1}$. Recharge varies between a minimum of 160 Mm^3 (1985; dry year) and a maximum of 334 Mm^3 (1979, humid year).

The balance of outputs from the Souss aquifer is mainly the result of pumping. Groundwater flow from the aquifer front toward the ocean is about 20 Mm^3 $year^{-1}$. The aquifer outputs have been 408 Mm^3 in 1985. Over the period 1971-1986, the average aquifer deficit has been 150 Mm^3 $year^{-1}$. This deficit fluctuates between 60 Mm^3 in 1971 and 250 Mm^3 in 1985 and 1986.

Table 2: Hydraulic balance variation in Mm^3, after Motor Columbus *et al.* (1989).

	Years			
	68/69	78/79	85/86	88/89
Infiltration from precipitation and dispersed flows	85	63	58	65
Infiltration in the river bed	229	208	50	345
Irrigation return flow	-	14	8	-
Ascendent drainage from deep aquifers	-	10	-	7
Inflows from others aquifers	65	49	44	46
Total inputs:	389	334	160	463
Groundwater flow toward the Ocean	18	20	15	19
Drainage by downstream Souss	-	60	0	-
Consumption of the agricultural traditional sector.	149	74	11	10
Consumption via pumping for the public and the modern private sectors.	158	278	365	375
Drinking water consumption	6	10	17	24
Total outputs:	331	442	408	428
Balance:	58	-108	-248	35

POTENTIAL

The aquifer balance shows a deficit in 1985-86 of 250 Mm^3 $year^{-1}$. This increasing deficit (60 Mm^3 in 1970 to 250 Mm^3 in 1986) results from the poor natural recharge during the last

20 years, and when the pressure has begun also from the demands on water resources for the economic and social development of this region.

Although many questions have not yet been answered, the available hydrogeological data can help estimate the aquifer potential to be about 40,000 Mm^3.

During the last 20 years, a volume varying between 2,500 and 3,000 Mm^3 was withdrawn from the aquifer reserves to face the deficit in water supply and to satisfy the different demands in the region.

These withdrawn volumes from the reserves have caused a generalized drawdown all over the Souss valley. The yearly average drawdown is equal to 0.75 m.

SOME HISTORICAL INDICATORS ON THE AQUIFER USE

The effective use of the Souss groundwater aquifer started in 1940. At that time, the pumping rate was about 250 $l\ s^{-1}$. Since the beginning of the sixties, pressures on groundwater demand have increased abstraction to 12 $m^3\ s^{-1}$ by 1990.

During the 1960s the pressure on water resources to meet the demands of the private sector on the one hand, and the introduction of modern pumping technics on the other, has led to an intensification of groundwater resource use.

The aquifer balance has thus shown a deficit of 60 $Mm^3\ year^{-1}$ since 1970. During the following 20 years this deficit has become more pronounced due to the increasing water demands and mainly to the deficit in the aquifer natural recharge because of dry seasons.

This situation has produced a drop in the traditional irrigation practices which use the emergences and 'rhettaras' draining the aquifer in close proximity to the soil surface.

Therefore, the emergence and rhettara flows have decreased significantly following continuous drawdown of the aquifer.

Table 3: Discharge variation in Mm^3, after Motor Columbus *et al.* (1990).

	Years		
	1969-1970	1978-1979	1988-1989
Emergences	70	35	1
'Rhettaras'	32	16	2
Freija drain	41	22	7

During the period between 1977-1990 the salinity has increased from 0.6 g l^{-1} in the south-eastern part of the aquifer, whereas in the coastal part it has increased from 1.85 g l^{-1} to 2.46 g l^{-1}.

In 1990, the yearly groundwater consumption in this region was about 426 Mm^3 distributed between 26 Mm^3 for drinking water (60% of this amount is for the large Agadir urban area) and 400 Mm^3 for irrigation.

ARRANGEMENTS TO OVERCOME GROUNDWATER MINING

To face the progressively decreasing groundwater reserves, a decision has been made to assure a coherent development of all the region's water resources through the realization of a maximum of integrated projects. The aim is to tend towards a plan of water resources realization and management which is able to face the increasing demands in the region. This plan can be achieved by:

- (a) a maximum mobilization of water resources,
- (b) an optimal aquifer recharge, particularly in the zones where the drawdown is excessive,
- (c) a reduction of the lost surface water flowing to the ocean,
- (d) technical methods for implementing these suggestions,
- (e) a protection against the progressive saltwater intrusion in the coastal area, and
- (f) an optimal enhanced value for water use, particularly for agriculture.

SURFACE WATER DEVELOPMENT OPTIONS

To achieve the objectives concerning the satisfaction of water demands, the following water development options need to be considered. Fig. 3 illustrates these objectives:

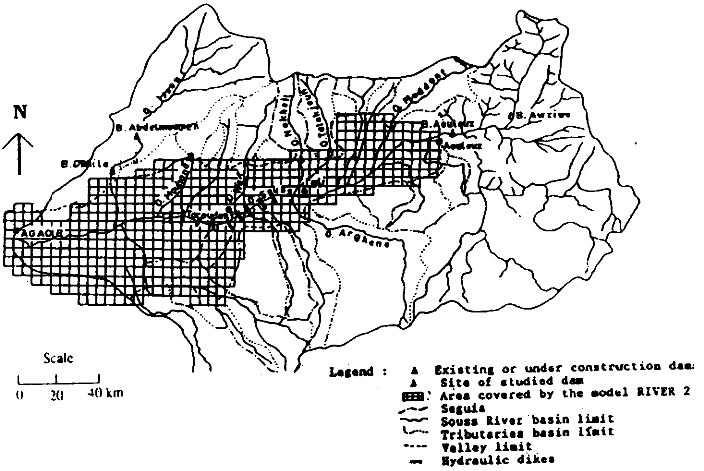


Figure 3: Location of existing and future hydraulic projects.

(a) realization of the Aoulouz reservoir upstream in the valley in order to stock floods and to modulate water deliveries downstream to enhance the infiltration process and to improve the aquifer recharge along the Souss river. This reservoir is under construction and is expected to start operating during 1991,
(b) realization of several small size reservoirs on the Souss river tributaries for flood control and the development of agriculture in the piedmont areas.
(c) realization of several dams to delay flow in the river channel and to create beaches where the infiltration can be enhanced, and
(d) realization, also, of medium size reservoirs in the basins north of the Souss basin to meet drinking water demands for the urban area of Agadir.

In fact, the average volume of surface water flowing to the ocean is 150 Mm^3 $year^{-1}$ and the aquifer water deficit per year exceeds this amount.

SYSTEM EFFICIENCY EVALUATION

A simulation model which allows consideration of the interactions between surface and groundwater resources has been developed to assess the performance of water development schemes from the points of view of water supply and the impact on the aquifer piezometric characteristics.

This model allows the coupling of surface and groundwater resources in order to control and include the aquifer recharge in the global hydrological balance of the Souss basin.

This model takes into consideration:

(a) hydroclimatological data for the basin,
(b) hydraulic characteristics of the different rivers in the valley,
(c) geometric and hydrodynamic characteristics and boundary conditions of the aquifer, and
(d) water withdrawals and their location and modulation in time.

The expected water management model includes an extra volume of 45 Mm^3 for irrigation of the Sebt El Guerdane area where the drawdown is very pronounced. The rest of the controlled inflows will be reserved for aquifer recharge. The maximum potential aquifer recharge volume is 105 Mm^3.

Water management should be in such a way that aquifer recharge should benefit first from the tributary inflows because of their low storage capacity before being enhanced by water delivered in an appropriate manner from the Aoulouz reservoir.

The confrontation between water demands and water resources for the horizon 2020-2030 shows that the expected development for the same horizon will cause the water balance to be largely in deficit and might lead to a depletion of groundwater resources in the region.

The performed simulations show that the balance deficit is about 140 Mm^3 over the period

1991-2030. This implies groundwater level drawdown and mining of an equivalent volume all over the aquifer reserves, but there will be a pronounced drawdown particularly in the areas where the aquifer is already threatened. In the zone of Sebt El Guerdane, South East of Agadir city, where the water table level is already at -130 m, it will show a maximum drawdown of -30 m.

In the case of water management based on aquifer recharge only, the piezometric level might drop to -45 m (Fig. 5). These simulations also show that drawdown varies from -10 to -30 m along the coast, causing the saltwater front to move towards the interior of the Souss valley. The aquifer recharge is about 240 Mm^3 and water flowing to the ocean is reduced from 20 to 10 Mm^3 on the average.

Considering these results, complementary studies are undertaken to test demand reduction scenarios to look for a solution which tends to equilibrate the water balance, or at the worst to accept a limited mining of the groundwater reserves of the valley.

Model validation was performed using 34 observation wells. Fig. 6 shows that there is a coherence between contour lines drawn from both the calculated and observed piezometric values. The differences between the observed amounts of surface water flowing to the sea and their corresponding values obtained from the model are small (Fig. 7).

These scenarios consider:

(a) a reduction in drinking water and irrigation demands,
(b) a resorting to the non-conventional desalination of seawater for the drinking water sector and reuse of water after purification for irrigation,
(c) a rational management of water demands,
(d) efficient control of withdrawals and adoption of a cost policy for water as a function of its scarcity, without forgetting the social impact on small farmers,
(e) modernization of drinking water services by looking for efficiency in the distribution networks and by heightening public awareness for saving water, and
(f) introduction of modern techniques (sprinkler irrigation) for a better use of water.

SOCIAL AND ENVIRONMENTAL IMPACTS

The intensification of groundwater use since 1960, parallel to the deficit in natural aquifer recharge, has been translated into a drawdown of the aquifer level and a depletion of the Souss bed resurgences.

These phenomena have affected, in the first instance, traditional farmers because of the depletion of their water resources.

The depletion of these resources has caused farmers of the traditional sector to shift to the irrigated modern sector as labourers.

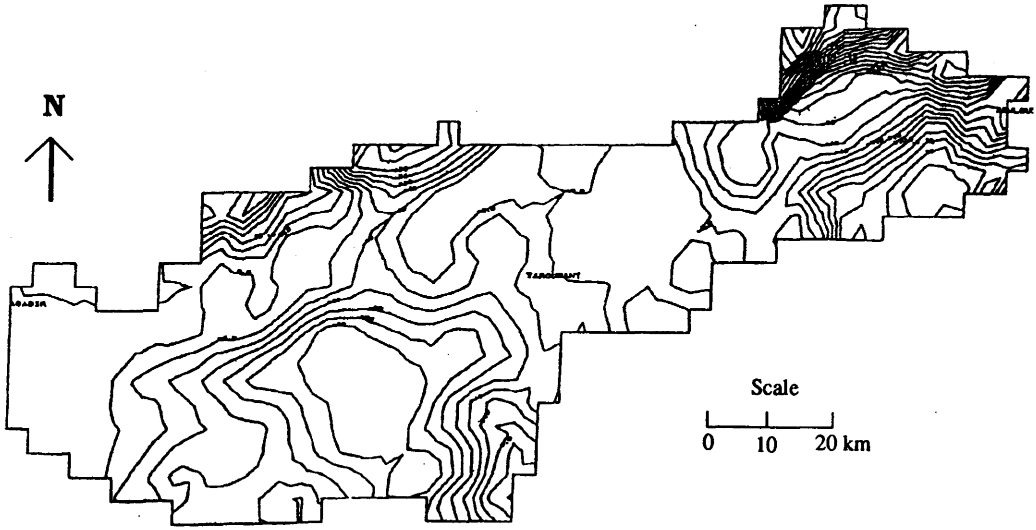


Figure 4: Difference of piezometric level in meters (1985-1967) in the Souss valley.

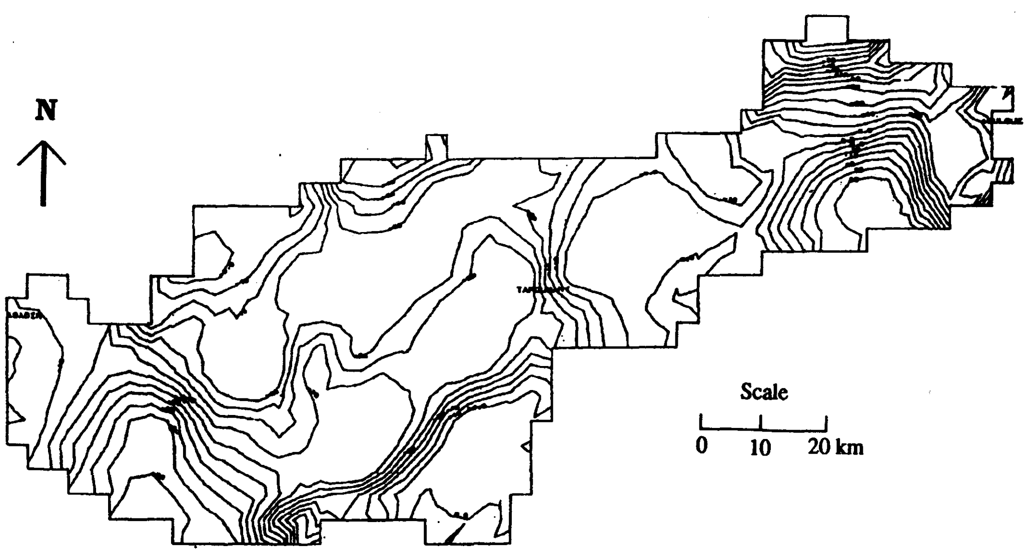


Figure 5: Difference of piezometric level in meters (1985-2030) in the Souss valley.

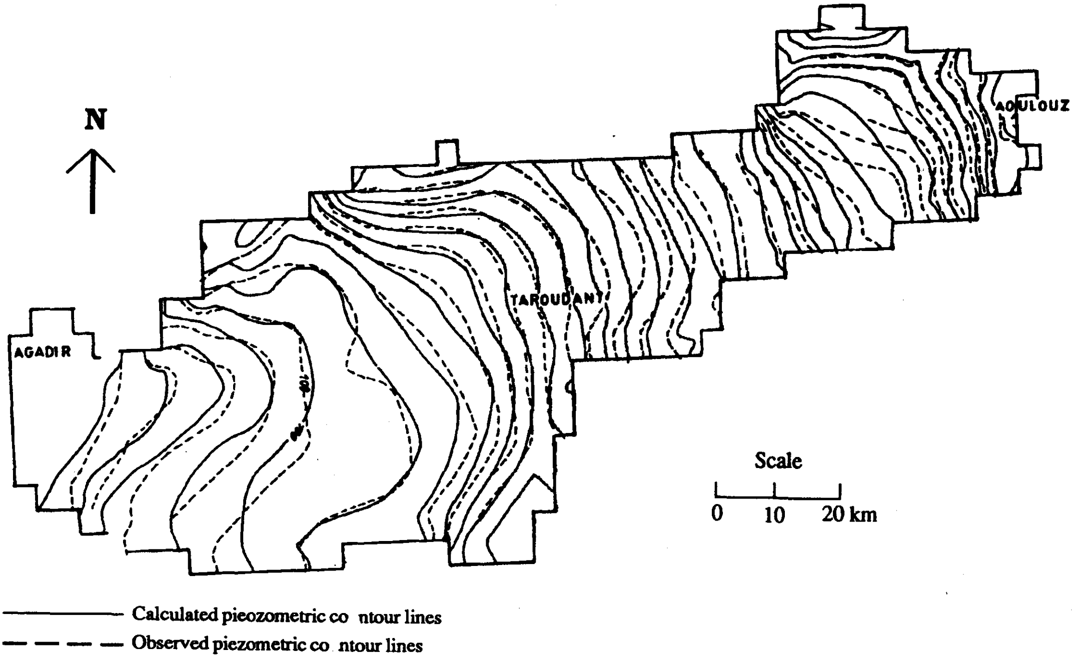


Figure 6: Comparison between observed and calculated piezometric contour lines in 1985, after Motor Columbus *et al.* (1990).

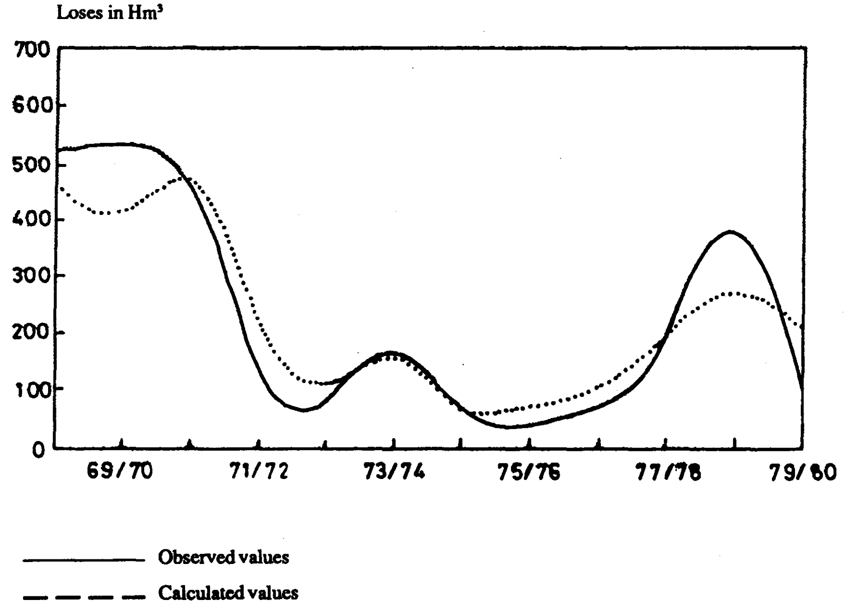


Figure 7: Comparison of water flowing to the ocean, after Motor Columbus *et al.* (1990).

In order to save this traditional sector its rehabilitation has been decided via the irrigation of 188,700 ha, supplied by 120 boreholes. Borehole depths vary between 80 and 140 m and the mobilized volume will be about 115 Mm^3.

The first part of a rehabilitation project covering 9,700 ha is already finished. It has consisted of the realization of 61 boreholes and 3 wells to mobilize 62 Mm^3. This first part will start operating in 1992.

The intensification of irrigation practices has also been accompanied by an increasing use of fertilizer and phytosanitary products. With a low performance in gravity irrigation, it is expected that the use of chemical products will increase in the future.

CONCLUSION

The intensification of water utilization observed until now has suffered from a lack of control and does not take into consideration the particular characteristics of the hydrology of the region, where the surface and groundwater resources are highly interdependent.

The social and economic development of the Souss region is still closely related to a rational utilization of the water resources and their conservation.

A strict planning of water use is urgently required to protect a region which plays a very dynamic role in the Moroccan economy:

(a) in the future it may be possible to protect the economy of this region by a maximum regularization of surface water, by constructing several reservoirs and allowing optimum aquifer recharge to ensure a reasonable level of the over-used aquifer storage,

(b) this is the equation which must be solved by those planning the use of water resources.

REFERENCES

Direction de la Région Hydraulique - BURGEAP. 1987. *Etudes des possibilités de Rècharge Artificielle de la Nappe du Souss à Partir d'un Barrage à Aoulouz.* Unpublished.

Motor Columbus-CID Coyne Bellier-Ingema. 1987. *Etude du Plan Directeur Intégré d'Aménagement des Eaux des bassins du Souss et Massa - Rapport Hydrogéologie.* Unpublished report.

Motor Columbus-CID Coyne Bellier-Ingema. 1989. *Etude du Plan Directeur Intégré d'Aménagement des Eaux des Bassins du Souss et Massa - Ressources en Eau - Rapport de Synthèse.* Unpublished report.

Motor Columbus-CID Coyne Belier-Ingema. 1990. *Etude du Plan Directeur Intégré d'Aménagement des Eaux des Bassins du Souss et Massa-Bilan Ressources Besoins.* Unpublished report.

THE EFFECTS OF OVEREXPLOITATION ON COASTAL AQUIFERS IN LEBANON, WITH SPECIAL REFERENCE TO SALINE INTRUSION

K. KHAIR, F. HADDAD & S. FATTOUH
Department of Geology, American University of Beirut, Lebanon.

ABSTRACT. Coastal aquifer overexploitation and bad management of natural water resources are becoming very common behaviors witnessed in areas with much water demand to balance their ever increased population needs. In Lebanon this is a critical problem encroaching most of its urban coastal centers already with population growth rates overcoming their delicate natural setting. Unfortunately, the civil war-crisis existing in the country since 1975 imposed damage on most of the potable water network and led to an unorganized and intensive exploitation of local aquifers. Simultaneously, ground water became increasingly saline, due to sea water intrusion, from 340 mg l^{-1} (1970-71) to 22000 mg l^{-1} in some wells in 1985. Hence this paper is to identify the controlling criteria of sea water intrusion to coastal aquifers mainly enhanced by the socio-economic effects, the geological characteristics of aquifers, and the fluctuating precipitation rates. Statistical projection of some selected wells and springs regarding their gradual salinity increase, monthly-wise and yearly-wise showed a sharp sea water intrusion trend. Therefore, unless an overall integrated system is innovated soon to hinder overexploitation and drilling activities, the current pessimistic status of underground water quality will never be overcome.

INTRODUCTION

Unfortunately, residential, commercial, agricultural, and industrial land-use in all the major Lebanese coastal cities Beirut, Tripoli, Saida, Sour, etc... has expanded randomly over many decades resulting in their erratic growth and notably their suburbs (Khawlie, 1986). On the other hand, the war-crisis dominating the country since 1975 (hopefully now ceasing for good) have also imposed great changes in population redistribution and urban expansion, which of course affected the water needs including the potable water network.

Historically, during the dry seasons of the year when the ground water was insufficient or not available, nearby rivers or springs were utilized. Thus the increasing demand for water and the ease of drilling for ground water in the complete absence of ground water pumping control, meant a worsening of the situation. At present and due to lack of public awareness about the fragility of the hydrogeological coastal regime, people drilled thousands of wells targeting underground aquifers in order to balance their water shortages.

In its balanced state, the underground fresh water has a summer-time level of only one meter above the sea water level. With intensive pumping from wells, required during dry times of the year, the cumulative drawdown around the boreholes caused salt water to intrude. This seems to have occurred before the twentieth century. In 1967- 1968 an attempt was made to increase the quantity of fresh water in certain areas artificially though rejuvenation. It proved to be a costly approach and may be was not done properly, therefore was not repeated (Lababidi *et al.*,1987). In the past and during spring time the ground water table used to rejuvenate to a level where the capacity of the aquifer, in spite of pumping , was sufficient until the end of summer. Nowadays salt water intrusion is very common in most Lebanese coastal ground water regimes. The coastal area is highly faulted thus permitting the easy channeling of more salty waters. Furthermore, the foundation levels of buildings in near shore areas reach 20 m, which is affecting critically the water table and clearly demonstrating urban problems. (Khawlie & Ghannam, 1987).

Hence, the purpose of this paper is to describe and understand the interactive current activities of the Lebanese urban centers - chaotically enlarged - that regulate the on-going deteriorating hydrogeological regime with respect to ground water overexploitation in order to pinpoint the occurred changes and the manner in which they are influenced by human actions.

METHODOLOGY

The fulfillment of this study was achieved by correlating the three main influencial parameters under such topics: population expansion and water demand, geology of the aquifers and precipitation rate yearly-wise and monthly-wise.

Needless to mention that population expansion in Lebanon is not unique but a part of that worldwide problem. Naturally, such a rapid expansion will go simultaneously with an increase in water demand among other essential needs. This will negatively unbalance the pumping status and unfortunately ensure more saline water encroachment. Moreover, the geological setting especially along coastal aquifers, can also play an important role in enhancing sea water intrusion. If the lithologies include karstified formations or unconsolidated deposits, as in the case of the Cenomanian and the Quaternary, salt water intrusion is aggravated in advance. In addition, any delay in the rainy season or any precipitation shortage, as is the trend at present, will inevitably deteriorate fresh water quality.

It is worth noting that the lack of statistical data between the early 70's and 80's is due to the prevailing war-crisis. Still, the study was backed up by 125 wells and 3 springs.

RESULTS AND DISCUSSION

The population of Lebanon has increased sharply over the last 40 years. Beirut, the capital city, is an example of a major metropolitan coastal center that has absorbed the bulk of the rural and urban migration. As a matter of fact, in less than a hundred years (1860-1950) its population increased at ratio of 1/15 (Table 1). (Gemayel, 1952; Stout, 1983; and Hariri, 1987).

Table 1: Population expansion of Greater Beirut Area.

Year	Population
1860	20,000
1912	120,000
1922	140,000
1935	220,000
1950	300,000
1970	938,940
1975	1,181,000
1982	1,250,000
1987	1,360,000

Figure 1 delineates the geographical expansion of Beirut through time. It is very obvious from this figure that population expansion has always targeted coastal zones rather than in-land areas. Moreover, migration into Beirut continued till 1982 to escape the deteriorating conditions in the South (Daouk *et al.*, 1985). Estimations indicate that its population will be approximately 1,700,000 in the year 2000. This means that Greater Beirut, today, accommodates almost one half of the 3-3.5 million country's population.

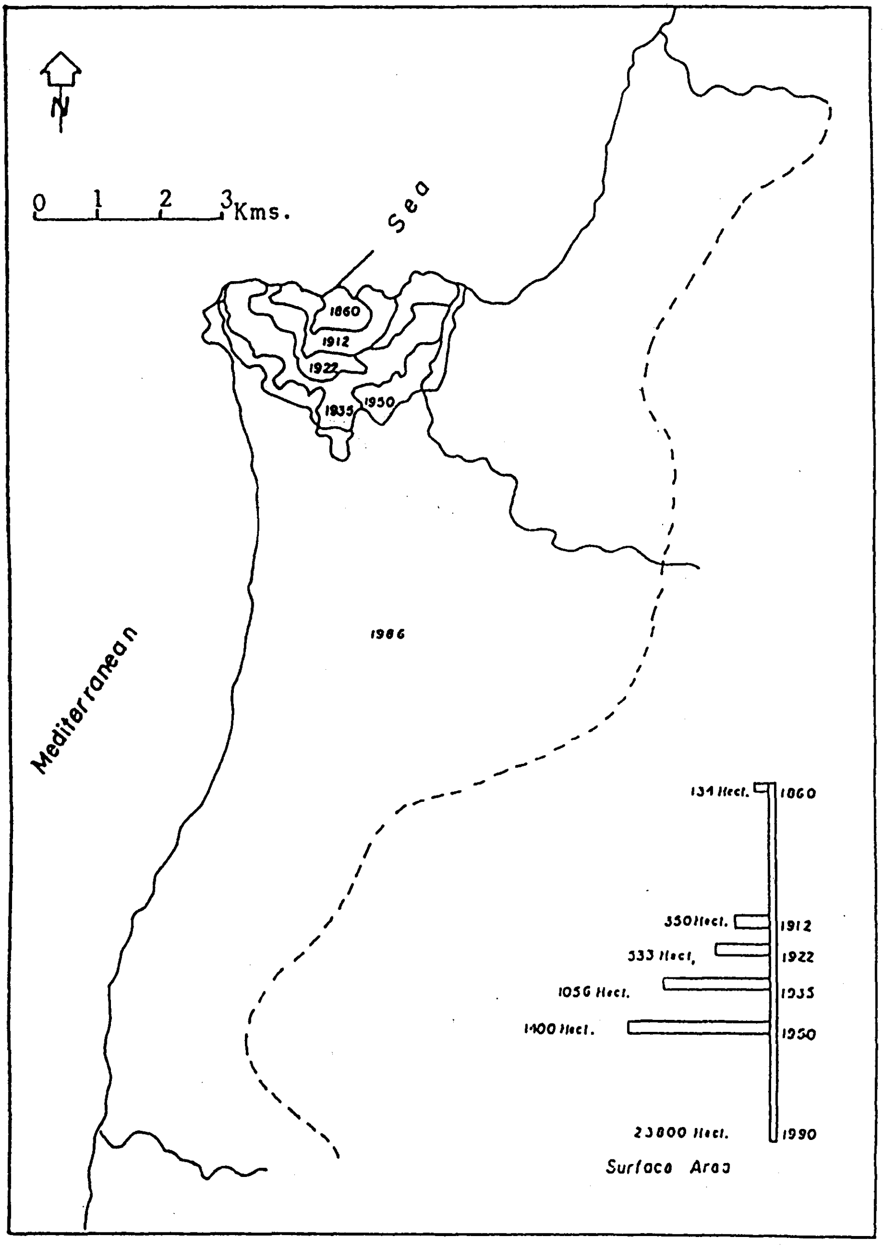


Figure 1: Geographical expansion plan for the city of Beirut (Gemayel, 1952; Khawlie, 1986).

From the above picture, a sharp increase in water demand is therefore highly expected. Unfortunately, a large proportion of the 285,000$m^3 day^{-1}$ of water supplied to Beirut and its suburbs is lost through leakage in the existing water distribution net-work (Lababidi *et al.*, 1987). In this respect, the projected water deficit in the Beirut area is estimated to reach about twenty million cubic meters per annum by the year 2000 (Daoud, 1973).

Because of the shortage in the public water supply needed for industry, agriculture and domestic uses, there has been a trend to accentuate private exploitation of ground water but unfortunately without management and control. As such, ground water is evidently contributing significant portions to the total water demand. It has been estimated that the number of wells drilled in Greater Beirut area till 1980 reached the staggering figure of about 3,000 (Daouk *et al.*, 1985) and now may exceed 10,000. This improper chaotic practice is already a common problem encountered in all Lebanese coastal cities. In fact, the number of water wells that have been sunk for the last three decades exceeds many times the total number of wells drilled since Lebanon came into existence (Khair *et al.*, 1989).

Recently, another problem has emerged in relation to ground water contamination, through those deep foundation levels of coastal buildings (10-20m) already reaching the water table level and affecting its quality. This is particularly critical as the underground fresh water has a summer time level of only one meter above that of sea water level. It is worth mentioning here that once sea water intrusion develops in a coastal aquifer, it is not easy to control for many reasons: the slow rate of ground water flow, the density differences between fresh and salt water and the flushing rate required. This contamination may take years to remove even if fresh ground water is made available again (Daoud, 1973).

There are other causes that aggravate the problem of sea water intrusion namely geology of the area and the variations in annual precipitation rates. Figure 2 is a simplified geologic map of the Lebanese coast. It is easily discerned from this figure that most of the coastal strip is of Cenomanian or Quaternary cover. The latter represents mostly unconsolidated highly porous and permeable deposits whereas the former constitutes the main aquifer of the coastal strip (Table 2). It is the second main aquifer of Lebanon following the Jurassic system.

Together the Cenomanian and the Quaternary have a thickness in the coastal areas ranging between 400m - 600m forming one water table aquifer whose deeper layers contain salt water (Baasiri *et al.*, 1986). Although natural infiltration to the above mentioned aquifer is about 300mm a year, the main discharge occurs by pumping water from the large number of wells of a flow ranging between 0.33 and 0.61 $m^3 s^{-1}$ (Baasiri *et al.*, 1986).

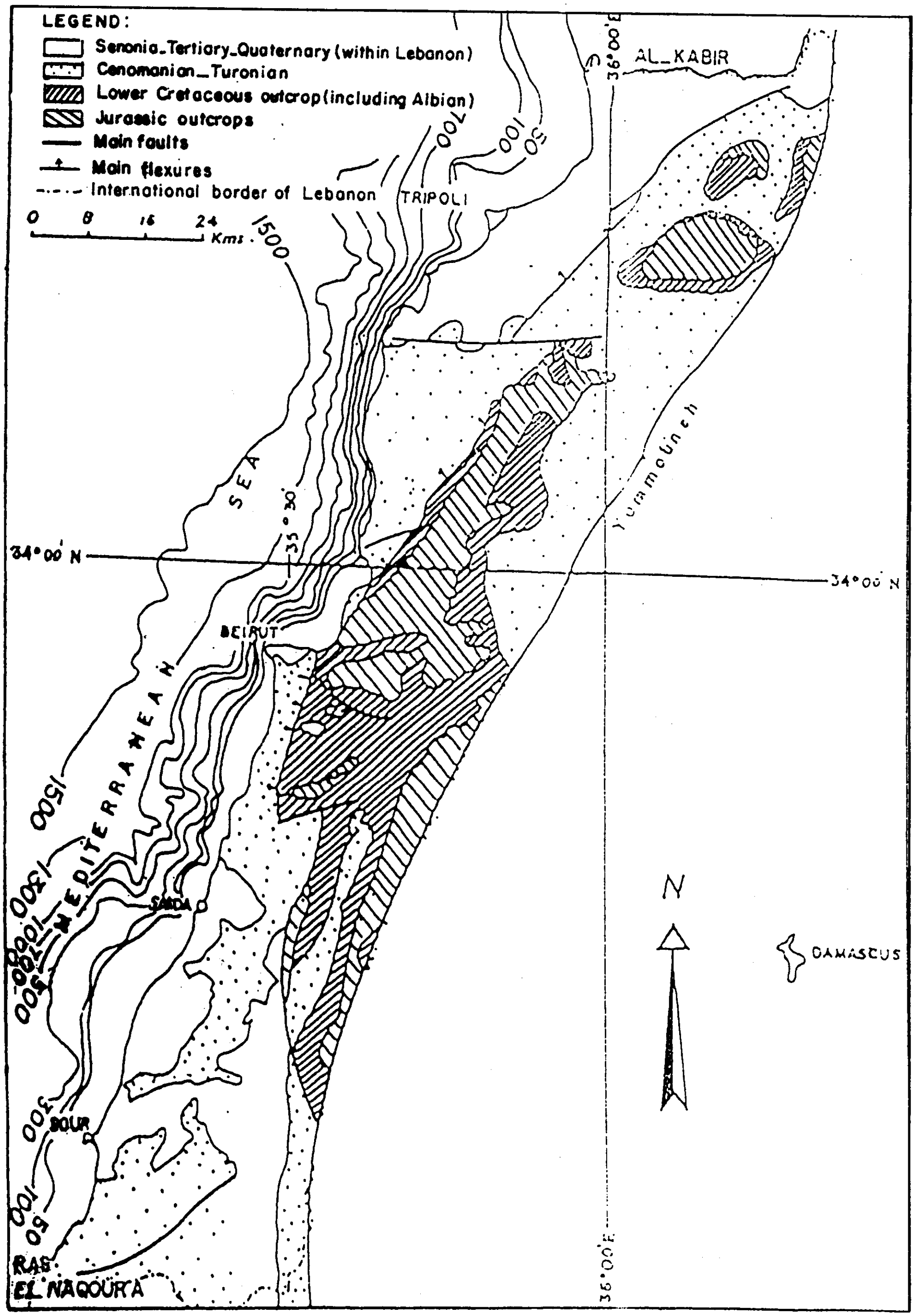


Figure 2: Simplified geological map of the Lebanese coastal strip.

Table 2: Comparative physical characteristics of major coastal aquifers. Compiled from: Daoud (1973), Baasiri *et al.* (1986) and Abbud & Aker (1986).

Period	Cretaceous	Quaternary
Formation(Age) & symbole	Cenomanian-C_4	Quaternary-Q
Transmissivity(T) m^3s^{-1}	2	10^{-2} - 10^{-3}
Storage coefficient(S) or effective porosity %	1-3	10-15
Lithology	Massive to thin bedded limestone, dolomitic limestone and Marl	Coastal or alluvial loose deposits
Thickness	700 m	Variable

In addition, the presence of certain geological features such as faults, fissures and joints would eventually enhance sea water infiltration, especially if these discontinuities run perpendicular to the shoreline Daouk *et.al.,* 1985).

In as much as geology plays an important role in accentuating salt water intrusion, so , also, does the fluctuation in precipitation. Normally, there is a reciprocal relationship between precipitation and salt water intrusion: as precipitation decreases salt water intrusion gets more effective (Abbud & Aker, 1986). In this study, interpretations are based on the chlorideconcentration in the form of Cl^- ion water. According to the International Standards for Drinking Water the highest desirable level for human drinking is 200 mg l^{-1} and the maximum permissible level is 600mg l^{-1}(Daoud, 1973). As such, it was found out that approximately 85-95% of the coastal wells are partially or completely brackish due to salty water. In this study, due to space limitation and nature of data, the chloride concentrations for most of the 125 wells are averaged as follows: 340 p.p.m. (1970-71), 1200 p.p.m.(1979) and 4270 p.p.m. (1985) (Daouk et al., 1985). Figure 3 shows some data from selected wells reflecting the monthly change of Cl^- ion concentration over a period of three years (1967-1969). Almost all the curves reflect a sharp increase in Cl^- concentrations during the fall of September, October and November, specially for 1968; because September marks essentially the end of the dry season, it is expected that the concentrations of Cl^- ions are high as no infiltration occurred since the end of April. This concentration will start decreasing as more rain water infiltrates. Moreover, September denotes the beginning of winter preparations, which means an increase in the demand for domestic water.

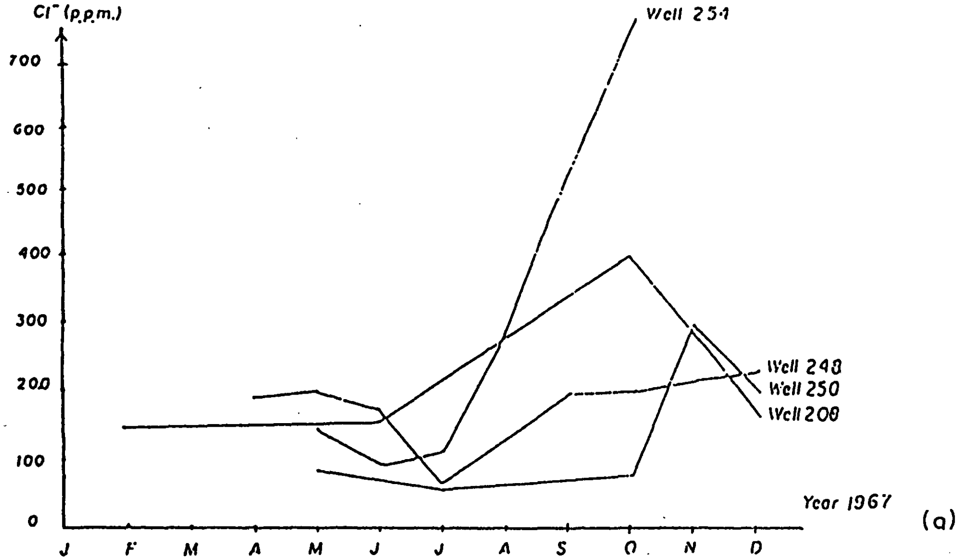


Figure 3 (a): Some data from selected wells, located in Beirut area, showing the Cl^- variation over 3 years: 1967.

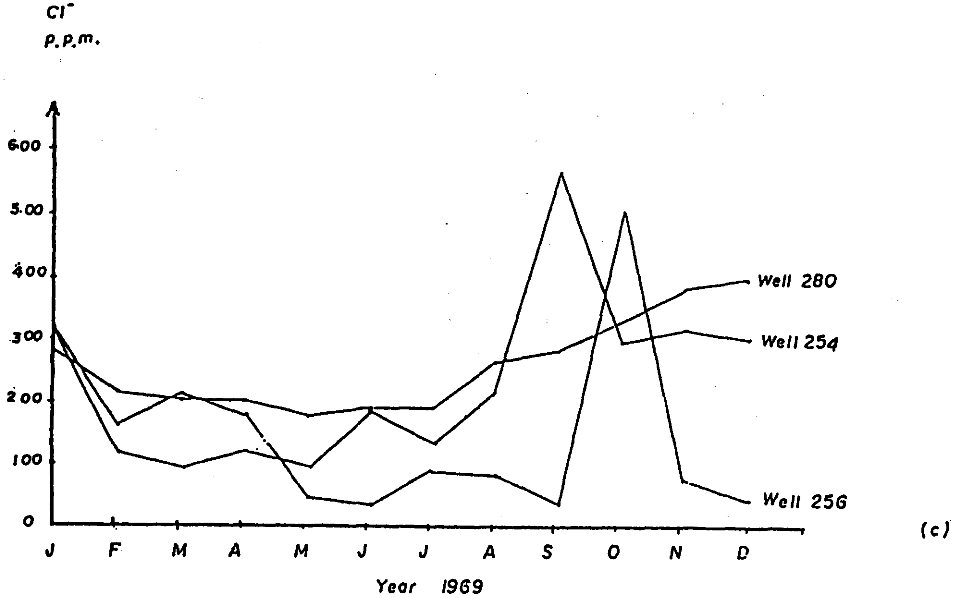


Figure 3 (c): Some data from selected wells, located in Beirut area, showing the Cl^- variation over 3 years: 1969.

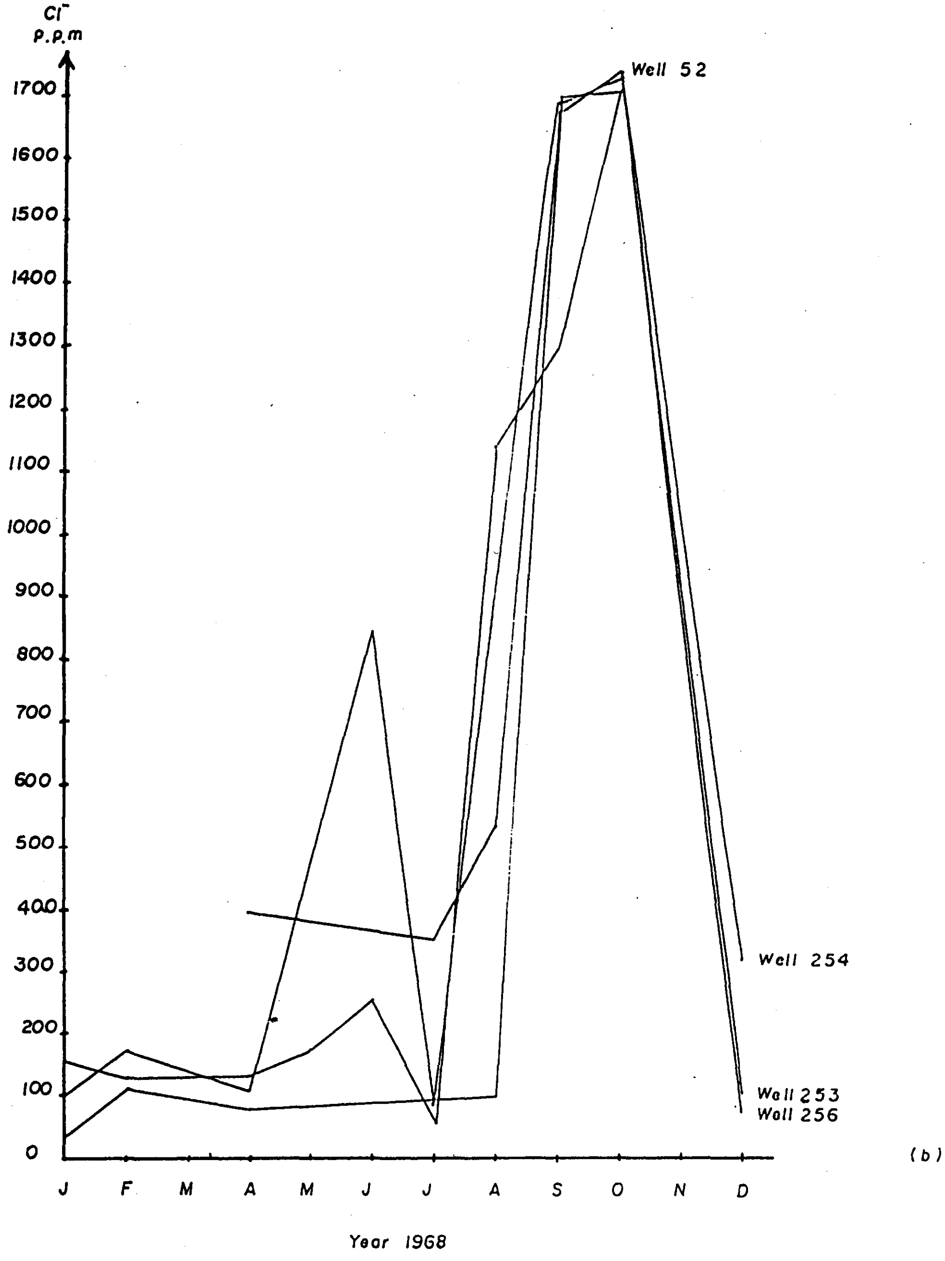


Figure 3 (b): Some data from selected wells, located in Beirut area, showing the Cl^- variation over 3 years: 1968.

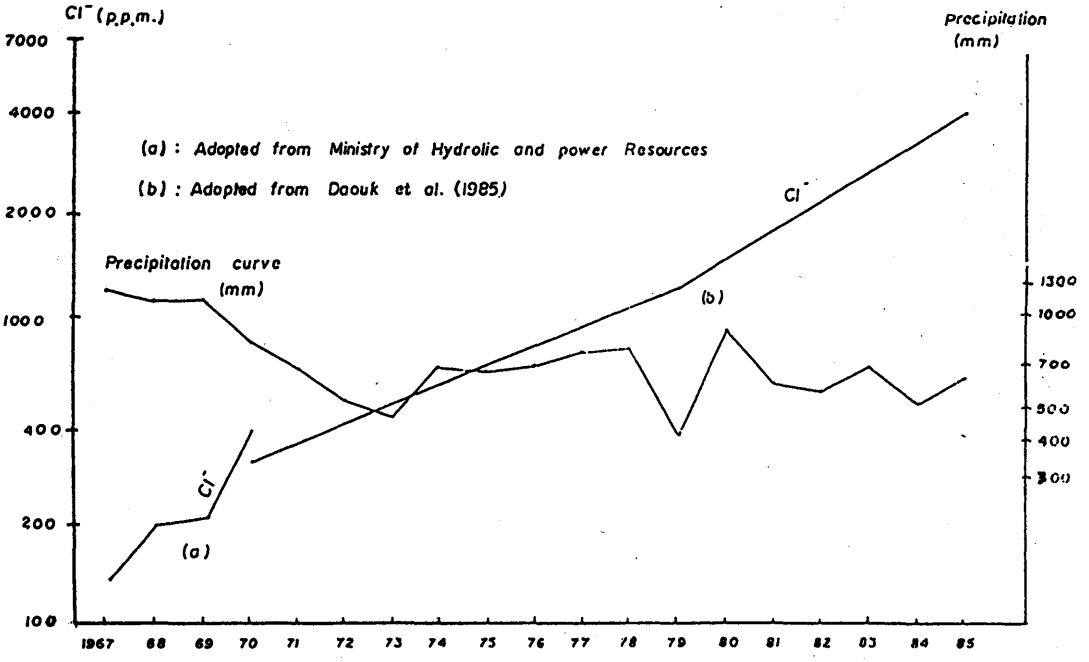


Figure 4: Some data from selected wells showing Cl⁻ variation between 1967 and 1985 in relation to precipitation rate.

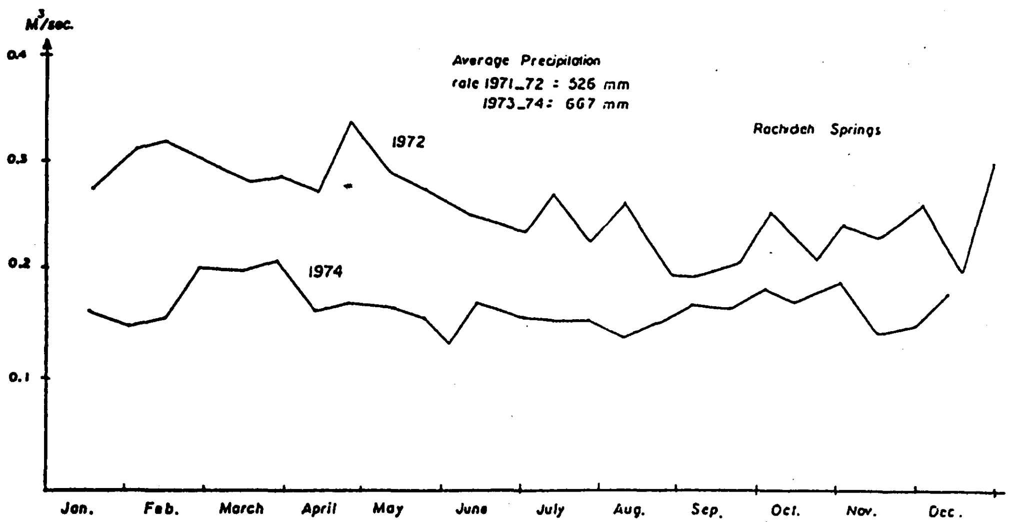


Figure 5: Effect of aquifer overexploitation on coastal Rachidieh springs.

Figure 4 shows average data from selected wells reflecting Cl^- concentration change between 1967 and 1985 as it relates to the precipitation rate. The inverse picture between the chlorine and precipitation curves is well defined, and also noticeable is the overall increasing salinity trend emphasizing the difficulty of flushing sea water.
In spite of the average annual precipitation over the Lebanese territory, which is about 9700 $M.m^3$ (Khair *et al.,* 1989), where overpumping took place it proceeded at faster rates to the extent of affecting the discharge of nearby springs.

Figure 5 clearly indicates a marked decline from 1972 to 1974 in the debit of Rachidieh springs, this is in spite of the increased average precipitation rate, from 526 to 667 mm, in the respective replenishing periods. A similar behavior was noticed for the nearby Ras El Ain spring (Sour).

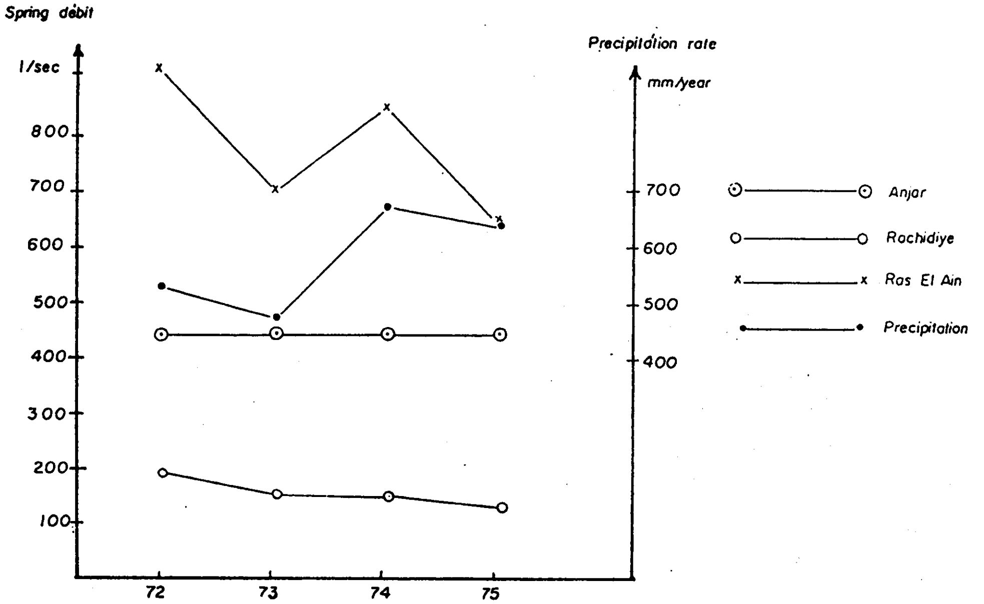


Figure 6: Effect of precipitation rate and aquifer overexploitation on different natural springs.

Figure 6 shows an over-all diminishing trend, for the period 1972-1975, in the debits of coastal springs mentioned above due to the increased number of wells. The exception to this is Ras El-Ain spring from 1973 to 1974, affected by a marked increase in the precipitation rate. The figure also indicates a relatively stable debit of the mountainous Anjar spring, which is affected neither by overpumping nor by precipitation rate. It is worth noting that the increased pumping of water from private wells is taking place at the expense of natural springs debit (public water use), thus creating many socio-economic problems.

RECOMMENDATIONS

Generally speaking, most data from springs and wells obviously show an overall increasing salinity trend. Hence, appropriate recommendations encompass essentially two main domains: statistical and executive.

(a) . Statistical

- Updating the number of existing wells and quantifying water pumped
- Estimating population distribution and water needs
- Delineating potential subbasins for future exploitation
- Carrying out a detailed hydrogeologic study for the entire Lebanese coast
- Selecting the optimum annual water yield from aquifers without exceeding the safe yield or allowing sea water intrusion, as based on recharge and pumping data
- Preparing and implementing a ground water monitoring plan at a national level

(b) . Executive

- Ceasing any new additional coastal-drilling wells
- Decreasing overexploitation activities to partially restore or stabilize water quality
- Drilling in-land wells of higher yield under proper scientific control
- Providing hydraulic barriers by recharging wells or by creating a coastal trough by pumping wells
- Considering alternative surface water supplies
- Improving municipal water supply
- Future planning to get water from deeper horizons (Aptian and/or Jurassic)

CONCLUSIONS

In this study, the various inputs necessary for obtaining criteria of overexploitation problems and causes clearly require functional specific actions and capabilities rather than exposing the subject matter.

Today a prerequisite would be, first, a rejuvenation or maintenance of the water potable net-work (40-60% already demolished) to control water leakages and losses (Ministry of Public Work and Transportation). Second, to obtain legal backing for a profitable plan to procure water from distant areas.

Initially, in a small country like Lebanon awakened from a devastating war, governmental policies and legislations are a must, especially to accomplish the executive part whereas the statistical data could be fulfilled through private institutions. In both cases, cooperation, help and information exchange between the public and private sectors are always required to attain an ultimate elimination in the long run or at least to decelerate this imminent existing danger, - sea water intrusion - , in the short run.

ACKNOWLEDGEMENT

Thanks to the Faculty of Arts and Sciences (F.A.S.) of the American University of Beirut, that has awarded financial assistance. Also thanks to the Ministry of Hydraulic and Power resources and to the Litani Water-Work Directorate.

REFERENCES

Abbud, M., & Aker, N. 1986. The study of the aquiferous formations of Lebanon through the chemistry of their typical springs. Leb. Sci. Bull.,2:2;5-20.

Baasiri, M., Shayya, W., Kaysi, S. , & Aker, N. 1986.Numerical modelling of ground water basins in Lebanon: a case study. Ground water in arid and semi-arid regions - Conference, Amman, May 5-8; 24.

Beydoun, Z.R. 1977. *The Levantine countries. The geology of Syria and Lebanon.* The ocean basins and margins, Vol. 4A,319-353, ed. by Nair, A.E.M., Kanes, W.H. and Stehli, F.G., New York, Plenum Corp.

Daoud, A. 1973. *Ground water recharge in the Beirut Area.*M.S. Thesis, american University of Beirut, Agriculture Dept., Beirut, (unpub).

Daouk, W., Lababidi, H., Dimashkiya, M., Masri, B., Ghandour, F. , Sarmin, M., Itani A., Shatila, A. & Shihab, M. 1985. *Sea water intrusion into coastal aquifers of Ras Beirut.* American University of Beirut, (Unpub).

Gemayel, M. 1952. *Les eaux de Beyrouth.* Imprimerie Saint Paul, Beyrouth.

Hariri, F.d. 1987. *Lebanon at present and its needs for rehabilitaiton and development.*Rept., Beirut.

Khair, K.,Aker, N. & Zahruddine, K. 1989.*Characterization and subdivision of hydrogeological units of Lebanon.*American University of Beirut, Geology Dept., Beirut, (Unpub).

Khawlie, M.R. 1986. Land-use planning for the development of a disrupted urban center: Beirut, Lebanon. *Intl. Jour. for Devel. Techn.*,vol. 4; 267-281.

Khawlie, M.R., & Ghannam, J. 1987. Land suitability and geotechnical studies for the development of Greater Beirut Area - Lebanon. *Geol.Soc. of Hong Kong Bull.,* No. 3; 97-114.

Lababidi, H., Shatila, A., & Acra, A. 1987. The progressive salination of ground water in Beirut, Lebanon. *Intern. J. Environmental Studies,* vol. 30; 203-208.

Ministry of Hydraulic and Power Resources, UNESCO district, Beirut, Lebanon.

Ministry of Public Work and Transportation, Chayah, Beirut, Lebanon.

Stout, S. 1983. *A health plan for Greater Beirut 1983.* American University of Beirut, School of Medicine, Rept.

OVEREXPLOITATION PROBLEMS IN SPAIN

B. LOPEZ-CAMACHO & A. SANCHEZ-GONZALEZ
Servicio Geológico de la Dirección General de Obras Hidráulicas
Avda. de Portugal, 81 - 28071 Madrid, Spain
A. BATLLE
Eptisa
Arapiles, 14 - 28015 Madrid, Spain

ABSTRACT. Groundwater overexploitation problems in Spain have been identified on the basis of a global study on delimitation of hydrogeological units, which includes the Peninsula and Balearic Islands, and on the last data known on exploitation and renewal of ground water resources.

Of the 369 units defined, overexploitation related problems have been detected in 74 of them, 41 being the number of those in which a persistent imbalance between recharge and extraction rates has been found. The resulting global deficit amounts to about 660 hm^3 $year^{-1}$, i.e. 13% of total ground water abstraction.

INTRODUCTION

The Spanish Water Law established that the Basin Authority can declare a determinate aquifer as 'overexploited or in danger of being it' (Hydraulic Public Domain Regulations, Section 171). This section sets the definition of the term 'overexploitation':

> 'An aquifer shall be deemed to be overexploited, or in danger of being so when the water uses generated by the said aquifer are in danger of immediate extinction as a result of carrying out annual withdrawals exceeding, or very close to, the average volume of annual renewable resources, or causing a serious degradation of the water quality'.
>
> 'The danger of overexploitation may also be declared when the quantity of the withdrawals carried out, referred to the renewable resources, generates an evolution of the aquifer which endangers the long term subsistence of the water uses'.

Given the composition of the Basin Authority Board and the administrative effects of the declaration, it is obvious that the latter is a sort of political decision, to be adopted considering the aquifer circumstances and the economic-social values of the water in the corresponding region.

The discretionary administrative margin is certainly wide according to the previous definition and so it has been understood by Basin Authorities, which have only formalized, to the present, 13 provisional declarations.

HYDROGEOLOGICAL UNITS DELIMITED

The legal definition of hydrogeological units is a responsibility of Basin Authorities, within the formal Document called the Basin Hydrological Plan. To facilitate this task, the Servicio Geológico (1988) of the Ministry of Public Works and Transport and the Instituto Tecnológico GeoMinero de España, with the colaboration of the Hydraulic Administrations of Cataluña and Balearic Islands, in 1988 made an exhaustive analysis of the existing basic hydrogeological information which resulted in the provisional definition of 369 hydrogeological units for the spanish territory, except the Canary Islands.

Table 1: Hydrogeological units defined. Summary of results.

BASIN	NUMBER OF DEFINED UNITS	SURFACE (km^2)	RECHARGE ($hm^3\ year^{-1}$)	PUMPING ($hm^3\ year^{-1}$)	PUMPING/RECHARGE (%)
NORTE	24	7,078	2,974	53	1.8
DUERO	21	54,834	1,610	390	24.2
TAJO	12	16,861	1,630	165	10.1
GUADIANA	12	12,935	792	729	92.0
GUADALQUIVIR	64	14,825	2,131	455	21.3
SUR	47	5,187	1,064	468	44.0
SEGURA	36	9,436	549	466	84.9
JUCAR	52	24,782	3,505	1,470	41.9
EBRO	45	16,770	2,923	209	7.1
PIRINEO O.	30	6,463	1,036	447	43.1
BALEARES	35	3,618	585	283	48.3
TOTAL	369	172,257	18,780	5,048	26.8

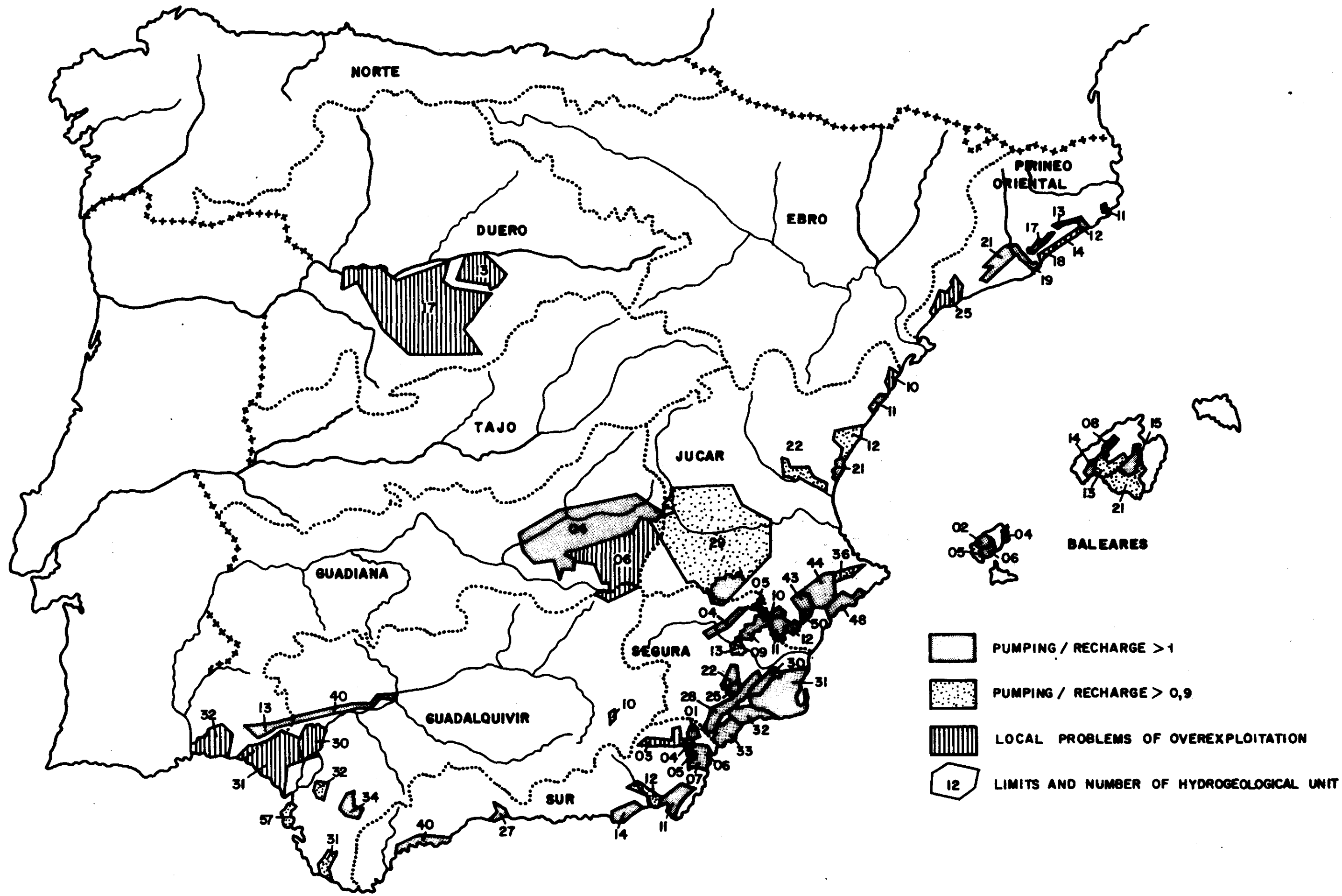


Figure 1: Location of overexploitation problems.

Table 1 is a summary of results by administrative basin, giving a global idea of ground water occurrence and exploitation in Spain. The 369 units cover 172,000 km^2 of permeable land surface, i.e. a third of the territory.

Mean annual recharge over all units is 18,780 hm^3, which includes infiltration of precipitation, surface runoff percolation and irrigation excess. Total water abstraction is about 5,050 hm^3 year^{-1}, i.e. 27% of the recharge. The pumping rate is related to the recharge as an index of exploitation within each basin. The Guadiana basin shows the highest value of this ratio (0.9), followed by the Segura (0.85) and another four mediterranean basins with percentages which vary between 0.41 and 0.48.

OVEREXPLOITATION PROBLEMS

Table 2 contains the relevant characteristics of hydrogeological units in which overexploitation problems have been detected. Problems refer to a negative overall balance between abstraction and recharge, to excessive space concentration of pumping, or to deterioration of water quality as a more frequent cause. These units spread over more than 22,000 km^2 (Fig. 1) over which total recharge and pumping amount to 2,520 hm^3 year^{-1} and 2,860 hm^3 year^{-1} respectively (see Table 3).

UNITS WITH A NEGATIVE BALANCE

The pumping versus recharge ratio is greater than one in 41 units out of the 74 listed (Table 4). The overexploitation deficit is evaluated as 660 hm^3 year^{-1}, updating previous estimations of 600 hm^3 year^{-1} (Batlle *et al.*, 1989).

Table 2: Hydrogeological units with overexploitation problems.

BASIN	HYDROGEOLOGIC UNITS N° DENOMINATION	SURFACE km^2	RECHARGE hm^{3}year^{-1}	PUMPING hm^{3}year^{-1}	P/R	DEFICIT hm^{3}year^{-1}
02 DUERO	13 Páramo de Cuellar	548	38	24	0.63	-
04 GUADIANA	04 Mancha occidental	5,000	340	580	1.70	240
	06 Campo de Montiel (alto Guadiana)	876	86	35	0.41	-
	12 Ayamonte-Huelva	600	98	45	0.46	-

Table 2 (cont.): Hydrogeological units with overexploitation problems.

BASIN	HYDROGEOLOGIC UNITS Nº	DENOMINATION	SURFACE km²	RECHARGE hm³year⁻¹	PUMPING hm³year⁻¹	P/R	DEFICIT hm³year⁻¹
05 GUADALQUIVIR							
	07	Cúllar-Baza	120	4	3	0.75	-
	12	Guadix-Marquesado	310	22	18	0.88	-
	14	Bédmar-Jódar	14	1.7	1.7	1.00	-
	17	Jaén	10	2.8	2.7	0.96	-
	43	Sª de Estepa	55	7	4	0.57	-
	49	Niebla-Posadas	280	18	28	1.55	10
	50	Aljarafe	350	28	14	0.50	-
	52	Lebrija	75	7	6	0.86	-
	54	Arcos-Bornos-Espera	63	7	7	1.00	-
	57	Rota-Sanlúcar-Chipiona	90	16	15	0.94	-
	61	Vejer-Barbate	145	35	30	0.85	-
06 SUR							
	01	El Saltador	60	4	3.5	0.77	-
	05	Ballabona-Sª Lisbona	45	2	6.2	3.10	4.2
	06	Bajo Almanzora	20	3	3	1.00	-
	07	Bédar-Alcornia	14	1	3.6	3.60	2.6
	11	Campo de Nijar	315	17	18	1.06	1
	12	Andarax-Almería	318	20	28	1.40	8
	14	Campo de Dalías	330	92	113	1.20	21
	20	Carchuna-Castellferro	8	4	3	0.75	-
	22	Río Verde	5	11	9	0.81	-
	27	Río Vélez	20	33	27	0.82	-
	40	Marbella-Estepona	80	26	23	0.88	-
07 SEGURA							
	02	Hellín-Tobarra	265	1.5	9	6.00	7.5
	05	Jumilla-Villena (08.35)	80	7	38	5.42	31.0
	06	El Molar	260	3	7	2.33	4.0
	09	Ascoy-Sopalmo	276	5	55	11.00	50.0
	10	Carche-Salinas (08.42)	90	4	15.5	3.89	11.5
	11	Quibas (08.51)	102	2.5	13	5.20	10.5
	12	Crevillente (08.52)	40	2	15	7.50	13.0
	22	Sª Espuña	75	4	8	2.00	4.0

Table 2 (cont.): Hydrogeological units with overexploitation problems.

BASIN	HYDROGEOLOGIC UNITS N° DENOMINATION	SURFACE km²	RECHARGE hm³year⁻¹	PUMPING hm³year⁻¹	P/R	DEFICIT hm³year⁻¹
07 SEGURA						
	25 Yéchar	28	0.3	3.5	11.66	3.2
	28 Valle del Guadalentín	200	29	105	3.55	76.0
	29 Sª Carrascoy	112	0.8	5.6	7.09	4.8
	30 Cresta del Gallo	36	0.7	2.9	4.14	2.2
	31 Campo de Cartagena	1,390	32.5	75	2.30	42.5
	32 Mazarrón	244	1.8	17.8	9.88	16.0
	33 Aguilas	126	1.3	10	6.92	8.7
	34 Cuchillo-Cabras	675	18.8	28.3	1.50	9.5
08 JUCAR						
	10 Vinaroz-Peñiscola	88	79	53	0.67	-
	11 Oropesa-Torreblanca	55	24	29	1.20	5
	12 Plana de Castellón	462	190	170	0.89	-
	21 Plana de Sagunto	125	50	70	1.40	20
	22 Liria-Casinos	475	95	86	0.90	-
	29 Mancha Oriental	3,300	340	330	0.88	-
	36 Yecla-Villena-Benejama	325	25	32	1.28	7
	38 Gandía-Denia	240	105	88	0.83	-
	41 Peñarrubia	44	4	11	2.75	7
	43 Argueña-Maigmo	125	8	11	1.37	3
	44 Barrancones-Carrasqueta	200	9	10	1.11	1
	48 Orcheta	120	6	11	1.83	5
	50 Sierra del Cid	60	1.5	7	4.66	5.5
10 PIRINEO ORIEN-TAL	10 Aubi	5	2.5	1.9	0.76	-
	11 Ridaura	8	4.5	4.5	1.00	-
	10 Tordera Baix	31	30	30	1.00	-
	13 Tordera Mig y Alt	25	8.7	8	0.92	-
	14 Maresme	80	68	45	0.66	-
	17 Cubetas Besós	30	19.5	21	1.08	1.5
	19 Baix LLobregat	120	133	139	1.04	6
	21 Penedés	297	5	7.2	1.44	2.2
	25 Camp de Tarragona	396	89	61	0.67	-

Table 2 (cont.): Hydrogeological units with overexploitation problems.

BASIN	HYDROGEOLOGIC UNITS Nº DENOMINATION	SURFACE km^2	RECHARGE hm^3year^{-1}	PUMPING hm^3year^{-1}	P/R	DEFICIT hm^3year^{-1}
11 BALEA-RES	08 S'Estremera	44	12	13.4	1.12	1.4
	13 Na Burguesa	55	5	7.1	1.42	2.1
	14 Llano de Palma	370	84	69	0.82	-
	15 Sierras Centrales	87	5	6	1.20	1
	21 Lluchmajor-Campos	615	62	53	0.85	-
	02 San Antonio	70	4.2	7.2	1.60	3
	04 San Carlos	60	2.5	3.5	1.40	1
	05 San José	74	2	1.9	0.95	-

Table 3: Overexploitation problems. Summary.

BASIN	SURFACE km^2	RECHARGE hm^3year^{-1}	PUMPING hm^3year^{-1}	DEFICIT hm^3year^{-1}
DUERO	548	38	24	-
GUADIANA	6,476	524	660	240
GUADALQUIVIR	1,512	148.5	129.4	10
SUR	1,215	213	237.3	36.8
SEGURA	4,499	114.2	408.6	294.4
JUCAR	5,619	936.5	908	53.5
PIRINEO	992	360.2	317.6	9.7
BALEARES	1,490	184.7	174.6	14.0
TOTAL	22,351	2,519.1	2,859.5	658.4

Table 4: Units with a negative balance. Summary.

BASIN	UNITS WITH NEGATIVE BALANCE		RECHARGE	PUMPING	DEFICIT $year^{-1}$	
	Nº	SURFACE km^2	$hm^3 year^{-1}$	$hm^3 year^{-1}$	TOTAL hm^3	UNIT mm
NORTE	0	0	-	-	0	0
DUERO	0	0	-	-	0	0
TAJO	0	0	-	-	0	0
GUADIANA	1	5,000	340	580	240	48
GUADALQUIVIR	1	280	18	28	10	36
SUR	5	1,022	132	169	37	36
SEGURA	16	4,499	114	409	294	62
JUCAR	8	1,054	127	181	54	51
PIRINEO	3	447	157	167	10	22
BALEARES	7	431	37	51	14	32
TOTAL	41	12,733	925	1,585	659	51

UNITS FORMALLY DECLARED AS OVEREXPLOITED

Only 13 hydrogeological units have been provisionally declared as overexploited since 1986, affecting a total of 9000 km^2. Their 'deficit' is 460 hm^3 $year^{-1}$, approximately 70% of the present total (Table 5).

The provisional declaration is the first step of a long legal and administrative process which basically requires the formulation of a management plan for the aquifer, elaborated with the participation of representatives of the water users. After the plan has been approved, the aquifer is definitely declared as overexploited and planned policies and measures become compulsory.

Table 5: Units with a provisional declaration.

BASIN	HYDROGEOLOGIC UNIT N°DENOMINATION	SURFACE km²	RECHARGE hm^3year^{-1}	PUMPING hm^3year^{-1}	DEFICIT hm^3year^{-1}
GUA-DIANA	04 Llanura Manchega	5,000	340	602	262
	06 Campo Montiel	876	126	35	-
	12 Ayamonte-Huelva	600	98	45	-
GUADAL QUIVIR	50 Aljarafe	350	28	14	-
SUR	01 El Saltador	60	4	3.5	-
	11 Campo de Nijar	315	16.5	17.5	1
	12 Andarax-Almería	318	20	28	8
	14 Campo de Dalías	330	92	113	21
SEGURA	05 Jumilla-Villena	80	7	38	31
	09 Ascoy-Sopalmo	276	5	55	50
	12 Crevillente	40	2	15	13
	28 Valle Guadalentín	700	29	103	74
	30 Cresta del Gallo	56	0.7	2.9	2.2
	TOTAL	9,001	768.2	1,071.9	462.2

REFERENCES

Batlle, A., García-Berrio, F., López-Camacho, B., Octavio de Toledo, F., Sánchez, A. & Vicens, J.M. 1989. Unidades hidrogeológicas con problemas de sobreexplotación en el territorio peninsular e Islas Baleares. In: *La Sobreexplotación de Acuíferos*, A. Pulido *et al.* (eds), Asoc. Intern. Hidrogeólogos (Grupo Español)-AEHS, Madrid; 3-19.

Servicio Geológico. 1988. Delimitación de las Unidades Hidrogeológicas del Territorio Peninsular e Islas Baleares y Síntesis de sus Características. *Informaciones y Estudios*, no. 52. Madrid.

PROBLEMS OF SALINIZATION IN MZI VALLEY AQUIFER (LAGHOUAT, ALGERIA)

O. MIMOUNI & M. CHETTIH
Department of Hydrogeology, University of Algiers (U.S.T.H.B.)
B.P. 32. El-Alia Bab-Ezzouar, Algiers
A. TADJ
Direction Hydraulique de la Wilaya
Laghouat-(DHW), Algeria

ABSTRACT. The use of the Mzi valley groundwater resources for Laghouat, a city of 250,000 inhabitants in southern Algeria at the edge of the Sahara desert, is limited not only by low reserves but also by decreasing quality.

As a result of severe climatic conditions and the particular geological environment, groundwater aquifers intersect the surface (naturally) as ponds with considerable salt content. This salty water could be the source of contamination when modifications to dynamic equilibrium take place, especially in connection with pumping.

REGIONAL GEOLOGY

The Mzi valley is a 300 km^2 basin located west of Laghouat, bounded to the north by the saharian platform, the dayas, and to the east by the Kabeg ponds.

Geologically the basin was formed by the combination of two phenomena:

(a) regressive erosion from the base level chott of south Aurès which was subsident until a recent period (Villafranchian);
(b) tectonic vertical deformation which explains the strong topographical and hydrological deformations.

Sedimentary series of the basin are of Mesozoic, Cenozoic and Quaternary age. Triassic formations outcrop along local dislocations. A short stratigraphic description can be given as follows (Fig. 1):

(a) Jurassic formations are seen in the center of an anticline of NE-SW axis (Djebel Lazreg and Djebel Ain Mahdi). Recent stratigraphic studies (Abed & Herkat, 1982) show four series:

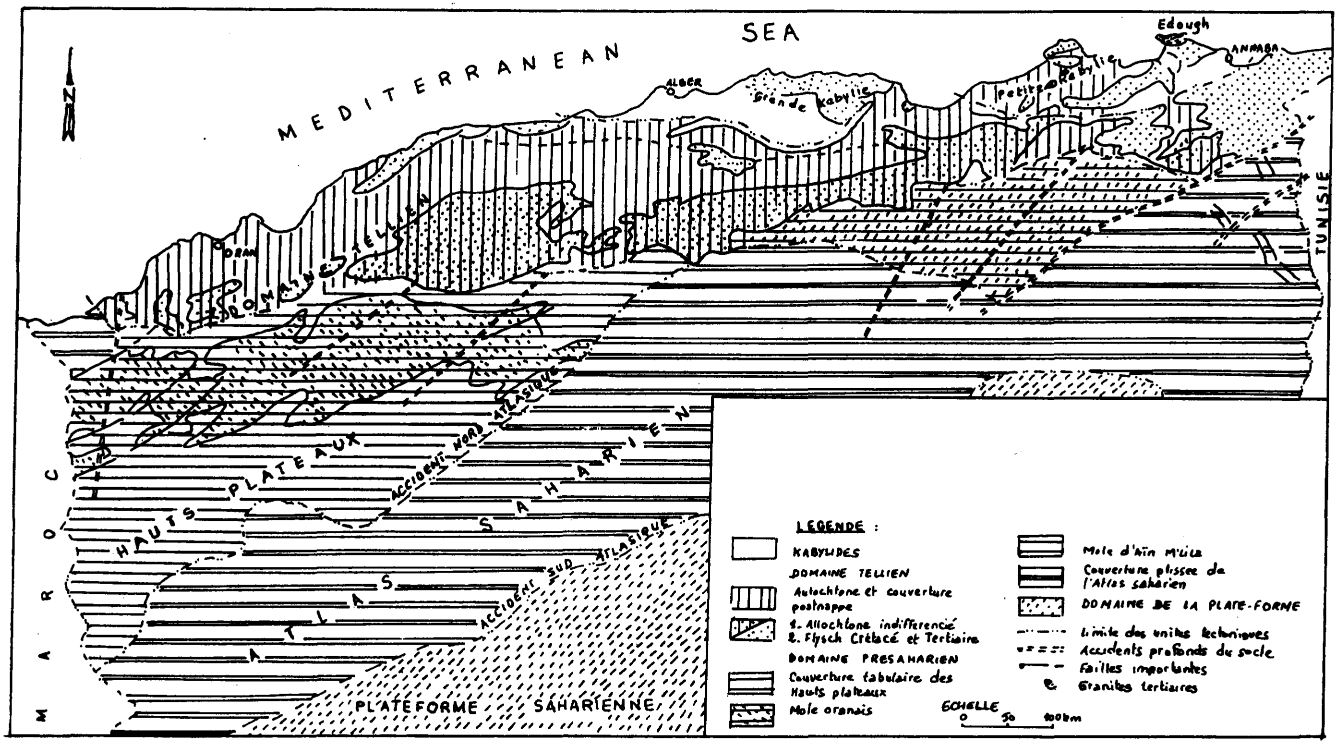


Figure 1: Geological Map.

(i) El Bayadh series (Bathonian and Callovo-Oxfordian) with:
- 400 m of silty clays
- carbonated, micaceous pyritaceous silty clays
- white sandstones with brachiopods.

(ii) El Brezina series (Kimmerdjian), subdivided into two reef subseries with an intermediate zone (carbonated marls and sandstones).

(iii) Laghoust series (upper Kimmerdjian to lower Portlandian). The thickest formation is encountered in Djebel Lazreg (1,300 m). Two other facies are observed:
- marls with lummachellic intercalation
- gypsiferous marls.

(iv) Ain Rich series (upper Portlandian), characterized by two formations:
- 180 m of gypsiferous marls
- oolitic limestone formation.

(b) Most of the Cretaceous formations outcrop in the region, essentially in a perched syncline, as opposed to the Jurassic series, where two geological stages are missing; the Lias and the Dogger.

(i) The Lower Cretaceous is essentially composed of sandstones found in large depressions between synclines and anticlines. The peculiarity of the sandstones is the presence of pills.

(ii) The Upper Cretaceous is evaporitic, clayey and carbonated, and constitutes the main perched syncline whose centre is filled with Tertiary slates.
After emergence of the Saharian Atlas, a preatlassic trough is formed at the Atlas step and then filled with detritic sediments.

(c) Tertiary formations can reach 600 m thickness with very rapid lateral facies variations. From bottom to top we encounter:

(i) 30 m of clays and sandstones

(ii) 250-300 m of clays, sands and sandstones with rare lacustrine limestones

(iii) gross detritic series, conglomeratic at the base, changing to red sands at the top.

(d) during the Quaternary one can distinguish three periods:

(i) The ancient Quaternary subdivided into two different morphological levels:
- high surfaces with conglomerates of limestone cement
- glacis with thick calcariferous crust and pebbles.

(ii) The Middle Quaternary during which two glacis were formed

(iii) The Recent Quaternary with formation of a new morphological level during climatic oscillations.

TECTONIC

The Central Saharian Atlas is characterized by rigid and flexible deformations typical of complex shear zones.

Anticlines and synclines are oriented roughly SW-NE and are characterized by two zones:

(a) a meridional zone of typical perched synclines with large flat bottoms, the center of which contain Upper Cretaceous and Tertiary continental formations:
  (i) Djebel Dakhla syncline
  (ii) Djebel Milok syncline
  (iii) Djebel El Houita syncline.

(b) a septentrional zone with narrow anticline, elongated, and with a flat center comprising Jurassic formations:
  (i) Djebel Lazreg anticline
  (ii) Ain Mahdi anticline.

Sedimentation and deformations were largely conditioned by thrusting occurring during Secondary and Tertiary eras. The most frequent faulting direction is E-W.

The South Atlassic flexure appears as a flexure, fault or disrupted fold and is characterised by low relief (Djebel Sidi Yagoub...). Location of flexure zones were determined by geophysical prospection.

Geophysical studies (electrical sounding and logging analysis) and data from borings (Fig. 2) led to the following classification:

(a) an alluvial superficial aquifer comprising coarse sands, gravels and pebbles;
(b) a deep aquifer in lenticular sedimentatary structures with fine sands, gypsum and some lacustrine calcareous elements;
(c) semipermeable layers of red clays with fine sands between.

HYDROGEOLOGY

Mzi valley waters are essentially of sulfate, calcium and magnesium composition and become sulfate sodium and chlorine magnesium in Kabeg.

Deep borings F14 and F15 showed that Mio-Pliocene terrains can contain pockets of salty waters (over 13 a l^{-1}).

In the Mzi valley soils are of fluvio-eolian origin and a real pedological cover was formed over its low topography. It is today an essentially agricultural region with low precipitation (150 mm $year^{-1}$) and an average temperature of 23°C, which explains why this presaharian region is arid.

In order to supply the increasing population (including increasing urbanization) with water and to be self-sufficient, the local community decided on a considerable program of borings (Fig. 3); over 50 boreholes and 1,000 wells were sunk, which led to an intensive pumping regime. The consequences of this unorganized and uncontrolled pumping have been a drawdown of the alluvial aquifer level (Fig. 4) and changes in water quality.

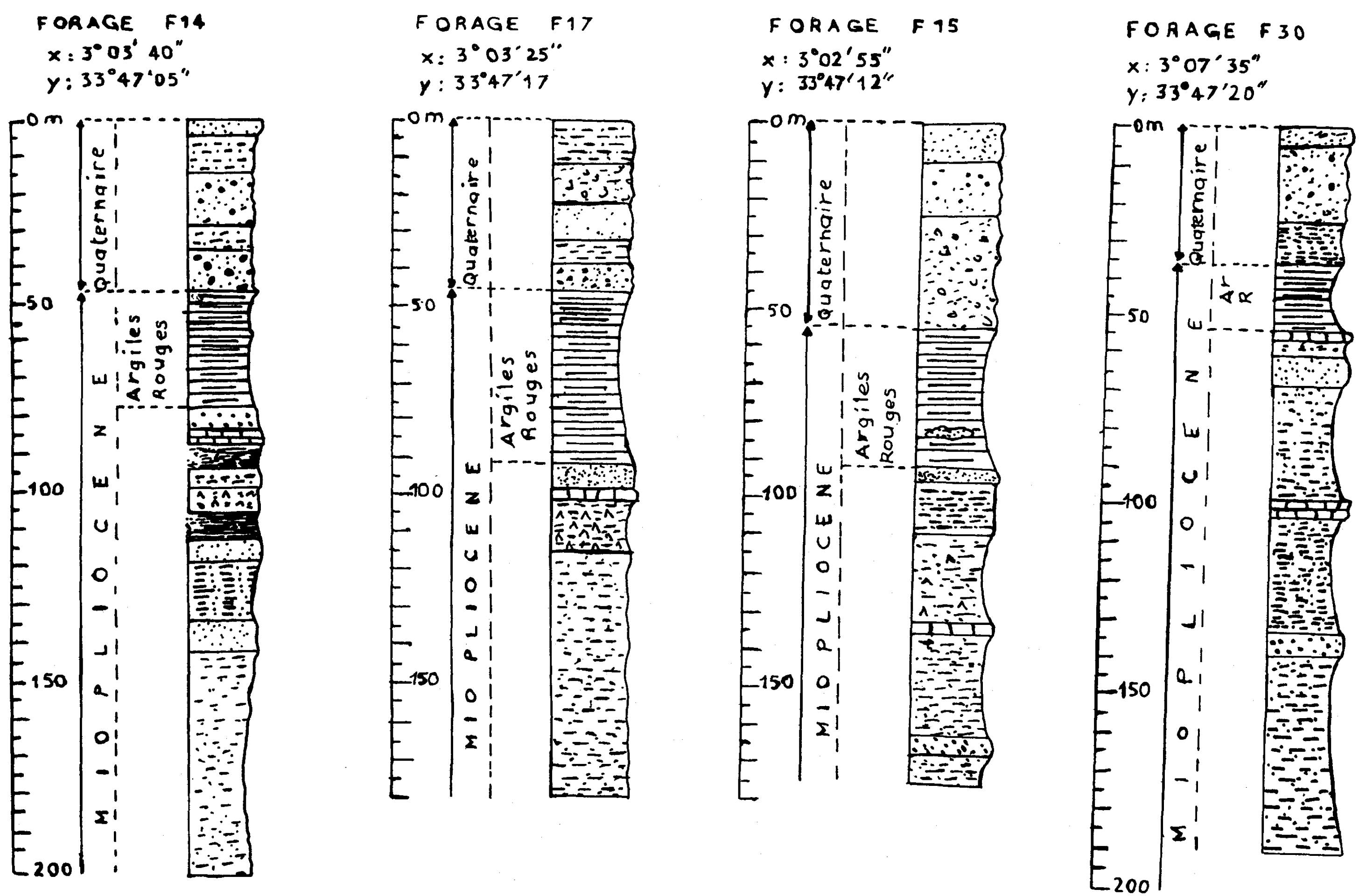


Figure 2: Deep borings in Mzi Valley aquifer.

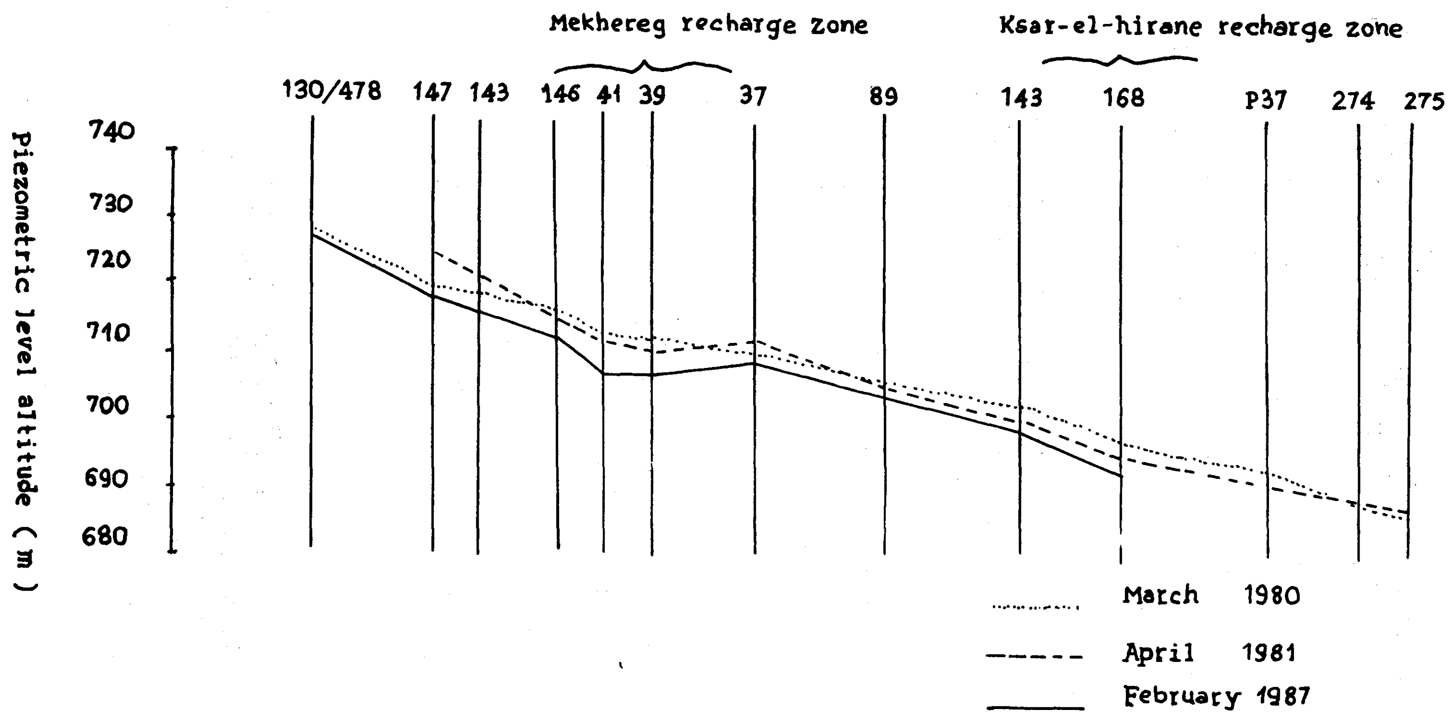


Figure 3: Wad Mzi valley aquifer profile.

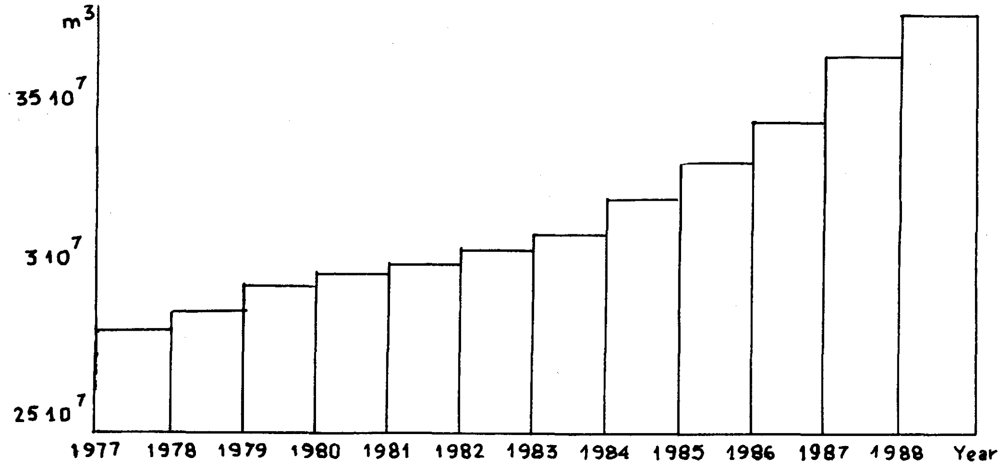


Figure 4: Annual withdrawal regime of the alluvial Mzi aquifer: 1977-1989.

Piezometric and drawdown maps and successive profiles show a general lowering of the water table and creation of two pumping cones. The lowest levels are seen in Mekhareg and Ksar-El-Hirane wells, with 10 and 8 m, respectively. The extension of pumping cones and the salinization of water in the Kabeg pond region has led to study of the movement of salt water in the deep aquifer.

Through water analysis, crop differentiation and salt deposits, high salt levels were confirmed.

The solute transport study will attempt to further clarify the overexploitation of the aquifer in Mzi valley.

Our aim is to propose a two-dimensional model of solute transport and dispersion. We will attempt to quantify the risk of salt contamination and predict the movement of salty water within the aquifer. It was a simple exchange by convection of dissolved matter according to dispersion theory. We schematized the phenomenon involved by limiting ourselves to a description of the salt movement within the aquifer and regarding the concentration of salt as constant.

REFERENCES

Abed, M. & Herkat, M. 1982. *Etude lithostratigraphic et sédimentologique du Jurassique supérieur dans l'Atlas Saharien central.* Thèse de 3eme cycle, Université de Pau, France.

Bonnel, M. 1982. *Méthologie des modèles desimulation en Hydrogéologie*. Documents du B.R.G.M., 34. France.
Cornet, A. 1964. Hydrogéologie Saharienne. *Revue de Géographie Physique et Géologie Dynamique*, vol. 6, fasc. 1.
Fabre, J. 1976. *Introduction à la Géologie du Sahara*. S.N.E.D., Alger.
Hannachi, A. 1981. *Hydrogéologie de la vallée de l'oued Mzi, l'Est de Laghouat*. Thèse de 3eme cycle, Université Scientifique et Médicale de Grenoble.
Rapports Direction de l'Hydraulique de la Wilaya (D.H.W.) 1984-1989. Laghouat, Algerie.
Viessman, W. Jr., Krapp, J.P., Lewis, G.L. & Harbaugh, T.E. 1977. *Introduction to Hydrology*. Harper & Row Publ., New York.

GROUND WATER OVEREXPLOITATION IN LIMA CITY

J.G. UCHUYA
Underground Project Division
Water Supply Service of Lima City (Sedapal)
Jr. Murcia 252
Urb. Javier Pardo,5[ta] Etapa
Lima-30, Perú

ABSTRACT. Lima, the Capital of the Peruvian Republic, is located in the middle of the Country; it is considered a desert climate because rainfall is only about 30 mm per year. Lima is a city with a population of 7 million, perhaps increasing in the near future. Water is supplied by treatment of the Rimac River and by the pumping of about 2,000 wells (including industrial and domestic wells). Sedapal cannot increase the Rimac River treatment for many reasons, so the remaining production is from ground water. This policy has decreased the water table as well as increasing well-drilling and producing a constant decline in productivity: i.e., we are exhausting the aquifer.

The object of this article is to show the danger of the overexploitation of Lima's aquifer and make the authorities take interest in care of the aquifer; otherwise our water supply problems will be increased.

INTRODUCTION

Lima is one of the most important cities in the world located in a desert area. The rainfall is about 30 mm per year, so the main surface water resources are only three rivers.These rivers are the Rimac, Lurin and Chillon. The Lurin and Chillon rivers have an irregular flow rate and only have an appreciable flow for four months of the year. The Rimac river is the only one which has a great flow; it is about 5 $m^3 s^{-1}$ at low flow and 44 $m^3 s^{-1}$ during flood flow; the great slope produces a high concentration of suspended material which makes it impossible to treat water with more than a 15 $m^3 s^{-1}$ flood flow. That was the reason why the treatment plant 'La Atarjea' was designed to treat 15$m^3 s^{-1}$.

The other main resource is aquifer exploitation of the Rimac and the Chillon. Ground water abstraction is from 350 domestic wells and about 2,000 industrial wells. The total abstraction is in constant decline and now has a pumping rate of about 7 $m^3 s^{-1}$.

LIMA'S WATER DEMAND

The water demand in Lima city has been increased in the last 20 years, due to migration of people from the farms; an annual increase in population of 3 %.

The truth is that the water supply is connected for a population of only 4.8 million. The remaining population do not have any form of regular supply and obtain water from public fountains or by buying tank water. In spite of this, the deficit in 1990 was still 5.3 $m^3 s^{-1}$.

Fig. 1 shows historical water production *v's* water demand until the year 2000.

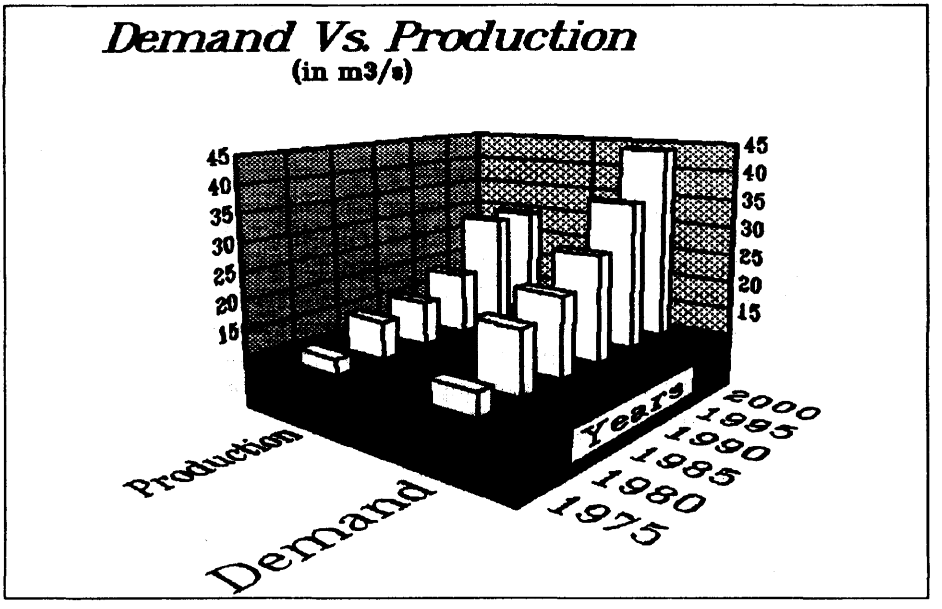


Figure 1: Historical Water Production.

Project and Surveys for Increased Water Supply

Several projects have been carried out since 1970, most of them considered temporary solutions; most involve an increase in ground water exploitation.

The principal survey was 'The Maestral Planning of Water and Waste Water to Lima' (1982). The following actions were recommended:

(a) the surface water resources are insufficient, so we need to import water from other basins. The most viable project (which can guarantee a sizeable flow) is the 'Transfer of Water from the Upper catchment of the Mantaro River to Lima city'. This project can provide 32 $m^3 s^{-1}$ when finished.

(b) this project has many phases and cannot be finished before 1996. The only way to maintain the supply in the meantime is to carry out a programme of drilling wells in addition to a rehabilitation operation.

There were two ways to carry this out:

(i) the first is to drill 18 wells to investigate the deep aquifer. With the first plan results we must begin to drill 51 wells.

(ii) in addition to that we need to make aquifer artificial recharge possible.

(c) to expand the treatment plant 'La Atarjea' from 15 $m^3 s^{-1}$ to 20 $m^3 s^{-1}$ to receive the surplus flow.

(d) to carry out the building of Yuracmayo dam.

(e) when water from the Mantaro river reaches the Rimac river a conjunctive scheme should be used.

In Fig. 1 for the water supply from 1993 to 2000 it is presumed that the Yuracmayo dam has been finished and is in operation, the plant treatment has been expanded and the pumping rate would be about 13.3 $m^3 s^{-1}$.

To satisfy the demand we need to finish the Mantaro transfer before the year 2000. In fact, the authorities are still only thinking about all the recommendations.

We are nearly in 1992 and have only just begun to build Yuracmayo. We do not know when the government will accept bids for the transfer of the river Mantaro. The treatment plant has not expanded and well rehabilitation is going slowly. With respect to artificial recharge Sedapal could only drill some wells near the river area to produce induced recharge, because it could not find big enough areas near the city to develop other techniques for artificial recharge.

On the drilling side, Sedapal has just finished 69 wells (only 18 of them are in operation). These should have been finished in 1984. Ground water is the only resource to be intensively exploited (Fig. 2). More exploitation is necessary to satisfy the increasing demand. The question is: how long will it take?

LIMA'S AQUIFER

Physical Characteristics of the Aquifer

The Quaternary aquifer system of the Rimac lies in unconfined alluvial deposits, but in some places evidence suggests a confined aquifer near the Ocean Callao's Port. The aquifer has the typical characteristics of most of the coastal Peruvian basins. It is composed of the material than was eroded, transported and deposited by the Rimac and Chillon rivers.

The sedimentation is irregular, with thin intermediate layers of clay, which makes it very difficult to establish lateral correlations. Another characteristic is the high hydraulic gradient due to the considerable surface slope.

The latest geophysical investigations of the aquifer and the lithological composition indicate two different layers of permeability. That at the top is composed of sand, gravel and other kinds of coarse material; thickness could be 50 or 60 m. This first layer has good permeability and conductivity.

The second layer is composed of clay, silt and other fine elements. This layer is located below the top layer and the thickness could be from 100 m to 180 or 200 m; in this layer the permeability decreases with the depth. Impervious rock is estimated to be at 400 to 450 m depth.

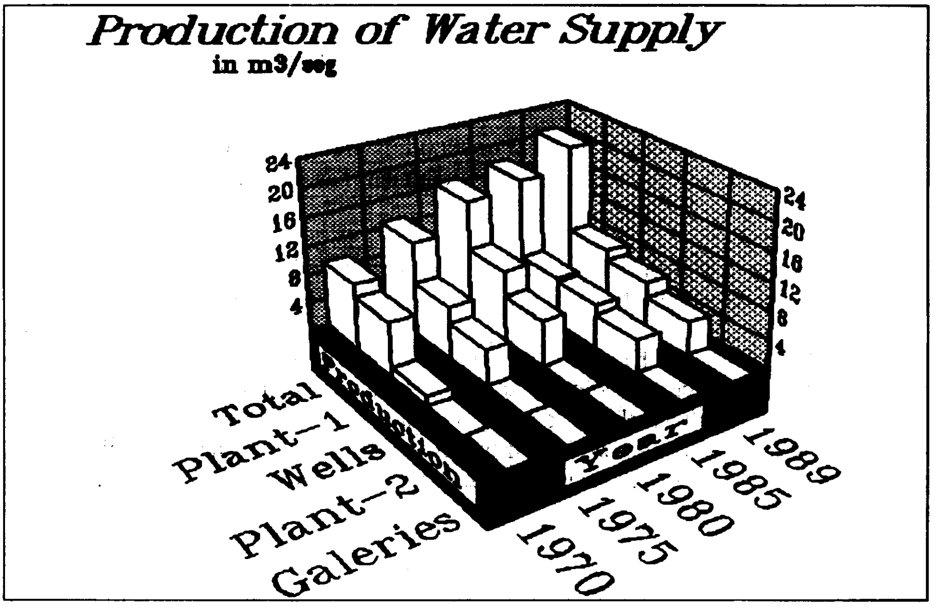


Figure 2: Production of Water Supply.

Evolution of the Water Level

The natural recharge sources for the aquifer are:

(a) ground water flow,
(b) infiltration from Rimac and Chillon river beds,
(c) infiltration from channels and agricultural areas,
(d) infiltration from the leakage of piped water supply.

Lately greater Lima has experienced disorganized urban growth. Agricultural areas were transformed into urban areas; consequently, agricultural areas close to the city began to decrease and natural recharge of the aquifer has also decreased. In adition, these new urban areas needed to drill many wells to obtain a water supply.

In some areas of Lima the water level decline was very rapid so the Agricultural Minister had to forbid well drilling in some zones like Canto Grande and the industrial zone near Argentina Avenue. From 1980 to 1989 the water level decrease was very significant and in some areas it reached about 3 m year^{-1}. From observation wells of the piezometric network we could make graphs for different zones of the city. These graph show the water level decrease (Figs. 3 and 4) in areas like 'La Molina' and 'Surco'. In these two figures the water table began to decline in the 80s faster than in the 70s.

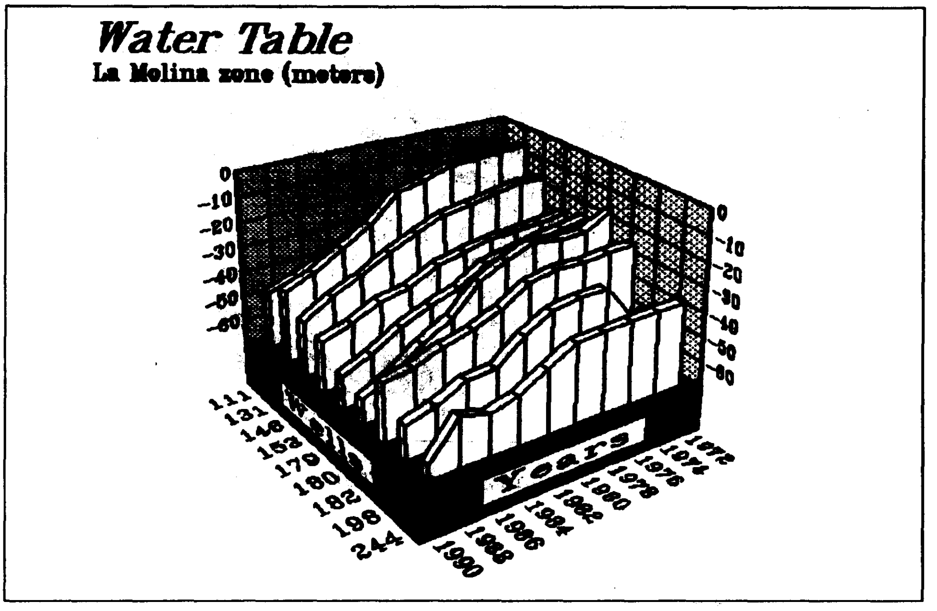


Figure 3: La Molina Zone, Water Table Levels.

Problems due to Water Table Decrease

Due to the water table decline we are now pumping from the second thick layer, wich means that the permeability, the hydraulic conductivity and also the transmissibility coefficient are less than in the top layer.

There is now evidence that we have lost the best permeability layer and are pumping from the worst one.

This decrease in specific capacity, together with the water level decrease, causes not only hydrogeologic but also pump equipment problems.

Hydrogeologic Problems

Because of the water level decrease the most important problem is the continued diminishing of specific capacity in the largest part of the wells, due to less permeability that does not permit good hydraulic conductivity. As a consequence, the last 10 years of drilling have only maintained a balance in the supply of ground water.

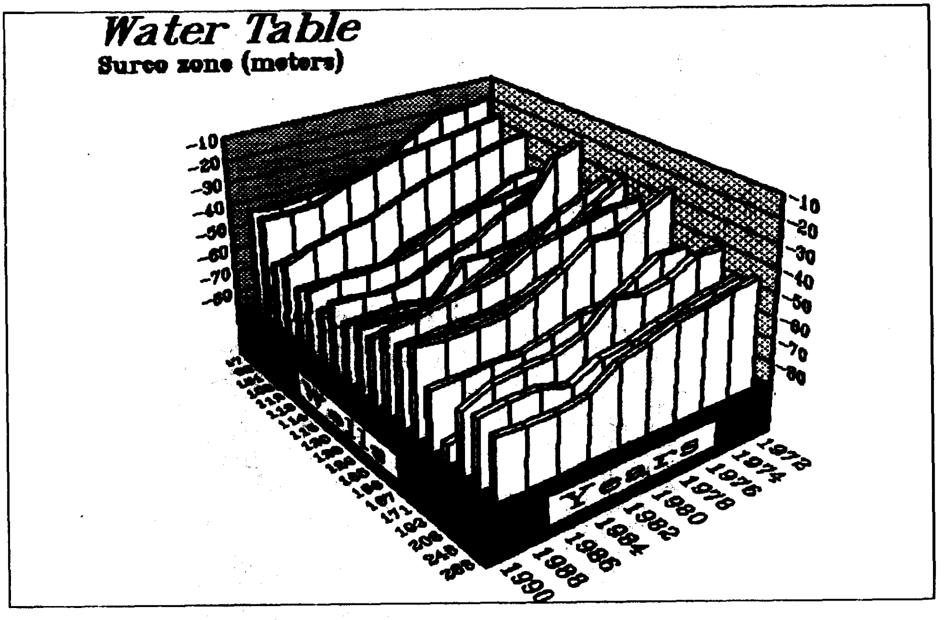


Figure 4: Surco Zone, Water Table Levels.

Fig. 5 shows that for the same flow rate we needed to increase the total of drilled wells during the last years. However, a greater number of operating wells does not mean that we will obtain a greater flow rate; contrary to the expectations of surveys made in Lima city.

The majority of wells in 1960 were perforated. At that time drilling techniques were not familiar. Pipes with slots produced by any of several means were commonly used.

These openings were slots cut with a saw or an oxy-acetylene torch, slots punched through with a chisel and die or crudely cut with a casing perforator.

As we now well know, these kinds of casings could not be closely spaced, covering a low percentage of the area; openings are inadequate. They could not control fine or medium sand, and were not corrosion resistant. Most methods of perforating the pipe tend to hasten corrosive attack on the metal where the water is at all aggresive.

In spite of this, water production in the 1960s was surprisingly good. Now, when the drawdown curve is near these screens, it produces considerable incrustation that, together with the lesser permeability, causes a continued decrease of flow rate in the wells.

This can be observed in Fig. 6; the flow rate has decreased in the last 35 years from 70 l s^{-1} in 1965 to 20 l s^{-1} in 1989 - a common situation in a majority of Lima's wells. Of course there are some areas near Chillon river that do not show this phenomenon, but there are only a few wells.

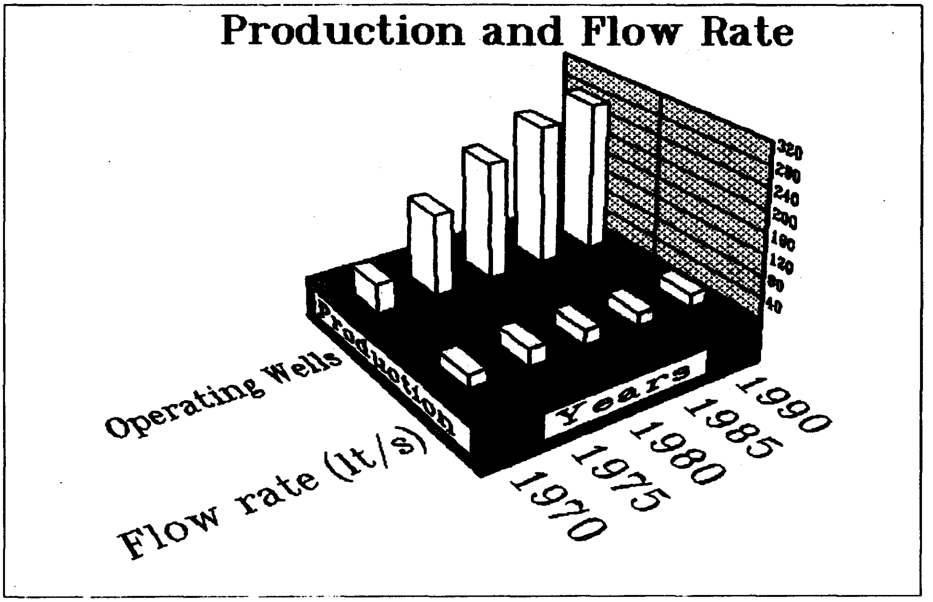


Figure 5: Wells Operating by Sedapal.

Another problem is due to the drawdown curve being close to the well bottom, so we are running out of wells.

The following problems are likely to reduce the amount of ground water production faster in the coming years:

(a) increased corrosion in the slot screens makes the entrance velocity higher than the design standard (3 cm s^{-1}). This causes sand to enter the well. This sand produces constant abrasion in the pumps. The problem is so common that we need to change impellers very often;

(b) increasing the entrance velocity to the wells produces a major head loss. This head loss produces a major pressure head. Another consequence is the change of water quality due to exploitation wells tapping different lithological materials with less porosity but with a high concentration of salts. This is the reason that some wells are out of service in Comas, Carabayllo and Independencia zones, in the north of the city; many wells will probably follow;

(c) sea water intrusion is another problem due to water level decrease. It occurs in the Callao zone. This is a serious problem because there is only a ground water supply. We have already lost several wells in this part of the city.

Pump Equipment Problems

Concerning pump equipment, due to the water level decline, we have several problems, as follows:

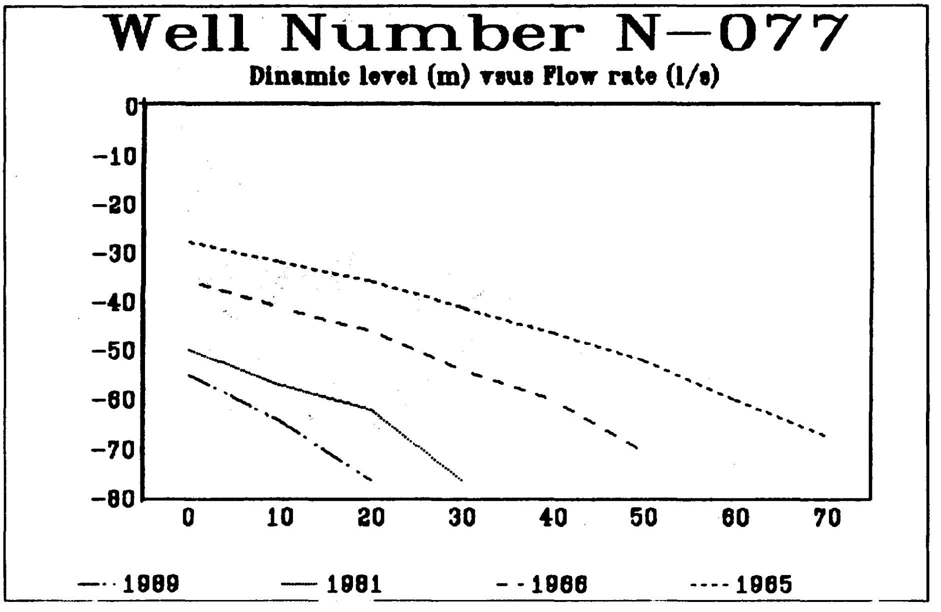


Figure 6: Performance Well Curve.

(a) wells are producing less but with more pressure head;
(b) the rapid decrease in flow rate has put the pumps out of their efficiency range. This produces high electrical power costs;
(c) the decrease of pressure head does not permit use of the high storage reservoirs;
(d) the entrance of sand into wells reduces the useful life of the pumps;
(e) with drawdown near the well screens, we have to increase the depth of pumps to take care of the net required suction head.

ACTIONS TAKEN BY SEDAPAL TO CARRY OUT THESE PROJECTS

Since 1984 Sedapal has had a contract with Binnie & Partners, British consulants, who are working on the Management of the Aquifer Resources of Greater Lima. Together they produced an emergency plan for ground water with the following points:

Conjunctive Scheme

The main objective is to use more surface water resources and reduce the use of ground water, except for balancing the water demand.

The requirements for the conjunctive scheme are:

(a) to carry out all the projects that can increase the surface water supply;

(b) to increase the treatment plant from 15 $m^3 s^{-1}$ to 20 $m^3 s^{-1}$;
(c) to take all the necessary steps to allow the supply system to use the surface and ground water either jointly or independently.

This project is based on a mathematical ground water model. The model indicated that an alternative would be to reduce the abstraction of ground water to 3.7 $m^3 s^{-1}$; this abstraction to be balanced by 6.95 $m^3 s^{-1}$ from surface water resources.

Artificial Recharge

Because we have lost about 20,000 ha in agricultural area, and hence a proportion of the natural recharge, we need to introduce artificial recharge. Induced recharge is the only practical technique to make this artificial recharge possible.

The main objective is to have a pumped yield near the river to increase the hydraulic gradient, thus inducing infiltration to the aquifer.

We are using this project as a pilot study to determine how much infiltration there is, and also to monitor the pumping effects for these 12 wells during low water and the effects of production on the treatment plant. This scheme bears in mind that we will pump 1 $m^3 s^{-1}$, and we estimate input of water from the river to be 0.7 $m^3 s^{-1}$. The scheme will be in operation next year when all the drilling and well equipment is finished. If good results are indicated we can drill several wells near the river bed.

Well Rehabilitation

In 1985 Sedapal, with Binnie & Partners, inspected 70 wells. These are now ready for rehabilitation. The work has not begun for financial reasons. This project is of prime importance to reduce the head loss in the wells and hence reduce the pumping costs.

Leakage Control

Sedapal have a program to reduce the leakage and waste in the pipe systems. This program began with study of the pipe system and must continue with analysis of the ground water.

This analysis of underground water is based on a mathematical ground water model, and includes the well control system and automation of the infrastructure. In addition, the system needs to have an interface with the commercial system. With this kind of system, Sedapal could control the macro- and micro-measurements of the water supply wells.

CONCLUSIONS

The actual surface water resources cannot satisfy the water supply demand, so it is necessary to use ground water abstraction. Intensive use of this resource causes a constant decline of water level and has a direct negative effect on well production, according to location, local hydrogeology and aquifer thickness.

Several geophysical surveys and well drillings indicate less permeability when the well depth is increased. This means that the larger the amount of water extracted the more the water level falls.

It is necessary for the Government to provide money to Sedapal to begin well rehabilitation and to buy new pumping equipment to decrease the costs of electrical power.

Well drilling will be only for places where it is realy necessary, after verifying the excess of consumption. If we do not control the present wasteage any increment in resources will only become increased waste.

Priority must be given to obtaining other water resources and to putting them in service before the year 2000.

It is fundamentally important to commence the project 'Transfer of Water from the Upper Catchment of the River Mantaro to Lima City'.

Provided the Mantaro project has a reasonable cost, it is necessary for the Peruvian Government to obtain the finance to develop this project. At the moment Peru's financial situation makes it impossible to fund these projects, but it is imperitive to insist on loans from the international community. Otherwise, water in Lima will be considered a treasure.

Table 1 shows the cost of investment now needed for water supply to Lima city.

Table 1: Valuation of the investments needed.

PROJECT		VOLUME OF FLOW $m^3\ s^{-1}$	COST US x 10^6 (1992)	PERIOD Month	ACTUAL SITUATION
1	Exten. treat. plant	5.0	15	19	Just to begin
2	Yuracmayo dam	2.5	25	30	In execution
3	Increment of under-ground water (1)	5.0	29	24	Financial stage
4	Leakage control (2)	5.0	85	34	Without Financial
5	Tranfer Mantaro (first step only water)	4.0	131	36	Without Financial
6	Transfer Mantaro (completed)	16.0	400	84	Without Financial
7	Transfer Mantaro (water+water power plant)	35.0	1,800	72	Without Financial

(1) Includes the drilling of recharge wells and rehabilitation.
(2) Includes the conjuctive scheme.
In this valuation the integral expert system of Sedapal, that includes control of flow in pipes and macro and micro measurement jointly with the commercial system, is not considered.

REFERENCES

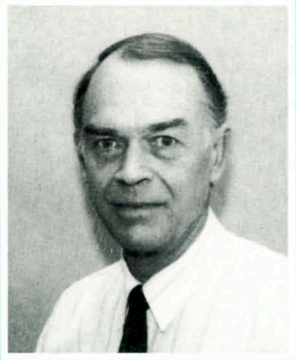
Binnie & Partners, 1970. *The water Resources for greater Lima.* Study for the Upper Catchment from Mantaro River to Lima City.

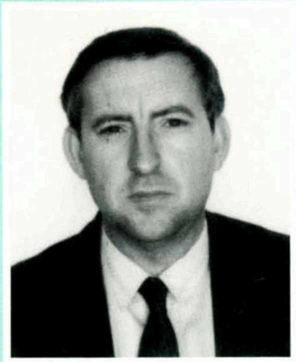
Binnie & Partners, 1986. *Managment of the Aquifer Resources of Greater Lima.*

Engineering Science, 1982. *The Maestral Planning of Water and Waste Water to Lima City.*

Gianella C. 1990. *The water Supply for Lima City.* Forum: Water for Lima City.

Valenzuela C. 1987. *Exploitation of underground water and its perspectives.* Hydrogeologic Symposium of Lima Underground Water. National Engineering University.





I. SIMMERS

Professor at the
Faculty of Earth Sciences,
Free University,
Amsterdam (The Netherlands)

Editor in Chief of the
I.A.H.

F. VILLARROYA

Professor at the
Faculty of Geological Sciences,
Complutense University,
Madrid (Spain)

President of Spanish N.C. of the
I.A.H.

LUIS F. REBOLLO

Professor at the
Faculty of Sciences,
University of Alcalá de Henares,
Madrid (Spain)

Secretary of Spanish N.C. of the
I.A.H.

This volume contains 30 papers from 16 countries, selected from the 91 articles presented at the **23rd International Congress of I.A.H., held at Puerto de la Cruz**, Tenerife (Canary Islands), Spain.

The first section deals with the characterization of aquifer overexploitation and contains 5 papers. The first two deal with the meaning of the term 'Overexploitation' in different scenarios of exploitation, and the following three deal with the type of overexploitation in three interesting cases of aquifers in Argentina (Mar de la Plata), Mexico (San Luis Potosi) and Greece.

The 2nd section, containing eight papers devoted to environmental effects, begins with three cases affecting wetlands in Spain. A case of subsidence caused by the over-exploitation of aquifers is analysed in the following three articles referring to karst terrane, the Po Plain and the Gulf of Mexico. Finally, a problem of contamination by fluoride in the Senegalese Basin, which was accentuated by overexploitation, is discussed as well as various environmental impacts in arid and semiarid areas in China.

The 3rd section is devoted to protective and corrective measures and to legal and socioeconomic aspects; it contains 6 papers. The first two are centred on the corrective and preventive aspects of overexploitation and examples are given of measures taken in Qatar, Barbados, etc. and the Gangetic Basin. The economic aspects are dealt with extensively in the last four articles giving the Segura Basin in Spain as an example.

The 4th section begins with an extensive description of the case of the Ogalalla Aquifer (USA). Overexploited aquifers in water resources management are discussed with various examples concerning Spain, the Republic of S. Africa, Mexico and the Lebanese Republic.

Finally, the 5th section comprises six case studies from Latin American, Souss Valley (Morocco), the coastal area of Lebanon, Spain, Mzi Valley (Algeria) and Lima City (Peru).

The present edition of Selected Papers (Volume 3) provides a view of the wide spectrum of issues relating to aquifer overexploitation and testifies to the great interest shown in defining and analyzing the positive and negative effects of overexploitation present in different parts of the world.

ISSN 0938-6378
ISBN 3-922705-62-6

Verlag Heinz Heise GmbH & Co KG, P.O.B. 610407, D-3000 Hannover 61, FRG