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Aquifer overexploitation: what does it mean?

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Abstract Groundwater overexploitation and aquifer overexploitation are terms that are becoming common in water-resources management. Hydrologists, managers and journalists use them when talking about stressed aquifers or some groundwater conflict. Overexploitation may be defined as the situation in which, for some years, average aquifer abstraction rate is greater than, or close to the average recharge rate. But rate and extent of recharge areas are often very uncertain. Besides, they may be modified by human activities and aquifer development. In practice, however, an aquifer is often considered as overexploited when some persistent negative results of aquifer development are felt or perceived, such as a continuous water-level drawdown, progressive water-quality deterioration, increase of abstraction cost, or ecological damage. But negative results do not necessarily imply that abstraction is greater than recharge. They may be simply due to well interferences and the long transient period that follow changes in the aquifer water balance. Groundwater storage is depleted to some extent during the transient period after abstraction is increased. Its duration depends on aquifer size, specific storage and permeability. Which level of "aquifer overexploitation" is advisable or bearable, depends on the detailed and updated consideration of aquifer-development effects and the measures implemented for correction. This should not be the result of applying general rules based on some indirect data. Monitoring, sound aquifer knowledge, and calculation or modelling of behaviour are needed in the framework of a set of objectives and policies. They should be established by a management institution, with the involvement of groundwater stakeholders, and take into account the environmental and social constraints. Aquifer overexploitation, which often is perceived to be associated with something ethically bad, is not necessarily detrimental if it is not permanent. It may be a step towards sustainable development. Actually, the term aquifer overexploitation is mostly a qualifier that intends to point to a concern about the evolution of the aquifer-flow system in some specific, restricted points of view, but without a precise hydrodynamic meaning. Implementing groundwater management and protection measures needs quantitative appraisal of aquifer evolution and effects based on detailed multidisciplinary studies, which have to be supported by reliable data.

Resumé La surexploitation de l'eau souterraine et la surexploitation des nappes sont des termes qui deviennent d'usage commun en gestion de l'eau. Plusieurs hydrologues, aménageurs et journalistes en font usage quand on parle d'une nappe exploitée intensivement et qui présente des situations conflictives. On peut définir la surexploitation comme étant la situation dans laquelle l'extraction moyenne d'eau souterraine est plus grande ou proche de la recharge moyenne pendant quelques années. Mais le taux ansi que la surface de cette recharge sont souvent tres incertains et peuvent changer dûs a des activitées humaines et à l'exploitation de la nappe elleméme. Du point de vue pratique on souvent considère qu'il y a surexploitation quand on observe or on s'aperçoit de certains résultats négatifs de l'exploitation, tels qu'une diminution continue du niveau de l'eau, une detérioration de sa qualité, une augmentation du coût d' extraction, ou dommages écologiques. Mais ces effets négatifs n' impliquent pas nécessairement que l'extraction soit plus grande que la recharge. Ils peuvent étre simplement le résultat d'interférences ou d'une longue période transitoire qui suivent les changements dans les termes du bilan hydrique. Cette période transitoire a une durée que dépend de la taille de la nappe, et de son coefficient d' emmagasinement et de sa perméabilité. Les extractions d'eau de la nappe comportent une diminution de l'emmagasinement d'eau souterraine pendant le période transitoire. A fin de pouvoir décider du degré de "surexploitation de la nappe" conseillé ou admisible on a besoin de la description detaillée et à jour des effets de l'exploitation et des mesures de correction adoptées.

Received: 30 March 2000 / Accepted: 20 December 2001

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Hydrogeology Journal (2002) 10:254–277

DOI 10.1007/s10040-002-0188-6

Cette décision ne peut pas être prise uniquement à partir de regles générales et l'appui de quelques observations indirectes. On a besoin de controle, d'une bonne connaissance de la nappe, et de calculer ou modeliser le comportement, en faisant appel à l'ensemble des objectifs et politiques établies par une institution de gestion, avec l'implication des personnes qui sont intéressées par l'eau souterraine, et tenant compte des conditions environementales et sociales. La surexploitation de nappes, qui souvent est associée a quelque chose éthiquement nocive, n'est pas necessairement ainsi pendant un certain temps, et peut être une étape dans l'évolution vers un développement durable. Réellement la designation de surexploitation de nappes est surtout un adjectif que a pour but de qualifier une évolution préoccupante sous certains points de vue, mais sans une signification hydrodynamique précise. Pour adopter des mesures de gestion et protection, on a besoin de l'évaluation quantitative de l'évolution de la nappe et de ses effets, ce qui doit déboucher sur des études detaillées dans un contexte multidisciplinaire, et sur de bonnes données.

Resumen La sobreexpolotación del agua subterránea y la sobreexplotacion de acuíferos son conceptos que se están convirtiendo en términos de uso común en gestión hídrica. Muchos hidrólogos, gestores y periodistas las usan para referirse a un acuífero explotado intensamente o que presenta situaciones conflictivas. La sobreexplotación se puede definir como la situación en la que durante varios años la extracción media de agua subterránea de un acuífero supera o se aproxima a la recarga media. Pero la tasa y también la superficie sobre la que se realiza esta recarga son a menudo muy inciertas, y pueden cambiar por actividades humanas y por la propia explotación del acuífero. Sin embargo, en la práctica se suele considerar que hay sobreexplotación cuando se observan o se perciben ciertos resultados negativos de la explotación, tales como un descenso continuado del nivel del agua, un deterioro de su calidad, un encarecimiento del agua extraída, o daños ecológicos. Pero estos efectos no están necesariamente relacionados con el hecho de que la extracción sea mayor que la recarga, puesto que pueden ser simplemente el resultado de interferencias o del dilatado período transitorio que sigue a los cambios en los términos del balance de agua, y cuya duración depende del tamaño del acuífero, y de su permeabilidad y coeficiente de almacenamiento. Las extracciones del acuífero suponen una disminución del almacenamiento de agua subterránea durante este periodo transitorio. Para decidir que grado de "sobreexplotación del acuífero" es aconsejable o admisible hace falta la consideración detallada y actualizada de los efectos de la explotación y las medidas de corrección que se adopten. Para esa decisión no basta con reglas generales y el apoyo de algunas observaciones indirectas. Se necesitan observaciones de control, buen conocimiento del acuífero y cálculos o modelación del comportamiento, y todo ello en el marco de un conjunto de objetivos y políticas establecidas por una institución de gestión, con la implicación de aquellos que tienen un interés en el agua subterránea, y teniendo en cuenta los condicionantes ambientales y sociales. La sobreexplotación de acuíferos, que con frecuencia suele asociarse a algo éticamente malo, no tiene por qué ser necesariamente así durante cierto tiempo, sino una etapa en la evolución hacia un desarrollo sustentable. En la realidad la designación de sobreexplotación de acuíferos es principalmente un adjetivo que trata de calificar a una evolución preocupante bajo determinados puntos de vista, sin que tenga una significación hidrodinámica precisa. Para adoptar medidas de gestión y de protección se necesita la evaluación cuantitativa de la evolución del acuífero y sus efectos, que se derivan de estudios de detalle en un contexto multidisciplinar y de datos fiables.

Keywords Groundwater management · Aquifer overexploitation · Groundwater mining · Intensive aquifer development · Sustainable development

Introduction

Groundwater is an important component of the hydrologic cycle on the Earth with two essential roles, one in nature and the other as a source of water to supply human needs.

In nature, groundwater is a key factor in many geological processes, the components of which sustain spring discharge and river base flow, as well as different types of lakes, lagoons and wetlands; it also transports dissolved mass in the ground, supports habitats, and serves as a geotechnical factor with regard to soil and rock behaviour.

As a source of water to supply human needs, groundwater is a key resource for urban and rural supplies, a strategic resource in case of failure of other water sources (droughts, major breakdowns and pollution accidents), a socially important resource for irrigation development and farming, and a reliable resource for industrial uses.

In many regions, especially where rainfall is scarce and the area is favourable for human settlements, aquifer development may be intensive, since groundwater is often the fresh-water resource that is most accessible, cheap and reliable. The pressure for development may be enormous, especially by the private sector, and may often exceed the control capabilities of classical water authority agencies. Intensive aquifer development is currently a well-established situation in the central and southwestern USA, Brazil and the areas around the Mediterranean Sea such as central and eastern Spain and its archipelagos, also, more recently in large areas of China and India, and under dramatic situations in the oil-rich but water-poor countries of the Near and Middle East. The intensively exploited aquifers around megacities, such as Mexico, Sao Paolo and Lima, are their main source of fresh water. Groundwater is also the main, or the only, source of fresh water in many densely populat-

DOI 10.1007/s10040-002-0188-6

ed islands, such as the Balearic, Canary and Cape Verde archipelagos, Malta, Cyprus and Reunion. Countries such as Denmark depend almost entirely on groundwater for human supply.

Using groundwater to supply human needs has great advantages, but there are also some negative side effects, as with the development of any other natural resource. These effects depend on specific characteristics of the resource: they are essentially different for groundwater (large ratio of storage/flow, and sluggish water movement) and surface water (small ratio of storage/flow, and fast water movement), but they may be combined to take advantage of the different characteristics in integrated or conjunctive-use schemes (Sahuquillo 1991).

When development is the dominant concern, preserving the beneficial use of the groundwater resource is the main objective. This was the basis of concepts such as "safe yield", to define how much groundwater can be abstracted from an aquifer, assuming that groundwater is a renewable resource. The safe-yield concept was introduced in the 1920s (Meinzer 1920), mainly in the western USA, when widespread use of drilled wells and electrically driven turbine pumps dramatically changed the method of developing aquifers by allowing large abstractions from deep boreholes. Safe yield is explained in many textbooks and manuals (Todd 1958; ASCE 1961; Custodio and Llamas 1976) and was further developed by Bear and Levin (1967) and Young (1970), among others.

The safe-yield concept is flawed and may be unsustainable in the long term (Bredehoeft 1997; Sophocleous 1997), since it does not adequately consider interaction with other aquifers, long-term effects and environmental impacts. Besides, it has been erroneously used to establish water rights. It may happen that the optimal aquifer use is not necessarily linked to aquifer recharge when economic and water quality effects are taken into account.

In the 1980s the concept of "sustainability" was developed (WCED 1987) and is being applied to groundwater use. The sustainable development of a natural resource is the development that meets the needs of the present without compromising the ability of future generations to meet their needs. But future needs and technologies are uncertain, as are some resources themselves. This is the case of groundwater. Its characteristics allow and involve the use of part of the reserves (storage) before adapting to the rate of renewable resources.

Sustainable development is a powerful and dynamic concept that has to be refined and whose principles have still to be turned into achievable policies (Sophocleous 2000). In reality, the groundwater successes of the twentieth century have left a series of complex, site-specific water-resource problems. Water authority agencies, technical organisations and technological regulations are ill-designed to address them (Lant 1999). Their solution is a major challenge for the twenty-first century.

Current intensive use of groundwater in many areas, greater environmental concern, and long experience with aquifer development are the reasons for paying more attention to negative aspects of development, as will be discussed below. There is the feeling of something negative to be fought. The background consists of a large variety of poorly defined situations, which rely on some real, assumed, or imagined perception of negative, and perhaps irreversible, evolution in common. All this is behind what is often called "overexploitation", as will be mentioned later on. Overexploitation and other related terms, such as over-draft, over-use, over-extraction, over-development and unsustainable use, are terms that have become increasingly used by large sectors of society since the 1970s, often without a precise meaning and definition. They are used more in arid and semi-arid regions where aquifers are often intensively exploited, mostly for irrigation, but they are also being used to refer to problems of simple interference between wells or of mismanagement.

The International Association of Hydrogeologists has shown an interest in this topic. The concept, practical meaning and conditions of aquifer overexploitation were discussed in a meeting convened by the Spanish Chapter in Almeria (Pulido et al. 1989), and later on during an international congress in Puerto de la Cruz, Tenerife, Spain (Candela et al. 1991; Simmers et al. 1993). These were followed by a United Nations meeting in Las Palmas de Gran Canaria (Spain), which reported on the world situation (Dijon and Custodio 1992). Most of the current knowledge on the subject was presented at these meetings, but knowledge on stressed aquifers has been increasing and the use of the term overexploitation has spread. However, recent specialised literature on groundwater and aquifer overexploitation is relatively scarce. This paper attempts to update how aquifer overexploitation is perceived, and discuss its significance and meaning.

Effects of Groundwater Development

Negative Aspects

Negative aspects and drawbacks of groundwater development were recognised early on (Margat 1977). Aquifer development modifies groundwater heads and flow patterns, with the following well-known consequences (Custodio 1993, 2000b; Bacchus 2000):

1. There is a progressive groundwater head drawdown, which lasts until some stable situation is attained, provided abstraction is less than actual recharge. Actual aquifer recharge under aquifer exploitation may be greater than under natural conditions. Increased drawdown leads to an increased cost of development, due to more energy consumption, the early replacement and deepening of wells and pumps, and the need to enlarge energy facilities.
2. Progressive decrease in spring discharge, river base flow and surface area of wetlands in order to compensate for the difference between actual recharge and

DOI 10.1007/s10040-002-0188-6

abstraction (Llamas 1989, 1992). There is a final equilibrium state or possible progressive depletion. Some tracts of allochthonous rivers that were formerly effluent (draining water from the aquifers) may start to lose water by infiltration into the ground, which means that river flow decreases downstream. Even if abstraction is less than recharge some discharge areas may dry up or become potential recharge areas.

3. The groundwater flow pattern is changed. This may favour the infiltration of contaminated surface water and the slow displacement of saline and low-quality (e.g. rich in F, As, Mn, V, Se,...) groundwater bodies, some of them in deep-seated aquifers and in aquitards. Seawater intrusion rate and the final state depend on how much groundwater flow is available to be discharged into the sea (Custodio and Bruggeman 1982).
4. Groundwater head potential in and along wells or boreholes, or around a spring or discharge area, is changed, thus modifying how waters of different depths or origins mix. This means that abstracted water quality may be changing progressively.
5. Pore-pressure decrease. This may result in land subsidence where sediments are unconsolidated. If lithology and thickness do not change abruptly, subsidence only produces smooth surface-elevation changes, but otherwise may cause elevational differences following linear patterns, which reflect variations of lithology or thickness. Subsidence may vary from almost imperceptible to many metres (Poland 1985). As a consequence, the drainage pattern may be modified, the area may become more prone to flooding and down-cutting erosion, and coastline regression may be enhanced; thus canals, pipes, roads and railways may be offset. In soluble hard rock, such as carbonates and gypsum (and evaporite rocks), the decrease of hydrostatic pressure due to water-table lowering and fluctuations may increase the rate of local, sudden collapses (Lamoreaux and Newton 1993). Collapses around or near boreholes and wells can also be produced when sand from the formation is pumped out with the water due to poor well construction and operation.

Delayed and Transient Effects

To understand aquifer behaviour and the effects of groundwater use, the delayed response and the long transient stages involved in the development should be understood. The effect of a recharge event or of modification of the abstraction regime is propagated through an aquifer as an evolving change in the water head, which progressively stabilises when aquifer discharge or recharge is modified to compensate this change. Time for close-to-stabilisation of groundwater-level evolution can be measured by $\alpha L^2 D^{-1}$ (Rorabaugh 1960; Custodio and Llamas 1976), in which α is a problem-dependent, dimensionless factor, which normally varies from 0.5–2.5; L is a linear measure of the dimensions of the groundwater-flow system being observed; D is the hydraulic diffusivity = T/S; T is the aquifer or aquifer-system transmissivity (horizontal permeability times the aquifer thickness) and S is the storage coefficient of the aquifer. At a given moment, the difference between recharge less abstraction and natural discharge is compensated by a decrease or increase of groundwater storage. Figure 1 shows the case of a pumping well in an alluvial aquifer discharging into a river. The ratio of storage variation to withdrawal becomes small, less than 0.1 for $\alpha > 1.5$ or less than 0.01 for $\alpha > 2.5$. The result is another interpretation of the classical stream-depletion factor (Jenkins 1968).

These effects mean that immediately after a modification in recharge, or abstraction, the aquifer-system discharge does not change. Later, recharged or abstracted groundwater goes into, or comes out of, aquifer storage. Thus, early hydraulic-head modifications adapt to the rate of the change, and afterwards slowly fade away.

Often an aquifer is not an isolated unit. It may behave as partially or totally open from above and below, or laterally. That is to say, it may receive, lose, or exchange water, and may be part of a larger, vertically or laterally interlinked set of aquifers and aquitards (Tóth 1995; Carrillo- Rivera 2000), which form the aquifer system.

When groundwater is abstracted from a given aquifer or an aquifer system, groundwater drawdown is initially concentrated locally, but progressively spreads to the whole system by interaquifer leakage. This means that apparently the effective value of L may progressively increase, while D often decreases. The result may be a progressive slowdown of the rate of change, which is a well-known phenomenon in groundwater hydraulics. But in practice the consequences are often ignored by decisionmakers and even some hydrogeologists. When data are interpreted by means of simplistic or inappropriate approaches, mostly based on ill-applied surface-water experience, this will lead to erroneous assumptions and misinterpretation.

While in small, highly transmissive aquifers the transient effects fade away in a few days or weeks, in a relatively low transmissivity aquifer and/or in large aquifer systems, a recharge or withdrawal change may be accompanied by large water-table and hydraulic-head changes that progress at a slow pace. This explains why these effects go unnoticed in the short term. In large unconfined aquifer systems, groundwater may be not in equilibrium with present conditions and represent a transient stage from past circumstances (Burdon 1977; Lloyd and Farag 1978). Such was the modification of aquifer recharge associated with the climatic change of the Pleistocene–Holocene transition. Something similar happens when the base level of natural groundwater discharge progressively changes its elevation due to erosion, sedimentation, obstruction, coastline modification, or eustatic-level change. Salinity and water-quality changes still evolve at a slower pace than groundwater-head changes since they depend on physical water movement in the

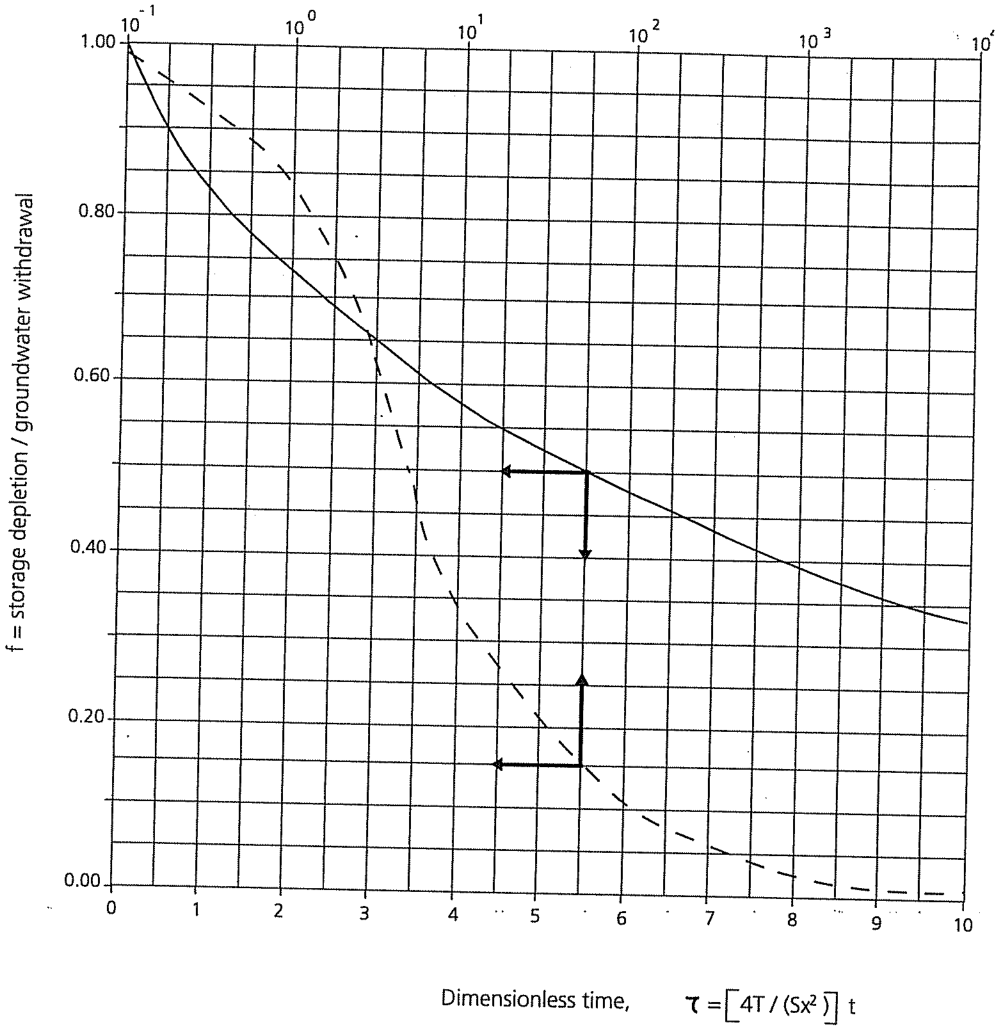


Fig. 1 Graph of storage depletion/groundwater withdrawal vs. time for a pumping well discharging into a river. The *curves* (two time scales, one linear, the other potential) show the evolution of the fraction of well withdrawal coming from aquifer-storage depletion (modified from Balleau 1988). Initially, all abstracted water is from aquifer storage, which progressively decreases with time. *T* is aquifer transmissivity, *S* is aquifer storage coefficient, *x* is distance from the well to the river, and *t* is elapsed time. The magnitude *x* plays the role of *L* in the text

ground, both in the unsaturated and saturated zone, while head changes only imply small water displacements.

Well developments are often concentrated in specific layers of the aquifer system, depending on well yield, water quality and temperature, lithology, depth and actual protection from contamination. When a given confined aquifer of the aquifer system is selected for preferential development, a large groundwater-level drawdown may soon develop in the aquifer, until leakage from other formations and reduction of outflow tend to level the trend, if it is possible. But water-table depth, groundwater head and water quality in adjacent, hydraulically connected aquifers may be little changed in the short term. What may appear as a short-term effect of intensive development for the exploited aquifer layer may show up as a mild effect for other layers.

Hydrogeological Uncertainty

Uncertainty means not only the introduction of errors, due to shifts in average values, but also a wide dispersion. It is the combination of poor knowledge of the phenomenon (e.g. rainfall) and its associated stochastic components, the simplifications introduced to describe the system under consideration, the variability and heterogeneity of the physical media, the difficulty in describing complex situations quantitatively, and even delayed effects. This is a common situation when dealing with nature. Uncertainty affects the evaluation of both surface and groundwater resources, since many hydrogeological variables and parameters are uncertain. But this is not always recognised and uncertain figures, water balances, or other calculations based on them, are often illusorily presented as accurate. It happens that the specialist is often pushed to present very uncertain figures as accurate because non-specialists and politicians tend to think that doing otherwise means poor knowledge or malpractice.

Aquifer recharge may be very uncertain when it has to be calculated. It does not only depend on the rate – which is variable spatially and over time, and affected by land-use changes – but on the extent of the surface area, which is often unclear, especially when there are lateral inflows, and vertical flows from other aquifers. But long-term monitoring, through more accurate calculation and mathematical modelling of aquifer behaviour under a given set of conditions, generally helps to refine the estimated recharge value, provided exploitation rate and pattern, and hydraulic circumstances of the aquifer do not change significantly in the evaluation period.

When a part of an aquifer system is in the early stages of development it may be difficult to obtain a value of recharge from the outside (from rainfall, surface runoff, snowmelt) since most of the groundwater that is pumped may come from interaquifer leakage and water reserves in the aquitards. This is especially true for deep aquifers, but also the water-table layer may receive significant inflows from below for some time, or phreatic water evaporation by deep-rooted vegetation may be reduced after water-table lowering.

Uncertainty is not a major problem for aquifer development in the initial stages. The large quantity of water stored in aquifers – except if it is very small relative to the yearly rate of recharge and abstraction – allows starting development with scarce and uncertain previous information. Afterwards, the knowledge can be progressively refined and the degree of development may be technically adjusted to attain some goals, such as estimating the sustainability, provided legal tools exist to enforce the adaptation to its limits. This is not necessarily, and often it is not, the case with surface-water development, which is less progressive and more susceptible to the unforeseeable yearly fluctuations in rainfall and runoff.

The Concept of Overexploitation

When the total amount of abstraction from an aquifer is, or will be close to, or greater than the total recharge over several years, it is often said that there is overexploitation. This apparently easy definition has some flaws, as does the concept of safe yield. If groundwater use is equal to recharge, then streams, springs and wetlands may eventually dry up, phreatophytes may disappear, and a groundwater head drawdown may progressively develop. The actual situation is often poorly known, since the amount of total aquifer recharge is uncertain, especially at the start of aquifer development. Also aquifer recharge and discharge, as well as groundwater abstraction, may change during aquifer development.

Therefore, to decide on the seriousness of this kind of overexploitation, other, often indirect warnings are used, such as continuous groundwater-level decline, decrease of spring discharge or river flow, and also water-quality changes which are assumed to be due to the displacement of groundwater in the aquifer system. However, as commented above, these warnings may not necessarily be the consequences of the amount of abstraction being close to, or exceeding, recharge, but the result of the delayed and transient effects due to an increase in groundwater abstraction, or other causes, such as base-level deepening or reduction in recharge due to land-use changes.

According to the Regulations for the Public Water Domain of 1986, of the Spanish Water Act of 1985 (Art. 171.2), an aquifer is considered to be overexploited, or at risk of overexploitation, when the sustainability of existing uses is in immediate threat as a consequence of abstraction being greater, or very close to, the annual mean volume of renewable resources, or when abstraction may produce a serious water-quality deterioration.

Consequently, overexploitation is now a legally defined term in Spain. However, the definition provided has the same flaws as the definition of safe yield given earlier in this report, but with a further inconvenience: how to decide what is a serious water-quality deterioration. When an aquifer is declared overexploited, there are legal steps to be followed such as groundwater-use reduction, enacting specific rules for aquifer development, and forming a water user's association. But in practice, with a few exceptions, these actions have proved to be too difficult to carry out, especially against the will of groundwater users, and by understaffed, unmotivated and poorly trained personnel of water authority agencies. These flaws have not been corrected in the reform of the Water Act of 1999 (Alcaín 2000).

Taking into account that "overexploitation" may represent mostly a feeling and a concern for undesirable negative effects, definitions of broader scope are possible, such as including the effects of groundwater abstractions, whose final results are negative for present and future generations, taking into account physical, chemical, economic, ecological and social aspects (Llamas 1992). It is clear that this definition only points to issues to be addressed, but it does not indicate how to measure them, and does not show what to do. From an economic point of view, Young (1993) considers that overexploitation is a non-optimal exploitation. These two definitions do not necessarily link overexploitation to the absolute and relative values of recharge and groundwater use. In fact, some groundwater problems of intensive exploitation, often called overexploitation, may also appear in mildly exploited aquifers. Lloyd (1994) points them out as groundwater-management problems. But little by little the term overexploitation is being applied to problems of aquifer exploitation, which are often only temporal interferences among wells, or among wells and rivers and springs. Thus its meaning is becoming more diffuse and technically useless.

Groundwater overexploitation may mean that total actualised benefits of groundwater withdrawal are less than total actualised costs of aquifer use. But such a simple equation may present serious practical difficulties (Howe 1987; Azqueta and Ferreiro 1994; Aguilera 1996), since it should include not only direct terms, the easiest to be accounted for, but also indirect terms (not due directly to the abstraction of groundwater, also called externalities), which are more difficult to evaluate and identify, and also intangible terms, which may be speculative, difficult to recognise and to reduce to figures, and the subject of socio-political decisions. In order to analyse costs and benefits, subsidies and taxes should be deducted when carrying out economic evaluations, although this is still something controversial (Alfranca and Pascual 1993).

Moreover, the discount rate used for actualisation, which may significantly change the results of the cost–benefit analysis, is difficult to agree upon. All these topics are well known, but controversial, in natural-resources economics.

Indirect costs should also include the cost of preserving and maintaining the aquifer or aquifer system as a natural infrastructure for water supply, which include not only the aquifer itself but the water abstraction works and transport mains, as well as the protection and improvement of the recharge environment, and also monitoring, surveys, studies, modelling and restoration of damages produced and unaccounted for in the past.

The European Union doctrine, which is reflected in the Water Directives, and which will be more explicit after the development of the recently approved Water Framework Directive (Directive 2000/60), considers that aquifer overexploitation has to be eradicated except under special circumstances. In reality, aquifer overexploitation is poorly perceived in Europe and is rarely mentioned in reports, but it may be a sound temporal and unavoidable management option in southern Europe, as it is in Spain.

Serious water-quality deterioration due to "natural" circumstances, mostly a salinity increase, when it is linked to aquifer development, may also be called overexploitation (Custodio 1993), although the causes, and whether it is a local or a regional problem, may not be clearly known. Salinity increase due to progressive seawater intrusion into coastal aquifers is one of the commonly adduced overexploitation problems, but displacement and upconing of deep-seated saline water, when part of fresh-water reserves are depleted, is also a problem for concern (Lahm and Bair 2000), as well as the accelerated dissolution of evaporite salts, when there is induced groundwater flow.

The negative aspects that are considered as aquifer overexploitation (Margat 1992, 1993; Custodio 1993) may be real, but also they may be the point of view and feelings of overconcerned protectionists, of those suffering some real or assumed damage, or simply of people responding to biased information. Sometimes this may be an unconscious or incited overreaction to a given situation (Collin and Margat 1993) and the result of deeply entrenched "hydromyths" (Custodio and Llamas 1997). The perception of negative effects and the feeling of overexploitation are commonly enhanced during a long dry period.

The perception of considering an aquifer as overexploited also changes over time. By way of example, evapotranspiration reduction by water-table lowering was considered beneficial in the past, e.g. in the 1960s and 1970s, but this is currently in serious conflict with environmental preservation. Therefore, what was considered good development practice some time ago, may currently be considered aquifer overexploitation.

As a result, defining overexploitation is difficult and not amenable to simple formulations. It remains essentially a loose concept since no unique, constant value of sustainable use can be attached. As such, overexploitation may be a useful term to point out that some negative effects of aquifer development are of concern to some social groups, and corrective action is called for or is convenient. But the actual appraisal of what is happening and the subsequent action should not be the result of applying a qualifier, but of a detailed multidisciplinary analysis of the situation and its evolution, taking into account short- and long-term goals. In this respect the term "overexploitation" does not help at all.

The feeling of overexploitation is to some extent entrenched in the development of aquifers. They derive from so-called "wicked" problems as opposed to "benign" ones. According to Rittel and Webber (1973), benign problems are those with clear and logical definitions of their nature; problem solvers know exactly what their mission is. But wicked problems involve multiple definitions as to their nature because they are the object of multiple and conflicting criteria for defining solutions. A "solution" to one interested party is a "problem" to others, a kind of overexploitation when dealing with groundwater, and there are no obvious rules for stopping that define when enough has been accomplished. This is made even more complex when the framework changes, as in the case of environmental concern. Wicked problems often appear in natural-resources development and are unavoidable. In this sense, the term wicked does not mean ethically deplorable, but a set of negative and positive aspects to be managed with some trade-off.

Recently the term overexploitation has been applied to total water-resources use (Martínez-Fernández and Esteve-Salma 2000). This is the case when public water-transportation systems, water-storage reservoirs or well fields do not operate at nominal capacity due to design failures or unforeseen legal problems, but water use develops according to nominal values. This produces what is sometimes called structural drought. It is often solved by pumping from the local aquifers far beyond sustainable use, to cover water deficits, which often become permanent. Thus "overexploitation" is the combined result of mismanagement of water resources and water-supply facilities, as well as short-sighted land-use management. Often groundwater overexploitation is considered groundwater mining, but they are different concepts although they produce observable effects that are similar in many aspects.

Groundwater mining may be defined as the exploitation of groundwater at a rate that is much greater than recharge. In this instance the objective is the magnitude of the reserves and not the renewable resources. Water is considered as a mineral under conditions similar to oil or natural gas, although in some cases developers may not be aware of this circumstance. Groundwater mining means that the total volume of fresh water is reduced and/or replaced by poor quality or saline water, that part of the aquifer may become depleted, and that some springs, oases or other types of surface discharge may dry up.

Considering groundwater as a non-renewable resource, groundwater mining is economically justified by considering that if it is not used, it does not benefit anyone. In most cases this is not true since groundwater reserves are needed to sustain the renewable flow. Only in arid lands, where recharge is almost nil, can groundwater mining be justified to some extent. Even in these circumstances, however, the small renewable part, or the residual flow resulting from past climatic conditions, often plays an important environmental role, sustaining springs and wetlands (oases), creating valuable landscapes and habitats, and providing the required, shallow groundwater resources for the local population. Therefore, some ethical issues should be considered.

Case Studies and Responses

Some typical cases pointed out by some experts as serious aquifer overexploitation are found in central and northern Mexico, and the southern and southwestern USA. Of the 106 subregions of the USA considered by the US Water Resources Council (CEQ 1981; Leeden et al. 1990) in 1975, in eight of them overexploitation exceeded 700×10^6 m^3 yr^{-1} (southern and southwestern USA) and in another 30 it was between 30 and 700×10^6 m^3 yr^{-1} (southern, central, and western USA). There are areas in which the accumulated groundwater head drawdown may be greater than 12 m, scattered throughout the western, southwestern, and southern parts of the USA, and in large areas in the north-central part (USGS 1984).

Overexploitation in California was estimated at about 5×10^9 m^3 yr^{-1} in the mid 1950s, but during the 8-year drought in the late 1980s and early 1990s it was reckoned at 2.5×10^9 m^{3}per year (Howitt 1993) for a total yearly water supply of 40×10^9 m^3 (45% with groundwater). Estimated groundwater reserves are $1{,}600\times10^9$ m^3, but only 140x109 m^3 are assumed usable.

In the southwestern part of the USA, around Tucson, Arizona, where groundwater is the only significant water resource, recharge is assumed to be less than half of the abstracted 0.4×10^9 m^3 yr^{-1} (Charles 1991). Average groundwater-level drawdown has been about 1 m yr^{-1} since the early 1900s.

In the large Ogallala aquifer in the High Plains of south-central USA, initial reserves were reckoned at about 840×10^9 m^3, although groundwater quality decreases with depth. By 1980 about 160×10^9 m^3 of groundwater reserves had been removed, with a mean drawdown of 3 m in 40 years and up to 30 m locally (Johnson 1993; Sophocleous 2000).

In northwestern Mexico the situation is similar to that in the southern and southwestern USA (Canales 1991). There are some cases which, since the 1960s, have been presented as dramatic overexploitation leading to serious social disruption. This happens in the Hermosillo and Guaymas aquifers, in Sonora. According to Rodríguez-Castillo (1993), in the Guaymas coastal aquifer (Sonora), abstraction was three times the estimated recharge due to the relatively low cost of abstracting water. Progressive salinisation resulted in damage to 8,000 ha of irrigated soil, the abandonment of more than 50 wells (about three per year) and internal displacement of people. In the Hermosillo and Sahuaral valleys aquifer, covering an area of about 3,000 km^2, abstraction is reported to exceed recharge (420×10^6 m^3 yr^{-1}) by 264×10^6 m^3 yr^{-1} (Steinich et al. 1998) after the river Sonora was retained by a dam; groundwater-head drawdown is up to 50 m below sea level, and salinisation problems are often mentioned as the cause of well abandonment. This is partly due to upward seepage from a deep-seated, saline aquifer.

In the area of Mexico City the ratio of groundwater use to recharge is reckoned to be 1.6 (Downs et al. 2000) for a total abstraction rate of 40 m^3 s^{-1}. The water-table drawdown rate is about 1 m yr^{-1}, which is partly responsible for a land-subsidence rate up to 0.40 m yr^{-1} and a total subsidence of 7.5 m in 100 years in the city centre. Aquifer inter-leakage explains a decrease in the drawdown rate. This effect has been studied by Carrillo-Rivera (2000) in two semiarid areas of Mexico (San Luis Potosí and San Juan B. Londó).

Some classical examples of land subsidence related to groundwater use (overexploitation, according to some) are the Avra Valley (Tucson, Arizona, USA), the San Joaquin Valley (California, USA), and Mexico City, as mentioned above. Values from 0.2–9 m have been reported in the USA, over areas up to 6,000 km^2 (Poland 1985). Problems of enhanced flooding by continental waters and seawater occur in Venice, Bangkok, and Tokyo among others. In China, land subsidence is reported (Wang 1992), especially in flat coastal areas.

In the Hueco Bolson aquifer, which supplies El Paso, Texas (USA) and Ciudad Juárez (Mexico), Hibbs (1998) shows a compound problem of overexploitation, comprising water-level drawdown, early abandonment of wells because of the increase in water salinity, but also of agricultural and urban nitrate contamination and biological pollution, due to induced and enhanced recharge. Something similar happens in Lima, Peru, where the aquifer, which is the key water source for the urban area, is considered as severely stressed and "overexploited" (Uchuya 1993).

In the arid Middle East and North African countries, groundwater mining is a fact. In the Sahara and in the Arabian peninsula, about 6.5×10^6 km^2 of territory may contain more than $80{,}000\times10^9$ m^3 of fresh water (Houston 1995). In Libya almost non-renewable groundwater from the central and southern part of the country (Fezzan, Satin, Tazerbo, and Kufra) is transported by 1,900 km of pipes to the Mediterranean coastal area, 500–900 km away, by means of the so-called Great Manmade River, at a total cost greater than 4 billion Euros, initially to foster irrigation and farming. Some experts reckon that the scheme may work for three to four centuries at present rates. But the project has raised doubts about long-term water quality, and economical, social, and environmental issues.

Israel applies an integrated approach in which groundwater use and, to some extent "overexploitation",

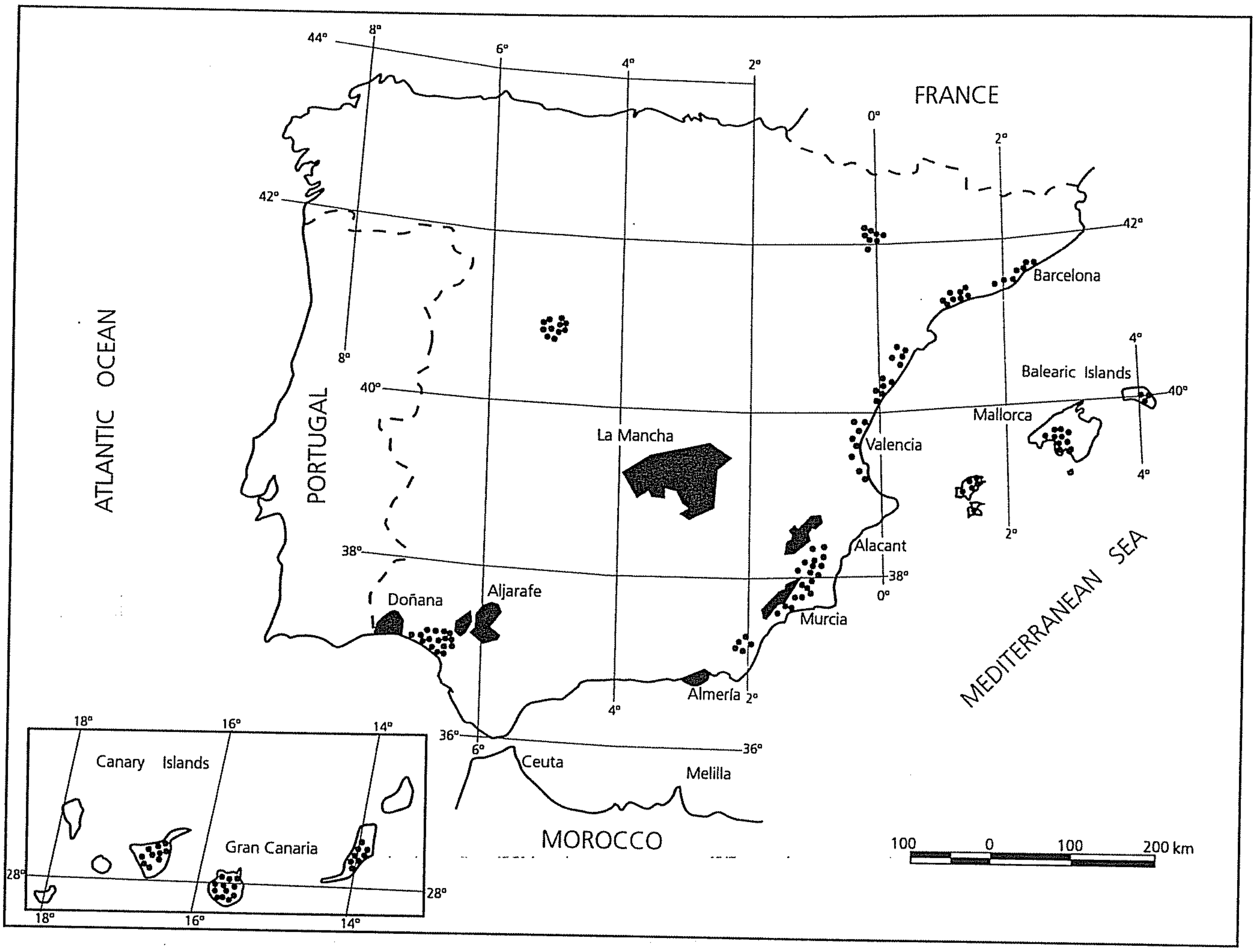


Fig. 2 Aquifer units officially considered as overexploited in Spain. The aquifer units (after MIMAM 1999) are in *black*. *Dotted areas* correspond to aquifers in which some kind of "overexploitation" has been mentioned or where special surveillance has been mandated to avoid the legal consequences of declaring them legally overexploited (as in Catalonia, northeastern Spain)

is a stage in developing natural resources to foster the country's economy (Shamir 1993), although some redrafting may be needed as the Palestinian autonomy develops. The coastal aquifer has been supplying close to 0.45×10^9 m^3 yr^{-1} of water since the 1950s, of which about 0.34×10^9 m^3 yr^{-1} are assumed to be derived from natural replenishment. Besides groundwater-level drawdown, there are salinity problems resulting from upconing and upward movement of deep-seated saline water. These problems have been known in some places since the 1930s, have been increasing in some areas since the late 1960s, and have continued even since 1990 when total abstraction was significantly reduced (Vengosh et al. 1999).

In Spain, the Water Administration has identified 51 hydrogeological units in the national territory which, in agreement with the Water Act, are officially considered as overexploited (MINER-MOPTMA 1994; MIMAM 1998). The assumed total water deficit (amount of abstraction in excess of recharge) is 0.70×10^9 m^3 yr^{-1} (23 m^3 s^{-1}) for a total groundwater withdrawal of 5.5×10^9 m^3 yr^{-1} and a total reckoned recharge of 29×10^9 m^3 yr^{-1}. In these 51 "overexploited" hydrogeological units, the ratio of groundwater use to renewable resources is reported to be 1.0–1.2. It is also reported that in 23 other units the ratio is in the range 0.8–1.0. In the other 25 hydrogeological units, in which the ratio is less than 0.8, significant local water-level drawdown rates or quality deterioration, are reported. These figures have been changing, however, as data on groundwater abstraction amounts and estimates of recharge have been updated. In spite of creating deep concern in official sectors and in the mass media, these rates are far lower that those of southern and southwestern USA, both per unit of surface area and per inhabitant. Figure 2 shows the officially overexploited aquifer units and other areas in which aquifer overexploitation-like problems have been, or are, frequently mentioned.

Reasons adduced to consider that there is overexploitation, or risk of overexploitation, in Spain are often based on rough recharge calculations, a first appraisal of withdrawal, a perception of continuous head drawdown derived from some wells and boreholes, and occasional

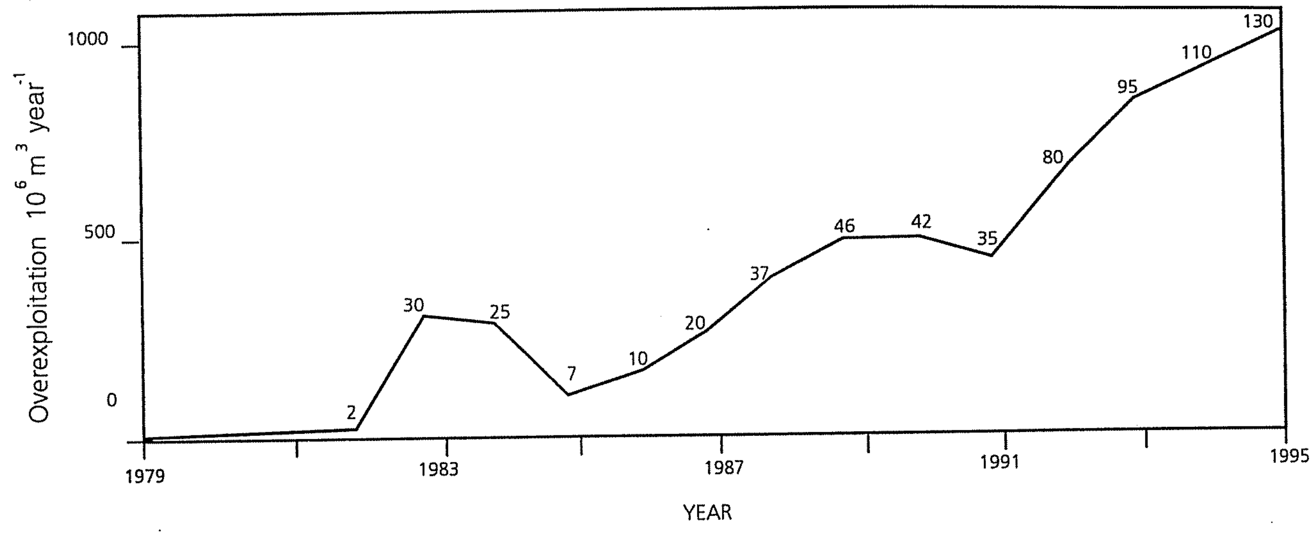


Fig. 3 Groundwater-storage depletion (overexploitation) in the aquifers of the Segura River Basin (Murcia and part of the Alacant provinces, Spain), after Martínez-Fernández and Esteve-Selma (2000). The *figures* on the plot indicate the ratio of groundwater-storage depletion to available total renewable water resources (%), including imported water (50–250×10^6 m^3 yr^{-1}). The gross size of the irrigated area is close to 200,000 ha. The storage depletion mentioned here is higher than that quoted in the case studies and responses, since it is based on a different estimation. The level of uncertainty is high

Table 1 Groundwater reserves and depletion rate in eastern Spanish aquifers and in Murcia (after internal data from Dirección General de Obras Hidráulicas, Instituto Tecnológico Geominero de España). Figures are very uncertain. The areas include small, highly productive aquifers. Climate is semiarid; flash floods are common

Area and year of estimation	Groundwater reserves, ×10^6 m^3			Depletion rate ×10^6 m^3 yr^{-1}	Assumed years to depletion (range)
	Used (1980–1995)	Remaining	Usable		
Almería (1995)	800	1,100	750	50	15 (10–75)
Murcia (1995)	2,000	10,000	7,100	125	60 (10–800)
Alacant (1995)	1,000	7,000	6,000	50	120 (10–400)
Valencia (1995)	100	2,500	2,000	15	130 (20–350)
Murcia (1985)	–	–	6,000–11,000	300	(20–40

data on water-quality deterioration, e.g. salinisation in some wells. Other aspects, such as long-term trends and forecasts, economic considerations, land stability, and environmental impacts, are generally not included. In fact, some hydrogeological units considered as overexploited do not seem intensively exploited, but are only suffering localised or temporal problems. Water authority agencies may have decided to consider them as overexploited as a preventive measure, or as a result of yielding to external pressure by overconcerned institutions and mass media, or just to have a tool to intervene in some areas of conflict by carefully using legal provisions of the Water Act, even if there is no actual overexploitation. Progressive groundwater drawdown, however, is a conspicuous fact in some areas. In some aquifers of eastern Spain, the observed drawdowns exceeded 2 m yr^{-1}, at least for some years. In the volcanic islands of Gran Canaria and Tenerife water-table drawdown may be up to 10 m yr^{-1} in some operating wells and water galleries in the highlands. But these figures should be taken with caution, since they may represent long-term transient conditions and local effects near well fields in low-permeability formations or aquifers of small extent; groundwater abstraction is not necessarily greater than recharge. Some cases of conspicuous sustained groundwater-level drawdown, at least during the monitoring period, have not been declared legally overexploited to avoid the difficult-to-apply provisions of the Water Act. In some cases the term "overexploitation" has been avoided and instead the term "special surveillance" has been used to categorise the situation.

The "feeling" of aquifer overexploitation is at its height in the southeastern part of Spain as reflected in many official reports. Table 1 shows some summary data and Fig. 3 shows how aquifer overexploitation has evolved since the early 1980s in the Segura River Basin, eastern Spain, with an increasing rate of about 15% per year. Figure 4 shows the evolution of groundwater levels in some of the wells in the most critical areas in the basin. The expansion of irrigation is to some extent due to prospects of water importation and a partial failure to import enough external water resources. The deficit has

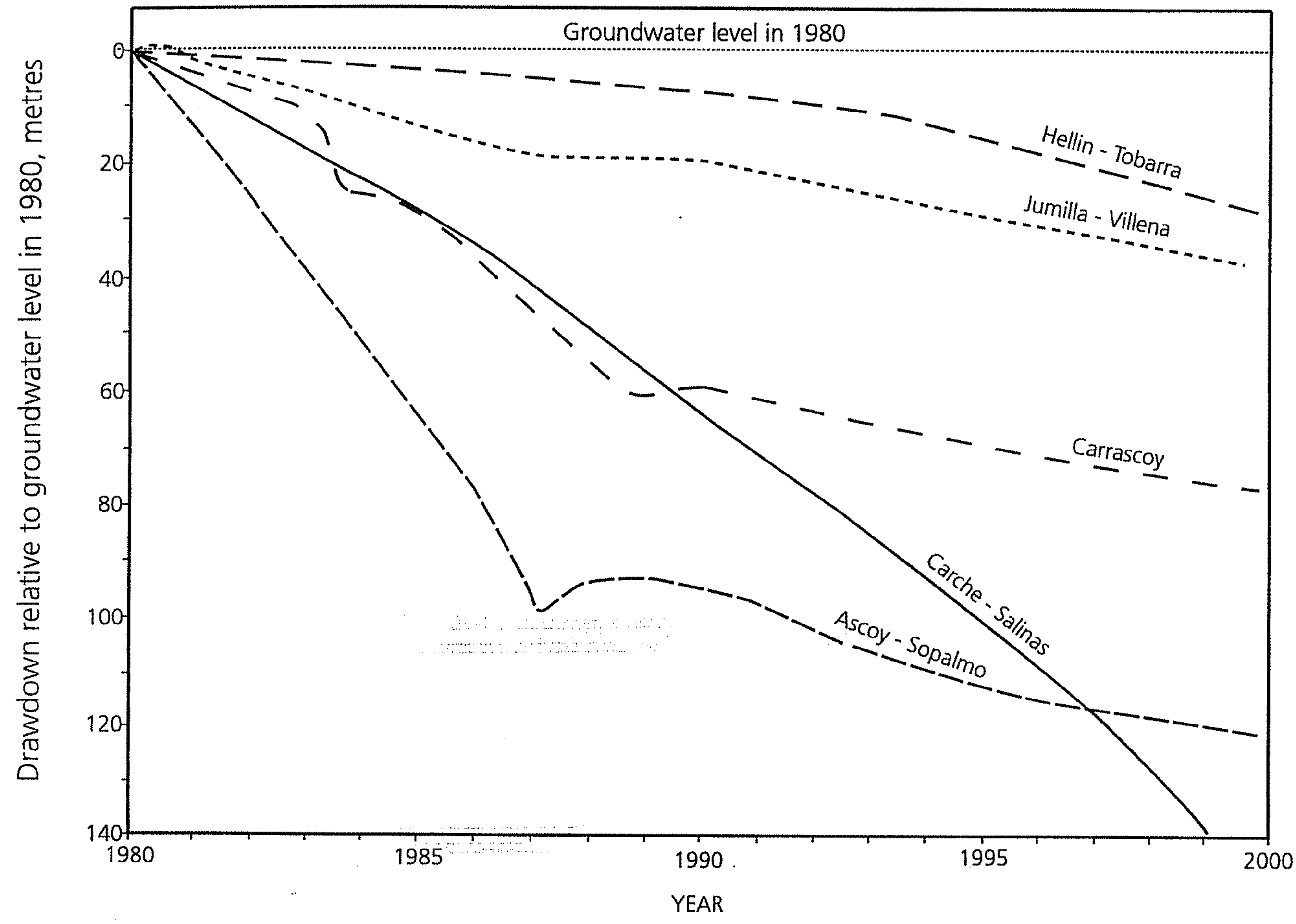


Fig. 4 Groundwater-level evolution in some small "overexploited" aquifers in Murcia (drawdown from position of groundwater level in 1980). The curves have been manually smoothed; inflections are mostly due to changes in pumping rates (from MIMAM 2000)

been solved by intensive aquifer exploitation, sometimes with dramatic "overexploitation" results, from the local point of view. Figure 5 shows the groundwater-level evolution in one of the most stressed areas, in the Alt Vinalopó valley, in southern Alacant province, eastern Spain (see Fig. 2). About 90×10^6 m^3 yr^{-1} are abstracted from a series of small aquifers spread over 1,100 km^2; the rate of reserve depletion is assumed to be 35×10^6 m^3 yr^{-1}, from a total reserve volume of 4,500×10^6 m^3. The dramatic rate of drawdown may be the result of groundwater-level evolution in the small aquifers where the areas of abstraction are concentrated; this type of development draws groundwater from other nearby formations. Long-term groundwater-quality changes due to mobilisation of brackish and saline deep-seated groundwaters, derived from evaporite-rich formations, may be of major concern.

The La Mancha limestone aquifer (area 5,500 km^2) in the centre of Spain has been intensively exploited since late in the 1970s to transform dominantly dry-farming areas into extensive irrigated lands. The widespread water-table drawdown from 1980–1997 (Fig. 6a, b), besides increasing the water cost, has depleted the springs where the lower Guadiana River begins, and has cut off the underground flow to the Tablas de Daimiel wetland (Llamas 1993), which is an important wildlife resort of continental significance. In the period 1974–1987 the irrigated area increased from 300–1,250 km^2, total groundwater use increased from about 60×10^6 m^3 yr^{-1} to 600×10^6 m^3 yr^{-1}, with a decrease of groundwater reserves of 350×10^6 m^3 out of a total storage of 3,000×10^6 m^3. The average water-table drawdown was 20 to 30 m.

Figure 7 shows the evolution of natural recharge and net abstraction, and accumulated abstraction versus groundwater-level drawdown in the La Mancha aquifer, central Spain (after MIMAM 2000). Net abstraction (abstraction less return flows) is higher than calculated natural recharge, except in wet years when abstraction decreases. The result is progressive water-table lowering with some recovery in wet years.

In another of the significant wetlands and natural wildlife areas of Europe, Doñana, southwestern Spain, the development of a 10,000-ha irrigation scheme with groundwater has produced some cause for concern (Custodio and Palancar 1995; Custodio 2000a). Figure 8 shows the evolution of groundwater-level elevation in two observation wells in the irrigated area around El

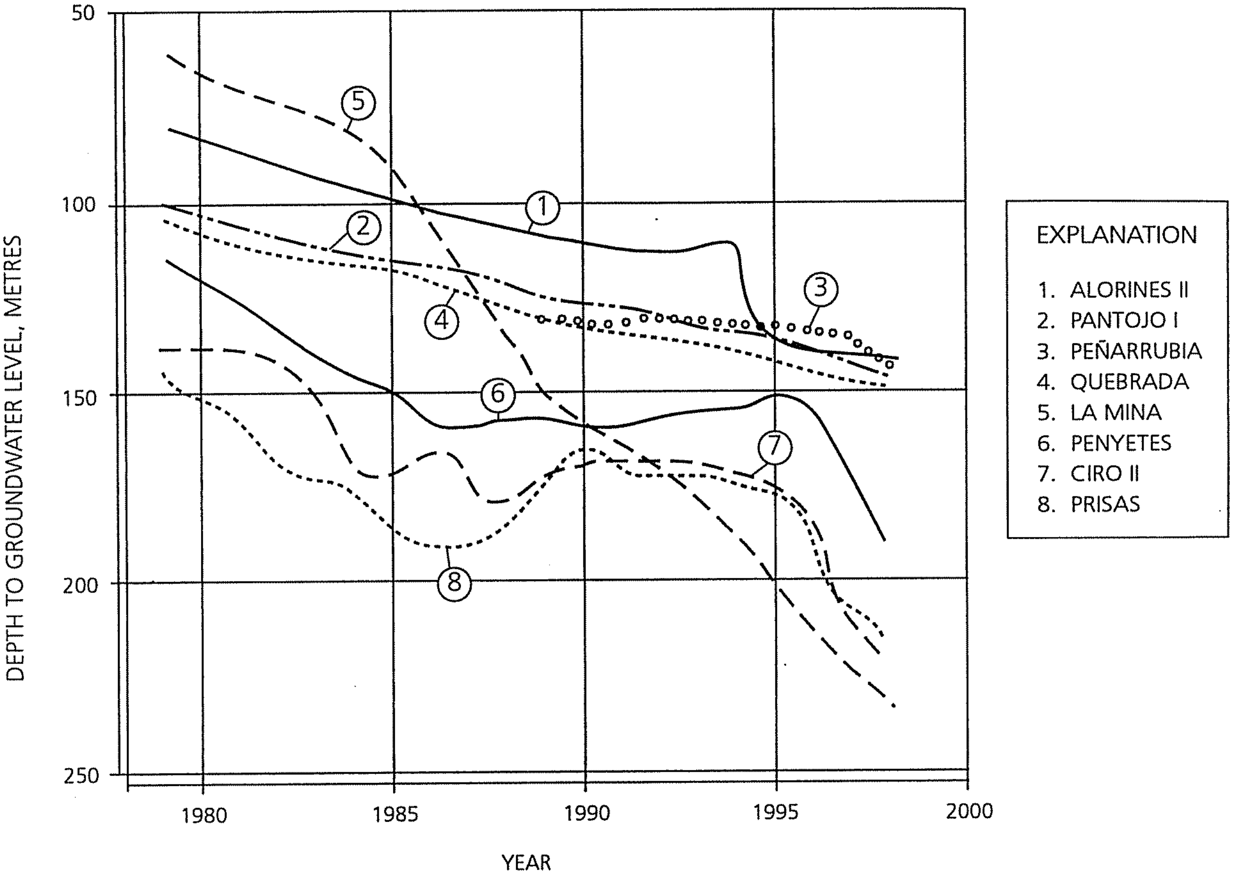


Fig. 5 Examples of fast rates of groundwater-level drawdown in the Alt Vinalopó valley, Alacant, Spain (after Selva 1999)

Rocio, Doñana, southwestern Spain (after Llamas 1989). The downward trend was of concern, although the current trend is towards stabilisation after reducing aquifer discharge into the natural habitats. This situation sometimes has been qualified as serious overexploitation even though total groundwater use (about 70×106 m^3 yr^{-1}) is much less than recharge (about 250×10^6 m^3 yr^{-1}). The main effects have been the decrease in flow of a main creek and the depletion of others; also the lowering of the watertable, which has affected some perennial vegetation and habitats and reduced the frequency of appearance of temporary lagoons (see Fig. 9). Also, phreatophyte growth has become progressively intense in long dry periods. Additional effects include nitrate pollution and reduction of well yields in some areas, which have forced the displacement of pumping areas.

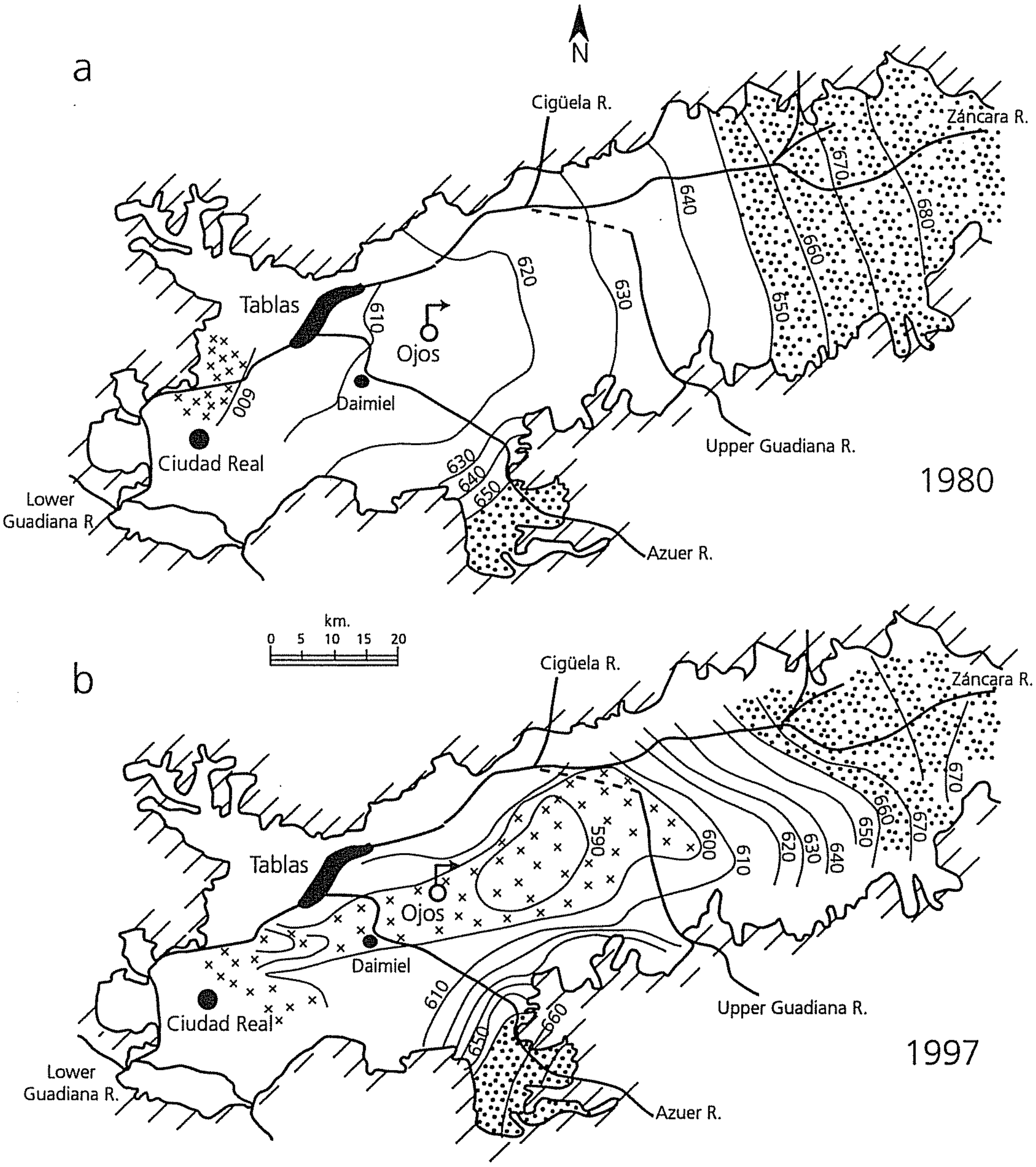
Issues Related to Intensive Aquifer Exploitation and "Overexploitation"

Many natural resources, such as air, oil, vegetal resources, and aquatic life, although extractable, are characteristically migratory. They are subject to the unrestrained rule of capture. In such a case, there is a lack of incentive for conserving the resource, and each possible or authorised developer intends to get as much as possible according to the profit to be made from investment in and sale of a product; otherwise others will get their share. This is the problem of the "common-pool resource" (Aguilera 1991; Young 1993; Azqueta and Ferreiro 1994). The result is qualified as collective economic inefficiency. This seems to apply to intensively exploited, or "overexploited", groundwater systems in which, before reaching a final steady state, there is a long transient evolutionary period during which a part of the freshwater storage is depleted or replaced by poor-quality water.

Besides the problem of the common-pool resource, the number of groundwater users of a given aquifer or aquifer system is generally large, especially when compared with surface-water developments. Dealing with an often very large number of players and interested people (stakeholders) is a new added difficulty for water institutions, which in most cases are prepared to deal with technical and administrative issues, but not with social ones.

As already explained, the development of a given aquifer of significant size, or of importance to a region or country, is generally a progressive one. As groundwater use develops there is an increasing groundwater-level drawdown and other negative effects, which may be delayed and dependent on the well locations and construction features. When some of the negative effects begin to be noticed, there are two extreme management attitudes,

DOI 10.1007/s10040-002-0188-6



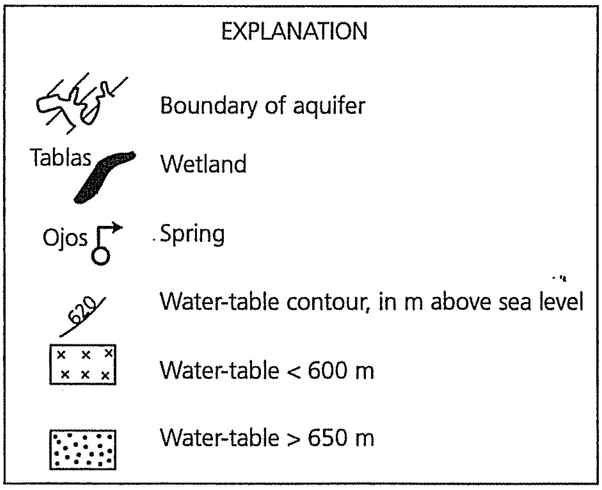
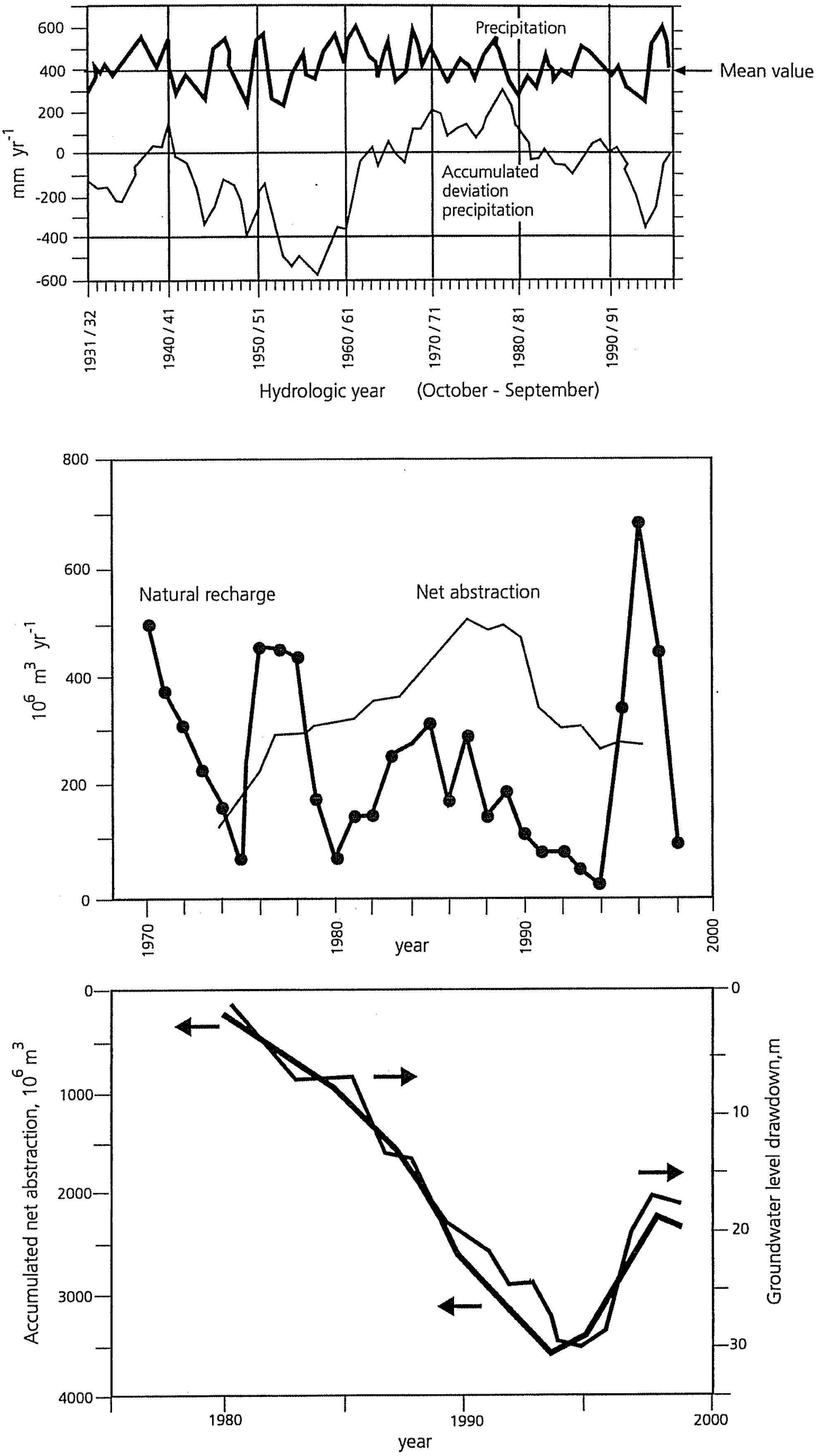


Fig. 6 "Overexploitation" effects in the La Mancha aquifer, central Spain, resulting from water-table drawdowns between 1980–1997 (modified from Cruces et al. 1997)

Fig. 7 Evolution of natural recharge and net abstraction, and accumulated abstraction versus groundwater-level drawdown in the La Mancha aquifer, central Spain (after MIMAM 2000)



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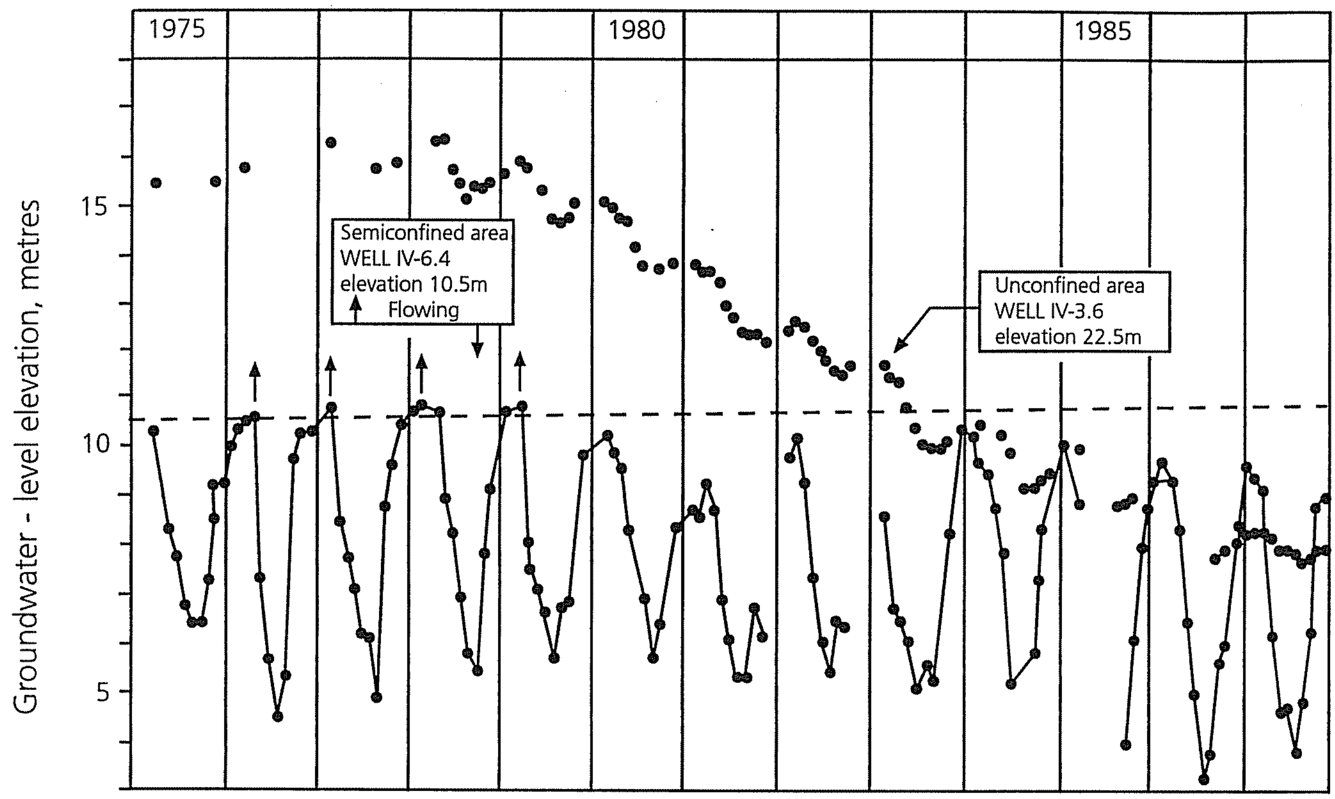


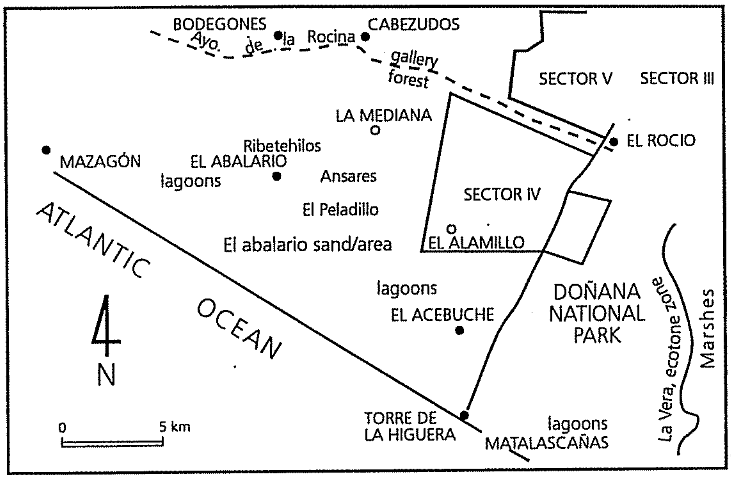
Fig. 8 Evolution of groundwater-level elevation in two observation wells in the irrigated area around El Rocio, Doñana, southwestern Spain (after Llamas 1989)

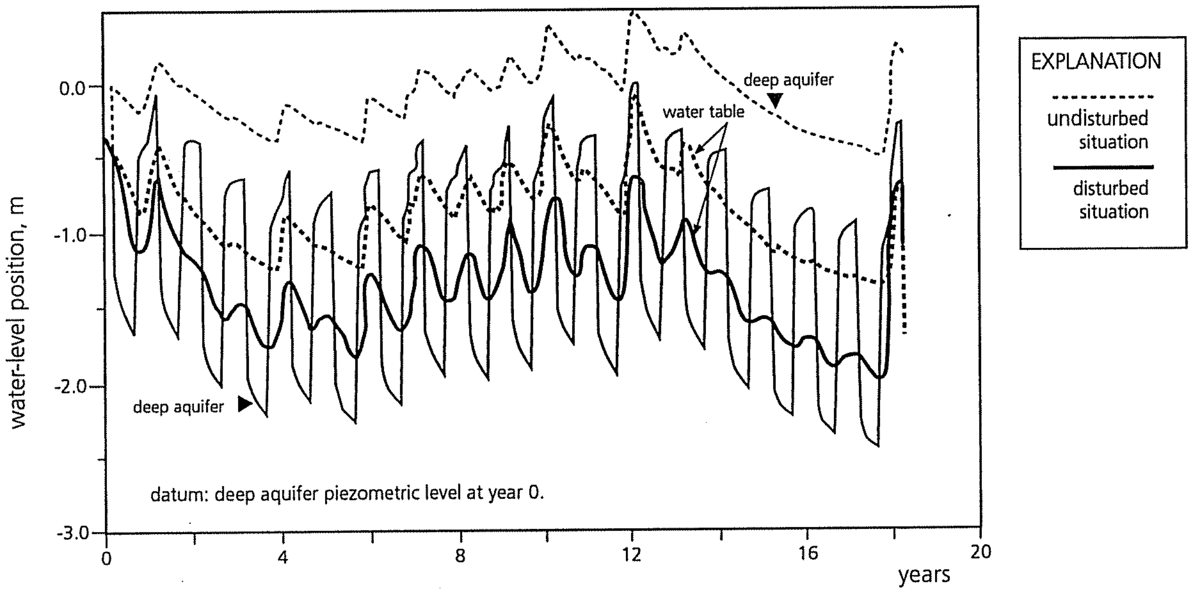
as were highlighted in the late 1960s in the southwestern USA and explained elsewhere (Custodio 1989, 1993; Foster and Foster 1989). One is stopping aquifer development (strict control). The other is no intervention, i.e. allowing further development to proceed (loose control).

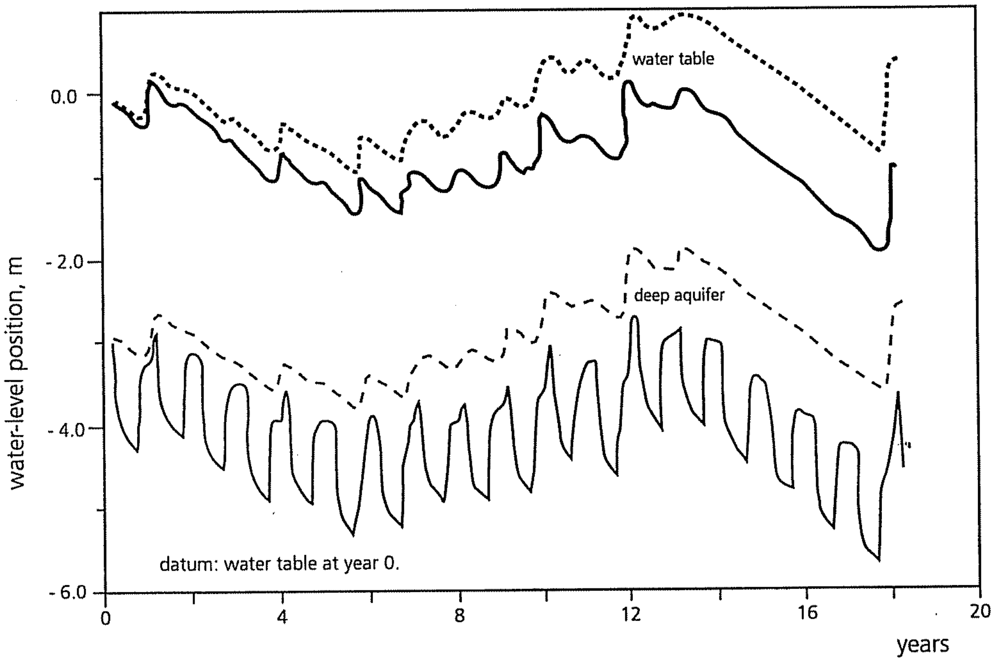
Strict control keeps groundwater abstraction costs low for existing well owners. This is what is generally desired by those overconcerned with groundwater use "problems" and "overexploitation". The objective is short-term, steady-state aquifer development by controlling well construction and keeping the total abstraction small with respect to recharge. Groundwater quality is stabilised or evolves slowly. But there are no incentives for efficient use of water, since its cost is low. To induce water-use efficiency, taxation or restrictions on water use may be needed. As the area develops, further water needs have to be supplied by water importation, often at a higher cost. This also means that those who previously obtained permits to develop the aquifer may now try to benefit from selling their water at the imported water cost. This is a speculative enrichment, but helps to promote more efficient water use. But since this may be unpopular, regulations are needed, either to forbid this practice or to allow the trade of water rights after making imported water cheaper by means of subsidies. All the above-mentioned activities may seriously decrease economic efficiency. But local environmental damage is kept small, although "aquifer overexploitation problems" and environmental damage may be transferred to the areas from which water is imported.

The loose-control option means no restriction to groundwater development which results from the increased demand. This increase is fostered by initial low water costs. But costs go up progressively as groundwater-level drawdown develops, due to increased energy consumption for pumping and the early modification or replacement of groundwater abstraction works. This means that some investments are abandoned before attaining their economic and technical life, or have to be refitted to increase water-use efficiency. Marginal water uses, which are unable to pay for the increasing water cost, are wiped out. Then, after some time, water-demand growth slows and afterwards decreases. Finally, total abstraction adapts to some aquifer-system perennial yield, often at a higher abstraction cost than under the strict-control situation. This is due to the long-term evolution of deeper groundwater levels, and eventually to

Fig. 9 Simulated water-table and deep piezometric-level evolution over 16 years in the two-layer aquifer (upper fine-to-medium sand layer, water-table aquifer, resting on a coarse sand and gravel formation) of El Abalario, in the southwestern part of the Doñana region, southwestern Spain. One of the curve sets shows the reference (undisturbed) evolution (measured groundwater heads) and the other the effect of a new battery of wells abstracting 160 Ls^{-1} from the deep layer at the irrigation Sector IV during half the year, every year. The *middle figure* refers to a monitoring location close to Cabezudos, near the Rocina creek, and the *lower one* refers to a monitoring location near El Abalario, in the centre of the recharge area (after Trick 1998) ▶







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the need for more expensive new water (imported, desalinated, or reused). The large drawdown may be accompanied by a reduction in size of the usable portion of the aquifer and in groundwater-quality deterioration, which may result in reducing the ultimate aquifer yield, and in local problems for some of the existing wells. There may be possible large indirect costs and serious environmental damage. Progressive taxation or subsidies may be needed to cope with present and future situations, as well as the establishment of a management institution. Sudden economic charges may be highly unpopular and may result in social conflict and political stress. Subsidies may be an economic distortion if they are not linked to taxation, and thus accelerate the depletion of reserves, which means fostering "aquifer overexploitation".

When what is described above happens relatively fast, the self-corrective action may arrive late and the negative effects show the worst economic and social results. The rapid reduction of groundwater availability and its high cost are usually blamed as the causes of investment loss, social unrest, and unfair treatment to the weakest and the poorest. This point of view is found in various papers and reports, mostly referring to small aquifers, and some authors add that the consequences may outweigh the human and financial resources needed to follow a sustainable development path. But in practice, as worldwide experience shows, the large amount of groundwater storage in aquifers often provides enough time for a progressive adaptation. Even in the case of small aquifer units, obtaining external water resources, or perhaps displacing relatively small communities that are unable to pay high water costs, or are affected by poor groundwater quality, may not be too high a social price, especially when it is amenable to reasonable social solutions and fair economic compensation. But some type of institutional control is needed to cope with the present situations and to solve those that have been inherited. However, local damage due to aquifer overexploitation may be of concern for isolated, poor regions in which mining of scarce groundwater resources from isolated, small aquifers has been fostered by inexpert developers or as a result of speculative practices.

A positive side of slowly, but progressively, increasing groundwater costs, especially when other cheap water sources are not available, is the possibility of obtaining dramatic water savings without decreasing quality of life and by maintaining employment. In agricultural areas this means moving from low added value, irrigated agriculture to high added value, intensive agriculture, especially if it is accompanied by low water demand agro-factories and by developing service industries. This is what has been observed in many areas, as will be discussed later, if excessive administrative interference and well-intentioned, but poorly drafted water management rules do not crush private initiatives. This is a positive side of aquifer "overexploitation". However, besides protecting the environment, there are some social issues to be taken into account to prevent the wiping out of marginal water uses from destroying the human complex around them, especially in rural areas where they are essential to control landscape degradation and desertification. In this case, some kind of clearly-defined subsidies are needed to pay for the social services rural populations carry out.

What has been said does not mean that loose control is a better economical and managerial option to deal with aquifer "overexploitation" than a strict one, since both are extreme theoretical situations. Intermediate solutions may bring improvements, provided instabilities are solved. The desirable position is a combination of existing regulations, institutional capability, social acceptability, stakeholder involvement and political will. Since all of them evolve, the capacity to adapt is essential. The final goal is sustainable water development, considering the whole set of resources rather than any one in particular. To attain this situation, which is not a fixed one, some temporary "aquifer overexploitation" may be needed, even if it results in some environmental damage.

Actual Results of "Aquifer Overexploitation"

In spite of some "doomsday" perceptions about the fate of aquifer intensive development, current experience shows that the catastrophic forecasts that were presented for aquifers, on the whole have not taken place at least in the last 30 to 40 years. This does not mean that the evolution of the impact of intensive development has been problem-free (Foster 1993). In some cases there has been significant environmental and habitat damage, which may be partly due to mismanagement.

In most circumstances, an evolution similar to that resulting from the loose control described before is what has actually happened, but with a relatively slow recession after reaching the abstraction maximum. This is the expected evolution, which has been aided by the introduction of measures intended to control aquifer use or to ease the recession period after the maximum level of exploitation. Often these measures are imperfect, inefficient, arrive somewhat late, are difficult to apply and lead to some speculation, but they have helped the aquifer achieve a condition of more or less sustainable use. However some problems may have been transferred to nearby areas, and even to far away regions in the case of distant water transfers.

Some of the most commonly applied measures have been some combination of incentives to abstraction reduction by increasing water-use efficiency (reducing distribution losses, better irrigation practices, industrial recycling, use of closed cooling systems with towers instead of open systems, control of water flow in heat exchangers), restriction of new well development and expansion of irrigation farming, improved surface–groundwater joint use (including artificial and enhanced recharge), protecting and increasing natural recharge by land-use management (terracing, creek management, reduction in planting phreatophyte forest areas), and purchasing of irrigated land to be transformed into natural parks, or areas of groundwater supply reserves, etc. The real measures, and how they are combined, depend not only on the local conditions, but also on economic, legislative, administrative, and political circumstances.

This is the experience of the last three decades and is probably what will happen in the future. Scientific and technical progress, together with social advances, may, and surely will, help in solving what currently is a matter of concern (Tierney 1990). But new challenges can be expected since the circumstances, regional effects, and other issues will be different.

In the USA "aquifer overexploitation" continues, although it is on the decrease, and this is not considered an issue of concern by many hydrogeologists and water managers. There is an evolution towards more efficient groundwater use after depleting a fraction of aquifer reserves and eventually restoring some of them. In the last two decades the irrigated area over the Ogallala aquifer of the western USA has decreased. This is the result of more efficient farming practices and of adjusting agricultural output to market conditions. In the Edwards aquifer in Texas (southern USA), a pilot irrigation-suspension programme was started in 1997 to increase spring flow and provide water-supply relief to municipalities during droughts. This means paying farmers to stop or reduce water use according to surface area, even at a price higher than rental rates of farms (Keplinger and McCare 2000). Other possible alternatives are subsidising more efficient irrigation technology and buying land. From an economic point of view, this last alternative seems the most effective one.

In northwestern Mexico, the Hermosillo and Guaymas aquifers continue to be a source of fresh water after decades of alarm, although the areas are forced into progressive adaptation. One of the main concerns was seawater intrusion, which was apparently modelled, but groundwater-salinity problems are due, at least in part, to upconing of deep-seated saline water in the aquifer system. The situation in Mexico City is more complex, since the huge metropolitan area is constantly expanding. But what is considered as serious aquifer overexploitation by some is simply considered mismanagement by others. Land subsidence, although spectacular, is not an intractable issue, and neither is it fully due to groundwater use.

In Israel, the aquifers continue to supply about one fifth of the country's total water consumption after more than 30 years of intensive use (Shamir 1993).

Intensive groundwater development has resulted in some serious, persistent environmental problems in Spain. Many of them involve coastal aquifers affected by seawater intrusion. But this is not always the case, since salinity increase may be the result of inflow of deep-seated or poor-quality aquitard water, and even return flows from large irrigation areas. In other cases, what seems to be aquifer overexploitation is the result of pollution, poor aquifer management and improper well siting, construction, and maintenance. Some examples can be found in areas close to Barcelona, in Catalonia (northeastern Spain) such as the Besós and Tordera deltas, and partly in the Llobregat delta, Garraf and Tarragona plain. In the Besós delta, long-screened wells have permanently depleted and connected the two-layer coastal aquifer, and disposal of industrial and urban sewage has severely polluted part of the aquifer by induced recharge. But in spite of these aquifers being important sources of water, they are small and behave as parts of a larger system. Consequently, the problems have been ameliorated by means of the development of other areas and by water transport. Now some of the aquifers are being restored as natural-storage reservoirs for emergency use and as a complementary fresh-water supply, due to their strategic location. The "highly concerning overexploitation" of the Camp de Tarragona aquifers (southern Catalonia, northeastern Spain) in the 1970s was corrected, in some aspects overcorrected, when about 30×10^6 m^3 yr^{-1} of water were initially imported to the area, which is much less than the aquifer overexploitation that was considered in some unpublished reports of the water authority agency (up to 150×10^6 m^3 yr^{-1}).

The most acute situation in Spain is that of the Segura River Basin, especially in the Murcia region and south of the community of Valencia (Fig. 2), on the semiarid Mediterranean side of the Iberian Peninsula (eastern Spain), where intensive aquifer use has been fostered to some extent by favourable prospects for water importation. The fast growth of irrigated agriculture was favoured, among other reasons, by low water prices, and the use of an underpaid labour force, mostly immigrants.

Water mismanagement and prospects of new water resources have the perverse effect of stimulating uncontrolled groundwater use and of fostering "illegal" exploitations. Solving this by successive arrangements for amnesty erodes management objectives, besides increasing the risk of desertification and exhausting optional alternatives, such as the use of aquifers in nearby areas. What seems to be the final solution to this situation is drastic reduction in water use with severe reconversion of the socio-economic system. This is something that seems achievable in a reasonable time and with a minimum of stress, provided negative economic side effects are eliminated.

The situation in eastern Spain is attracting much local attention and now is central to Spain's water policies, due to overreaction and protectionist water policies. Currently, an important new water transfer is under active discussion. This seems an interesting case of "aquifer overexploitation" to be followed and analysed, but actually there is more emotion and politics than data. The case has some similarities to what happened two decades before in other aquifers in the southwestern USA and northwestern Mexico.

In the La Mancha aquifer (Fig. 2), central Spain, there is a change towards sustainable use (Cruces et al. 1997; Llamas 1999). From 1987–2000, total groundwater use had been cut in half, and now the depletion of aquifer water reserves has been halted, and there is even some recovery of water levels, as pointed out in official re-

DOI 10.1007/s10040-002-0188-6

ports. In part, this is due to some control of abstractions and of the drilling of new wells by the water authority agency, the progressive involvement of associations of groundwater users, and a programme to try to reduce farm groundwater use with some monetary compensation for lost income. Although these measures are still very crude and controversial, they pave the way to sustainable use. Natural wetland restoration, however, is a long-delayed process, if it is feasible at all. Some artificial restoration, with imported water and management of neighbouring river basins has been carried out with some partial success, but canal excavation and land drainage have seriously damaged other previously untouched wetlands, which would have been an effective, although less spectacular, alternative to the destruction of habitats.

In the Doñana aquifer, southwestern Spain (Fig. 2), the "overexploitation" situation is partly under control since the number of wells and groundwater abstraction are not increasing. The damage does not progress except for the still poorly known, and delayed effect of agricultural pollution on habitats. The incorporation of some of the areas that had been subjected to irrigation into protected areas is part of the reason for success, as well as the progressive replacement of large tracts of planted eucalyptus forest in shallow-water-table areas by native brush vegetation, which results in increased net recharge.

Identification of "Aquifer Overexploitation"

Since "aquifer overexploitation" is mostly a qualifier resulting from the perception of some undesirable results of groundwater use, which varies with the point of view and the social group, there is no sure warning sign to decide on what is happening in the aquifer. This is further obscured by the delayed and transient effects of aquifer behaviour in response to prolonged pumping and the over-imposed variability derived from natural processes, e.g. recharge and river flow, and aquifer use. There is no rule-of-thumb permitting a water authority official to decide confidently, and with a low error risk, that an aquifer is being exploited at a rate greater than recharge. Besides, this is not needed from a technical point of view. This is a handicap for application of the Spanish Water Act (Law 29/1985) and perhaps of some provisions of the recent European Union Water Framework Directive (Directive 2000/60). There is no substitute for a sound understanding and quantification of aquifer behaviour, as commented below, especially for effective action.

Some of the easy-to-see warning signs are associated with continuous groundwater-head drawdown, spring-flow decrease, and progressive water-quality deterioration, but they are not certain since a mild exploitation may produce a similar behaviour. Other changes, such as river-flow decrease, wetland-area reduction, displacement of poor-quality groundwater, and land subsidence generally occur at too slow a pace; meaningful decisions need a long monitoring time to reduce the variability effect, which obscures the trends.

"Aquifer overexploitation" can only be declared with some reliability after the concept is bounded and explained, and after the aquifer and/or aquifer-system behaviour adequately known. This knowledge needs a realistic conceptual model that is based on monitoring of data on aquifer behaviour. It often has to be supported by flow and mass-transport calculations and numerical modelling. Once the current consequences of aquifer development are quantified, and projected into the future if required, and the effects are studied, is it possible to decide on issues of intensive aquifer exploitation. Science and technology, however, can be used to explore the implications of different interpretations of sustainability and overexploitation, but they cannot choose which interpretation society will adopt (Sophocleous 2000). This may be frustrating for water managers and decisionmakers, who generally ask for on-the-spot decisions. Fortunately, in most circumstances, aquifer management can progress in accordance with the slow pace of changes and the generally low rate of economic investments. But this progress, or advancement by small steps, needs an administrative and legal framework that allows progress to continue in this manner. Issues, such as water rights, protection of investments, water-use preference and aquifer-use quotas have to be adapted to step-by-step changes in a relatively flexible and responsive administrative framework. This may be a major difficulty when groundwater rules are based on surface-water and real-estate rights.

Management Options and Solutions for "Aquifer Overexploitation" Situations

Most of the major negative effects of aquifer use can be forecasted and quantified. This allows for anticipating the behaviour, devising corrective action, and taking into account externalities. Therefore, many of the situations that may be qualified as "overexploitation" can be solved, and the benefits of aquifer use can be adequately developed. Externalities should be included in any rational groundwater development plan, although some terms are the subject of argument (Azqueta and Ferreiro 1994). Otherwise the costs are passed on to others, now or in the future, without due compensation. This form of non-sustainability is one of the facets of "aquifer overexploitation".

Environmental, economic, and social impacts, which have to be considered as well (Llamas 1999), are much more difficult to quantify. But they are often much smaller and more delayed than the impacts produced by large surface-water works. In any case they should be evaluated and incorporated in some way into the price users should pay for groundwater. Bacchus (2000) includes in these costs the depletion of strategic fresh groundwater reserves, the loss of habitat in continental and coastal wetlands, the effect on riparian and massive benthic organisms, the increased risk of large-scale wildfires, the need to remove diseased and dead trees, and

DOI 10.1007/s10040-002-0188-6

the contravention of existing water rights. Although land subsidence and collapse may be dramatic in some cases, they may not constitute an unbearable local and/or social burden when compared to the economic and social benefits of groundwater development. However, the costs involved may be difficult to quantify.

A trade-off is needed to try to balance the direct and indirect costs and the non-easily evaluated environmental damages from one side, with the benefits to direct users and society on the other side. This provides elements for a sustainable development in an extensive water-resource and economic context, including preservation and restoration of the environment, and compensation of damages. But the changing nature of water requirements and demand, and the expected future scientific, technical and social evolution and improvements are factors to be considered. Some groundwater must be depleted, however, before the aquifer system approaches a new equilibrium after establishing some level of groundwater use. For large, low-diffusivity aquifers the response is so slow that storage depletion and water-quality changes will continue well beyond any reasonable planning horizon. In this case, a declining trend of groundwater levels in response to aquifer development is characteristic, which means an increasing water cost, at least in the early stages, although this cost increase may not deter groundwater abstraction for domestic and industrial supplies or for irrigation of valuable crops.

To deal with groundwater management issues and the concerns behind "aquifer overexploitation", a water authority agency associated with some kind of institution empowered to set objectives and rules seems unavoidable. It is also needed to collect funds and to redistribute and invest them, in order to try to compensate for some inefficiencies. But the degree of involvement may vary from very loose to strict control of groundwater-development activities, as commented above.

Groundwater users should be involved in the management process, as should other people and organisations (stakeholders) who are directly or indirectly affected by aquifer use and who may be concerned for aquifer overexploitation. This includes groundwater developers, farmers, town authorities, water managers, land-use planners, decisionmakers, environmentalists, ecological organisations, groundwater scientists and experts, local people, and the mass media.

What appears to be the best solution to this situation is the creation, organisation and involvement of an aquifer users' association or collective entity (Galofré 1991; Aragonés et al. 1996; Freeman 2000), representing common interests and sharing some responsibility for aquifer management with a water authority agency, including setting, collecting and applying funds, and supported by adequate rules to set objectives, carry out general activities, and correct any deviant attitudes of the members.

Groundwater mining may be economically admissible and justified in arid countries (Margat and Saad 1982; Barber 1992; Dabbagh and Abderrahman 1997; Lloyd 1997, 1998) if the physical, water-quality, environmental and social damage is bearable and can be compensated under widely accepted rules. Groundwater mining is a transient situation with an end. This leads to the initial local situation, after abandoning investments and applying benefits, as in a mine, or to a new alternative local economy with a different freshwater source, which is often more expensive but affordable if groundwater mining has created a sustainable socio-economic development in the area. Groundwater mining can be carried out by developers up to the withdrawal of the total water volume for which increasing actualised costs become equal to the final decreasing actualised benefits. But at this point, social benefit is nil and there are no economic resources left to compensate for the damage and to develop a new water source and/or human opportunities. From a social perspective, the exploitation should end earlier, in terms of the volume of withdrawn reserves, when the actualised net benefit is maximum (Young 1993). This can be achieved by a groundwater-mining plan or through water abstraction taxation. How to use the collected funds is not a simple issue, but the goal is sustainable economic development.

To cope with what are often called overexploitation situations, and to solve some of the effects and feelings involved, there is a necessity for: (1) making the role and value of groundwater and the aquifer-flow system known; (2) preparing, analysing and explaining future aquifer-use and water-availability scenarios; (3) applying part of the economic benefits for the protection, restoration and enhancement of aquifer recharge; (4) integrating existing water "problems" into a global framework, taking into account all available water resources, the economic issues, the social values, the environment, and the current land-use situation and planning; (5) maintaining effective water-management institutions, with good aquifer knowledge, efficient and trained staff, good monitoring facilities, adequate economic resources and adequate regulations that are capable of integrating stakeholders, keeping people informed and optimising water resources in a regional framework; and (6) encouraging rational use and conservation of groundwater and other freshwater resources.

Nevertheless, hydraulics and economics are not enough to evaluate groundwater overexploitation, since ethical considerations are involved, as are the exploitation of other natural resources and the environment, as stated by John-Paul II (1991). They have to be evaluated in at least a regional context and by introducing solidarity as a necessary background. All this is beyond science and engineering, and even common economics.

Conclusions

Any groundwater development has some negative side effects, which also happens with any other natural-resource and water-resource development. These negative effects should be reasonably small, bearable, compensable, and legally tolerable, taking into account groundwater quantity, quality, availability in space and time, cost, technical and administrative readiness for use, and the reasonable preservation of the environment and related habitats. There is not a unique solution, but a trade-off which may evolve over time. Initial groundwater development conditions will surely evolve and deteriorate but, on the whole, net benefits will increase up to some level. The fear of change should not prevent some advanced development, provided it is sustainable in regional terms.

Aquifer overexploitation has become a term that is increasingly used to point out negative aspects of groundwater development. It is not directly related to groundwater abstraction being greater than or close to recharge, in spite of the fact that this relationship is often qualitatively mentioned. Progressive groundwater-head drawdown and water-quality deterioration, reflected in an increase in the cost of water and a reduction in availability, is what is finally used to qualify the situation. The perception may change and evolve according to knowledge, technology, water needs, and socio-political constraints.

A persistent groundwater-level drawdown trend is not a sure criterion for deciding whether abstraction is equal to, or greater than, recharge, nor is the fact that the water quality in some wells is progressively deteriorating. Long-term transient effects may be important in aquifers. Moreover, recharge may change with development, and the aquifer response depends on the distribution of wells.

Depending on the restrictions imposed, any groundwater development could be considered "overexploitation", which would lead to the impossibility of using aquifers under severely restrictive legal conditions. This is an overreaction that is unsound in practice. There is a benefit from using groundwater, which compensates technical, economical, and environmental costs if withdrawal is regulated, but there is some unavoidable use of groundwater storage. This means that some temporary "aquifer overexploitation" may be acceptable, and even convenient, provided that its characteristics are known, the costs are internalised, it is considered within the whole set of the available present and future water resources, and the social benefits are optimised. This includes considering how much environmental change is acceptable or compensable. There is no unique solution.

The increased groundwater costs due to "overexploitation" have the positive effects of reducing groundwater abstraction and thus introducing some feedback that levels the withdrawal rate. If this reduction is slow and steady, as is the case in most large- and medium-size aquifers, it helps to improve groundwater-use efficiency and to eliminate uneconomical marginal uses. It also favours the early formation of stakeholders' associations for managing the abstraction scheme. But there is some loss of investment and greater environmental damage to be compensated, for which some taxation revenue may be needed. Too fast a change may result in some social stress and suffering for the less adaptable, but in practice this does not happen in large groundwater systems, and in small ones there is often the possibility of making a correction and sustaining bearable damage to a relatively small region.

It is possible for concerns over "aquifer overexploitation" to go unsupported because of poor information about the aquifer system or biased knowledge. It is also possible for these concerns to be introduced to promote other water-supply sources, which are often more expensive, with large infrastructures, and are less acceptable environmentally. This would result from perverse subsidies that often unrealistically decrease the cost of other water sources, as the outcome of promotional activities for other purposes: political goals, promoting employment, maintaining some business activities, or yielding to popular pressure, and again it reflects poor knowledge of the aquifer system and groundwater behaviour.

What may be called "aquifer overexploitation" may also be due to speculative activities, the adoption of inadequate technical solutions, low water-use efficiency, poor well construction, contamination, and poor water-resources management.

It is not possible to provide a sure and widely acceptable definition of overexploitation based on simple rules. Not only are scientific and technical factors involved, and quantity and quality issues at stake, but also economical, social, and political ones. All this is compounded with the long transient responses of aquifers that are due to the large volume of groundwater storage, and the slow and complex pattern of groundwater flow. In fact, many of the situations considered as "overexploitation" are based on an evolution linked to the transient period after groundwater development started, and have no clear relationship with aquifer recharge and development, but with aquifer characteristics.

The term aquifer overexploitation may be a qualifier to denote that some negative evolution is being produced, and as such it varies according to the point of view of the group: abstractor, non-abstractor, supplier, farmer, local inhabitant, manager, environmentalist, politician, journalist, and with time. What is needed for aquifer management and decisionmaking is a measure of negative effects of aquifer development in the framework of short- and long-term aquifer-water balances under realistic scenarios. This may require flow and mass-transport modelling, based on sound aquifer-system knowledge and adequate monitoring, in order to counterbalance popular pressures and feelings, and the water manager's reaction, when facing some unforeseen problems, that some action is needed from someone to halt groundwater development, to develop and/or to import other water resources, and to declare that aquifer use is intrinsically unsustainable.

Overexploitation, and even groundwater mining, are not necessarily bad from an ethical point of view when considered in a regional context. Some negative effects are necessarily linked to groundwater use as a means to produce an economical and social benefit to develop an area and to have better and more effective use of water in the future. The unethical side appears when no social benefit will be derived and applied in the area, and social and environmental damage and increased water costs are transferred to others and to future generations that lack economic resources to cope with them.

DOI 10.1007/s10040-002-0188-6

Although loose control of intensive groundwater development is often blamed as the source of overexploitation, with consequent serious water problems and social disruption, in practice this is not the case, except in small aquifers, and even in this case alternative and complementary solutions can be sought. But medium- and long-term environmental damage may be of concern and needs due consideration and correction.

Many of the negative aspects of aquifer development leading to the perception of overexploitation can be easily internalised, and environmental damage can be corrected or compensated monetarily. But regulations are needed, as well as an adequate water-management institution and the effective participation, involvement and shared responsibility of groundwater stakeholders and developers.

The difficulties in defining overexploitation and the inherent uncertainty of the magnitude of recharge should not hinder groundwater use. Large groundwater storage, which means slow hydraulic changes, allows for aquifer-system management and correct decisionmaking, provided that progressive adjustments are possible.

In spite of the currently reasonably well-developed hydrogeological science and technology, especially from the point of view of aquifer use to satisfy human needs, less than half a century of intensive development, and in many cases only a few decades, is too short a time to fully understand all the side effects involved and to make people aware of the pros and cons. Therefore, it is not surprising that old and new "hydromyths" pervade aquifer management. They are reflected in many of the aspects of aquifer overexploitation and the forecast of future disasters, even if they have only become reality in some extreme and local situations. There is an urgent need for well-documented case studies, presented and analysed from a multidisciplinary approach. This may prevent future mistakes, avoid damage, tame fears, improve efficiency, protect social values, increase respect for nature, avoid losing opportunities, and save economic resources.

Acknowledgements Many of the ideas expressed in this paper are the result of the author's collaboration with colleagues at the former Eastern Pyrenees Water Authority, Barcelona, at the Department of Geotechnical Engineering of the Technical University of Catalonia, Barcelona, at the Instituto Geológico y Minero de España (Geological Survey of Spain), Madrid, and at the Foundation International Centre for Groundwater Hydrology, Barcelona. Some ideas in this report have been taken from Spain's CICYT Projects PB.87.0842, AMB.92.636 and AMB.95.0372 on Doñana, and European Union Projects EV.5 V.CT94.0471 (GRACE), EN4. CT95.0156 (PALAEAUX) and EVKI-CT-1999-0006 (BASELINE). But the ideas expressed are the author's responsibility. This report derives from a summer course held in Roquetas de Mar, Almeria, Spain, in summer 1999, and is a fully redrafted and updated version of a monograph issued by the Fundación Marcelino Botín (Custodio 2000b). Useful comments have been received from Dr M.R. Llamas (Universidad Complutense de Madrid) and Dr A. Sahuquillo (Universidad Politécnica de Valencia), as well as reviews by Dr J. Carrillo (Universidad Autónoma de Mexico), Dr Peter Cook (Australia), and an unknown person.

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