USO INTENSIVO DE LAS AGUAS SUBTERRÁNEAS
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THE COMPLEX CONCEPT OF OVEREXPLOITED AQUIFER

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PAPELES DEL PROYECTO AGUAS SUBTERRÁNEAS

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THE COMPLEX CONCEPT OF OVEREXPLOITED AQUIFER

ABSTRACT

An aquifer could be considered as overexploited when abstraction is greater or close to recharge, considering long-term mean values. However, recharge and even abstraction are uncertain terms, which may present a large variability range. Also, mean recharge is not constant since it may be modified by human activities and aquifer development. Nevertheless, in practice overexploitation is a concept preferentially linked to the observation or perception of some persistent negative results of aquifer development such as continuous water level drawdown and quality deterioration. These results are not necessarily linked to asbtraction being greater than recharge. They may be the result of the long transient period after changes are introduced and depend on aquifer water storage, aquifer size, and permeability. In addition, overexploitation is often linked to negative and undesirable economic, ecological, social and political results. This makes impossible a simple, accurate, universal definition of overexploitation. But it is now a legal term after the Spanish Water Act of 1985. The detailed and updated description of intensive (or not so intensive) development effects, based on monitoring, good aquifer knowledge and calculation or modelling is what provides the information needed to decide what level of aquifer development is advisable or bearable at a given place and time. This refers to a set of objectives set by a management institution, following existing regulations, with the involvement of groundwater stakeholders and taking into account relevant economic, social, ecological and political constraints. Overexploitation is often associated to something ethically bad, but it is not necessarily so, even for the extreme situation of groundwater mining. In many cases some kind of aquifer overexploitation may be a necessary and desirable stage in the evolution towards sustainable development.

RESUMEN

EL COMPLEJO CONCEPTO DE ACUÍFERO SOBREEXPLOTADO

Cuando la extracción supera, o se aproxima, a la recarga se puede decir que un acuífero está sobreexplotado, considerando valores medios a largo plazo. Pero la recarga, e incluso la extracción son términos inciertos y que presentan un amplio intervalo de valores. Asimismo la recarga se puede modificar por actividades humanas y por la propia explotación del acuífero.

En la práctica se dice que hay sobreexplotación cuando se observan o se advierten ciertos resultados negativos de la explotación, tales como un descenso continuado del nivel del agua o un deterioro de la calidad.

Pero estos efectos no están necesariamente relacionados con el hecho de que la extracción sea mayor que la recarga. Pueden ser el resultado del dilatado período transitorio que sigue a los cambios de extracción, y que dependen del almacenamiento de agua en el acuífero, del tamaño del acuífero y de su permeabilidad.

La sobreexplotación se relaciona a menudo también con aspectos negativos de carácter económico, ecológico, social y político. Todo esto hace que no sea posible llegar a una definición precisa y universal de sobreexplotación.

No obstante, actualmente es un término legal después de la promulgación de la Ley de Aguas española de 1985. Para decidir qué nivel de explotación del acuífero es aconsejable o soportable hace falta la descripción detallada y actualizada de los efectos de la explotación intensiva (o no tan intensiva), de acuerdo con observaciones de control, buen conocimiento del acuífero y cálculos o modelación.

Esto se refiere a un conjunto de objetivos establecidos por una institución gestora, de acuerdo con las leyes y reglamentos en vigor, con la implicación de los que tienen un interés en el agua subterránea, y teniendo en cuenta los condicionantes económicos, ecológicos, sociales y políticos que sean relevantes.

La sobreexplotación suele asociarse a algo éticamente malo, pero no tiene por qué ser así necesariamente, incluso en su manifestación más extrema, que es la minería del agua subterránea. En muchos casos alguna forma de sobreexplotación puede ser una etapa necesaria y deseable en la evolución hacia un desarrollo sostenible.

INTRODUCTION

In arid and semiarid areas in which climate and soil are favourable there is a large potential for developing human settlements and the related economic activities. This means large and increasing freshwater demand, which becomes progressively a scarce commodity. Irrigated agriculture, as well as artificial grassland, and gardening, are often the main freshwater consumers, well ahead of the strict home water demand.

Much attention has been paid to groundwater development, which is often the more accessible, cheap and reliable freshwater resource. This is now a well established situation in Central and South-western United States, and also in the areas around the Mediterranean sea, as in Central and Eastern Spain and its archipelagos, and more recently in large areas of China, and even under dramatic situations in the oil rich but water poor countries of the Near and Middle East. Also aquifers around megacities such as Mexico, Sao Paulo, and Lima, are intensively exploited and constitute the main source of freshwater. As it will be commented afterwards there are large advantages from using groundwater but also negative side effects, like also happens in any other human activity and in the development of any natural resource. Preserving the beneficial use of the resource is the main concern under non-stressed circumstances. However, as some negative aspects become or are perceived as socially detrimental the emphasis moves towards damage control and sustainable use, and it is not rare that then some doomsaying begins to appear. The first aspect refers to approaches such as the safe yield of what is assumed to be a renewable resource. It was introduced mainly in the 1920's in western United States (Meinzer, 1920), when widespread use of drilled wells and electrical turbine pumps dramatically changed the way of developing aquifers by allowing large abstractions from deep boreholes.

The concern about the negative aspects, although recognised from the 1920's as well, is much more recent and shyly appears around 1970 in some regions of the United States and Europe. This is due to growing awareness of progressive groundwater level drawdown, water quality deterioration and sometimes land subsidence (Margat, 1977). Then overexploitation, and other designations such as overdraft and overuse, are terms that become increasingly used. Aquifer overexploitation was converted into a legal term in the 1985 Spanish Water Act (Villarroya, 1994), but a simple, accurate and widely accepted definition is missing. Overexploitation is now a common designation of a large variety of poorly defined situations that have in common some perception, real or not –often deviated– of negative and perhaps irreversible evolution by some sectors of Society. This situation applies to the development of many natural resources when societal forces intervene but act with poor information, insufficient knowledge and taking as obvious what is really a partial and biased appraisal of reality.

The International Association of Hydrogeologists, leaded by its Spanish Chapter, discussed the concept and the real meaning and situation of aquifer overexploitation in a national meeting in Almería, Spain, in 1989 (Pulido et al., 1989) and later on during an international congress in Puerto de la Cruz (Tenerife, Spain) in 1991 (Candela et al., 1991; Simmers et al, 1992). They were followed immediately by an 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 was already presented at those meetings. Most of the later papers deal with the same aspects, under different points of view, but with little new developments, as does the present paper, which does not contribute new concepts and improvements but an attempt to update the situation about how aquifer overexploitation is perceived and its significance, following what was said in former papers (Custodio, 1992, 1993).

Recent literature on the subject of groundwater and aquifer overexploitation is relatively scarce and mostly limited to arid and semiarid areas or to some aquifers. But old misconceptions persist and sometimes continue their spreading, mostly propagated by water managers and administrators and by some hydrologists who do not have a sound understanding of groundwater and its long-term behaviour, or who look for too simplistic, deviated approaches, mostly based on surface water experience. Both situations explain some water regulations in Spain (Llamas and Custodio, 1985; Llamas, 1998), although this happens in many others countries as well.

BASICS ON GROUNDWATER BEHAVIOUR AND CHARACTERISTICS

Surface water, except for large natural or artificial lakes, exists only in linear form over a very small fraction of continental surface, often away from water demand areas. It flows relatively fast and with a short turnover time (days to weeks). Thus, climatic variability is reflected in large fluctuation of surface runoff. To make it less variable Nature counts on the limited storage or the soil-vegetal cover complex, wetlands, and lakes. Often, to be able to supply man's needs dams have to be constructed to increase surface water storage.

Groundwater and its external manifestations as river base flow, spring flow and more or less perennial wetlands are naturally associated to the large storage in the ground pores and fissures. Groundwater flow is commonly very slow, from a few m/day to less than one m/year, which means turnover times of some years to millennia.

Often the natural groundwater system contains aquifers and aquitards. Both of them contribute to the water reserves, although groundwater flows mainly through the aquifers, which are the formations able to contribute water to abstraction wells.

The large storage capacity of aquifer systems transforms the variable recharge into a much more constant discharge. Common aquifer recharge sources are precipitation, surface runoff, surface water, leakage from reservoirs, tanks and pipes, excess irrigation water and transfer from other aquifers, laterally or through aquitards bounding the aquifer from above or/and from below. These terms are given following the common decreasing degree of temporal variability.

Discharge is by means of springs, diffuse seepage, river base flow, direct evapotranspiration from the saturated zone by phreatophytes, wetland areas and lakes, artificial abstraction through wells, galleries and drains, and flow to other aquifers.

Recharge is dominantly produced over large areas, directly on aquifer outcrops and indirectly on the aquifer system surface area. Discharge is generally concentrated in relatively small areas at local and regional land surface depressions. These areas may be isolated spots, or continuous or spotty elongated areas along land surface features.

The horizontal dimension of aquifers is much larger than thickness. This means that groundwater flows in layers following their geometrical layout. Nevertheless, when the aquifer system is considered the water head potential may change with depth and the dominantly horizontal flow in aquifers is changed into vertical flow through aquitards.

Thus, actual flow is three dimensional, especially in preferential recharge areas, where head potential decreases with depth, and more conspicuously near natural discharge areas, where water head increases downwards. Artificial abstraction from some layers and some special natural conditions (preferential discharge through vertical discontinuities, such as faults, or at far away outcrops through high permeability layers) may modify the *normal* flow pattern.

A sudden change in recharge or in abstraction is propagated through the aquifer by means of a water head evolution –hydraulic response– and fades out when discharge is adjusted to this change. Time for stabilisation can be measured by $\alpha\ L^2/D$ (Custodio and Llamas, 1976; Freeze and Cherry, 1979; Rorabaugh, 1960; Lloyd and Miles, 1986), in which:

α = factor which normally vary from 0.5 to 2.5

L = measure of the dimension of the groundwater flow system being observed (eg. width of a depression or valley)

D = hydraulic diffusivity = T/S

T = aquifer or compounded aquifer system transmissivity (horizontal permeability times the thickness)
S = aquifer or aquifer system storage coefficient

When the perturbation is produced in a given aquifer of an aquifer system, the effect initially concentrates in it, but slowly affects the whole system by interaquifer leakage. This means that the effective value of L increases and that of D decreases. Even S values corresponding to initially confined conditions evolve towards regional drainable porosity around the water table position. The result is a slowdown of fading out of perturbations. Initially, after the change of recharge or abstraction, discharge remains as it was. This means that water head changes are produced at the expenses of increasing or decreasing groundwater storage, initially at the rate of the change, and then slowly fading out.

All this is well known groundwater hydraulics and can be found –although not always explicitly enough– in any Hydrogeology and Groundwater Hydrology book (Freeze and Cherry, 1979; Fetter, 1980; Custodio and Llamas, 1976). However, it seems ignored by many hydrologists and by decision-makers without sound knowledge of groundwater. This is the reason to include in this paper such elementary considerations, already presented in the above-mentioned former paper (Custodio, 1992) and in other papers of the same book (Simmers et al., 1992).

In relatively low permeability and/or large aquifer systems a change of recharge or withdrawal can be accompanied by large, long-term water table and water head changes, that progress at a slow pace. This explains why the effects may go unnoticed in the short-term.

In some cases of very large, low hydraulic diffusivity aquifers, the natural change of groundwater recharge, due to climatic change at the Pleistocene-Holocene transition, or that suffered afterwards when sea temperature and circulation adjusted to the new conditions, is still in the transient stage and natural aquifer behaviour still corresponds to an unsteady situation. Something similar happens when the base level of natural discharge changes its elevation (erosion, sedimentation, obstruction, coastal line modification, eustatic level changes).

Water quality changes still evolve at a slower pace since they depend on physical water movement in the ground, both in the unsaturated and in the saturated zone. Groundwater velocity follows Darcy's law: $v = -(k / m)$ grad h, in which:

v	=	mean groundwater velocity through a given formation
k	=	mean formation permeability
m	=	mean total effective (kinematic) porosity open to flow
h	=	water head (piezometric level)

Groundwater velocity is relatively high in large fissures and discontinuities, small in aquifers and very sluggish in aquítards. Thus, in an aquifer system groundwater movement is very different from one layer to another. Heterogeneity plays a dominant role in the resulting pattern, which is decomposed in dominantly horizontal and vertical flows. But the final result is a delayed to very delayed breakthrough of changes.

Actual mass transport of almost conservative (non interactive and stable) solutes, such as chloride and bromide, sulphate and nitrate in oxidising environments, and tritium and water isotope concentrations, follow the groundwater velocity pattern (advective transport) with some hydrodynamic dispersion due to differences in the microscopic velocity. However, the picture is more complex since there is transversal diffusive mass flux between closed and open pores and fissures, and between layers with different flow velocity. When pores are very small, as in aquitards, ionic exclusion may reduce effective porosity for the transport of ions (mainly cations), which means making it faster.

In hard rock aquifers, discontinuities (joints and fissures) may play a significant role since groundwater moves preferentially through them, but storage is produced mainly in the blocks limited by the discontinuities. In the unsatured zone the existence of discontinuities (joints, cracks, tubes) may condition recharge and mass transport in a complex manner.

The compound effect of spring flow and long screen wells is a mixing of water from different permeable layers. This effects water sample chemistry and isotopic composition. As a consequence, ages derived from environmental radioisotopes or environmental changes are only apparent. The mixing pattern changes and evolves with the duration and distribution of pumping and recharge events, with short-term variations due to fast water head modification, and long-term ones due to advection and diffusion. Macroscopically this appears as a dispersive-like effect represented by a large value of a fictitious dispersion coefficient. This coefficient increases with heterogeneity, distance and time. For a given fully confined, homogeneous layer with a small recharge area the value of this dispersivity coefficient may vary from a few to some hundreds of metres, but in heterogeneous multilayer aquifer systems it may grow up to a value close to the aquifer system size in the flow direction. In theory it is about twice this value (Maoszewski and Zuber, 1980; Zuber, 1986).

When the solute being considered interacts with the solid matrix by ion exchange or adsorption the transport is delayed and the fronts smoothened, which enhances dilution of discrete inputs of the substance. Absorption (fixation) and degradation also delay and smooth the fronts, and enhances dilution, but degradation, chemical reaction and radioactive decay may imply the incorporation (addition or introduction) of the reaction products along the groundwater flow path. Often the changes due to these phenomena mostly concentrate in strips in the unsaturated zone and in the different layers of the saturated zone, producing dissolution-precipitation fronts (important in redox condition changes) or chromatographic patterns for reactive ions transport. These strips shift their position with time, not only due to modification of permeability and of the sorbed complex but to recharge changes (including the mass supply) and the effect of aquifer development.

GROUNDWATER DEVELOPMENT ISSUES

Groundwater development to supply human needs has its positive and negative aspects, as happens to any other human activity and interference with Nature. They must be balanced in a trade-off to compensate the direct and indirect costs and the non-easily valued environmental damages with the benefits to direct users and to society. This provides the necessary elements for sustainable development in a wide water resources and economic context. It requires taking into account the dynamic nature of water needs and demand, and the expected future scientific, technical and social evolution and improvements. This evaluation involves taking into consideration environment preservation, restoration, and the compensation of damages.

Recognising and evaluating costs (disadvantages) and benefits (advantages) is a necessary step in the rational use of water resources, and specifically in developing a groundwater system as a source of water, while preserving as much as possible its environmental role.

The development of surface water resources has costs and benefits as well. Many important cost items, and especially indirect and intangible ones have often been neglected or downscaled to favour major, high investment costs (often hidden behind subsidies or the direct use of public funds) but easy-to-see and politically rewarding projects. Unfortunately this is an almost universal situation. Alternative or combined solutions to minimise environmental damage and maximise the net economic and social benefits are rarely considered or only mentioned to be later discarded without detailed studies. Often what are called development alternatives are really only variations to optimise a given project or to overcome local construction difficulties. In many cases, although not always, groundwater development is a better, less aggressive and less constraining option, at least in the stage of economic development and for distributed demand. Joint use of surface and groundwater resources is often a sound, long-term alternative.

In any case, the common trend of offering as much cheap water as demand can absorb is an environmentally unfriendly and unsustainable attitude, which may involve long-term large costs. The alternative is progressive reduction of water demand by savings and improving its use efficiency. From a macroeconomic point of view, preservation or increase of economic and social benefits such as quality of life and employment should accompany this reduction. These aspects are outside the objectives of this paper but have a definitive influence on aquifer development and especially in the appraisal of *overexploitation*, its perception, and its solutions. The advantages of groundwater development are associated to the large storage capacity and the sluggish groundwater flow velocity. This is reflected in:

a) small variability of natural and artificial discharge, water quality and temperature, except for short-term changes of water mixing produced by long-screen or multiscreen, variable discharge wells.

b) closer location of wells to the water demand due to the generally large surface area of the land above the aquifer system. This means lower investment, faster availability, much less land occupation, and less permits to pass through land properties. This is not only favourable for distributed water demand in rural areas but for town supply as well, since the water supply network can be fed from different points and storage facilities can be reduced to a minimum or even unneeded.

c) large storage reserve to allow for intensive abstraction during short periods of time. This is adequate to cope with peaks of demand, water needs during droughts or emergency situations as backup facility for supply failures and natural hazards, human failures, accidental pollution of other water sources, criminal action and even situations of conflict and war (Khair et al., 1992). These aspects, and especially those to cope with drought (Sahuquillo, 1991) are now widely recognised and accepted by those who tend to ignore and dismiss groundwater as a reliable source of water supply. However, at the same time this is often used as an excuse to assign to groundwater only this role, as stated in MOPTMA (1995). This attitude ignores other advantages of groundwater and even the increase in regulation provided by the delayed response when water demand is variable.

d) the sluggish flow through small voids. This means that besides the filtering effect on particulate matter and microorganisms, there is enough time for the progress of chemical reactions, for pathogens and short and medium lived radioisotopes decay, and for smoothing temperature changes. This means that in many cases, if wells are correctly sited, designed, constructed and maintained, groundwater can be used directly for drinking purposes provided it does not contains inconvenient natural or artificial substances, since biological quality is generally good and it is free of suspended particles. Many of the quality problems groundwater is blamed for are due to poor abstraction works, cross-contamination among aquifers and sometimes to failures in avoiding or isolating some layers, and to poor siting in the case of coastal aquifers.

e) the slow groundwater movement and the delayed transport of reactive substances. This provides some important protection against accidental pollution of the groundwater body in the short term, since there is some time to carry out corrective measures. This does not mean that groundwater is protected against contamination and pollution. Aquifers are susceptible to be affected by point and diffuse contamination sources, with delayed, long-lasting effects and difficult and costly restoration (Sahuquillo, 1998).

f) the relatively easy and reliable knowledge of groundwater resources and aquifer system behaviour. This is susceptible to be updated as development progresses, when better information is needed. Besides, the large reserves relative to annual flow allow preparing reliable future scenarios in which climatic fluctuation and variability is downscaled.

Major negative aspects and drawbacks of groundwater development refer to water quantity, water quality, and other effects. They include hydrodynamic, physico-chemical, environmental, social, and economic aspects. Groundwater development modifies the flow pattern. This results in:

a) groundwater head progressive drawdown until some stable situation is attained if abstraction is less than actual recharge (Fig. 1). Actual recharge under disturbed conditions is often greater than under natural conditions if land use changes do not introduce additional impairment. Progressive drawdown means increasing water cost due to more energy consumption and the early replacement and deepening of wells and pumps, and the enlarged energy facilities. Figure 2 shows the change and evolution in a simple case.

b) spring flow, river base flow and wetland surface area progressively decrease down to some value (to compensate for the difference between actual recharge and abstraction) or dry out (Llamas, 1989; 1992b; Acreman and Adams, 1998; Rodríguez-Estrella and López-Bermudez, 1992). Some tracts of allochtonous rivers –those coming from other areas– may start to lose water by infiltration, thus recharging the aquifer but reducing downstream river flow. Even when recharge exceeds abstraction some natural discharges may dry up or are transformed into recharge areas, depending on the aquifer characteristics and location of wells. But, as was said before, for a large, low diffusivity aquifer the evolution can be very slow and thus may progress unnoticed. Calculation and modelling allow making acceptable forecasts.

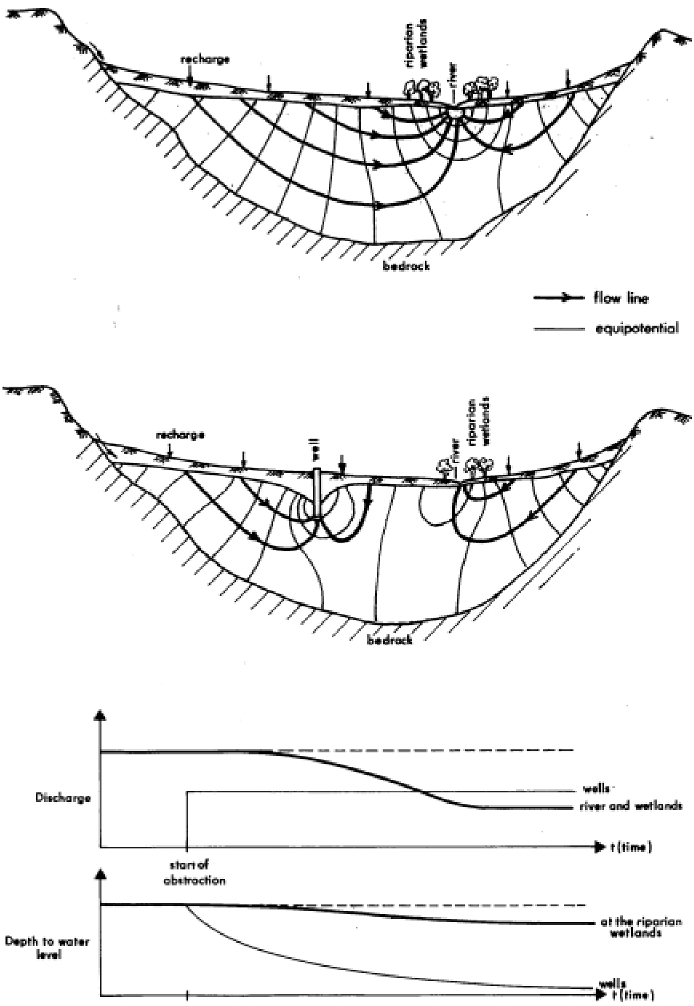

Fig. 1 Schematic cross section of a graben containing an aquifer discharging into a main river. The indicative flow net under undisturbed (natural) conditions (upper figure), and the result of groundwater abstraction concentrated at some distance from the river (lower figure) are shown. Below, it is indicated qualitatively how discharge and groundwater head evolve. Scales depend on aquifer properties.

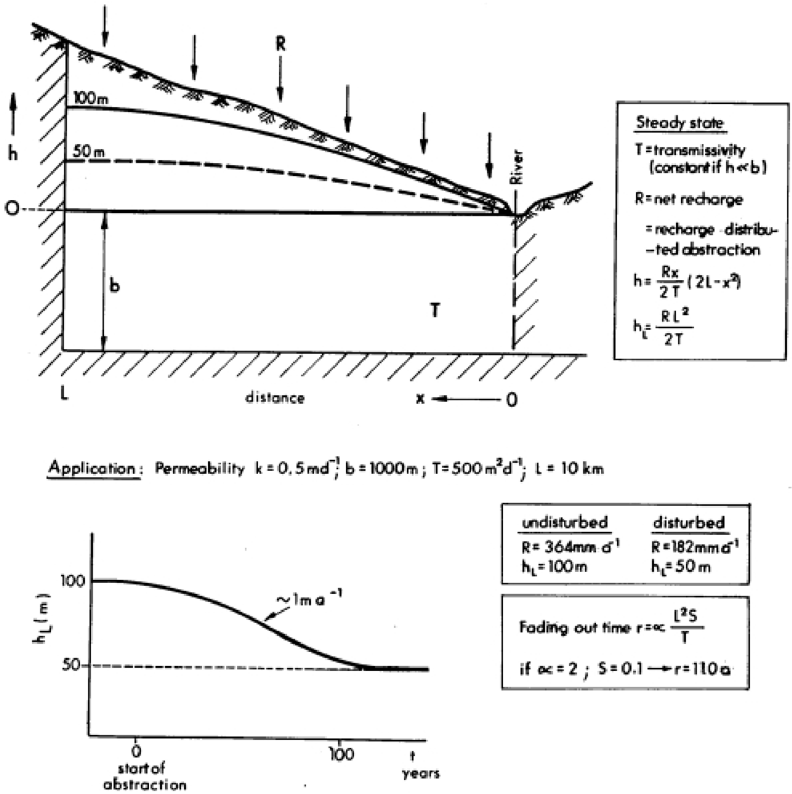

Fig. 2 Simplified effect of abstracting half of the recharge in a thick, low permeability aquifer discharging into a river. Recharge and abstraction are assumed distributed functions. The initial and final water table position is shown as well as the water table elevation (above river level) at the boundary. Time to stabilisation is about 110 years. Progressive groundwater level drawdown becomes noticeable after some decades, then evolves at a rate of about 1m a^{-1} and finally the groundwater head stabilises after a total drawdown of 50 m.

c) flow pattern changes that favours the slow displacement of low quality and saline groundwater bodies, some in deep seated aquifers and in aquitards, and the progressive encroachment of sea water. Sea water intrusion into coastal aquifers is a dynamic phenomenon in which saline water penetration is a function of discharge to the sea with transient stages that depend on aquifer properties (Custodio and Bruggeman, 1982). In addition, the infiltration of contaminated surface water may be enhanced.

d) water head potential changes along a well or borehole, or around a spring or discharge area. This affects the mixing pattern in them and thus outflow may be progressively modified.

e) pore pressure decrease. This may result in unconsolidated sediment subsidence, which is regional if changes of lithology and thickness are smooth, but may produce linear surface differences otherwise. See Poland (1985) for a general inventory and De Justo and Vázquez (1999) for explanations. Subsidence may vary from almost imperceptible to many metres, which is enough to modify the drainage pattern, to make an area more prone to flooding and downcutting erosion, to enhance coastal line regression, and to offset canals, pipes, roads and railways. However, subsidence is a complex phenomenon that may be the result of several causes (Sharp, 1992). In soluble hard rock such as carbonates and gypsum (and evaporite rock) the water table lowering may increase the rate of local sudden collapses, which may be enhanced, among other causes, by fast fluctuations due to localised recharge and irrigation pumpage stoppage in rainy days (La Moreaux and Newton, 1992). Collapses around or near boreholes and wells can be occur when sand from the formation is taken out with pumped water due to poor well construction and operation.

All these major negative effects can be forecasted and quantified, and thus the involved costs can be internalised. They should be included in a rational groundwater development plan. Doing otherwise could be considered irresponsible operation since the costs are passed to others, now or in the future, without due compensation. Subsidence and collapse costs may be difficult to quantify. Although they are sometimes spectacular, often they do not constitute an unbearable local and/or social burden when compared to the economic and social benefits of groundwater development.

Environmental and social impacts are much more difficult to quantify, but tend to be smaller than those produced by large surface water works, although they show up differentially along time.

GROUNDWATER DEVELOPMENT INTENSITY

To try to graduate groundwater development intensity it has to be compared to some magnitude. The most immediate one is recharge. A tentative classification proposal is given in Table 1, in which, besides the designation of the class or category, some qualitative evaluation of the effects is included. But below the apparent simplicity there are complex aspects. Then it has to be used cautiously and always based on a sound knowledge of aquifer properties and behaviour.

Firstly, groundwater development is often concentrated in some layers of the aquifer system. They behave differently from the whole system, at least in the short term, both with respect to water quantity and quality. When a given confined aquifer of the aquifer system is selected for preferential development (better water quality, higher transmissivity, adequate depth, good protection) soon a large groundwater level drawdown may develop until leakage from other formations and interference with outflow tend to level the trend. But this leakage may slowly modify the water quality. Initially water table depth, water head and water quality in other aquifers may be little changed. Then, what appears as a short-term intensive development for the considered aquifer layer, appears as a mild exploitation for other layers. Straightforward interpretation becomes more difficult when monitoring is insufficient or inadequate. Only a good knowledge and adequate monitoring may provide the correct picture, jointly with calculation and / or numerical modelling.

Secondly, when a part of an aquifer system is developed it may be difficult to assign a value to recharge since most of it may come from interaquifer leakage and even the use of water reserves in the aquitards. This is especially true for deep aquifers, but also the water table layer may receive during some time non-negligible contribution from below. Interpretation of long-term monitoring will provide a progressive evaluation.

Thirdly, recharge values are uncertain, sometimes very uncertain. Uncertainty means not only shifts in mean values but also a wide range of variability. It also depends on land use

TABLE 1. - Proposal of development intensity categories and some of the related effects

EFFECTS

Designation	*R/Q*	*Draw-down*	*Interfe-rences*	*At the site*	*Cost*	*Quality*	*Evolution*	*Stabili-sation*	*Land*	*Self-correction*
Mild	>>1	+	+	+	+	+	--	Yes	--	Yes
Intensive	>1	++	++	++	++	++	+	Yes / No	+	Yes
Very Intensive	≥ 1	+++	+++	+++	+++	++	++	Yes/No	++	Yes
Overuse	≤ 1	+++	+++	+++	+++	+++	+++	No	+++	Yes / No
Water mining	<<1	++++	++++	++++	++++	++++	++++	No	++++	No

Drawdown: ground water level decreases with development

Interferences: spring and river base flow decrease; wetland area is reduced

At the site: well yield or groundwater quality is not sustainable in the well field

Cost: groundwater abstraction cost increase

Quality: increasing salinity and/or hazardous components; contamination risk increases

Evolution: persistent drawdown trend and quality deterioration

Stabilisation: negative effects tend to level

Land: problems of land subsidence, collapse or fracturing (only in some cases)

Self-correction: water supply problems can be corrected without new water sources

- by improving water use efficiency
- re-arranging economic and social framework

R = recharge

Q = abstraction

+ : nil to small; rare

++ : small to noticeable; some

+++ : noticeable to large; frequent

++++ : very large; disappearance; general

All categories:

* present positive and negative aspects
* depend on the whole system
* depend on how groundwater development is carried out
* can be acceptable / rejectable

changes, the stage of aquifer development and artificial actions. This is a common situation when dealing with Nature and affects both the evaluation of surface and groundwater resources. But this is not always recognised and uncertain figures are presented as illusorily accurate. This is in many cases the source of failures, errors, and disappointment. Uncertainty is the combination of poor knowledge of the phenomenon (eg. rainfall), the associated stochastic component, the simplifications introduced to describe the system under consideration, the variability and heterogeneity of the physical media, the difficulty to describe with figures complex situations and chemical and biological reactions, and even the delayed effects of recharge, especially when the unsaturated zone is thick or water level drawdown is fast (Francés et al., 1992).

The uncertainty of water inflow and of physical and chemical parameters, which may greatly influence the results of large surface water projects, is not so important for the development of groundwater if it is progressive, as it generally occurs, and at the same time knowledge and monitoring is improved.

The large groundwater storage smoothes variability and provides enough time to evaluate and correct development deviations from operational objectives and environmental goals. They can be adjusted as physical, economical, social and political circumstances evolve.

Table 2 presents some key issues on groundwater development according with what has been discussed above and what will be commented in the following sections.

The fact that evapotranspiration reduction is considered as beneficial —this was often argued in the past— may be in conflict with current environmental concern on Nature preservation. Then, what some time ago was not considered overexploitation today might be considered as such.

GROUNDWATER OVEREXPLOITATION

As it was stated in the introduction, groundwater overexploitation —and the alike designations of overdraft, overuse, overdevelopment and unsustainable use— are becoming common talk in hydrogeology and groundwater resources since the decade of 1970. They were and are predominantly applied in arid and semiarid lands, especially when large groundwater quantities are abstracted to irrigate extensive areas, but they are also applied to aquifers in other regions when exploitation produces consequences that are considered undesirable. They appear when

TABLE 2. - Some key issues on intensive aquifer development

ON RECHARGE

* It is uncertain (as well as the other components of the water cycle)

* It is variable, and depends on
- abstraction pattern
- drawdown
- land conditions and use
- climate change

* Uncertainty can be reduced as development progresses
- adequate monitoring is needed

* Recharge generally increase with aquifer system development

ON EFFECTS

* Transient effects of exploitation such as
- progressive level drawdown
- displacement of groundwater bodies
- increased recharge

may last years to centuries

* A persistent negative evolution does not necessarily means abstraction > recharge

* In large, small hydraulic diffusivity aquifers
effects must pass unnoticed in the short-term

ON DEVELOPMENT

* Any groundwater development has negative side effects
- as does any other water development

* Depending on the political, social and economic restrictions imposed
- any development may be considered overexploitation
- beneficial water development may be not possible
- many positive opportunities may be lost

* Focusing on local effects the global vision my be lost
- a holistic approach is needed

* Overexploitation and groundwater mining may be a rational use of an aquifer if
- known
- costs are internalised
- future solutions are prepared for
  - changing of economical activity
  - living and producing with less water
- social benefits are optimised

* Water management decisions depend on economical and socio-political trade-offs
- the framework progressively changes as
  - . technology
  - . water needs
  - . socio-political background

  evolve

abstraction is estimated greater than recharge —often there is no clear proof of it— or serious water quality deterioration, mostly salinity increase, although the causes are often not clearly started and whether it is a pure local or a regional problem is not clearly known. The overexploitation concept deals mainly with negative aspects (Margat, 1992, Custodio, 1992; Delgado, 1992; ITGE, 1991) and it is predominantly the point of view of overconcerned conservationists, of those suffering some real or assumed damage, and of not always well informed people.

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; Llamas, 1992c).

The converse position, which focus on beneficial use and represents the point of view of groundwater developers, is that represented by the concept of safe yield, and some other designations such as perennial yield or rational exploitation, and to some extent the economicist side of sustainable use. Mainzer (1920) defined safe yield as the water flow that can be artificially abstracted from an aquifer without reducing the resource beyond the point in which the abstraction becomes economically unfeasible. Safe yield is a less and less used concept but it subsists when groundwater policy institutions try to determine how much groundwater can be developed in order to grant abstraction permissions or to establish some limitations on development and groundwater use.

Both designations, overexploitation and safe yield, are dominantly static and short-term interpretations of aquifer system behaviour. Some essential facts, as those discussed before, are ignored, such as the large groundwater storage, the long-term effects, the contribution from aquitards, the salinity and water quality issues, the system recharge and discharge changes, and the uncertainty. This makes those concepts poorly bounded, subject to controversy, probably impossible to be accurately and universally defined, and no substitute for a good knowledge and understanding of aquifer behaviour.

The Regulations for the Public Water Domain (1986), of the current Spanish Water Act (1985), define overexploitation by its effects: it will be considered that an aquifer is overexploited, or in risk of overexploitation, when the sustainability of existing uses are in immediate threat as a consequence of abstraction being greater than, or very close to, the annual mean volume of renewable resources, or when they may produce a serious water quality deterioration.

Llamas (1992a) prefers to introduce the notion of strict overexploitation –leaving room for broader scope definitions– as a groundwater abstraction producing effects whose final balance is negative for present and future generations, taking into account physical, chemical, economic, ecological and social aspects. This has been refined recently (Llamas, 1998). Other authors put the accent on groundwater storage reduction and possible non reversible effects on quantity and quality, on the rock matrix (subsidence and fracturing), and other regional effects (on economics, technological development, infrastructure works, health, and environment).

After Young (1992), from an economic point of view, aquifer overexploitation is a non-optimal exploitation. The optimal value of pumping rate is not necessarily linked to mean recharge, as commented before.

Sustainability, a concept developed for natural resources development (Brundtland et al., 1987), is based on intergenerational equity. It points to the interdependence between economy and natural environment and the conservation of the natural capital, and it calls the attention on irreversible damages and improved management. The major principles for natural resources management are: a) the use rate of a renewable resource must be less than the natural regeneration rate, and b) the flow of wastes to the natural environment have to be kept less than its assimilative capacity. But even if acceptable in a global or regional long-term perspective, the concept does not take into account the impossibility of complete matter recycling (Georgescu-Roegen, 1971) and the fact that an unused, non-renewable resource makes no benefit to anyone, as is the case of minerals and large aquifers in arid lands. This explains the numerous attempts to improve the definition or to substitute it, and to apply it to local situations. There are similar difficulties than those found for defining aquifer overexploitation. Sustainable water development is discussed by Biswas (1992), Plate

(1993) and Simonic and Fahmy (1999). Sophocleous (1997) and Bredehoeft (1997), using ideas from Theis (1940) and Bredehoeft et al. (1982), explain why safe yield is not sustainable. Table 3 presents a summary of what has been said.

But how overexploitation is perceived depends on the point of view, as shown in Table 4, according to the person, the background behind the perception and the professional orientation. It can be expected to find irreconcilable differences between the views of groundwater developers and conservationists, deep rooted differences between scientists and engineers on one side and lawyers on the other, or between well informed people and laymen influenced by biased information and *hydromyths* (Custodio and Llamas, 1997).

Table 5 summarises a list of reasons, which explain why the definition of overexploitation is difficult and not amenable to simple formulations. It remains essentially a loose concept. As such, it may be a useful term to declare that negative aquifer development effects are of concern and some action is asked for. But the actual appraisal of what is happening and the subsequent action should not be the result of applying a qualifier but of detailed multidisciplinary analysis of the situation and its evolution, taking into account short and long-term goals.

SOME ECONOMIC ASPECTS OF GROUNDWATER OVEREXPLOITATION AND MINING

The economics of developing natural renewable and exhaustible resources, taking into account their limits and in the framework of global sustainable development, is considered by some authors (Aguilera, 1996; Azqueta y Ferreiro, 1994; Constanza, 1991; Erhard–Cassegrain and Margat, 1983; Faber, 1985; Georgescu–Roegen, 1971; Howe, 1987; Sánchez–González, 1992; Young, 1992; Young and Haveman, 1985). From the economical point of view, as for any other commodity, a sound groundwa-

TABLE 3.- Some simplified definitions related to aquifer overexploitation

SAFE YIELD

Strict: abstraction < recharge

Adapted: abstraction that does not produce undesirable (??) effects

SUSTAINABLE USE

Development that satisfies present needs without compromising the ability of future generations to satisfy their own

OVEREXPLOITATION

Strict: abstraction ≥ recharge

Adapted: development that produces undesirable effects on:

- * **Water quantity**
  - drawdown of
    - water table
    - piezometric levels
  - decrease of (fresh) water in storage
  - reduction of
    - spring flow
    - base flow
- * **Water quality**
  - increasing salinity
  - appearance of hazardous components
  - enhanced pollution and contamination
- * **Environment**
  - reduction / disappearance of
    - wetland area
    - groundwater dependent vegetation
    - springs and seepages
- * **Water cost** → it increases
- * **Groundwater availability** → it decreases
- * **Land stability**
  - subsidence
  - collapses
  - soil cracking
- * **Social perception** → something wrong happens
- * **Temporality** → water is unavailable when it is needed

They may appear even if abstraction < recharge

MINING

Strict: abstraction clearly greater than recharge

Adapted: freshwater reserves reduce at a fast pace

TABLE 4. - Viewpoints that influence perception of overexploitation

According to the persons involved • the abstractor itself • other groundwater abstractors • water resources administrators / managers • water users and farmers • ecologists / conservationists • Nature developers and tourists • mass media • citizen
According to the position respect the problem • well informed / with good understanding • with personal interests • with incomplete information / poor understanding • biased / deformed / manipulated
According to the professional background • Science • Engineering • Economics • Management / policy • Environment • Law • Social • Political • Mass media communication

TABLE 5. - Why overexploitation definition is difficult

- **It varies with perception**
- **Terms are variable**
  - **naturally**
  - **artificially**
    - **with time**
    - **spatially**
- **A persistent level drawdown trend is not a sure criterion**
- **Aquifer recharge is**
  - **difficult to calculate**
  - **uncertain**
  - **variable**
- **Water quality has to be taken into account**
- **Long-term effects may be important**
- **Local effects have to be put into a holistic picture**
- **Social perception and priorities change with time**
- **Water use technology improves**
- **Socioeconomical net benefits have to be considered**
- **Calculation of costs and benefits is not straightforward**
- **Often**
  - **scarce**
  - **poor**
  - **inappropriate**
    - **data are**
      - **used**
      - **the only information source**

ter development should produce total actualised benefits greater or at least equal than total actualised costs. Such simple equation presents practical difficulties since:

a) it should include not only direct terms —the easiest to account for— but also indirect terms, more difficult to evaluate and identify, and also intangible terms which may be highly speculative, difficult to reduce to figures and the subject of political decisions (Llamas et al., 1992).

b) subsidies and taxes should not be considered, although this is something still controversial (Alfranca and Pasqual, 1992).

c) the discount rate used for actualisation may significantly change the results; it is difficult to agree upon and controversial. Its increase favours energy comsuption (increased abstraction), even if water becomes more costly.

Economic analyses should be carried out to help in decision making and in the selection of competing alternatives (Custodio and Gurguí, 1989; Howitt, 1993), but what is often carried out tend to be too simplistic and many indirect items are not taken into account. In many other cases what is called an economic analysis includes only direct water costs (subsidies not deduced) and is used mainly to decide if it is advisable to proceed with the planned development or project, to introduce variations or to look for subsidies to reduce the water cost for the consumer.

Indirect costs take into account possible damage to others and to the environment but should also include the cost of preserving and maintaining the aquifer or aquifer system as a natural infrastructure. This includes not only water abstraction works and water transport mains but also protection and improvement of recharge, monitoring, surveys, studies, modelling and restoration of damages produced in the past and unaccounted before.

Groundwater intensive development, in which a large use of water reserves is done, suffers from what is called the problem of the common pool resource (Young, 1992; Aguilera, 1991), which is shared by other natural resources such as air, oil and vegetal resources, and refers to a migratory, substractible resource and/or an unrestrained rule of capture. There is no incentive for saving and each possible or authorised developer intend to get as much as possible according with his possibilities to invest and to sell the product; otherwise others will get his share. This produces collective inefficiency. This is also partly true for systems which will finally reach a final long-term steady state during which a large part of the freshwater reserves are depleted or substituted by water of degraded quality.

Besides the problem of the common pool resource the large number of actors and interested people (stakeholders) is a new added difficulty. What seems the best solution to this situation is the creation, organisation and involvement of an aquifer system user's association with responsibilities on management (Galofré, 1991; Aragonés et al., 1996), jointly with a water authority acting with adequate rules to set objectives, carry out general activities, and correct deviations.

The need for a water authority associated with some kind of empowered institution to set objectives and rules is generally admitted as necessary, but the degree of involvement may vary from very loose to full control of groundwater development activities. It is also needed to collect funds and to redistribute and invest them, if the groundwater user's association itself does not do this. Custodio (1989) and Foster (1992) have already discussed this.

Strict control minimises costs, which is what people over-concerned about groundwater use problems and overexploitations generally ask. It looks for a short-term, steady state aquifer development by controlling wells and keeping total abstraction low with respect recharge. Groundwater is available at small cost but in relatively small quantity, and its quality is kept steady or evolves slowly. But there are no incentives for savings since water cost is low. To get incentives for savings, taxation is needed or rules to limit water use have to be implemented. This needs a large and difficult to operate organisation. Often new water needs have to be supplied by importation and this imported water may be more expensive.

This also means that those who previously got permissions or authorisations to develop the aquifer now may greatly benefit from selling water at the imported water cost. In fair play the extra benefit should be collected as a tax to compensate for the water importation cost. But what really happens in many cases is that water importation is subsidised (the construction, the operation, the use, or all of them). This is an economic distortion that lowers economic efficiency (Myers and Kent, 1998).

The loose control option means no restrictions to groundwater development, which follow demand increase fostered by initial low water prices. But prices go up due to increased energy pumpage costs and the early modification or substitution of abstraction works. This means that demand first slows its growing rate and finally decreases to adapt to some aquifer system perennial yield, often at a high exploitation cost due to decreased groundwater level, and to expensive imported water (or desalinated water, or water reuse). The large drawdown may be accompanied by reduction of usable aquifer size and/or groundwater quality loss, which means correction or abandonment of part of the aquifer system, thus reducing final yield. Possible large indirect costs and environmental damage is another item. This needs taxation or subsidies to cope with, and then an institution has to be created. Taxation should be progressive and if possible anticipating future scenarios; otherwise its sudden appearance may be highly unpopular and may create social conflict and unwanted political stress. Subsidies become an economic distortion if not linked to taxation.

When the evolution is relatively fast, the corrective action may arrive late. The reduction of water use is blamed as the cause of lost of investments, social unrest, and unfair treatment for the weakest and the poorest. Many people, who add that the consequences will usually outweigh the human and financial resources needed to follow a sustainable development path, share this point of view.

But in practice, as worldwide experience shows, the large groundwater storage in most cases provides enough time for a progressive adaptation, except for small aquifer units. But even in this case obtaining external water resources or the possible displacement of relatively small human communities unable to pay high water costs does not seem a too high social price and is amenable to feasible solutions. But some institution –local, of the state or international– is needed to cope with the present and to solve inherited situations. This is also true for isolated, poor regions in which true mining of scarce groundwater resources in low storage formations has been fostered by inexperienced developers or by speculation abusing external financial help.

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 maintaining employment. In agricultural areas this means moving from low value irrigated agriculture to high added value intensive agriculture accompanied by low water demand factories and facilities, and by developing services. This is what has been observed in many areas, if an excess of administrative interference does not freeze private initiatives. What has been said does not mean that loose control is a better economical and managerial option than strict control since both are extreme situations. Intermediate solutions may bring improvements. The right position is a complex combination of existing regulations, institutional capability, social acceptability, stakeholder involvement, and political possibilities, all of them subject to changes and evolution. The capacity to adapt and evolve is essential to good management. When developable groundwater resources greatly exceed recharge, water mining is a possibility. This is economically admissible (Barber, 1992), although environmental and social issues also intervene and have to be considered. Developers can carry out water mining up to a total water volume withdrawal for which increasing actualised costs become equal to the finally decreasing actualised costs. But at this point, net benefit is nil and there are no social economic resources left to compensate for the damage and to develop new water and / or human opportunities. Socially the exploitation should finish earlier (in terms of volume of reserves), when the actualised net benefit is maximum. By means of strict water mining planning or through water abstraction taxation this can be achieved. How to use the collected fund is not a simple issue, but it should be used to make the development sustainable. Table 6 summarises some ideas. Some comments on groundwater mining and overexploitation can be found in Dabbagh and Abderrahman (1997); Lloyd (1994, 1997, and 1998); Margat and Saad (1982, 1983); Orr and Rissar (1992).

Groundwater overexploitation and mining involve ethical considerations, as do the exploitation of other natural resources and the environment, as stated by John Paul II (1990). 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 beyond common economics. Scientific and technological progress, jointly with social advances, may help to solve what currently is a matter of concern, as happened in the past, but with new challenges (Tierney, 1990). It is often mentioned the incoming crisis due to freshwater shortage. But the water problem stems not from a shortage of water but from its unsustainable use and quality deterioration. After Pearce (1999), the water industry is the most inefficient business in the World. Also the widespread and increasing use of drinking quality water for purposes that do not need this high quality standard is threatening much needed groundwater resources, especially in arid and semiarid regions. This is a clear lack of economic and management efficiency, which is to some extent supported and fostered by international and state policies set by persons who are only concerned by some aspects but miss the global perspective.

ACTIONS TO COPE WITH OVEREXPLOITATION-LIKE SITUATIONS

Most of the actions that may correct and redress overexploitation–like situations have already been presented before. They are summarised in Table 7, which is self–explanatory. Similar ideas are also expressed by Abdel-Rahman and Abdel-Magid (1993) for the arid Middle East. Hosseinnpour and Gho-

TABLE 6.- Considerations relative to groundwater mining in arid lands

- **Groundwater in the aquifer does not produce economical benefits to anyone**

  but { **the small recharge hydrologic conditions** / **the transient evolution from past hidrologic conditions** } **sustain**

  → **cheap shallow well water**
  → **some springs and wetlands**
  → **special landscapes and ecosystems**

- **Groundwater mining means**
  - **total fresh groundwater volume is reduced**
  - **parts of the aquifer become dry**
  - **freshwater may be replaced by** { **saline** / **poor quality** } **water**
  - **some springs, rivers and wetlands may dry out**

- **Groundwater mining can be justified if**

  → { **physical ecological** / **ecological** / **water quality** } **damage is** { **bearable** / **can be compensated** }

  → **it is a transient situation leading to**
  - **the former situation after** { **abandoning investments** / **applying benefits** } **as in a mine**
  - **a new alternative economy**

  → **there is a future alternative freshwater source (more expensive)**

badian (1998) insist in avoiding the irrigation of high water demand crops. Some collective policy decisions are needed (Young, 1992). They include managing water (annual rate of pumping, geographic distribution of pumping, increase of recharge and decrease of supply) and coordinating people by distributing abstraction rate among users or by applying rules. Some options are taxes, subsidies, permits, and exchange of pumping entitlements, education, and research.

The development of alternative freshwater resources is a possibility, worth considering by the management water institutions and water authorities. However, this should to be formulated in a regional framework. The economic disturbance created by subsidies, both direct and indirect, such as tax and fiscal reductions should be avoided or subtracted when making evaluations, as well as unaccounted labour charges. Subsidies are always welcome by water users since they directly benefit from them, but this should not be the case of general policies, which should consider equity issues.

In this context the development of alternative freshwater resources should be carried out only if they are affordable and when local sources use cannot be improved and water savings are not enough or economically unfeasible beyond a given point. Reduction of water demand is a key step and the most immediate one to cope with overexploitation. This includes reutilization and considering dual quality domestic water to meet high water quality needs (Pettersen, 1994; de Marsily, 1994).

Alternative freshwater resources include developing other local aquifers, increasing surface water availability for direct use and/or aquifer recharge, importing water, introducing irrigation with poor chemical quality or brackish water, reusing treated waste water, desalting local brackish groundwater, using water and irrigation return flows, introducing dual urban supply systems and in some cases atmospheric water harvesting, although this last action is currently something more anecdotal than real.

TABLE 7. - Possible solutions to overexploitation-like situations

- **Involve aquifer users and concerned people**
  - Groundwater abstractors
  - Farmers
  - Town authorities
  - Water managers
  - Land-use planners
  - Environmentalists
  - Experts
  - Local people
- **Make known the { role / value } of { the aquifer system / groundwater }**
- **Prepare and analyse probable future scenarios**
- **Collect part of the economic net benefits**
  - to { monitor / protect / restore / enhance } { aquifer / recharge }
- **Integrate the problems into a global framework**
  - including
    - waterresources
    - economics
    - social values
    - land-use
- **Have effective water management institutions**
  - This means
    - good knowledge
    - prepared staff
    - good enough monitoring
    - adequate economic resources
    - integrating aquifer users and concerned people
    - have adequate regulations
    - informing the people
    - optimizing water resources in a regional framework
- **Encourage fresh water savings under rational rules**
  - in
    - agriculture
    - industry
    - urban supply

COMMENTS ON SOME SITUATIONS

In Spain, the Water Administration identifies 51 hydrogeological units nation–wide which are considered as overexploited (MIMAM, 1998 a, b; MINER-MOPTMA, 1994; SGOP, 1990; Batlle et al., 1989; López-Camacho et al. 1992; Navarro, 1993). The assumed total water deficit (abstraction in excess of recharge) is 0.70×10^9 m^3 a^{-1} (22 m^3 s^{-1}) for a total groundwater withdra-wal of 5.5×10^9 m^3 a^{-1}. In fact, these figures have a wide range of uncertainty.

According to Batlle (1993) surface water resources are also *overexploited* since evaporation loses from a mean water surface area of 1630 km^2 are reckoned at 2×10^9 m^3 a^{-1} or about 4% of the 54×10^9 m^3 of total reservoir capacity to regulate 42×10^9 m^3 a^{-1} of the 115×10^9 m^3 a^{-1} of runoff. Furthermore capacity reduces 0.33 % per year (average value) and may be 1 to 3.6 % a^{-1} in some areas, due to sediment trapping, with a cumulative loss of about 10 % of initial capacity. Soil erosion is the cause, which may be as high as 200 ton ha^{-1} a^{-1}.

More than 1/3 of the total quoted groundwater deficit corresponds to La Mancha Occidental aquifers (Central Spain), almost other 1/3 to Murcia (Eastern Spain, mostly the Guadalentin river basin), and most of what remains to other Eastern areas of Spain in Alacant (Vinalopó river basin) and Almería (Dalías and Níjar). Other deficits correspond to the Canarian and Balearic archipelagos. In some Eastern Spain aquifers observed drawdowns may exceed 2 m a^{-1} during some years (Gutiérrez-Escudero, 1985; Selva, 1999). In Gran Canaria and Tenerife islands, drawdown may be up to 10 m a^{-1}, at least in some operating wells and galleries. But these figures should be taken with caution since they may represent only the transient situation as explained before and local effects near well fields in low permeability formations or small aquifers. Detailed studies are scarce. Groundwater salinity and chemical impairment may be in some cases a more serious concern, but the knowledge is still fragmental.

In these 51 *overexploited* hydrogeological units, the ratio of water deficit to resources is reported to be 1.0 to 1.2. It is also reported that in other 23 units the ratio is in the range 0.8 to 1.0 (corresponding to an *effective* deficit of 1.1 x 10^9 m^3 a^{-1} or 0.7 x 10^9 m^3 a^{-1} of *strict* deficit). In other 25 units, the ratio is less than 0.8, but important local water level drawdown rates or quality deterioration is reported. In MIMAM (1998b) the values of the ratio is often notably modified with respect MIMAM (1998a) as updated data on abstraction and new calculations on recharge are available. It is also quoted that about 3.9 x 10^9 m^3 a^{-1} out of the 5.5 x.10^9 m^3 a^{-1} of groundwater withdrawal present some kind of problem. This seems a clear overstatement. Fifteen hydrogeological units are legally declared as overexploited, but only two are definitive, the rest being provisional.

In most cases, even in the River Basin Water Plans, there are no detailed studies on aquifer behaviour. Adduced reasons for overexploitation or risk of overexploitation consideration are often rough recharge calculations, a first appraisal of withdrawal, a perception of continuous drawdown derived from some observation wells and boreholes, and occasional data on water quality deterioration or salinisation in some wells. Other aspects such as long–term trends and forecasts, economic considerations and land stability are not specifically included, in general.

Really some hydrogeological units seem not strictly *overexploited* and even do no reach the situation of intensive development, although the Water Authorities have decided otherwise. Probably this is the response to a preventive attitude or the yield to external pressure by overconcerned institutions. But progressive groundwater drawdown is a fact in some areas as shown in Figure 3, although the meaning is not as evident, as commented before.

Groundwater use was promoted by the state water administration to cope with a series of dry years early in the 1990's, as a last measure, solving with them some acute problems by creating a new abstraction capacity of 8 m^3 s^{-1}. This has been translated into a non–written policy applied by some officials — called rational use (MOPTMA, 1995) — which reserves ground-

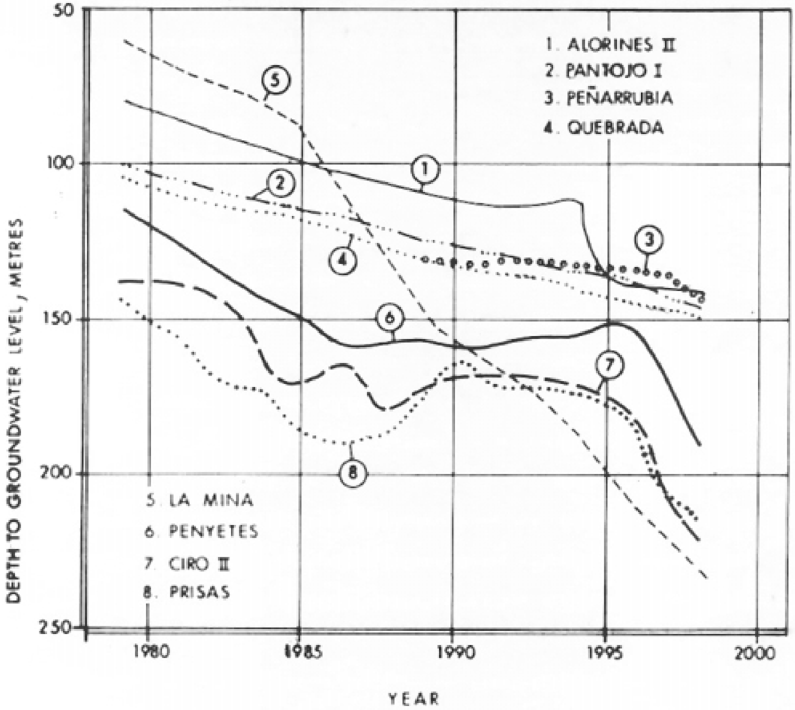

Fig. 3 Example of progressive fast groundwater level drawdown in the Alto Vinalopó valley, Alacant, Spain (after Selva, 1999). About 90 x 10^6 m^3 a^{-1} are abstracted from a series of small aquifers spread over 1100 km^2. About 35 x 10^6 m^3 a^{-1} are assumed to be reserve depletion, from a total of about 4500 x 10^6 m^3. Reserve depletion is deduced as the difference of estimated recharge (very inaccurate) and abstraction. The current aquifer specific yield of 0.015 seems too low. The long-term storage coefficient is poorly known and may change the figures of water reserve depletion rate. The dramatic rate of drawdown may be the result of the transient period shown in Figure 2. In the long term, groundwater quality changes due to mobilisation of brackish and saline deep-seated groundwater (effect of evaporite rich formations) may be a major concern.

water abstraction for dry periods. This half-true assertion has been used to downscale continuous aquifer development and to promote new large surface water investments. In some cases there is the perverse result that part of the new drilled wells lack adequate maintenance. This means that they and the associated groundwater resources will not be available next time. Corominas (1998) discusses how this affects agriculture in Andalucia.

Water administrators often have to carry out decisions with poor knowledge on groundwater or without adequate data and information. This is also in agreement with the fact that some aquifers and aquifer systems are rapidly deteriorating but have not been included in the list due to lack of pressure and insufficient information at the right level, or simply to avoid conflicting decisions. Also the legal action which is needed after the Water Act is being delayed since the overexploitation declaration is difficult to carry out, local people does not share it or means are not provided to implement actions.

In the Canarian Archipelago, where dramatic groundwater level drawdown and some serious groundwater quality deterioration has been produced in the last decades, groundwater is still and will continue to be the main freshwater source, now combined with desalination and reuse. But unfortunately subsidies, the lack of long-term water policy, inadequate detailed studies and monitoring, and some erratic politics are distorting water economy, the general economy and social development, which means becoming too dependent of external financing.

Two main cases effecting wetlands and river flow are those of La Mancha, which includes the Ruidera lagoons and the Tablas de Daimiel wetland (Cruces et al., 1997; Llamas et al., 1996; Llamas, 1989) and the Doñana area (see Custodio, 1999, for explanation and references).

These, to some extent negative considerations, are brought in not to blame the country's water administration, but to show common problems facing groundwater resources development and management in Spain; something similar happens in other countries, often more seriously. Institutions have to withstand the pressure of other interests and poor popular understanding, which is reflected in biased political decisions. Even with these problems some rationality in water resources management is being introduced in Spain little by little and in sounder way than in other countries under similar circumstances. The European Union doctrine, which is to some extent reflected in the WTD, and will be more explicit in the future Water Framework Directive, considers overexploitation inadmissible –although no clear definition is provided as yet– but this reflects mostly the point of view of countries in which groundwater is mainly used for town and factory supply, and rarely is intensively exploited. Their major problem is groundwater quality and contamination. Overexploitation is poorly perceived, and rarely is mentioned in reports (RIVM-RIZA, 1991), while this is a feasible water management option in Southern Europe, like in Spain and Greece (Lambrakis, 1997; Llamas 1998b). Some typical cases designated as serious aquifer overexploitation are found in Central and Northern Mexico and Southern and South-western United States, with figures per unit surface area or per inhabitant that far exceed those of Spain in regional figures. This causes a moderate concern in California, Arizona and New Mexico, where water demand and resources development are evolving after using groundwater reserves.

Overexploitation in California was about 5×10^9 m^3 a^{-1} in the mid 1950's, but during the 8 year long drought of the late 1980's and early 1990's it was reckoned at 2.5×10^9 m^3 a^{-1} (Howitt, 1993) for a total water supply of 40×10^9 m^3 (45 % from groundwater). Estimated groundwater reserves are 1600×10^9 m^3, but only 140×10^9 m^3 are assumed utilisable. Around Tucson, Arizona, groundwater is the only significant water resource, but recharge is less than half the abstracted 0.4×10^9 m^3 a^{-1} (Charles, 1991). General groundwater level drawdown is about 1m a^{-1} from the 1900's.

In the large Ogallala aquifer in the High Plains of the 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 were removed, with an average drawdown of 3 m in 40 years and up to 30 m locally (Johnson, 1992). This means increasing water cost. In the last two decades, irrigated surface area is decreasing to adjust agricultural output to market conditions, after incorporating more efficient farming conditions. This goes in the direction of sustainable development, as in many other areas.

In Mexico, although some similar behaviour exists (Canales, 1991), there are some cases that in the past (from 1960) were presented as dramatic overexploitation leading to serious social disruption. Such are the cases of Hermosillo and Guaymas aquifers, in Sonora. Recognising that there is a water stress and general concern (Foster, 1992), and some local failures of investments and unsustainable human settlements, as a whole there is no major breakdown of the water and social system after more than 30 years of doomsaying, but only local problems which can be solved by efficient management. After Rodríguez-Castillo (1992) in the Guaymas coastal aquifer (Sonora), abstraction is three times the estimated recharge, due to the low cost of water. Progressive salinization is responsible for damage to 8000 ha of irrigated soil, the abandonment of more than 50 wells (about 3 for year) and internal displacement of people. But the aquifer continues to be a source of freshwater and also of employment after adjustments come out.

In the Hueco Bolson aquifer, supplying El Paso (USA) and Ciudad Juarez (Mexico), Hibbs (1998) shows a compound problem of drawdown, early abandonment of wells and salinity increase, but also of agricultural and urban nitrate contamination and human biological pollution. Something similar happens to Lima, Peru (Uchuya, 1992), where the aquifer is the key water source in spite of existing stress and claims of overexploitation.

Classical examples of land subsidence due to groundwater use are the Avra Valley, Tucson, Arizona, up to 5 m (Charles, 1991), the San Joaquin Valley, Arizona, and Mexico City. In Mexico City subsidence is also due to consolidation of recent sediments and the result of the weight of buildings. Problems of enhanced flooding by continental and seawater occur in Venice, Bangkok, and Tokyo. Mijatovic (1998) mentions a small subsidence of about 5 cm in the Panonian plain of Hungary and Serbia due to a groundwater level drawdown of about 0.8 m a^{-1}, with cumulative values of 14 m (up to 30 m). In China subsidence is often reported (Wang, 1992), especially in flat coastal areas, prone to flooding. A summary table can be found in De Justo and Vázquez (1999).

In the arid Middle East and Northern Africa countries groundwater mining is a fact. In the Sahara and Arabia about 6.5 million km^2 of territory contain more than 80.000 km^3 of freshwater (Houston, 1995), but the long-term response to intensive development is not well known, and a progressive water salinity deterioration is possible. In the larger aquifer systems, it is assumed that groundwater is not in equilibrium with present conditions and represents a transient stage from past circumstances (Burdon, 1977; Lloyd and Farag, 1978). In Libya almost non renewable groundwater from the central and southern part of the country (Fezzan, Satin, Tazerbo, Kufra) is transported by 1900 km of pipes to the Mediterranean coastal area, 500 to 900 km away through the so called Great Man-made River, at a cost greater than 4 billion euros, initially to foster irrigation and farming. Experts say that the scheme may work for 3 to 4 centuries at present rates. But the project has raised doubts with respect economical, social and environmental aspects. Israel applies an integrated approach in which groundwater use and to some extent overexploitation is an stage in developing natural resources and the country (Shamir, 1993), although some rethinking is now needed after the Palestinian autonomy. The coastal aquifer supplies 400 to 450 x 10^6 m^3 a^{-1} of water since the decade of 1950, of which about 340 x 10^6 m^3 a^{-1} are assumed natural replenishment (Vengosh et al.,1999). Besides groundwater level drawdown depressions, in some areas salinity is increasing since the late 1960's (in some spots they are known since the 1930's) and continue even since 1990, when total abstraction was significantly reduced. This is the result of upconing and upward displacement of deep-seated saline water. However, the aquifer continues to supply about 1/5 of total water consumption in Israel. Some groundwater problems of intensive exploitation, unduly called overexploitation, appear in fairly recharged aquifers as well. Lloyd (1994) points to them as groundwater management problems.

CONCLUSIONS

Overexploitation is a term that is generally used to point out negative aspects of groundwater development. Strict overexploitation is produced when abstraction is greater or close to recharge. Nevertheless, even in this case, the evolution —such as progressive groundwater head drawdown and water quality deterioration, reflected in increasing water winning cost and water availability reduction— is what finally is used to qualify the situation. In any case recharge is a term associated to a large natural uncertainty. Also it may change due to human activities on the territory. In addition, groundwater abstraction is often poorly known.

It is not possible to provide an accurate and widely acceptable definition of overexploitation based on observables. Not only scientific and technical factors are involved, and quantity and quality issues are at stake, but also economic, social and political ones. All this is compounded with the large transient situations linked to the large groundwater storage, and the sluggish and complex groundwater flow. Really many of the overexploitation situations referred to as such are based on an evolution linked to the transient period after groundwater development started and has no clear relationship with aquifer recharge and development, but with aquifer characteristics.

Overexploitation (strict or not) and groundwater mining are not necessarily bad when considered in a regional context since they are the means to produce a net economic and social benefit to develop an area and to get future better and more effective use of water. The unethical side appears when no net social benefit is obtained, and environmental damage and increased water costs are transferred to others and to future generations lacking economic resources to cope with them.

In theory, loose control of groundwater intensive development may create serious water problems and social disruption, but in practice this is not the case, except at the local level. Even in this case, alternative and complementary solutions can be sought. Many of the negative aspects of aquifer development leading to the overexploitation perception can be easily internalised and environmental damage can be corrected or compensated, but regulations are needed as well as an adequate water management institution and the effective participation and involvement of groundwater users and stakeholders, not only developers.

The difficulties in defining overexploitation and the inherent uncertainty of recharge does not hinder groundwater and aquifer system management, and correct decision making if progressive adjustments are possible. The slow rate of change of aquifer reserves is the key factor.

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