CHAPTER 1

Intensive use of groundwater: a new situation which demands proactive action

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ABSTRACT: Groundwater is an essential freshwater resource since old times, yet its role has increased dramatically in the last half century and in many areas in the last decades. As a consequence many aquifers have become intensively used. This means that the hydrogeological conditions have changed, often to a significant extent, with groundwater storage being modified substantially. The benefits have been clear and important in most cases, like more reliable domestic water supply and increased food security through irrigation. But there are associated effects that may increase the direct costs and also the externalities, or the intangible costs. These side effects are commonly referred to as problems of groundwater development. Focusing on these problems without real data and a sound analysis on a wider-scale perspective can backfire and give a general perception that groundwater development is un-sustainable to the detriment of the many benefits that may be produced. This may lead to an undesirable preference for other water supply alternatives, which more carefully evaluated inside an integrated system, may result more expensive, less environmentally friendly and less easily available. General rules should not be given since solutions are heavily site-dependent and have to be analysed on a case by case basis. Otherwise large errors can occur. Proactive actions are needed in order to take this into account and solve these problems. Among these actions the following are suggested: a framework to assess costs and benefits, stakeholder education and participation, and the implementation of institutions for collective groundwater management.

1 INTRODUCTION

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 most accessible, cheapest and most reliable freshwater resource. Groundwater development has significantly increased during the last half century in most semiarid or arid countries, and has been mainly undertaken by a large number of small (private or public) developers. Control and management of groundwater development has often been weak or even non-existent by the responsible Water Administration, devoting few economic and human resources. In contrast, surface water projects in the same period are usually larger in dimension and have been designed, financed, and constructed by Government Agencies, which normally manage or control the operation of irrigation or urban public water supply projects.

About half of the world's population drink groundwater. This proportion is higher in some countries like Denmark (90%) and in many coastal areas and small islands, such as the Balearic, Canary and Cape Verde archipelagos, Malta, Cyprus and Reunion. The main source of freshwater around megacities such as Mexico DF, Sao Paolo and Lima are intensively used aquifers. In Spain, although only 28% of urban water comes from groundwater, in medium and small-size municipalities (of less than 20,000 inhabitants) this proportion increases up to 70%. The widespread use of simple pumps in rural areas in poor developing countries has greatly improved health conditions (Arlosoroff *et al*. 1997).

Intensive aquifer development for irrigation is currently a normal situation in Central and Southwestern USA, Brazil, and the areas around the Mediterranean Sea, like in Central and Eastern Spain and its archipelagos. More recently, groundwater intensive use has carried out 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. Shah *et al*. (2000) state: "in developing countries of Asia and Africa groundwater development has become the livelihood creation progress for the poor".

2 WATER STRESS AND SUSTAINABLE DEVELOPMENT

During the last decade the expression *water stressed regions* has become pervasive in the water resources literature. This usually means that these regions are prone to suffer now or in the near future from serious social and economic problems due to freshwater scarcity. Some authors even insist on the probable outbreak of violent conflicts – water wars – among water stressed regions.

The usual threshold used to consider a region under water stress is 1,000 m^3/yr per person (UN 1997), but some authors almost double this figure. When this ratio is only 500 m^3/yr per person the country is considered in a situation of absolute water stress, or *beyond the barrier* (Seckler *et al.* 1998, Postel 1999, Cosgrove & Rijsberman 2000).

This simplistic approach of only considering the ratio between water resources and population –*per capita* availability of freshwater, or Falkenmark Index– has scarce practical application and may mislead, since this indicator pays no attention to other socio-economic conditions of the country, or to the influence of world-trade. In fact, when food or manufactured goods are imported, there is implicit a water use in the exporting region which is a kind of water transfer to the importer, or *virtual water*. The use of such *first generation* water indicators is too simplistic and therefore may lead to wrong diagnosis and decisions. This means that the foreseen scenario for the year 2025 by the World Water Vision (Cosgrove & Rijsberman 2000) needs a thorough review, with more adequate indices.

In its last Assessment of Global Water Resources, the United Nations did a more realistic classification of countries according to their water stress (UN 1997). This assessment not only considered the ratio water/population but also the Gross National Product (GNP) *per capita*. Other experts are also beginning to use other more sophisticated indices or concepts in order to diagnose regions with current or future water problems. It seems that a certain *water stress* may be an incentive to promote the development of that region. For example, during the last few decades in many semiarid or arid areas, tourism or the production of high value crops has significantly increased. The costs due to low rainfall are cancelled out by the enhanced productivity of the increased sun hours and solar energy received. This happens in the *sun belt* in the USA and in most of the European Mediterranean coastal areas. Groundwater is probably the most frequently used water resource, but water may also be imported from other regions, reused or desalinated. Currently a large seawater desalinating plant (40 Mm^3/yr for greenhouse supply) is being completed in Southeast Spain, and a large number of small brackish water desalination plants are currently operating in the Canary Islands and in Southeastern Spain.

One example of a more realistic index is the Social Water Scarcity Index (SWSI), which is obtained by dividing the Falkenmark Index by the Human Development Index (HDI). The HDI is a composite index based on life expectancy, education and GNP *per capita*.

Using the SWSI, countries such as Poland, Cyprus, UK, Belgium and Peru can no longer be classified as water-stressed. Due to their higher social adaptive capacity (as measured by a higher HDI), they are now classified as relatively self-sufficient in water. Countries such as the United Arab Emirates and Oman move from water-scarce to merely water-stressed. On the other hand, countries such as Burkina Faso, Eritrea and Nigeria move from relative sufficiency to water-stressed, and Ethiopia moves from water-stress to water scarcity due to its low adaptive capacity as measured by the HDI. The adaptive capacity of countries due to their industrial transformation is important in order to attain sustainability through the levelling and even the reduction of environmental pressure (Vellinga 2001).

Although probably the SWSI seems better than the Falkenmark Index, it is still far from being adequate to accurately represent the real situation. For example, Israel has less than 400 m^3/yr per person; it is *beyond the barrier* according to the Falkenmark Index and becomes water-scarce with the SWSI. Nevertheless, this water scarcity is not an obstacle to have a good quality of life. The situation is similar in Malta, and in some regions of Spain, such as the watersheds of Catalonia, the Balearic and the Canarian archipelagos, and the Madrid autonomous region. All of them are also *beyond the barrier* (i.e. less than 500 m^3/yr per person) but are economically and socially prosperous areas in Europe.

In the last decade, the concept of sustainability has been proposed as a philosophy oriented to solve most water problems or conflicts. In 1987, the United Nations Commission on Environment and Development (WCED 1987), commonly known as the Bruntland Report, defined sustainability as “the ability to meet the needs of the present generations without compromising the ability of future generations to meet their needs”. The European Union Water Framework Directive, enacted in December 2000, states that it is necessary to promote or foster sustainable water use. Probably most people agree with this general principle, but its practical application in natural resources management is far more complex and challenging (Wood 2001). For instance, in terms of water resources management even the concept of minimum basic water needs, estimated to be 20 to 50 L/d per person, is heavily debated.

Other terminological problem is related to the concept of future generations. Does it refer to the people that will live in this planet in the 22nd century, or in the whole 3rd millennium, or only in two generations, that is, within the next fifty years? No scientist is able to predict the situation one thousand years from now, and very few dare to present plausible scenarios for the 22nd century. The fast pace in Science and Technology has dramatically altered the social scenario in the last decades and certainly this will continue in the future. This means a need for new approaches to problems and new challenges, which are currently unforeseen. Most current predictions refer to human needs in one or two generations, no more than fifty years from now.

It is clear that environmental problems have a natural science base but also –and mainly– a social science basis. There is no doubt that the issue is complex. For instance, Latin America and the Caribbean are rich regions based on ecological indicators, but because of their economic, social and political situation, reflected in the corresponding indicators, their sustainable development is in jeopardy.

Water scarcity is not usually the problem behind un-sustainable use of groundwater resources (Llamas 1992). The real issue is poverty and widespread water mismanagement, and the main result of mistaken management is water quality degradation. Every expert knows that groundwater quality degradation or pollution is a more serious problem than surface water pollution. Lundqvist (1998) has defined this degradation as a *hydrocide*.

More and more authors consider that the way to solve the existing water problems, like lack of drinking water and sanitation, is not to insist on gloom and doom unrealistic campaigns, trying to create *environmental scares* and predicting *water wars in the near future* (see Kessler 1998, The Economist 1998, Asmal 2000, WHAT 2000, Lomborg 2001).

Aside from non-consumptive hydroenergy uses of water and for cooling purposes in energy facilities and factories, most water is needed for domestic supply and irrigation. Irrigation uses about two thirds of all the water worldwide diverted from rivers and aquifers for beneficial uses. If consumptive use is considered this ratio raises up to 80% or more.

In arid and semiarid countries, the main water use is always irrigation, and its proportion of total water use is from 80 to 95%. Therefore, a good assessment of water use in irrigation is crucial in order to prevent the so-called *looming water crisis,* or simply to improve the world's economy and welfare, and especially in developing countries. This is why the irrigation issue is dealt in some detail in this book.

According to the Director General of the International Water Management Institute, as referred by Shah *et al.* (2000): "few irrigation technologies have had as wide-ranging and profound an impact as the small mechanical pump; and this becomes evident in the Ganga basin and in sub-Saharan Africa where poor households could transform their farming and their livelihoods if only they could lay their hands on a pump…" "No wonder, then, that in developing countries of Asia and Africa groundwater development has become the central element of livelihood creation programs for the poor".

In the Second World Water Forum saving water in irrigation through different actions was considered one of the most important goals in order to avoid the looming water crisis (Cosgrove & Rijsberman 2000). In this respect the motto *more crops and jobs per drop* has been included in almost every conference on water resources during the last decade.

3 INTENSIVE USE OF GROUNDWATER

There are great advantages of using groundwater to supply human needs, but there are also some negative side-effects, as happens in the development of any other natural resource. These side-effects depend on resource characteristics which are specific to groundwater (large ratio storage/flow, and sluggish water movement) and in contrast of surface water (small ratio storage/flow, and fast water movement); often these characteristics may be advantagedly combined to in integrated or joint use schemes (Sahuquillo 1991, Llamas 1999).

When development is the dominant concern, preserving the conventional beneficial use of groundwater resources is the main objective. This was the basis of approaches, like the *safe yield*, to define how much groundwater can be abstracted from an aquifer, assuming 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 way of developing aquifers by allowing large water abstractions from deep boreholes. *Safe yield* concept was explained in many textbooks and manuals and has been modified into other similar terms such as *sustainable yield* and *perennial yield* (ASCE 1961, Bear & Levin 1967).

The *safe yield* concept is flawed and may be unsustainable in the long-term (Bredehoeft 1997, Sophocleous 1997) since it does not adequately consider long-term interaction effects and environmental impacts. Besides it has been mistakenly used to establish water rights. It may be that optimal aquifer use is not necessarily linked to aquifer recharge when economic and water quality effects are taken into account (Custodio 2002).

Sustainable groundwater development is a powerful and dynamic concept that has to be refined and its principles have still to be turned into achievable policies (Sophocleous 2000). The groundwater successes of the 20th century have left a series of complex, site-specific water resource problems. Water Authorities, technical organisations and technological regulations are ill-designed to address them (Lant 1999). Their solution is a major challenge for the 21st century.

Problems of groundwater use, as will be commented later on, have been frequently magnified or exaggerated by groups with a lack of hydrogeological know-how, or because of professional bias or vested interests. For instance, the World Water Council (WWC 2000) states that: "Aquifers are being mined at an unprecedented rate; 10% of world's agricultural production depends on using mineral groundwater…", but this estimate is not based in any reliable data. In recent decades, groundwater overexploitation has become one of the *hydromyths* that pervade water resources literature (Custodio & Llamas 1997, López-Gunn & Llamas 2000). A usual corollarium is that groundwater is an unreliable and fragile resource that should only be developed if conventional large surface water projects are not feasible (Seckler *et al.* 1998, Postel 1999). Another usual *hydromyth* is to consider that groundwater mining –the development of non-renewable groundwater resources– is always an overexploitation; this seems to imply that groundwater mining goes against basic ecological and ethical principles, when this is not necessarily true.

The concept, real meaning and situation of aquifer overexploitation were discussed in several meetings about one decade ago (Pulido *et al*. 1989, Candela *et al.* 1991, Dijon & Custodio 1992, Simmers *et al*. 1992). Most of the current knowledge was presented at these meetings, but knowledge on intensively exploited aquifers has been increasing and the use of the term overexploitation has spread. However, recent specialised literature on groundwater and aquifer intensive use is relatively scarce.

In fact, the journalistic literature on the problems caused by groundwater use is more abundant that the literature on its benefits. It often stresses local problems as if they were general issues. This is mainly a corollarium of the general attitude of the media, as it is described by Lomborg (2001): "It is an often heard cry: Global water crisis, the major issue of the 21st century. But it is needlessly rhetorical and intimidating. It is unreasonable to expect that wells are going to run dry. We need better water management, pricing and impact substitution".

The concepts of *safe yield*, *overexploitation*, *sustainability*, *water stressed aquifer* and similar terms are not exclusively technological. They are frequently related more to the Social Sciences than to Hydrology. However, a correct understanding of the hydrological or scientific basis of those terms –in a quantitative form– is a crucial need. For instance, saying that intensive use of groundwater has created social havoc in a region may be meaningless without some information about the aquifer. For example, data on the size of the aquifer, its hydrogeological parameters, the amount of water pumped, the number of groundwater stakeholders, the economic value of activities affected by intensive use and the actual damage produced on Nature. A 5,000 km^2 aquifer with 100,000 ha irrigated and 20,000 water wells is not comparable to a 200 km^2 aquifer with 1,000 ha irrigated and 100 water wells.

Also the economic and cultural background of the area are of paramount importance. Usually poverty and the accompanying lack of knowledge and of robust institutions are the main limitation to solve problems. The proposed solutions usually have to be rather different if the people in the area have a dayly per person Gross National Product of 1–2 €/d than if they have 50–100 €/d. In this context, ethical aspects may be relevant for the analysis and solutions of certain problems.

Groundwater development during the last half century has significantly contributed to alleviate poverty and to improve public health. These improvements should be maintained and increased, but in a different way. The generally uncontrolled and unplanned groundwater development has to be rationalised, and the externalities of groundwater extraction and temporary or intrinsic uncertainties related to water management should be taken into account. The implementation of sustainable groundwater use requires the participation of educated and informed groundwater users and other stakeholders in groundwater management decisions. This needs the development of institutional arrangements for groundwater management where users can work jointly with the corresponding Water Authorities.

The evaluation of intensive use of groundwater is the result of balancing benefits against costs in the particular framework of each case and under the constraints of nature preservation, laws and rights.

4 BENEFITS OF GROUNDWATER USE

The benefits of groundwater use have been pointed out by many authors and are presented in most hydrogeology books (see Todd 1958, Custodio & Llamas 1976, Freeze & Cherry 1979, Fetter 1994, NRC 1997). They can be summarised as easy accessibility, great areal distribution, progressive development, low capital intensity, relative low cost, ease of available technology, widespread use by a large number of users, relative resilience to droughts, and the general good chemical quality of water, which is also free of disease-bearing microbiological components when it is obtained by well-designed groundwater works. Groundwater offers unique opportunities for human development in poor areas (Shah *et al.* 2000).

Table 1. Comparison of irrigation using surface and groundwater in Andalusia, Southern Spain (Hernández-Mora *et al.* 2001).

Irrigation indicator	Source of irrigation water			Ratio of groundwater to surface water
	Groundwater	Surface water	Combined	
Irrigated surface, 10^3 ha	210	600	810	0.35
Average use at origin, m^3/ha/yr	4,000	7,400	6,500	0.54
Water productivity, €/m^{3*}	2.16	0.42	0.72	5.1
Employment generated, 10^{-6} EAJ/m^{3**}	58	17	25	3.4

* 1 € ~ US$ 0.90 (2001)

** EAJ stands for Equivalent Annual Job, which is the work undertaken by one person working full-time for a one year period.

Using groundwater in irrigated agriculture improves water use efficiency through the greater control of water application and the close-to-full-cost economy that is involved. Few studies are known where the differences between efficiency of surface and groundwater irrigation are compared. Nevertheless, the higher socio-economic productivity of irrigated agriculture using groundwater compared to surface water seems to be the general situation. Table 1 shows the main results of a study done for Andalusia, Southern Spain. Economic productivity of groundwater irrigation is five times greater than irrigation using surface water and generates more than three times the employment per m^3 used. While good climatic conditions in Spanish coastal areas may influence the results, the situation seems similar in other continental regions of Spain. Other comparable works in Europe have not been found.

Studies in India seem to point to similar results. India has a special interest because groundwater development has been crucial in order to feed an increasing population of nowadays more than 1,000 million. According to widespread predictions of those who Dyson (1996) defines as *pessimistic neo-malthusian*, India's population should have starved to death about twenty years ago, when its population was about 600 million. As Kessler (1998) states: "mistakes have been made, and will certainly continue to be made but in the process the lives and health of many people have been improved immensely and will continue to improve given the incentives and opportunities for economic development and scientific research". The grim predictions for India have not occurred mainly because of the green technological revolution and the increase in groundwater irrigation. Seckler *et al.* (1998) focus on the negative effects of such development, which will be commented later on.

Other potential benefit of groundwater development is the increase in net recharge in those aquifers that, under natural conditions, have the phreatic surface close to the land surface. The drawdown of the water table can result in a decrease in evapotranspiration, an increase in recharge from precipitation that would be rejected under natural conditions, and an increase in indirect recharge from surface water bodies. This process was already described by Theis in 1940 and was later developed by Bredehoeft *et al.* (1982). After Johnston (1997), in nine out of eleven American regional aquifers, intensive groundwater development has resulted in significant increased recharge.

A clear example of this situation is the increase in available resources for conventional beneficial uses that followed intensive groundwater pumping in the Upper Guadiana basin in Central Spain (Figs. 1, 2). Under disturbed conditions, average renewable resources may have increased between one third and one half (Cruces *et al.* 1997, Llamas *et al.* 2001). Intensive pumping for irrigated agriculture started in the early 1970s and reached a peak in the late 1980s. As a result, wetlands that under semi-natural conditions had a total extension of about 25,000 ha today only cover 7,000 ha. In addition, some rivers and streams that were naturally fed by the aquifers, now have become net losing rivers.

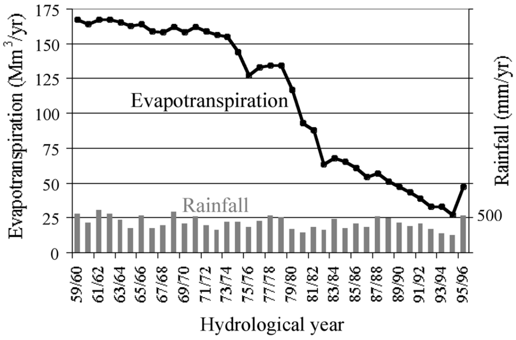


Figure 1. Temporal evolution of evapotranspiration from the water table in the Upper Guadiana basin, caused by water table depletion (after Martínez Cortina 2001, as cited in Llamas *et al.* 2001).

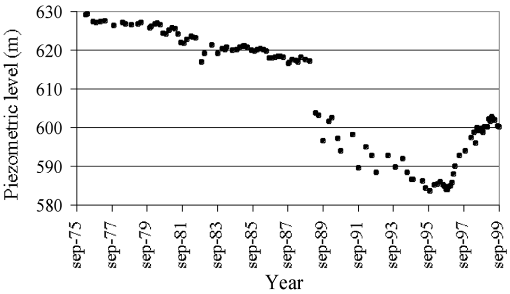


Figure 2. Water table evolution in Manzanares, Upper Guadiana basin, Spain (after Martínez Cortina 2001, as cited in Hernández-Mora *et al.* 2001).

The resulting drawdown in the water table has produced a significant decrease in evapotranspiration from wetlands and the water table, from about 175 Mm^3/yr under quasi-natural conditions to less than 50 Mm^3/yr at present. At the same time, there has been a significant increase in indirect recharge to the aquifers from rivers and other surface water bodies. Consequently, more resources have become available for other uses, mainly irrigation. Clearly, it is important to keep in mind the associated negative impacts that the drawdown of the water table has had on groundwater-dependent natural wetlands, as it will be explained below.

Groundwater use may also have important ecological indirect benefits when its use means new, large and expensive hydraulic infrastructures are no longer needed. These infrastructures stress countries' economies, and might seriously damage the natural river regime, and can create serious social problems from displaced people (WCD 2000).

5 COSTS OF GROUNDWATER USE

Costs of groundwater use, often called *problems*, can be summarised in the drawdown of groundwater levels and groundwater quality deterioration. This means increased exploitation costs and in some cases loss of well yield, as well as problems for using groundwater as drinking water supply or irrigation source. Collateral problems are linked to land subsidence and in some cases, land collapse (Custodio 2001). Many of them are hydrological consequences of aquifer properties and are susceptible of being foreseen and duly internalised. In practice these costs are often not considered due to poor knowledge, lack of controlling institutions and lack of awareness by groundwater users. Such *problems* should not be a deterrent to groundwater development, but a warning that the system is changing. This means there is a need for continuous accommodation, rather than the complete abandonment proposed by some decision-makers, the mass media and politicians. For example, car production would not be halted because roads are narrow and dangerous; instead highways are to be put in place, or the benefits of easy transportation would be lost.

Many problems of groundwater use can be reduced to costs, both direct and indirect, but other problems are much more difficult to measure, especially ecological changes and social values, but their description and consideration is a useful exercise.

It is important to clearly identify the real causes of problems to dispel the *hydromyth* of groundwater vulnerability. Groundwater development for water supply and irrigation might be the main factor to overcome the poverty threshold. Ironically, according to Shah *et al.* (2000), in Africa less than 1% of the renewable groundwater resources are presently used.

The observation of a continuous significant decline trend in groundwater levels or water table depth is frequently considered an indicator of imbalance between abstraction and recharge. While this may be the case, the approach might be too simplistic and manage-

Box 1. Advantages and benefits of using groundwater.

ADVANTAGES AND BENEFITS OF USING GROUNDWATER

◆ LARGE WATER STORAGE

- Small variability of water
  - discharge (natural/artificial)
  - quality
  - temperature

  ⇨ Adequate for supply in case of
  - peaks of demand
  - droughts
  - emergency situations
- No large artificial storage facilities are needed
- Essential water storage in small islands and coastal areas

◆ SLUGGISH FLOW THROUGH SMALL VOIDS IN A 3-DIMENSIONAL PATTERN

- Mixing of flow paths ⇨ homogeneisation
- Time for
  - progress of chemical reactions
  - biological decay of pathogens
  - decay of short/medium lived radioisotopes
  - temperature equalization
  - fighting contamination incidents

  ⇨ natural depuration
  ⇨ often water can be safely drinked without treatment
- Filtering effect ⇨ clear water

◆ SPACE PROPERTIES

- Easy access
- Availability close to water demand areas
  - small investment
  - few land-use problems
- Groundwater abstraction facilities occupy a small surface

◆ OTHER

- Aquifer development may increase recharge
- Security against
  - natural hazards
  - human failures
  - criminal actions

NOTES : ☆ MOST ADVANTAGES ARE LINKED TO AQUIFER PROPERTIES
☆ WELLS HAVE TO BE CORRECTLY CONSTRUCTED AND OPERATED

Box 2. Drawbacks and costs of using groundwater.

DRAWBACKS AND COSTS OF USING GROUNDWATER

◆ WATER QUANTITY EFFECTS

- Groundwater level drawdown
  - ⇒ increased water pumping cost
  - ⇒ early replacement of
    - wells
    - pumps
    - facilities
- Decrease of
  - spring flow
  - river base flow
  - wetland surface area
- Longer tracts where rivers may lose water to the ground

NOTE: these effects can be foreseen

⇒ internalisation may be
- technically easy
- socially complex if rules are not clear

◆ WATER QUALITY CHANGES

- Progressive flow pattern modification
  - ⇒ Displacement of low quality water bodies
  - ⇒ Sea water encroachment in coastal aquifers
  - ⇒ Enhanced surface water infiltration
  - ⇒ Background quality evolves along time
- Mixing of different groundwaters
  - inside long-screened wells and boreholes
  - due to different groundwater inflows to the well

⇒ water quality changes due to variable pumping rates

◆ OTHER EFFECTS

- Land subsidence
- Increased collapse rate
  - in karstic areas
  - near poorly constructed wells

☆ NOTE: THESE EFFECTS ARE POSSIBLE. THEY DO NOT NECESSARILY APPEAR

☆ MOST NEGATIVE CONSEQUENCES ARE RESULT OF AQUIFER PROPERTIES

☆ CHANGES CORRESPOND TO THE TRANSIENT PERIOD BETWEEN INITIAL AND FINAL STATE

☆ TRANSIENT PERIODS MAY VARY FROM MONTHS TO MANY YEARS ment decisions might sometimes be misguided. According to well-known aquifer hydrogeological principles every groundwater withdrawal causes an increasing in piezometric depletion until a new equilibrium is achieved between the pumpage and the recharge under new conditions (Custodio 2000a, Sophocleous 2000). This transient situation can be quite long-lasting depending on the aquifer characteristics, such as size, transmissivity, and degree of stratification and heterogeneity (Box 3). In large unconfined aquifers the time necessary to reach a new equilibrium state in water table levels can be decades, even centuries when transmissivity is low. On the other hand, in large confined aquifers water level declines do not necessarily imply a significant decline in storage but rather a change in the flow conditions of the system.

In arid and semiarid countries significant recharge may occur only every 5 to 10 years. Therefore continuous decline in the water table during a dry climatic sequence of a few years, when recharge is low and abstraction is high, may not be representative of long-term trends.

Declines in water levels do however indicate the need for further analysis. When water levels indicate that abstractions are possibly greater than recharge, a case-by-case analysis must be carried out, taking into consideration the hydrogeological characteristics and size of the aquifer, as well as climatic sequences.

In any case, declines in the water table can result in decreasing well production as well as increased pumping costs. This economic impact can be more or less significant depending on the value of the crops obtained. For instance, in some zones of Andalusia, Southern Spain, the value of crops in greenhouses may reach from 40,000 to 60,000 €/ha/yr. The water volume used is between 4,000 and 6,000 m^3/ha. The energy needed to pump 1 m^3 up 100 m is about 0.3 kWh. This means that the increase on the costs of pumping in the event of a drawdown of 100 m is almost irrelevant for this type of agribusiness. On the other hand, if the value of the crops is only about 1,000 €/ha/yr, and the water needed is about 10,000 m^3/ha, obviously the increase of energy cost due to a drawdown of 100 m can make that agriculture economically unfeasible.

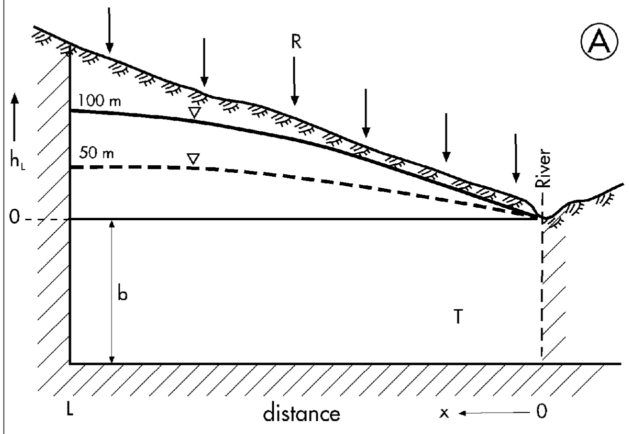
The socio-economic situation created by water table depletion in rural areas of poor developing countries may be more complex and prone to social inequity, if wealthier or more entrepreneurial farmers produce a drawdown that depletes the water table below the bottom of the shallow wells of their poor neighbours (Janakarajan 1999, Moench 1999). In both cases, a possible solution would be to require the one causing the water table depletion (the rich farmer), to compensate in money or water the farmer(s) whose well becomes dry or sees his/her yield reduced. This is what the Spanish Water Act requires. An added problem may be that the officers of the corresponding Water Authority have neither the knowledge nor the necessary means to enforce regulations. Nevertheless, it should be considered that limiting drawdown to preserve existing shallow wells might not be a sound policy to use the aquifer efficiently. It is often said that the *poor farmers* deprived of water will tend to migrate to some urban area. Yet the question is whether this frequent emigration towards urban areas would be stopped or significantly reduced if groundwater development is forbidden in order to avoid such water table depletion.

The evaluation and extrapolation of real situations to other areas cannot be done without considering the actual circumstances for each case, not only hydrogeological ones but the economic and social conditions as well. Thus a case by case study is needed. What is a correct analysis in one place may be not applicable in another place. Thus, the circumstances in Spain, which have some similarities with California and Northwest Mexico, are very different to those of India, Bangladesh and Nepal, where the average income is between 1–2 €/d per person, that is, between 30 and 50 times less than in most of the developed countries. Analyses based on global trends and simplistic indices are often misleading and may lead to unrealistic conclusions.

Groundwater level drawdown in some areas of India is a fact, and is reported to range 2 to 4 m/yr. After a report by Seckler *et al.* (1998): “The extraction of water from aquifers in India exceeds the recharge by a factor of two or more. Thus almost everywhere in India freshwater aquifers are being pulled down by 1–3 m/yr. This increases the energy and other costs of pump irrigation and reeks havoc with supplies of freshwater to villages. Lakes and rivers dry up as the aquifer recedes and the problem is

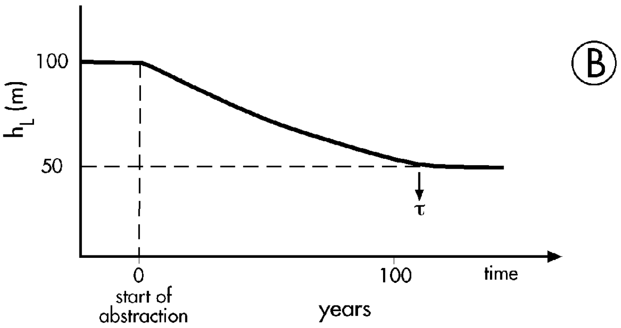
Box 3. Effect of groundwater development in groundwater level in an aquifer-river system.

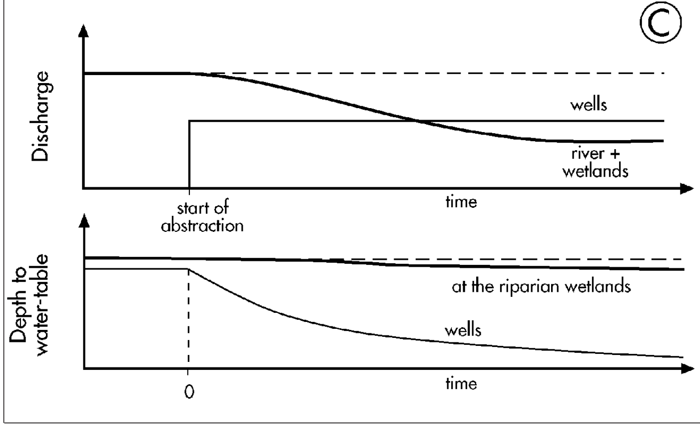
- *Changes in water recharge (or abstraction) may need a long time to attain a new steady state.*
- *Groundwater level depletion often cannot be interpreted as abstraction being greater than recharge.*



Results of a change of recharge rate in an idealised valley aquifer discharging into a river. For constant aquifer transitivity (T), when the water table elevation above the river (h) is much less than saturated thickness, in a cross-section perpendicular to the river (Fig. A) which contains the flow lines, limited by impervious formations (shaded areas) and a divide below the river (no flow across it), it can be deduced (Custodio & Llamas 1976): $H = R \times (2T)^{-1} (2L - x^2)$ in which R = uniform recharge rate, L = aquifer width, x = distance from the river. The maximum elevation is produced at the inner boundary, $h_L = R L^2 (2T)^{-1}$. For L = 10 km, T = 500 m^2/d, the two water-table positions (∇) are: for R = 364 mm/yr, h_L = 100 m; for R = 182 mm/yr, h_L = 50m. If R is modified, the water table moves slowly to a new position. A uniform, intensive abstraction of groundwater over the aquifer of half the original recharge, makes h_L = 100 m to change to h_L = 50 m in the long term.

The drawdown trend (Fig. B) levels after a time $\tau \sim 2 L^2 S T^{-1}$, in which S is the aquifer storage coefficient. For S = 0.1 (truly unconfined aquifer) the initial drawdown rate is 1.8 m/yr, and little by little fades out and levels off after $\tau \sim 110$ yr. Along this period the contribution to the river flow (base flow) is also progressively modified, to adjust to the new recharge rate (halved in the example). This means that the abstraction of half the renewable resources starts a long lasting, sustained drawdown trend, that may be mistaken as abstraction exceeding actual recharge.





In such an aquifer-river system, river discharge reduction due to groundwater abstraction include a reduction of riparian wetland surface area by lowering the water table, as shown in Figure C, in which groundwater abstraction is more than half the original river and wetland discharge. Part of wetland discharge goes to the river and part is evapotranspirated.

compounded. Eventually, the cost of pumping become so high that the pumps are shut down and the whole house of cards collapses. It is not difficult to believe that India could lose 25% or more of its total crop production under such scenario". Nevertheless, such report does not include any scientific basis for such strong statements.

Several documents seem to indicate that the situation in India is quite different. For example, a report by the Indian Water Resources Society (IWRS 1999) estimates that:

1) 54% of the total irrigated surface in India (50 million ha) uses groundwater.
2) Renewable groundwater resources are over 400,000 Mm^3/yr.
3) Groundwater pumpage for all uses is about 115,000 Mm^3/yr, including urban and industrial uses (about 10% of total groundwater use).
4) The *overexploited* or *almost overexploited* aquifer systems are about 200 out of a total of 5,000 aquifer systems, although no data on size and pumpage in these aquifer systems are given. Therefore, it seems that less than 5% of total aquifer systems have problems.

According to Indian Water Resources Society (IWRS 1999) and the Regional Study of Southeast Asia (2nd World Water Forum), the amount of water used by surface water irrigation (16,000 m^3/ha/yr) is four times that applied to groundwater irrigation (4,000 m^3/ha/yr). Although no data have been found on the productivity (in money and jobs) of Indian surface and groundwater irrigation, a paper by Dains & Pawar (1987) seems to indicate that groundwater irrigation was significantly more productive than surface water irrigation. Dhawan (1995) considers that yields in areas irrigated with groundwater are 1.3 to 1.5 higher that those of areas irrigated with surface water. This seems to indicate that economic productivity of 1 m^3 of groundwater may be up to 5 to 10 times higher that the economic productivity of 1 m^3 of surface water. This possibility is not mentioned in the main book of the 2nd World Water Forum (Cosgrove & Rijsberman 2000). Therefore, even keeping in mind the strong uncertainties that are attached to hydrological data, there is evidence of the greater general productivity of groundwater irrigation. This should not be attributed to any quality intrinsic to groundwater. Rather, the causes are found in the greater control and safe supply that groundwater provides, mainly during droughts (see Llamas 2000). Additionally there is the greater dynamism that has characterised farmers who have sought their own sources of water and who bear the full (direct) cost of drilling, pumping and distribution (Hernández-Mora & Llamas 2001).

Groundwater intensive use does not only could affect the quantity of groundwater available, but also induces changes in groundwater quality. These are mostly related to changes in potenciometric heads, which induce the displacement of groundwater bodies and may redirect saline or poor quality groundwater towards the abstraction wells. The risk of groundwater quality degradation increase with (Custodio 2000a):

1) Proximity to saline water bodies: risk of saltwater intrusion, which not only depends on the amount of abstraction relative to recharge, but also on the well-field location and well design, and on the aquifer's geometry and hydrogeological parameters.
2) Hydraulic connection to low quality surface or groundwater bodies. Changes in the hydraulic gradient as a result of groundwater abstraction may result in the intrusion of poor quality water into the aquifer from adjacent water bodies.

In these cases, the problem is often related to inadequate well location and not necessarily to the total water volumes abstracted.

One of the most serious threats to sustainable use of coastal aquifers is seawater intrusion and mobilisation of old marine water in the sediments (Custodio & Bruggeman 1987, Falkland & Custodio 1991). There are real cases of serious losses of aquifer volume, but in many cases it is just a situation of poor well location and design, inadequate management and a deviated interpretation of reality, e.g. designating the aquifer as at high risk when only a few wells show high salinity. Coastal aquifers, even small ones, are often key elements for water resources management in areas that lack space for freshwater storage.

It is well known that aquifer use may produce poor groundwater quality due to the presence of some natural components such as As, V, F, heavy metals, U, excess hardness, aggressiveness due to acidity, presence of sulphide ions, etc. Many works deal with the geochemistry of such components (Stumm & Morgan 1981, Morel & Hering 1993).

Recently the presence of As in groundwater has attracted the mass media and public attention due to the serious problem it has generated over large areas. This has affected millions of inhabitants of West Bengal and Bangladesh (Fazal *et al*. 2001). However this is not a new problem since it has been known for many years in the dry part of the Pampa Argentina and El Chaco (South America), in areas of the USA and in Mexico. It also appears near Madrid and Valladolid, in Spain. Excess fluoride in groundwater is also a problem in areas of Chile and Peru, in Mexico and in India.

These problems are not always related to intensive exploitation of aquifers, but in some cases this can happen. This may happen when increased drawdown has induced well deepening, and the deeper wells have cut through formations with a low renewal rate in which noxious components may be present. This may also happen when the drawdown dewaters parts of the ground previously saturated with water in a reduced ambient in which many substances are held insoluble. The penetration of oxygen from the surface or through the abstraction wells may create oxidising conditions that free these components, e.g. by oxidising arsenic-rich sulphides (Schreiber *et al.* 2000). Acidity production may also dissolve iron and manganese oxyhydroxides containing heavy metals and arsenic. Ion exchange that reduces the alkaline-earth content may favour fluoride dissolution. All these changes are often subtle and modify the baseline (background) quality of groundwater. Warning signals can be found by adequate monitoring, although this is a difficult and expensive task in developing countries.

Aquifers in young sedimentary formations are prone to compaction as a result of water abstractions. For example, this has been the case in the aquifers underlying Venice, Mexico City, Bangkok, or the Central Valley of California. In karstic landscapes, oscillations in the water table as a result of groundwater abstractions can enhance the occurrence of karstic collapses. This is a result not only of the amount of groundwater withdrawal, but also of well field location, design and operation, and the frequency and amplitude of groundwater level oscillations.

Drawdown of the water table as a result of groundwater withdrawal can affect the hydrologic regime of connected wetlands and streams (Llamas 1993, Custodio 2000b). Loss of baseflow to streams, drying up of springs, desiccation of wetlands, and the transformation of previously gaining rivers into losing rivers may all be potentially undesirable results of groundwater abstraction. The Upper Guadiana catchment in Central Spain is a typical example of this type of situation (Hernández-Mora *et al*., this volume).

The ecological impacts of water table drawdown on surface water bodies and streams are increasingly constraining new groundwater developments (Llamas 1993). Examples are the drying up of wetlands, the disappearance of riparian vegetation because of decreased soil humidity, or alteration of natural river regimes. Reliable data on the ecological consequences of these changes is not always available, and the social perception of such impacts varies in response to the cultural and economic situation of each region.

The social perception of the ecological impacts of groundwater abstraction may differ from region to region and result in very different management responses. A European Union-funded project looked at the effects of intensive groundwater pumping in three different areas in Greece, Great Britain and Spain (Acreman 2000). In the Pang river in Britain, conservation groups and neighbourhood associations mainly drove management decisions with an interest in conserving the environmental and amenity values of a river that had been affected by groundwater abstraction. In the Upper Guadiana basin, drawdowns in the water table (30–40 m) caused jointly by groundwater abstraction and drought (see Fig. 2) resulted in intense conflicts between nature conservation officials and environmental NGO's, irrigation farmers and Water Authority officials. The conflicts have been ongoing for the last 20 years and have not been solved yet. Management attempts to mitigate the impact of water level drawdown on the area's wetlands have so far had mixed results (Fornés & Llamas 1999). On the other hand, in the Messara Valley, in Greece, the wetland degradation caused by drops in the water table has not generated any social conflict, since there is no current sensitivity towards these issues.

6 GROUNDWATER MINING

Intensive use of groundwater, as well as the background behind the overexploitation term, is associated with the assumed existence of renewable groundwater resources, which are taped to a certain degree, with or without using groundwater storage during some time. Groundwater mining is a different concept and refers to the use of groundwater storage at a rate much greater than the renewal rate. This mostly occurs in areas where recharge is small or non-existent due to low rainfall regimes. This would be the case of some aquifers in the Middle and Near East and North Africa (Charles 1991, Lloyd 1997). A discussion of sustainable resource use in these regions must not be undertaken using the usual points of view of humid and industrialised countries (Postel 1999). The discussion should primarily be an ethical one.

In this sense, some authors consider that the traditional view that arid countries should only develop their groundwater resources in relation to their renewable water resources is mistaken. In their view, the ethics on the sustainability of non-renewable water resources should be considered in terms of continuous technological improvements. With adequate management, many arid countries could use their non-renewable resources beyond the foreseeable future.

Zehnder (1999) argues that, in arid countries, the difference between available water resources (both from renewable and non-renewable sources) and total resources needed is made up in the form of *virtual water* or imported food. In Israel, for instance, *virtual water* amounts to 60% of total water used. In Libya, the country using the largest proportion of fossil (non-renewable) water, available renewable reserves amount to only 110 m^3/yr per person, whereas those of fossil water are 770 m^3/yr per person. The remaining 600 m^3/yr per person that are needed to meet Libya's water demand are imported in the form of food.

7 STAKEHOLDER PARTICIPATION IN GROUNDWATER MANAGEMENT

Most authors consider stakeholder participation as a must to achieve an efficient and equitable water management for intensively developed aquifers. This consensus is widely shared if such participation refers to a medium or large-size intensively used aquifer.

In many countries there is a long, multisecular tradition of Water Users Associations, yet this experience refers almost exclusively to surface water irrigation. This is logical because intensive groundwater use is a quite recent phenomenon, only a few decades old. Perhaps the region with more experience is California (Bachman *et al.* 1997). The exchange of experiences on the existence and operation of Water Users Associations to manage aquifers is one of the most important aspects in order to achieve a worldwide sustainable groundwater use and management.

Spain is a good example of a long tradition of collective management of common pool resources. The *Tribunal de las Aguas de Valencia* (Water Jury of Valencia), a famous example, has been meeting at noon every Thursday for many centuries at the main entrance of the Cathedral of Valencia, to solve all the claims among the water users of a surface irrigation system close to Valencia. All the members of the Jury are farmers. The decisions or sentences are oral and can not be appealed to a higher court. The system works and it is a clear proof that *The Tragedy of Commons* is not always true. As a matter of fact, in Spain there are several thousands of *Comunidades de Regantes* (Irrigation Communities or Water Users Associations). Some of them have also been in operation for several centuries.

The 1985 Spanish Water Act acknowledged the traditional *Comunidades de Regantes* as recognised and commendable institutions for surface water management. It also extended this type of collective institution to groundwater management. Moreover, the set up of *Comunidades de Usuarios de Aguas Subterráneas* (Groundwater Users Communities) is required when an aquifer system is to be legally declared overexploited. Nevertheless, the implementation of this legal and institutional innovation has been difficult to achieve. Only a few Groundwater Users Communities are really in operation, although 16 aquifers have been declared overexploited. The importance of these communities is widely recognised (Aragonés *et al.* 1996).

The main reason for this failure is that these new Groundwater Users Communities were established top-down. The Water Authorities tried to impose their implementation without the agreement of farmers, who are the main stakeholders (Hernández-Mora & Llamas 2001, Llamas *et al.* 2001). Both the 1999 amendments to the 1985 Water Act and the 2001 Law of the National Water Plan have provisions to try to overcome these difficulties and to foster the implementation of these institutions for collective management of aquifers with a greater stakeholders participation under the supervision of Water Authorities. In reality the two oldest groundwater users associations and currently the more active and effective ones were created before the 1985 Water Act, in Catalonia, Northeastern Spain, and were at the initiative of the groundwater users themselves, on the advice of the local Water Institution (Eastern Pyrenees Water Authority).

In Spain, independently of these officially created Groundwater User Communities, there exist a good number of mostly private collective institutions to manage groundwater. Some have been in operation for decades. Those existing in the Canary Islands were created to finance through shares expensive wells and water galleries; the water obtained is distributed to the shareholders or sold in *water markets* (see Hoyos-Limón 1997, Rodríguez Brito 1997, Hernández-Mora & Llamas 2001).

Although it seems that there exists a general consensus on the crucial need to implement these institutions, it will be necessary to wait some years to know if the incentives (economic, fiscal, operational) offered to the stakeholders are the right ones to achieve this implementation.

8 ETHICAL ASPECTS OF INTENSIVE DEVELOPMENT AND MANAGEMENT OF GROUNDWATER

Publications on ethical aspects of water management have steadily increased during the last years (Asmal 2000, Burke & Moench 2000, López-Gunn & Llamas 2000, Selborne 2000, Llamas 2001). In this last section, many of the issues previously discussed will be analysed from an ethical perspective. Groundwater development has significantly increased during the past fifty years in most semiarid or arid countries. This has been brought about by a large number of small (private or public) developers, often with poor scientific or technological control by the responsible Water Administration. In contrast, surface water projects developed during the same period (dams, canals, etc.) are usually of larger scale and have been designed, financed and constructed by government agencies that normally manage or control the operation of irrigation or urban public water supply systems. Many groundwater managers have limited understanding and poor data on the current groundwater situation and its real value. These results in problems like the depletion of the water level in wells, decrease of well yields, water quality degradation, land subsidence or collapse, affection to streams and/or surface water bodies, and ecological impact to wetlands and/or gallery forests. Reports on these impacts are often exaggerated, resulting in the myth that groundwater is an unreliable and fragile resource that should only be developed if it is not possible to implement conventional large surface water projects (López-Gunn & Llamas 2000).

The term overexploitation includes the perception of *undesirable effects* as a result of groundwater development. However, this *undesirability* depends mainly on social perceptions around the issue, which is sometimes more related to legal, cultural and economic background of the region in question than to simple hydrogeological facts. What may be perceived in one area as a benefit, e.g. developing much-needed irrigation, may well cause conflict elsewhere, e.g. if it causes degradation of wetlands, which may be viewed as an unacceptable environmental cost.

Most countries consider that groundwater abstraction should not exceed renewable resources. Some specialists believe that groundwater mining (or development of fossil aquifer or of non-renewable groundwater resources) is contrary to the concept of sustainable development and should be socially rejected, if not legally prohibited. Nevertheless, there are those who argue that, under certain circumstances, groundwater mining may be a reasonable option as long as available data assure that it can be economically maintained for some time (for example, more than fifty years) and that the ecological costs are compensated by its socio-economic benefits. With careful management, many arid countries will be able to utilise resources beyond the foreseeable future without major restructuring. It might be said that fossil groundwater has no intrinsic value if left in the ground except as a potential resource for future generations, but that raises the question of how to determine whether they will need it more than the present generation. In many cases this fossil groundwater is needed to allow some groundwater flow to springs and oases, which may disappear some time after fossil water development. This adds to the complexity of the issue. Clearly, it is not easy to achieve a virtuous middle way. There is a tendency to move from one extreme to the other, and there are potential risks associated with both extremes.

The crucial importance of preventing groundwater contamination in order to avoid a future water crisis has begun to be understood in only a handful of countries. The old proverb *out of sight out of mind* expresses what is yet a sad reality. A strong educational effort must be implemented in order not to bequeath to posterity aquifers that are almost irreversibly polluted. This is the real problem in most countries, be they humid, arid, or semiarid, poor or rich. The depletion of groundwater storage (classical concept of overexploitation) is not generally as serious a problem as groundwater quality degradation, and often may be partly corrected without great difficulty if water-use efficiency is improved. Groundwater contamination may be the result of aquifer intensive use, but often is mainly caused by manmade changes in land use.

Real or imagined ecological impacts are becoming an important new constraint in groundwater development. These effects are mainly caused by water table depletion, which can culminate in decreasing or drying up springs or the low flow of streams. It can also cause reduction in soil humidity to the extent that it prevents the survival of certain types of vegetation, and changes in microclimates because of the decrease in evapotranspiration. In some cases, the ecological result of such changes is obvious. For instance, if the water table that was previously at land surface is lowered by more than 10 m during more than 20 years, it is clear that peatlands or gallery forests that might exist on that aquifer are not going to survive. But if the water table is depleted only during one or two years and no more than one or two meters, yet it cannot be assumed that the ecological impact will always be irreversible. Unfortunately, detailed and quantitative studies into this type of problem are still scarce in most regions. Another proverb that comes to mind is *prevention is better than cure*. But here, too, the precautionary principle should be applied with considerable prudence. In general, groundwater development should not be rejected or seriously constrained if it is well planned and controlled. During recent decades, groundwater withdrawal has made possible undisputed socio-economic benefits. Particularly in developing countries where nowadays it is a major source of potable drinking water, with 50% of municipal water supplies worldwide depending on it, as do many rural and dispersed populations. Groundwater irrigation has allowed the increase in food production at a faster rate than population growth; 70% of all groundwater withdrawals are used for this purpose, particularly in arid or semiarid regions. It should also be pointed out that using groundwater for irrigated agriculture is often more cost-effective than using surface water, mainly because farmers generally assume all abstraction costs (development, maintenance and operation). Groundwater abstraction usually produces more jobs and a substantially higher income per m^3 than surface water does.

Despite the complexity of the question and the variety of possible responses depending on place and time, there are several overarching issues that have ethical implications in trying to achieve sustainable, reasonable groundwater use. Firstly, subsidies (some hidden and some openly disclosed) that have traditionally been a part of large hydraulic works projects for surface water irrigation, have encouraged the neglect of groundwater resources by water managers and decision makers. More careful consideration of cost and benefit could reveal that many proposed surface water projects are economically unsound, thus fostering serious consideration of options on groundwater planning, control and management.

Availability and consistency of information is a prerequisite for successful groundwater management. Development of adequate hydrogeological knowledge has to be a continuous process in which technology and education improve stakeholder participation and a more efficient use of the resource.

There is an urgent need to create appropriate institutions to manage aquifers so that all who benefit from them are made aware that if they pump permanently in excess of the renewable recharge of groundwater, they may incur serious problems for themselves and for their children and grandchildren. Considering the aquifer as a shared common good brings with it the obligation to manage it in a participatory and responsible way.

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SECTION 2

Technical issues