CHAPTER 12

Specific aspects of groundwater use in water ethics

M. Ramón Llamas
Royal Academy of Sciences, Madrid, Spain
Complutense University (UCM), Madrid, Spain

Luis Martínez-Cortina
Spanish Geological Survey (IGME), Spain

ABSTRACT: Groundwater use has spectacularly increased during the last five or six decades. It is estimated that this use has increased in half century from 100–150 km^3/year to 900–1,000 km^3/year today. This intensive use has been described as a *silent revolution* performed by millions of farmers with scarce planning and control by the conventional governmental water agencies. Although the accuracy of most water data is generally illusory, it seems that today half of mankind drinks groundwater and more than 50% of the economic value of the irrigated agriculture is obtained with groundwater irrigation.

This *revolution* has produced great benefits in providing drinking water and decreasing malnourishment to the poor. But it has also produced different problems in some regions. These problems have been frequently exaggerated because of ignorance, inertia or corruption of some high-level water decision-makers. A series of *hydromyths* or wrong paradigms are pervasively found in many places and are discussed in this chapter.

Keywords: Groundwater (GW) intensive use; Silent revolution; Hydromyths; GW sustainability; GW economics; GW management institutions; Corruption

1 INTRODUCTION

This chapter aims to discuss how recent groundwater development and new concepts can shift our perceptions on the *looming water crisis* repeatedly forecasted in the media and in academic circles.

The current crisis is less due to water scarcity than to a crisis in water governance. The solutions, thus, have to be found elsewhere. This chapter proposes a shift away from pure technological fixes based on surface water infrastructures, predominant in the past, or so called the *hard path*, towards a *soft path* in water governance (Gleick, 2003). The *UN Reports on Human Development* clearly state this point of view (UNDP, 2006).

From the ethical point of view, it is important not to mix two connected and relevant issues: a) the ethical obligation of providing drinking water to the poor (the right to water or social ethics); and b) the ethical obligation of avoiding ecological disasters in aquatic ecosystems (*saving the planet* or environmental ethics).

The chapter focuses mainly on the agricultural sector, since the *lion's share* of the *blue water* consumptive use corresponds to irrigation, which is about 80%. This proportion can be higher than 90% in arid and semiarid regions. Any advances made in irrigation will translate in gains by other sectors—which often have higher economic returns or added value, such as industry, public water supply and sanitation, or environmental services.

First civilizations, known as *hydraulic civilizations* (Wittfogel, 1957), were born in the valleys of arid areas about 50 or 60 centuries ago. In these valleys, hunter and gathering societies settled into the land thanks to small irrigation infrastructures that could guarantee the regularity of crops. This required a collective effort, which facilitated the settlement of tribes, and led to the creation of *civic* or small urban centers. These so called *hydraulic societies* relied heavily on *hard infrastructure* and often economies of scale to re-organize land use planning, whilst facilitating the strengthening of the central state as founder and coordinator of infrastructure. With few exceptions, most of the large water infrastructure built in the last 100 years has been due to collective action on the part of the state, funded and controlled by the state administration.

Intensive use of groundwater is a recent phenomenon, less than half a century old in most places. This situation has occurred mainly in arid and semiarid countries, in some coastal zones and near to a few megacities. This groundwater development has produced great socio-economic benefits, mainly in developing countries. It has provided cheap drinking water that has helped to improve public health. The new irrigated lands have contributed to eradicate, or at least mitigate, malnourishment among those living in poverty. Millions of modest farmers with scarce public or governmental planning, assessment, financing and control, have mainly performed this groundwater intense development. This intensive use has really been a kind of *silent revolution*. In most countries the corresponding public water or irrigation agencies have been mainly devoted to design, build and operate large surface water irrigation systems. The well-known American hydrologist Raymond Nace (1973), described as *Hydroschizophrenia* the attitude by some water decision-makers of strongly separating surface and groundwater projects, usually ignoring groundwater. This attitude has been commonplace in India, Mexico, Spain, and many other arid and semi-arid regions worldwide. As a consequence, certain adverse effects have ensued in some places. For instance, in South Asia the current situation concerning groundwater development has been frequently described as a *colossal anarchy*.

Most of the problems caused by this uncontrolled groundwater development could be avoided or mitigated if the corresponding government agencies had been more active in assessing and controlling groundwater use. On the other hand, surface water officials have frequently exaggerated such problems. This has created a pervasive *hydromyth* on the fragility or weakness of groundwater as a reliable resource.

Because of ignorance, vested interests, or more frequently because of the low credibility of the water official warnings about the potential threats, most farmers are not reducing their intensive groundwater abstraction. On the other hand, there are practically no documented cases where intensive groundwater abstraction from medium or large size aquifers has caused serious social or economic problems similar to those caused by soil waterlogging and salinization or by the people displaced or ousted by the construction of large dams.

2 A BRIEF CONSIDERATION ON WATER AND HUMAN DEVELOPMENT

Although this chapter is obviously not the most adequate place for a comment on the human development concept, it is nevertheless important to emphasize certain aspects of human development as much as they relate to groundwater. This topic is treated with more detail in Llamas (2001, 2005).

True human development cannot be equated with *having more*, but rather with *being more*. Cultural and spiritual values must always prime over purely materialistic or hedonistic goods. At the same time, it is universally accepted that in order for this to occur, a human being must have a minimum amount of material means such as food, drinking water, housing, education and an adequate level of public health care.

Those inhabitants of regions whose average annual rent per capita is lower than US$ 500 are considered to be living under extreme poverty. The estimate is that out of the 6,000 million inhabitants of the planet, about 1,000 million live under this poverty threshold. On the other hand, there are approximately another 1,000 million people, mainly living in developed countries, whose average rent per year is over US$ 10,000 (this is about 20 times higher than people living in poorer conditions). Since this comparison, based exclusively on per capita rent, is somewhat simplistic, the UN have been now for years using a more complex criteria which takes into account factors such as education and life expectancy (UNDP, 2005).

It would be reasonable for the onlooker to question why the *rich* should take an interest in raising the level of the *poor*. There are at least two commonly acknowledged ethical reasons not to accept this argument. First, the intrinsic dignity of all human beings; and second, the sense of fraternity—or solidarity—existing among all people. In addition, other practical (or even selfish) considerations point out that it is not possible to implement a global sustainable development while poverty exists. Thus the 2002 *World Trade Organisation* meeting in Doha concluded that it was necessary to reduce the tax barrier on farming products in a clear attempt to help poorer countries. Another reason, which has become more prominent after September 11, 2001, is the fact that poverty constitutes an ideal culture for future terrorists.

The role water plays in the eradication of poverty is essentially twofold. Firstly, it is necessary to provide drinking water, sanitation and hygienic education to less-developed countries in order to reduce the mortality and morbidity rate. Secondly is the need to implement small-scale irrigation systems so as to help provide enough food for those regions whose inhabitants suffer from chronic malnutrition or find themselves exposed to famine whenever prolonged drought periods occur (Polak, 2005).

In the year 2000, the United Nations released the *Millennium Declaration*. Such declaration consisted of an analysis of the general state of affairs in the planet, together with a series of action plans for the future. Two of these specific actions or goals aim to halve by the year 2015 the proportion of the Earth's population that does not have ready access to drinkable water or suffers from malnutrition. Other chapters in this book deal with the *Millennium Development Goals* (MDG) in more detail, e.g. Jimenez *et al*. (this volume).

International conferences, such as *Bonn's International Congress on Freshwater* (December 2001) or the four preparatory sessions for the *World Conference on Sustainable Development* also known as *Rio+10* (Johannesburg, August 2002), have upheld the conclusions of the aforementioned MDG.

The *International Conference in Bonn* (German Federal Government, 2001) pointed out that the necessary investment in order to provide a basic water supply and water treatment systems in developing countries (about 1,000 million people) would amount to about US$ 20,000 million in the next ten years. Developing countries are to contribute half of this quantity, while soft loans and donations should complete the total amount. The so called *Camdessus Report* (Camdessus, 2003) substantially increases the amount of investment necessary but it deals with all the hydraulic infrastructures.

This overall figure, which might appear high, adds up to merely US$ 10 per person each year for the 1,000 million persons living in the rich countries whose yearly rent per capita is over US$ 10,000. In other words, if each of these people in developed countries were able to donate US$ 10 a year, the problem would be solved in just one decade. This yearly donation would constitute less than 1‰ (one per thousand) the average income, less than the amount people in these countries spend, for instance, on domestic animal food or ice cream.

These data only show the tip of the iceberg of the serious problem that unsustainable consumption constitutes in developed countries. Catastrophist *neomalthusian* theorists, who prefer to emphasize the problems, real or fictitious, associated with the increase in the world's population, hardly ever mention this. It is also often forgotten that most developed countries are still far from fulfilling UN's proposal to contribute 0.7% of their *Gross National Product* to help developing countries.

Thus, it is noticeable that solving the problem of poverty for millions of people does not imply an extraordinary effort on the part of rich countries. The need for an adequate management of these investments, however, adds an extra complexity to the problem, since donations are meant to be catalysts to improve the institutional and organisational capabilities of developing countries, rather than being mere alms to the poor. On the other hand, it is a well-known fact that the final destiny of some of these donations has been the purchase of weapons or the personal profit of some politicians of certain governments.

In recent years, a good number of declarations of statements in favor of the right to water of the poor have been proposed. For example, on occasion of the 2007 *World Day of Water*, Cardinal Bertone on behalf of the leader of the Roman Catholics made a declaration reminding the no. 485 of the *Compendium of the Social Doctrine of the Catholic Church* [www.vatican.va], which tells: "By its very nature water cannot be treated as just another commodity among many, and it must be used rationally and in solidarity with others. The distribution of water is traditionally among the responsibilities that fall to public agencies, since water is considered a public good. If water distribution is entrusted to the private sector it should still be considered a public good. The right to water, as all human rights, finds its basis in human dignity and not in any kind of merely quantitative assessment that considers water as a merely economic good. Without water, life is threatened" (Bertone, 2007).

3 WATER AND GROUNDWATER USE IN THE WORLD

Before describing the current situation of groundwater it seems useful to summarize the basic data on the hydrological cycle and the relatively new concepts of *blue water* and *green water*. Neither the *virtual water* concepts nor the role of *desalinisation* are dealt with in this chapter. Readers interested in these topics are referred to Allan (2006), Cooley *et al*. (2006) or Llamas & López-Gunn (2007).

The basic functioning of the hydrological cycle is well known, and its quantitative evaluation calculated about 40 years ago. In summary, total rainfall on land is calculated at 115,000 Mm^3/year, of which 45,000 Mm^3 make up the flow of rivers and aquifers, and 70,000 Mm^3 evaporate from soil or evapotranspirate from vegetation (UN/WWAP, 2003: 77, 84).

Blue water is the surface- and ground-water in the hydrological cycle. It is also the part of the hydrological cycle that humans have used beneficially for their own use through the construction of water infrastructures, like canals and reservoirs. More recently, *blue water* has also included the spectacular rise in the use of groundwater.

Green Water is a term that started to be used two decades ago. *Green water* is the rainwater stored in the soil as soil moisture, also called soil water. It is the water in the soil that allows the growth and development of natural vegetation (forests, pasture lands, tundra, bush land, and others) as well as rain-fed agriculture. This water evaporates directly from the soil or through evapotranspiration from vegetation. Soil water has only recently started to be taken into account quantitatively. Its measurement and monetary valuation is still highly complex. It is calculated to be 70,000 Mm^3/year, of which about 3,000 to 4,000 Mm^3 are used by rain-fed agriculture. In most water and agricultural statistics *green water* is not included. This is the case of the FAO-AQUASTAT (FAO, 2003), which only refers to *blue water*, even when in many countries—particularly in the developing world—most crops are rain-fed.

Shah (2007) presents a recent review of the situation at global scale, although with a greater emphasis on the problems in the developing countries. One interesting aspect of his work is the warning about the accuracy of the global data. This author estimates that the values of the groundwater withdrawn might be between 25% and 40% higher that the number given by FAO-AQUASTAT. This is a frequent problem in water resources data, where most data have only an *illusory accuracy*.

A confirmation of this small reliability of FAO's data is shown in Shah's document (2007: Table 10.2) where Spain is not included in the list of the 20 countries using more groundwater. In many official documents the amount of groundwater used in Spain is over 6,000 Mm^3/year. This means that in that list Spain should be placed in the position 9th, ahead of Italy and Turkey.

In any case the key message of Shah (2007), as in other recent statements (Llamas & Martínez-Santos, 2005; Ragone & Llamas, 2006; Llamas *et al*., 2007), is that the increase in groundwater use during the last half century has been spectacular, from 100–150 km^3 in 1950 to 950–1,000 km^3/year in 2000. And in a good number of countries this increase continues.

4 WRONG OR OBSOLETE PARADIGMS (*HYDROMYTHS*) ON GROUNDWATER SUSTAINABILITY

The concept *sustainable development* was first coined in the 1980s, and has been expressed in a variety of ways over the years. Perhaps the better-known (and widely contested) definition of sustainability was established in the *Brundtland Report* by the *World Commission on Environment and Development* (WCED, 1987): "to satisfy current needs without compromising the needs of future generations". In a more recent book, Rogers *et al*. (2006) present a thorough study on the general concepts of sustainable development.

Sustainability means different things to different people probably due to the multi-dimensional nature of the concept. There may be as many as ten different aspects to be considered in assessing whether a given development can be labelled sustainable (Shamir, 2000). Even if all these are taken into account, it may not be so easy to reach an univocal conclusion. That is, the different dimensions of sustainable development may at times clash.

Let us take a look at an example. At a given aquifer, pumping rates for irrigation may prove *sustainable* from the hydrological viewpoint (provided that storage and/or average recharge are large enough). However, water table drawdown may induce degradation of valuable groundwater-dependent ecosystems such as wetlands, which may be considered unsustainable from the ecological point of view. Would a restrain from pumping be the most *sustainable* course of action? The answer to this question is difficult. If farmer livelihoods rely heavily on groundwater resources, a ruthless push towards wetland restoration may not be the most sensible solution to the problem. In that case, like in many real life situations, the social and economic aspects of sustainability come into play, and may eventually offset environmental conscience.

Llamas *et al*. (2007) provide a succinct overview of nine different aspects of groundwater sustainability: hydrological, ecological, economic, social, legal, institutional, inter- and intra-generational and political. Throughout that text, a distinction is often made between developed and developing regions. This is because perceptions as to what is sustainable vary across geographical boundaries, and are often rooted on cultural, political aspects and socio-economic situations. In this regard, the *Hydrogeology Journal* theme issue of March 2006 presents the socio-economic analyses of a dozen of case studies from all over the world. Perhaps the paper by Shah *et al*. (2006) about the main countries of South Asia is the most relevant for our analysis.

Whenever adverse effects of groundwater development begin to be felt, it is common to hear about *overexploitation*, a term usually equated to pumping in excess of the recharge. While this practice is often dismissed as *unsustainable*, the concept of *overexploitation* is conceptually complex. This is the reason why a significant number of authors consider it simplistic and potentially misleading (Selborne, 2001; Delli Priscoli *et al*., 2004; Llamas, 2004). Probably the most complete analysis is the one by Custodio (2002). As a consequence more and more authors are changing to the expression *intensive use of groundwater* instead of using *groundwater overexploitation*. Intensive groundwater use denotes significant changes on natural aquifer dynamics (Custodio & Llamas, 2003). In contrast with *aquifer overexploitation*, *intensive groundwater use* does not convey a positive or negative connotation. It merely refers to a change in flow patterns, groundwater quality or interrelations with surface water bodies.

5 THE GROUNDWATER INTENSIVE USE *SILENT REVOLUTION*

To the best of our knowledge, this *silent revolution* concept applied to describe the spectacular increase of groundwater use was firstly utilized in 2003 in the *Third World Water Forum* (Llamas & Custodio, 2003; Fornés *et al*., 2005; Llamas & Martínez-Santos, 2005). From then, this concept has been used by other authors such as Briscoe (2005) and by several experts from the *International Water Management Institute* (IWMI) (Giordano & Villholth, 2007).

The spectacular increase in groundwater development for irrigation has taken place during the last half-century in most arid and semiarid countries: a kind of *silent revolution*, carried out mostly by the personal initiative of millions of modest farmers in pursuit of the significant short-term benefits groundwater usually triggers or by a subsistence livelihood economy in the poorest countries.

Science and technology have played a key role in the *silent revolution*, since the advances in hydrogeology and well-drilling techniques, and the popularization of the submersible pump, have significantly reduced abstraction costs over time. The total direct cost of groundwater abstraction today—not taking into account externalities—is in many cases only a small fraction of the economic value of the guaranteed crop. Thus, the *silent revolution* is largely a market-driven phenomenon, except in those very poor regions where the drilling technology is still low and subsistence livelihood economy predominates.

Different authors consider that the driving forces of this silent revolution may be different according to the circumstances. But they can be reduced to two main causes: a) a subsistence economy in the poorest countries; and b) the market in most countries that are not under threshold of poverty.

Llamas & Martínez-Santos (2005) presented a qualitative overview of five water policy stages brought on by intensive groundwater use in arid and semiarid countries. Each of the five stages is roughly equivalent to one-generation or about 20–30 years. While the beginning of these can be traced back to the moment when intensive groundwater development begins, their end point might not be so easily identified. Thus some overlapping between stages may occur: take, for instance, *hydroschizophrenic* attitudes, which may still persist in many countries.

For example, in the USA, the *Western Water Policy Review Advisory Commission* (U.S. Government, 1998), appointed by the USA President reminded that state laws should recognize and take into account the substantial interrelations of surface- and ground-water, and that these resources should be administered and managed conjunctively. Nevertheless, this has not yet been achieved in the two main groundwater user states, California and Texas (Kretsinger & Narasimhan, 2006; Peck, 2007). The legal situation is similar in many other arid and semiarid regions worldwide.

Surface water is heavily subsidized in most countries and therefore its price for irrigation is generally cheaper than groundwater's. Yet, many farmers prefer groundwater. Several motives exist for this seemingly suboptimal choice: one is that groundwater can be obtained individually, thus bypassing negotiations with other farmers and government officers, often an arduous task, and reducing transaction costs. A second and more important motive is the resilience of aquifers to dry periods. In this regard, most farmers resort to conjunctive use when possible, using subsidized surface water whenever available and groundwater whenever surface water supplies fail. Many irrigated cash crops, which usually require large investments from farmers, depend today on groundwater, either totally or on conjunctive use with surface water.

Another important and seldom-mentioned benefit of the *silent revolution* is its positive effect on the social and economic transition of many farmers. Relatively low pumping costs, and the protection groundwater provides against drought, have allowed poor farmers to gradually progress into a middle class status, enabling them to provide a better education for their children. After one or two generations, those children have been trained as teachers, technicians, and so forth, thus contributing to the overall progress of society. At the same time, those who choose to continue as farmers are in a position to use better agricultural technologies to grow cash crops that demand less water.

Perhaps one of the most significant aspects of the *silent revolution* is the way in which farmers, as they become richer and more educated, move from low-value crops to cash crops. This is due mainly to the intrinsic reliability of groundwater: encouraged by the expectation of enhanced revenues, farmers invest in better technology, both from the agricultural (selective seeds, agrochemicals) and the technical point of view (drip irrigation), and in turn, shift to higher-value crops. As crop value is related to crop type, climatic and other natural and social variables of each site, and subject to trade constraints, it ranges widely: in Europe, for instance, between US$ 600 per hectare for cereals and more than US$ 60,000 per hectare for tomatoes, cucumber, and other greenhouse crops. Frequently the ratio between crop value and groundwater irrigation cost is greater than 20 (Llamas & Custodio, 2003; Albiac *et al*., 2006).

However, in aquifers with low permeability and storativity, located in densely populated areas, this ratio can be substantially smaller even if energy is heavily subsidized. This appears to be the case in the hardrock groundwater development in Tamil Nadu and other states of India. In these cases, the economic performance of these developments is very poor and they will probably disappear if the fast economic growth of India continues. The rural population of these groundwater poor areas will migrate to cities or change jobs.

A number of reasons suggest that newly implemented drinking water supplies and irrigation systems must be mainly based upon groundwater resources. Firstly, groundwater infrastructures are often cheaper than the equivalent surface water infrastructures. Secondly, groundwater related investments can be more easily scaled in time while yielding results almost from the beginning; instead, hydraulic works based on surface water resources rarely take less than 20 or 30 years to be fully-functional. Thirdly, groundwater-based supply and irrigation systems are usually smaller, thus allowing for a more progressive participation from potential beneficiaries. Past experience shows that in many countries, taking India as the most spectacular example, the government began building a modest quantity of irrigation wells about 20 or 30 years ago. However, the new technology was soon learned by local farmers, who developed new wells at their own expense and at a much faster pace than the government. It must be noted, though, that this higher rate can at times be excessive, and must be regulated by the government in order to ensure a sustainable and equal exploitation of groundwater resources.

In this regard, it is pertinent to note that groundwater development is less prone to corruption than traditional surface water irrigation systems, due to the aforementioned smaller investment and shorter time frame required for the implementation of equivalent groundwater supplies. In many cases, the issue might be more of an ethical nature, related to the lack of political willingness to fight ignorance, arrogance, institutional inertia, or corruption (Llamas, 2005; Ragone & Llamas, 2006).

However, intensive groundwater use is not a panacea that will necessarily solve the world's water problems (Mukherji, 2006). In fact, should the prevailing anarchy continue, problems may appear in the mid- or long-term (two to three generations). Some are already documented, although at a lesser scale, and are usually related to water table depletion, groundwater quality degradation, land subsidence or ecological impacts on aquatic ecosystems (Section 6).

6 HYDROLOGICAL AND ECOLOGICAL IMPACTS OF GROUNDWATER DEVELOPMENT

Here we summarize five indicators of typical problems of intensively used aquifers, but it is important to mention that they are sometimes wrongly used. This is either because of the lack of hydrogeological knowledge or because certain lobbies may have an interest in expanding the *hydromyth* of the unreliability (or fragility) of groundwater development (López-Gunn & Llamas, 2000).

6.1 *Groundwater-level depletion*

It has been usual—like in the Spanish 1985 *Water Law*—to define *overexploitation* as the situation when groundwater withdrawal exceeds or is close to the natural recharge of an aquifer. The observation of a trend of continuous significant decline of the levels in water wells during several years is frequently considered as a clear indication of an unsustainable situation. This is a simplistic approach that might be a long way from the real situation. Many times it corresponds to a transient state of the aquifer until reaching a new equilibrium situation.

Intensive groundwater use frequently depletes the water table. Depletions of the order of 0.5 m/year are frequent, although rates up to 5–10 m/year have been reported (Llamas & Custodio, 2003; Garrido *et al*., 2006). Farmers are seldom concerned with this issue, except in the case of shallow aquifers. The increase in pumping costs is usually a small problem in comparison with potential groundwater quality degradation or *equity issues* such as the drying up of shallow wells or *khanats* (infiltration galleries), owned by the less resourceful farmers and located in the area of influence of the deep wells. This may cause social equity problems in regions where many farmers cannot afford to drill new wells or the water authorities are not able to demand the just compensation in water or money to poor farmers. Nevertheless, some Indian researchers, such as Mukherji (2006), consider that the real situation is different because there exists *de facto* a trade of groundwater between the farmers that allows a good irrigation system.

The opposite phenomenon (rise of the water table due to surface water over-irrigation) is also a problem for example in Punjab, India and Pakistan or in San Joaquin Valley in California. Rising of the water table often results in significant social and economic troubles due to soil water-logging and/or salinization.

6.2 *Degradation of groundwater quality*

Groundwater abstraction can cause, directly or indirectly, changes in groundwater quality. The intrusion into a freshwater aquifer of low quality surface water or groundwater because of the change in the hydraulic gradient due to groundwater abstraction is a frequent cause of quality degradation.

This degradation of groundwater quality may not be related at all to excessive abstraction of groundwater in relation to average natural recharge. Other causes may be responsible, such as return flow from surface water irrigation, leakage from urban sewers, infiltration ponds for wastewater, septic tanks, urban solid waste landfills, abandoned wells, mine tailings, and many other activities not related to groundwater development. For instance, the groundwater quality degradation in many Central and Northern European countries is related to intensive rain-fed agriculture.

Saline intrusion may be an important concern for the development of aquifers adjacent to saline water bodies. This is a typical problem in many coastal regions of semiarid or arid areas. Also in this case, the relevance of the saline water intrusion not only depends on the amount of the abstraction in relation to the natural groundwater recharge, but also on the well field location and design, and on the geometry and hydrogeological parameters of the pumped aquifer. In most cases, the existing problems are due to uncontrolled and unplanned groundwater development and not to excessive pumping. As a matter of fact since half a century ago, the seawater intrusion is well controlled in the coastal plains of Orange County (California) and Israel.

6.3 *Susceptibility to subsidence*

When an aquifer is pumped, the water pore pressure decreases and the aquifer solid matrix undergoes a greater mechanical stress. This greater stress may produce compaction of the existing fine-grained sediments (aquitards) if the stress due to the decrease in water pore pressure is greater than the so-called *preconsolidation stress*. This situation has occurred in some aquifers formed by young sediments, such as those in Mexico City, Venice, Bangkok and others.

Caves and other types of empty spaces may exist under the water table in karstic aquifers. When the water table is naturally depleted the mechanical stability of the roof of such empty spaces may be lost and the roof of the cave collapses. This is a natural process that gives rise to the classical dolines and poljes in karstic landscapes. When the water table depletion or oscillation increases due to groundwater abstraction, the frequency of karstic collapses can also increase.

In both cases, the amount of subsidence or the probability of collapses is related to the decrease in pore water pressure, which is related to the amount of groundwater withdrawal. Nevertheless, the influence of other geotechnical factors may be more relevant than the amount of water abstracted in relation to the renewable groundwater resources of the aquifer.

6.4 *Interference with surface water*

Some anthropogenic activities may have a significant impact on the catchment hydrologic cycle. For instance, the intensive use of groundwater for irrigation in the Upper Guadiana basin (Spain), has resulted in a serious water table depletion (about 30–40 m). The most alarming consequences of the water level drops were the changes in the groundwater flow patterns and in the form, function and quality of many wetlands. Areas that had received the natural discharge from the aquifer became natural recharge zones (Hernández Mora *et al*., 2003). This has produced a spectacular decrease in total evapotranspiration from the water table and wetlands, evaluated between 100 and 200 Mm^3/year (Martínez-Cortina, 2001). From the point of view of the water budget there is an important increase (almost 50%) of the annual renewable resources, understood as the water that can be abstracted from the aquifer maintaining the water level as in the previous year, and calculated as the difference between aquifer recharge from precipitation and losses from evapotranspiration.

This artificial depletion of the water table can also change dramatically aquifer-streams relationship, as in the previous example. Gaining rivers fed by aquifers may become dry except during storms or humid periods when they may become losing rivers, an important source of recharge to the aquifer. Nevertheless, this new water budget may present legal problems if the downstream water users have previous water rights.

6.5 *Ecological impacts*

The ecological impacts, mainly caused by water table depletion as it has been showed in the Upper Guadiana basin case, are becoming an important new constraint in groundwater development in some countries. Decreasing or drying up of springs and wetlands, low flow of streams, disappearance of riparian vegetation because of decreased soil moisture, alteration of natural hydraulic river regimes, changes in microclimates because of the decrease in evapotranspiration, can all be used as indicators of ecological impact. Reliable data on the ecological consequences of these changes are not always available, and the social perception of such impacts varies in response to the cultural and economic situation of each region. The lack of adequate scientific data to evaluate the impacts of groundwater abstraction on the hydrologic regime of surface water bodies makes the design of adequate restoration plans difficult. For instance, wetland restoration programmes often ignore the need to simulate the natural hydrologic regime of the wetlands, i.e. not only restore its form but also its hydrological function. Similar problems result in trying to restore minimum low flows to rivers and streams. Oftentimes minimum stream flows are determined as a percentage of average flows, without emulating natural seasonal and year-to-year fluctuations to which native organisms are adapted (Llamas & Garrido, 2007).

7 SPECIAL ETHICAL ASPECTS OF THE ABSTRACTION OF FOSSIL GROUNDWATER

This section is taken mainly from Llamas (2004) and Delli Priscolli *et al*. (2004).

In most countries it is considered that groundwater abstraction should not exceed the renewable resources. In other countries—mainly in the most arid ones—it might be considered that groundwater mining is an acceptable policy, as long as available data assure that the groundwater development can be economically maintained for a long time, for example, more than 50 years and that the potential ecological costs and socio-economic benefits have been adequately evaluated. Nevertheless, some authors consider this option as unsustainable development or an unethical attitude with respect to future generations.

In contrast, few authors speak of the frequent unsustainability of most dams in arid regions. Some authors consider that the *useful life* of most dams in the North African Mediterranean countries is between 40 and 200 years because of their silting.

It has been stated that the frequently encountered view that the water policy of arid countries should be developed in relation to renewable water resources is unrealistic and fallacious. Ethics of long-term water resources sustainability must be considered with ever improving technology. With careful management many arid countries will be able to utilise resources beyond the foreseeable future without major restructuring.

In Saudi Arabia the main aquifers (within the first 300 m of depth) contain huge amount—a minimum of 2,000 km^3—of fresh fossil water, that is 10,000 to 30,000 years old. It is considered that these fossil aquifers can supply useful water for a minimum period of 150 years. Current abstraction seems to be around 15–20 km^3/year. During a couple of decades the Saudi government has pumped several km^3/year of non-renewable groundwater to grow low cost crops (mainly cereals), which were also heavily subsidised. The official aim of such activity was to help to transform nomadic groups into farmers. Apparently such *overdraft* has been a success. Now the amount of groundwater abstraction has been dramatically reduced and the farmer nomads have become high-tech farmers growing cash crops. Another example is the situation of the Nubian sandstone aquifer located below the Western desert of Egypt, where the fresh groundwater reserves are higher than 200 km^3 and the maximum pumping projected is lower than 1 km^3/year. Probably similar situations do exist in Libya and Algeria. Other examples of mining groundwater can be found in Llamas & Custodio (2003).

It is not easy to achieve a virtuous middle way. As Collin & Margat (1993) stated: “we move rapidly from one extreme to the other, and the tempting solutions put forward by zealots calling for Malthusian underexploitation of groundwater could prove just as damaging to the development of society as certain types of *excessive pumping*”.

8 ECONOMIC ASPECTS IN GROUNDWATER DEVELOPMENT

Groundwater unit volume cost increases with groundwater depth, as more energy is required for pumping and deeper wells might be needed. In our experience, these costs usually range between US$ 0.02/m^3 and US$ 0.20/m^3 depending on the country and the aquifer. However, according to Shah (2007) the economic cost (value) of groundwater is about US$ 0.20 to 0.30 per m^3. It would be worthwhile to study this aspect in more detail and worldwide. These values seem to us very high in comparison to the general economic situation of Southeast Asia. One possible cause is the low technology used in the drilling of the wells and in the performance of the pumping devices.

Groundwater irrigation cost per hectare also increases with time, albeit at a lower rate. This is because farmers begin to use a more efficient technology and switch (if soil and climate allow it) to less water consuming crops: from maize or rice to grapes or olive trees, for instance. It is estimated that groundwater irrigation cost in Spain generally ranges between US$ 20 to 1,000 per hectare and year.

Despite the illusory accuracy of global irrigation data and the variability of the existing estimates, rough calculations yield the following conclusion: groundwater-based irrigation seems to be twice as efficient as surface water irrigation in hydrological terms (m^3/ha), a ratio that increases to between three and ten times from the social and economic points of view (US$/m^3 and jobs/m^3). Regional scale analyses carried out in Spain seem to confirm these figures (Hernández-Mora *et al*., 2001, 2007). Thus, it appears relevant and urgent to assess the comparative hydrological and socio-economic efficiency of surface- and ground-water irrigation at a global scale, carrying out similar studies in other regions of the world. Assessing the implications of this *silent revolution* should constitute a valuable contribution to the debate about global irrigation needs as perceived by many water experts. The required investment to assess the value and efficiency of groundwater irrigation versus surface water irrigation can be afforded by most governments.

The *more crops and jobs per drop* motto has been considered crucial in order to avoid a *looming water crisis*. This is because of the large share of irrigation in global water use, and irrigation’s often low efficiency. However, few water experts or decision-makers are aware that the goal behind such a motto is often achieved by groundwater irrigation. Actually, in arid and semiarid regions in industrialized or rich countries the new motto is *more cash and nature per drop* (Llamas & López-Gunn, 2007).

Therefore, any study on economic sustainability of groundwater use should take into account the specific regional settings. The following circumstances may serve as a first attempt to establish a classification:

– Developing countries where easily-accessible unconfined shallow aquifers exist: Devices such as the treadle pump to access shallow water tables may constitute a catalyst for irrigation development (Polak, 2005, this volume), while environmental concerns are generally subordinated to human development. This is the case of many small African villages.

- Developing (or semi-developing or emerging) arid and semiarid regions, like India or regions of East Asia: Groundwater irrigation has experienced a spectacular development in recent years (Deb Roy & Shah, 2003). Such large regions may present a wide variety of conditions: from subsistence livelihoods to market economies, and from large alluvial aquifer systems (which may sustain long-term development) to hardrock aquifers (where small communities may rely on scarce resources and pumping may result too expensive).
- Developed arid regions endowed with good aquifers: This may correspond to countries such as Saudi Arabia or Libya, where groundwater mining is commonplace (see Section 7). Reliance on non-renewable resources, however, does not seem to render these economies unsustainable. Contrary to the perception of some environmental organizations, a good number of authors and the *UNESCO World Commission on the Ethics of Science and Technology* (COMEST) consider this practice to be acceptable under certain circumstances (Selborne, 2001; Delli Priscolli *et al*., 2004).
- Arid and semiarid regions of industrialized countries (e.g. California, Texas, Spain): Intensive groundwater withdrawals for irrigation are a well-established practice in these areas. Development is essentially market-driven, as the cost of obtaining groundwater generally amounts to a very small fraction of crop value. Some authors argue that the depletion of groundwater levels results in an increase of pumping costs, and may ultimately yield these developments economically unsustainable. However, empirical evidence in some areas seems to show the opposite. Farmers are undeterred from pumping despite depths in excess of 400 m (Garrido *et al*., 2006). This is because switching to higher value water-efficient crops may offset the increase of pumping costs, provided that groundwater quality does not worsen (Llamas & Martínez-Santos, 2005; Fornés *et al*., 2005).

9 SOCIO-POLITICAL AND INSTITUTIONAL ASPECTS OF GROUNDWATER DEVELOPMENT

In the preface of the last *Hydrogeology Journal* theme issue, Llamas *et al*. (2006) warn about the scarcity of analyses on the social science aspects about groundwater role in the general water resources policy. As a matter of fact, that theme issue tries to set the pace to increase these type of studies. This section has been mainly taken from Llamas *et al*. (2008).

9.1 *Social sustainability*

Most aquifers present a large storage volume of groundwater in relation to their renewable resources (often two or three orders of magnitude higher). A practical consequence is that the potential problems do not usually become serious in the short term (within one or two generations). By that time, farmers may have experienced a positive *social transition*.

Groundwater irrigation has proven an excellent catalyst for this *social transition* of farmers in arid and semiarid regions worldwide, as was explained in Section 5. Increased revenues result, and allow for a greater degree of social welfare. In addition, farmers become able to provide a better education for their children, who may either move on to other economic sectors (generally more productive), or return to agriculture with a more productive outlook. So, this transition means a reduction of global poverty (Llamas & López-Gunn, 2007).

This *social transition* triggered by groundwater together with the implementation of more efficient irrigation technologies can often result in a sustainable use in the mid-term. However, adequate groundwater management and governance remains an important challenge to ensure long-term sustainability.

Aquifers constitute an example of *common pool resources*, as in the majority of cases all actors have direct access (legal or illegal) to groundwater. Therefore, aquifers should typically follow the widely voiced *tragedy of the commons* pattern (Hardin, 1968). Nevertheless, after half a century of intensive groundwater use, the authors of this chapter do not know any cases of medium-sized or large *good* aquifers (those with a surface larger than 500 km^2, and medium to high transmisivity and storage capacity values) where the tragic outcomes outlined by Hardin may have taken place causing social or economic disturbances; at least not in the degree of magnitude of those caused by soil water-logging and salinization (India, Pakistan or California) or the serious social conflicts in relation to people displaced or ousted by the construction of large dams (Briscoe, 2005; Shah *et al*., 2006).

The situation may be different in small or poor aquifers, where storage is not large enough to sustain development for over two or three generations. Though still uncommon, cases of small communities that have *run out of groundwater* have been reported.

The reality is that even some poor aquifers, such as the Indian *hardrock aquifers*, have played a key role in increasing food production. In India groundwater irrigated surface has increased in more than 40 million hectares during the last decades (Shah *et al*., 2006; Shah, 2007). As a consequence, India, despite an almost 100% increase of its population in the last 50 years, has not only achieved food security in practice, but also become an important grain exporter. However, uncontrolled aquifer development in arid and semiarid regions worldwide raises sustainability concerns, particularly whenever the natural rate of recharge is low.

It might be appropriate to point out the situation of some large aquifers that have undergone *overdrafting* or groundwater mining for many decades. In many of such areas, pumping data are hardly reliable. Take for instance California's aquifers, where overdraft estimates range nothing less that between 1,200 and 2,400 Mm^3/year. Recent information tells that the overdraft in California aquifers has not been adequately analysed since the 1980s (Kretsinger & Narasimhan, 2006). It is perhaps the lack of willingness to monitor, rather than overdraft *per se* that may constitute the greatest intergenerational threat for groundwater resources.

9.2 *Institutional issues*

A bottom-up approach seems to be the best way to achieve participatory management. Surface water irrigation communities constitute a good example. 7,000 of such communities (some of them centuries old) currently exist in Spain (Murcia, Valencia and Alicante being the better known ones).

However, there is an essential difference between surface water and groundwater. A gatekeeper may ultimately control surface water, while groundwater is usually subject to the individual decisions of hundreds (perhaps thousands) of independent users with direct access to the resource. Thus, top-down control has proven insufficient in most places due to this intrinsic complexity of groundwater governance. This is the reason why user communities are often advocated as the most plausible solution to ensure adequate groundwater resources management.

Groundwater user associations are still fairly scarce. Under Spain's 1985 *Water Act*, an attempt was made to impose these communities in *overexploited* aquifers, although this initiative has been far from successful in most places. Water agencies in Texas and California are currently trying to organize these communities, albeit by means of economic incentives rather than by compulsion.

The few examples of groundwater user associations that have become effective resource managers have two things in common: they have successfully articulated common goals and objectives, and they have established mutually accepted rules regarding resource access and use, in order to guarantee the long-term sustainability of the resource and dependant uses. The variety of circumstances under which these user associations operate, their ability to bring together thousands of independent users and sometimes manage large and complex aquifer systems, or the way in which some are working cooperatively with water authorities to establish sustainable management regimes, are all promising developments (Hernández-Mora *et al*., 2003).

In any case, since groundwater user associations are a relatively new feature, their ultimate implications on groundwater sustainability are yet to be seen.

9.3 *Legal issues*

From the legal viewpoint, legislation on aquifers presents two main issues of concern. The first one relates to whether groundwater resources should be public or private property. For instance, in Texas groundwater from the Ogallala aquifer is mainly private (Peck, 2007). The second refers to the way groundwater rights should be inventoried and to whether the possibility to trade with them should be allowed. This second aspect, usually equated with *water banks* is perhaps subordinated to the first in terms of importance, even if significant informal markets already exist in some places (Mukherji, 2006).

In relation to property rights, groundwater is usually public and can be accessed by means of governmental permits (sometimes called *concessions*). This is the case of Israel, a number of states of the USA, Mexico and many other countries. In other places, such as California, Chile, India or Texas, groundwater is under private ownership.

Spain is a particularly interesting example of a mixed system. Wells drilled after January 1st, 1986, require governmental permission, while those operational before 1986 remain private. Private groundwater may remain so for 50 years (provided that the well-owners reach an agreement with the government in exchange for *administrative protection*) or perpetually (if the owner wishes to preserve his/her rights under the 1879 *Water Act*).

In any case, the Spanish situation is far more complex due to the lack of a reliable registry of groundwater rights. While the government is currently carrying out a series of remedial initiatives, these are insufficient in the eyes of some authors. Fornés *et al*. (2005), for instance, point out that these ignore a significant share of existing wells, and that the registry or inventory is therefore incomplete.

While some voices seem to disagree the current situation may be considered unsustainable in the long run, particularly if a strong political willingness to apply the laws is lacking. It seems clear that a reliable inventory of groundwater rights is desirable in order to ensure adequate management, whether it is transboundary or not.

9.4 *Political issues*

Politics has at times been defined as *the art of the possible* (rather than *the art of the reasonable*). Although in modern democratic societies decision-making is ultimately restricted to politicians, more or less powerful lobbies often influence these. These usually defend the interests of large corporations or different sectors of the population (unions, NGOs and others).

The motivations behind political decisions are so difficult to take into account that they are generally overlooked. In addition, they depend very heavily on social and cultural constrains, which are very different from country to country. Therefore this section is restricted to three brief examples as to how politics may come into play in regard to groundwater sustainability.

The first example refers to the 2005 events of the Upper Guadiana basin, in Spain. The *Guadiana Water Authority* (dependent on Spain's central administration) issued an order to shut down a series of wells. While law-in-hand this seemed an appropriate course of action, a social uproar ensued, mostly fuelled by farmer unions. This led the regional government to oppose the central government's orders. Up to date, the central water authority has been unable to shut down the wells.

A second case is described by Mukherji (2006). In 2004, the ruling political party of Andhra Pradesh (central India) stated that they would gradually stop electricity subsidies for pumping. This led to a significant resistance on the part of farmers. Seemingly as a result, the opposition won the 2004 election largely on the strength of opposing this measure. Electricity remains mostly free to this day.

Finally, the third example refers to California. In 2002, after a long and arduous work, Professor Sacks (Berkeley) developed a law to replace the old water act. This effort was motivated by the fact that the old law was conceptually obsolete since, among other erroneous assumptions, it practically ignored the unity of the hydrological cycle and equated groundwater to underground rivers. However, frontal opposition on the part of farmers and urban water supply companies eventually caused the project to be rejected and the obsolete code to remain. However, the Government of California has moved away from the *command and control* approach while implementing a policy of education and economic incentives with encouraging results.

These three examples show how political constrains (namely voters) may lead to potentially unsustainable situations. Education of the general public is perhaps the only means to avoid these kinds of occurrences in the future. In the case of transboundary aquifers, this is a particularly relevant issue, since integrated political actions are required on both sides of the border (Eckstein, 2007).

10 ESSENTIAL ETHICAL ASPECTS

Finally we summarize some of the main ethical aspects of groundwater management, following Fornés *et al*. (2005). A more complete and sophisticated classification can be found in Selborne (2004).

10.1 *Perverse subsidies to surface water projects*

The hidden or open subsidies that have traditionally been a part of large hydraulic projects for surface water irrigation, are probably the main cause of the pervasive neglection of groundwater problems among water managers and decision-makers. Surface water for irrigation is usually given almost free to the farmers; and its wasteful use is the general rule.

It is usual that water supply companies, farmer unions, etc. lobby the State for the construction of surface water infrastructures that are primarily paid for with general revenues, instead of advocating a responsible use of groundwater resources. At times, this may lead to social conflicts—like the cases of the Tagus-Segura transfer or the overruled Ebro transfer, both in Spain—between water-importing and water-exporting basins.

Progressive application of the *user pays* or *full cost recovery* principle would probably make most of the large hydraulic projects economically unsound. As a result, a more comprehensive look at water planning and management would be necessary and adequate attention to groundwater planning, control and management would probably follow.

10.2 *Public, private, or common groundwater ownership*

Some authors consider that the legal declaration of groundwater as a public domain is a *conditio sine qua non* to perform a sustainable or acceptable groundwater management. This assumption is far from evident. For many decades groundwater has been a public domain in a good number of countries. Nevertheless, sustainable groundwater management continues to be a significant challenge in many of those countries. Highly centralised management of groundwater resources is not the solution to promote solidarity in groundwater use as a *common good*. Groundwater management should be in the hands of the stakeholders of the aquifer, under the supervision of the corresponding *Water Authority*. Stakeholders' participation has to be promoted bottom-up instead of top-down.

10.3 *Lack of hydrogeological knowledge and education*

The education of stakeholders and widespread presence of groundwater user associations is crucial for an adequate participatory bottom-up management approach. It has to be a continuous process in which technology and education improve solidarity and participation to the stakeholders and a more efficient use of the resource.

10.4 *Transparency in groundwater related data*

Good, symmetric and reliable information is crucial to facilitate cooperation among aquifer stakeholders, and a prerequisite to succeed in groundwater management. All stakeholders should have easy access to good and reliable data on abstractions, water quality, and aquifer water levels. Current information technology allows information to be made easily and economically available to an unlimited number of users. Nevertheless, in a good number of countries it will be necessary to change the traditional attitude of water agencies of not facilitating the easy access to water data to the general public.

10.5 *The ethics of pumping non-renewable groundwater resources (groundwater mining)*

As was stated in Section 7, some arid regions have very small amounts of renewable water resources but huge amounts of fresh groundwater reserves, like for example the existing reserves under most of the Sahara desert. In such situations, groundwater mining may be a reasonable action if various conditions are met: 1) the amount of groundwater reserves can be estimated with acceptable accuracy; 2) the rate of reserves depletion can be guaranteed for a long period, e.g. from 50 to 100 years; 3) the environmental impacts of such groundwater withdrawals are properly assessed and considered clearly less significant than the socio-economic benefits from groundwater mining; and 4) solutions are envisaged for the time when the groundwater is fully depleted. Selborne (2001), former chairman of the *Water Resources Committee of the World Commission of the Ethics of Science and Technology* (COMEST), seems to agree with this approach.

11 THE WAY FORWARD

Suggestions to achieve a sustainable and ethical groundwater management were presented in the *Alicante Declaration* (Ragone & Llamas, 2006), and constitute a more comprehensive, if still general, call for action. We reproduce here the most relevant aspects.

- *First*: It is extremely difficult to provide a general guide to groundwater sustainability, as complying with all the different dimensions may not be possible in most cases. Emphasis on one or another is likely to depend on economic, social, cultural and political constraints.
- *Second*: Groundwater management requires a higher degree of user involvement than surface water developments. Experience shows that sustainable aquifer use cannot be solely achieved by means of top-down *control and command* measures.
- *Third*: User participation requires a degree of hydrogeological education which is still absent in most places. Steps should be taken to make the peculiarities of groundwater resources known to all, from politicians and water decision-makers to direct users and the general public. This should begin at the school level.
- *Fourth*: Appropriate groundwater management requires a significant degree of trust among stakeholders. This implies that groundwater data should be transparent and widely available (via Internet, for instance). In addition, the system should be able to punish those who act against the general interest.

REFERENCES

Albiac, J.; Hanemann, M.; Calatrava, J.; Uche, J. & Tapia, J. (2006). The Rise and Fall of the Ebro Water Transfer. *Natural Resources Journal*, 46(3): 727–758.

Allan, J.A. (2006). Virtual Water—Part of an invisible synergy that ameliorates water scarcity. In: P.P. Rogers; M.R. Llamas & L. Martínez-Cortina (eds.), *Water Crisis: myth or reality?* Marcelino Botin Water Forum 2004. Balkema, Taylor & Francis Group, London, UK: 131–150.

Bertone. T. (2007). *Message on behalf of the Holy Father on the occasion of the 2007 World Water Day*. [www.vatican.va].

Briscoe, J. (2005). *India's Water Economy: Bracing for a Turbulent Future*. The World Bank. Washington, D.C., USA.

Camdessus, M. (2003). *Financing Water for All. Report of the World Panel on Financing Water Infrastructure*. 3rd World Water Forum, Kyoto, Japan, March 2003. World Water Council and Global Water Partnership. 54 pp.

Collin, J.J. & Margat, J. (1993). Overexploitation of Water Resources: Overreaction or an Economic Reality? *Hydroplus*, 36: 26–37.

Cooley, H.; Gleick, P.H. & Wolff, G. (2006). *Desalination, with a grain of salt: a California perspective.* Pacific Institute, Oakland, California, USA. 88 pp.

Custodio, E. (2002). Aquifer Overexploitation: What does it mean? *Hydrogeology Journal*, 10(2): 254–277.

Custodio, E. & Llamas, M.R. (2003). Intensive use of groundwater: introductory considerations. In: R. Llamas & E. Custodio (eds.), *Intensive Use of Groundwater. Challenges and Opportunities*. Balkema, Swets & Zeitlinger Publishers, Lisse, the Netherlands: 3–12.

Deb Roy, A. & Shah, T. (2003). Socio-ecology of groundwater irrigation in India. In: R. Llamas & E. Custodio (eds.), *Intensive Use of Groundwater. Challenges and Opportunities*. Balkema, Swets & Zeitlinger Publishers, Lisse, the Netherlands: 307–336.

Delli Priscoli, J.; Dooge, J. & Llamas, M.R. (2004). *Overview*. Series on Water and Ethics, Essay 1. UNESCO, Paris, France: 31 pp.

Eckstein, G. (2007). Commentary on the U.N. International Law Commission's Draft Articles on the Law of Transboundary Aquifers. *Colorado Journal of International Environmental Law and Policy*, 18(3): 537–610.

FAO (2003). *AQUASTAT. Information System on Water and Agriculture.* Food and Agriculture Organization of the United Nations, Rome, Italy.

Fornés, J.M.; De la Hera, A. & Llamas, M.R. (2005). The Silent Revolution in Groundwater Intensive Use and its influence in Spain. *Water Policy*, 7(3): 253–268.

Garrido, A.; Martínez-Santos, P. & Llamas, M.R. (2006). Groundwater irrigation and its implications for water policy in arid and semiarid countries: the Spanish experience. *Hydrogeology Journal*, 14(3): 340–349.

German Federal Government (2001). *International Conference on Freshwater*. Bonn, 3–7 December 2001. [http://www.water-2001.de]. Accessed on March 2008.

Giordano, M. & Villholth, K.G. (2007). *The Agricultural Groundwater Revolution. Opportunities and Treath to Development*. CAB International Publishing, Wallingford, UK: 336 pp.

Gleick, P.H. (2003). Global Freshwater Resources: Soft-Path Solutions for the 21st Century. *Science*, 302(5650): 1524–1528. 28 November 2003.

Hardin, G. (1968). The Tragedy of the Commons. *Science*, 162(3859): 1243–1248. 13 December 1968.

Hernández-Mora, N.; Llamas, M.R. & Martínez-Cortina, L. (2001). Misconceptions in Aquifer Over-Exploitation. Implications for Water Policy in Southern Europe. In: C. Dosi (ed.), *Agricultural Use of Groundwater. Towards Integration between Agricultural Policy and Water Resources Management*. Kluwer Academic Publishers: 107–125.

Hernández-Mora, N.; Martínez-Cortina, L. & Fornés, J. (2003). Intensive groundwater use in Spain. In: R. Llamas & E. Custodio (eds.), *Intensive Use of Groundwater. Challenges and Opportunities*. Balkema, Swets & Zeitlinger Publishers, Lisse, the Netherlands: 387–414.

Hernández-Mora, N.; Martínez-Cortina, L.; Custodio, E. & Llamas, M.R. (2007). *Groundwater issues in Southern EU Member States. Spain Country Report*. Presented as Report of Spain in the Workshop of the European Academies of Sciences Advisory Council (EASAC) for the General Report on Groundwater Issues in the Southern EU Member States. Madrid, April 19, 2007.

Kretsinger, V. & Narasimhan, T.N. (2006). California's evolution toward integrated regional water management: a long-term view. *Hydrogeology Journal*, 14(3): 407–423.

Llamas, M.R. (2001). *Cuestiones éticas en relación con la gestión del agua en España [Ethical aspects related to water management in Spain]*. Lecture of entrance in the Royal Academy of Doctors of Spain, Madrid, 85 pp.

Llamas, M.R. (2004). *Use of Groundwater*. Series on Water and Ethics, Essay 7, UNESCO, Paris, France: 33 pp.

Llamas, M.R. (2005). Groundwater and Human Development. In: E. Bocanegra & E. Usunoff (eds.), *Groundwater and Human Development*. Selected Papers on Hydrogeology, 6: 3–8. Balkema Publishers, Leiden, the Netherlands.

Llamas, R. & Custodio, E. (2003). *Intensive Use of Groundwater. Challenges and Opportunities*. Balkema, Swets & Zeitlinger Publishers, Lisse, the Netherlands. 480 pp.

Llamas, M.R. & Garrido, A. (2007). Lessons from intensive groundwater use in Spain: economic and social benefits and conflicts. In: M. Giordano & K.G. Villholth (eds.), *The Agricultural Groundwater Revolution. Opportunities and Treath to Development*. CAB International Publishing, Wallingford, UK: 266–295.

Llamas, M.R. & López-Gunn, E. (2007). *The role of Science and Technology in the soft path to solving conflicts about water.* Presented in the Scientific Meeting: Water Management: Technology, Economics and Environment. 19–20 January 2007. Fundación R. Areces, Madrid, Spain.

Llamas, M.R. & Martínez-Santos, P. (2005). Intensive Groundwater Use: Silent Revolution and Potential Source of Social Conflicts. *Journal of Water Resources Planning and Management*, September/October: 337–341. American Society of Civil Engineers, USA.

Llamas, M.R.; Shah, T. & Mukherji, A. (2006). Guest Editors' preface. *Hydrogeology Journal*, 14(3): 269–274.
Llamas, M.R.; Martínez-Santos, P. & De la Hera, A. (2007). The manifold dimensions of groundwater sustainability. In: S. Ragone; A. de la Hera & N. Hernández-Mora (eds.), *The global importance of Groundwater in the 21st century*. Proceedings of the International Symposium on Groundwater Sustainability. National Ground Water Association Press, Ohio, USA: 105–116.
Llamas, M.R.; Martínez-Santos, P. & De la Hera, A. (2008). Hydropolitics and Hydroeconomics of Shared Groundwater Resources: Experience in Arid and Semiarid Regions. In: C.J.G. Darnault, *Overexploitation and Contamination of Shared Groundwater Resources*. Chapter 20: 415–431. NATO Science for Peace and Security Series C: Environmental Security. Springer Netherlands.
López-Gunn, E. & Llamas, M.R. (2000). *New and Old Paradigms in Spain's Water Policy*. Water Security in the Third Millennium: Mediterranean Countries Towards a Regional Vision. UNESCO Science for Peace Series, 9: 271–293.
Martínez-Cortina, L. (2001). *Estimación de la recarga en grandes cuencas sedimentarias mediante modelos numéricos de flujo subterráneo. Aplicación a la cuenca alta del Guadiana [Recharge estimation in large sedimentary basins using groundwater flow models. The case of the Upper Guadiana basin]*. Doctoral Thesis. University of Cantabria, Spain. 418 pp.
Mukherji, A. (2006). Is intensive use of groundwater a solution to World's Water Crisis? In: P.P. Rogers; M.R. Llamas & L. Martínez-Cortina (eds.), *Water Crisis: myth or reality?* Marcelino Botin Water Forum 2004. Balkema, Taylor & Francis Group, London, UK: 181–193.
Nace, R.L. (1973). On a 1972 American Water Resources Association Meeting. *Ground Water*, 11(1): 48–49.
Peck, J.C. (2007). Groundwater Management in the High Plains Aquifer in the USA: Legal Problems and Innovations. In: M. Giordano & K.G. Villholth (eds.), *The Agricultural Groundwater Revolution. Opportunities and Treath to Development*. CAB International Publishing, Wallingford, UK: 296–319.
Polak, P. (2005). Water and the other three Revolutions needed to end rural poverty. *Water Science and Technology*, 8: 133–146.
Ragone, S.E. & Llamas, M.R. (2006). The Alicante Declaration: Steps along the Pathway to a Sustainable Future. *Ground Water*, 44(4): 500–503.
Rogers, P.P.; Jalal, K.F. & Boyd, J.A. (2006). *An Introduction to Sustainable Development*. Harvard University Press: 404 pp.
Selborne, J. (2001). *The Ethics of Freshwater Use: A Survey*. Report of the Commission on the Ethics of Science and Technology (COMEST), UNESCO, Paris, France: 62 pp.
Selborne, J. (2004). Preface. In: C. Brelet (ed.), *Some Examples of Best Ethical Practice in Water Use*. Water and Ethics Series, UNESCO.
Shah, T. (coord.) (2007). Groundwater: a global assessment of scale and significance. In: D. Molden (ed.), *Water for Food, Water for Life. Comprehensive Assessment of Water Management in Agriculture*. Earthscan: 395–423.
Shah, T.; Singh, O.P. & Mukherji, A. (2006). Some aspects of South Asia's groundwater irrigation economy: analyses from a survey in India, Pakistan, Nepal Terai and Bangladesh. *Hydrogeology Journal*, 14(3): 286–309.
Shamir, U. (2000). *Sustainable Management of Water Resources*. Transition towards Sustainability. Inter-Academy Panel Tokyo Conference. May 2000, Tokyo, Japan: 62–66.
UN/WWAP (United Nations/World Water Assessment Programme) (2003). *1st UN World Water Development Report: Water for People, Water for Life*. Paris, New York and Oxford. UNESCO and Berghahn Books. 578 pp.
UNDP (United Nations Development Programme) (2005). *Human Development Report 2005. International cooperation at a crossroads: Aid, trade and security in an unequal world*. United Nations Development Programme, New York, USA. 372 pp.
UNDP (United Nations Development Programme) (2006). Human Development Report 2006. Beyond scarcity: Power, poverty and the global water crisis. United Nations Development Programme, New York, USA. 424 pp.
U.S. Government (1998). *Water in the West: Challenge for the next Century*. Western Water Policy Review Advisory Commission. Department of the Interior, Bureau of Reclamation. 250 pp.
WCED (World Commission on Environment and Development) (1987). *Our Common Future* (Brundtland Report). World Commission on Environment and Development, United Nations. Oxford University Press. 400 pp.
Wittfogel, K.A. (1957). *Oriental Despotism: A comparative Study of Total Power*. Yale University Press, New Haven, Connecticut, USA, 556 pp.