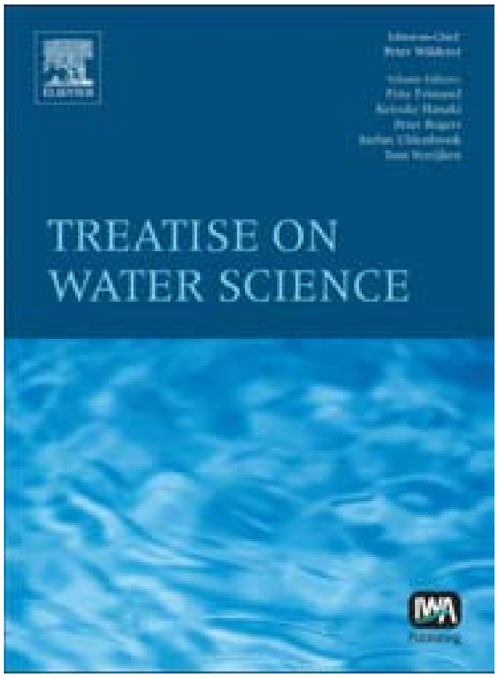

Lopez-Gunn E, Llamas MR, Garrido A and Sanz D (2011) Groundwater Management. In: Peter Wilderer (ed.) Treatise on Water Science, vol. 1, pp. 97–127 Oxford: Academic Press.

1.07 Groundwater Management

E Lopez-Gunn, Complutense University, Madrid, Spain
MR Llamas, Complutense University, Madrid, Spain
A Garrido, Polytechnic University of Madrid, Madrid, Spain
D Sanz, University of Barcelona, Barcelona, Spain

1.07.1 Introduction

The last half century has witnessed a spectacular development in groundwater use. Its use has increased from some 100 Mm^3 to almost 1000 Mm^3 in the period 1950–2000 (Shah, *et al.*, 2007). In this chapter, water volumes are referred to in million cubic meter (10^6 or Mm^3) and billion cubic meter (10^9, km^3 or bcm).

The table of conversions is as follows:

- $Mm^3 = 10^6\,m^3$
- $km^3 = 10^9\,m^3$
- $bcm = 10^9\,m^3$
- $hm^3 = 10^6\,m^3$.

This groundwater development has been mainly used for irrigation in arid and semiarid regions. Nevertheless, the use of groundwater for rural and urban water supply is very important; in some countries, like in Italy, it represents 90% of all of the urban water supply. Although the accuracy of available water-use data is still rather illusory, it seems that today the economic value of groundwater irrigation is even greater than the corresponding value of surface-water irrigation.

The main factors that have driven this spectacular development in groundwater use include (1) the availability of modern and relatively cheap rigs to drill water wells; (2) the invention and ease of use of the turbine pump that allows abstracting significant volumes of groundwater from deep water wells; and (3) the consolidation of hydrogeology as a reliable science and technology that has dispelled the mystery of groundwater (**Figure 1**).

This extraordinary development of groundwater use has been described as a silent revolution (Fornés *et al.*, 2005; Llamas and Martínez-Santos, 2005) because it was due to the efforts of millions of farmers, with scarce planning and control by conventional water authorities. These public government bodies have been occupied for more than 50 centuries with surface-water systems, beginning in the hydraulic civilizations located in the valleys of large rivers, such as the Nile, the Ganges, and the Yellow River. Therefore, it is not surprising that most high-level water decision makers suffer from hydro-schizophrenia. This disease was described for the first time in 1973 by the American hydrologist Raymond Nace, as the mindset of those that completely separate surface water and groundwater, and usually forget the latter (Llamas, 2004).

This silent revolution has produced great benefits to humankind because it has contributed significantly both to reduce malnourishment in poor countries and to provide drinking water to the rural and urban poor. Moreover, groundwater irrigation is generally a driver for positive social changes. However, the current and frequent situation of inadequate planning and control over groundwater development has also triggered problems, which are mainly related to negative ecological impacts on aquatic ecosystems and groundwater-quality degradation. These problems have been frequently exaggerated by many surface-water experts who have created the pervasive hydromyth of groundwater fragility in order to foster the traditional policy of surface-water infrastructure.

In summary, our main message is that it is crucial that high-level water decision makers seriously consider the real role that groundwater is playing and can play in current and future water policy. This role is going to increase even more if the predictions by the International Panel for Climate Change (IPCC) of an increase in temperature and a decrease in precipitation in most arid and semiarid regions become true (Bates *et al.*, 2008).

Our emphasis in this chapter is on groundwater management and not on groundwater hydrology. This is, first, because one of the volumes in this treatise deals with hydrology; second, because in our view, the main current problem is not lack of knowledge about aquifer location, characteristics, and functioning, but rather about better ways to manage the aquifers as a common-pool resource. We refer the interested reader to the work of Chevalking *et al.* (2008) for some useful citations of websites pertaining to the various aspects of groundwater management.

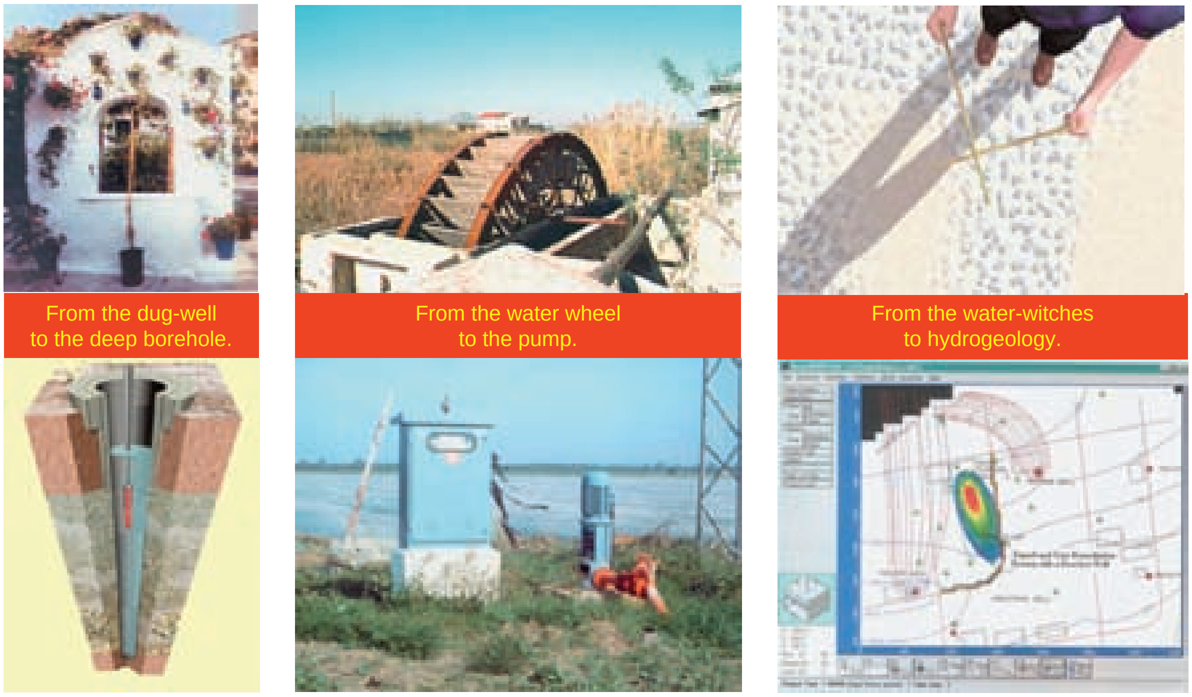

Figure 1 The silent groundwater revolution: changes in global water management.

Consequently, after this introduction, Section 1.07.2 is devoted to recall the value of groundwater as a strategic resource. The main specific characteristics of groundwater that require a different management style than surface water is emphasized. Data provided by the United Nations Economic Scientific and Cultural Organization (UNESCO)–International Groundwater Resources Assessment Centre (IGRAC), the International Association of Hydrogeologists and the book by Margat (2008) describe the location of the main aquifers and groundwater uses in most countries.

Developing (or semi-developing or emerging) arid and semiarid regions, such as India or regions of East Asia, have experienced a spectacular development in groundwater irrigation during recent years (Shah, 2005; Shah *et al.*, 2007). 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 groundwater development, to hard-rock aquifers, where small communities may rely on scarce resources and pumping may prove to be costly.

Some arid regions are endowed with good aquifers: these may correspond to countries, such as Saudi Arabia or Libya, where groundwater mining is commonplace (see Section 1.07.2.5.2). Reliance on nonrenewable 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 the use of nonrenewable groundwater resources to be acceptable under certain circumstances (Selborne, 2001; Delli Priscoli *et al.*, 2004; Llamas, 2004).

In arid and semiarid regions of industrialized countries, for example, the USA (California, Texas) and Spain, intensive groundwater withdrawals for irrigation are a well-established practice. Development is essentially market driven, as the cost of obtaining groundwater generally amounts to a very small fraction of the crop value. Some authors argue that the depletion of groundwater levels results in an increase of pumping costs, and may ultimately yield these intensive uses economically unsustainable. However, empirical evidence in some areas seems to show the opposite. Farmers are not deterred 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 and Martínez-Santos, 2005; Fornés *et al.*, 2005). It can also be explained by the so-called Gisser–Sanchez effect (see Koundouri (2004) for a detailed explanation), that is, "the no-management (competitive) dynamic solution of groundwater exploitation is almost identical (in terms of derived social welfare) to the efficient management (optimal control) solution" (p. 706). This is a management paradox because the serious depletion of aquifers is a major risk to many freshwater ecosystems; yet, the social benefits from managing groundwater extraction are numerically insignificant. This also has significant implication for water managers because it severely constrains the effectiveness of policy options, since implementing reduced extractions is not socially, economically, or politically costless.

1.07.2 The Global Silent Revolution of Intensive Groundwater Use

1.07.2.1 Introduction

This section summarizes the main hydrologic characteristics of groundwater occurrence, availability, and past and present uses. A detailed description of these aspects can be found in Margat (2008), in the UNESCO–IGRAC website, and is also treated in one of the volumes in this treatise.

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 close to a few mega-cities. This groundwater development has produced great socioeconomic benefits, mainly in developing countries. It has provided cheap drinking water that has helped improve public health. The new irrigated lands have contributed to eradication, or at least mitigation, of malnourishment among those living in poverty. Millions of modest farmers with scarce public or governmental planning, assessment, financing, and control have mainly carried out this intensive groundwater 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 designing, building, and operating large surface-water irrigation systems. The attitude of some water decision makers who strongly separate surface and groundwater projects, usually ignoring groundwater, was described as hydro-schizophrenia by the well-known American hydrologist, Raymond Nace, in the year 1973 (Llamas, 2004). This attitude has been commonplace in India, Mexico, Spain, and many other arid and semiarid 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 colossal anarchy (Shah *et al.*, 2007).

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 (Custodio, 2002; Lopez-Gunn and Llamas, 2008).

Due to ignorance, vested interests, or, more frequently, because of the low credibility of the official warnings of water-governing bodies about 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-sized aquifers has caused serious social or economic problems similar to those caused by soil water logging and salinization, or by the people displaced or ousted by the construction of large dams.

1.07.2.2 The Role of Groundwater in the Global Water Cycle

The inventory and the movement of water on planet Earth is well known and acceptably quantified, for at least a half century. According to Margat (2008), groundwater storage globally, that is, the volume of groundwater stored in the geological formations defined as aquifers, is huge, about 10^7 km^3. This is about 98–99% of all the liquid freshwater in the Earth, although it is only about 1% of the total volume on the hydrosphere (including oceans). The hydrological cycle indicates that water is continuously in motion, driven mainly by solar energy and gravity. This flow of water is very important. It is estimated that every year, precipitation is in the order of 100 000 km^3, river flow about 40 000 km^3, and groundwater recharge in the order of 10 000 km^3. This means that the storage is 1000 times greater than the annual recharge. A large part of this groundwater recharge or runoff feeds the rivers and is included in river flow.

However, these global numbers give only a preliminary idea and the specific situation in each region may be quite different. In Margat (2008) and in the UNESCO–IGRAC website, details can be found by country and continent. The main idea to keep in mind is that the volume of freshwater stored in the aquifers is usually huge in comparison with their yearly recharge (usually coming from precipitation) and with discharge (usually to rivers or wetlands). The annual recharge may change from practically zero in the most arid regions to more that 1000 mm yr^{-1} in very humid areas.

1.07.2.3 Location of the Main Aquifers

Most countries have made significant efforts to characterize the geological formations defined as aquifers, including their main parameters and functioning and relation with surface-water bodies. These data are usually synthesized in different types of maps, known as hydro-geological maps. The UNESCO–IGRAC is a center that collects these data from all over the world and makes them available to the general public.

The interested reader can find a good summary in the work by Margat (2008) of the situation in most countries (Figure 2) and a brief description of the main aquifer systems, with special emphasis on those that are transboundary (Figure 3). This means that they occupy areas in two or more countries. As an international transboundary resource, it is estimated that there are nearly 240 transboundary groundwater systems or aquifers (WHYMAP, Worldwide Hydrogeological Mapping and Assessment Programme; Lopez-Gunn, 2009).

Margat (2008) classifies the aquifers into four groups according to their main geological characteristics: karstic, alluvial, hard rock, and volcanic. Significant attention is devoted to the aquifers in arid and semiarid regions because in these areas, the recharge of groundwater is small and its use may be relevant.

1.07.2.4 Groundwater Uses: Past and Present

The use of groundwater coming from springs is as old as humanity. Margat (2008) mentions historical data of dug wells several millennia old. In Armenia, the first infiltration galleries to drain phreatic aquifers are recorded dating to 8 BC. This technology was soon extended to the whole Mediterranean region and to Asia. Hundreds of thousand kilometers of these galleries were constructed, some of them still in operation today. Nevertheless, the spectacular increase in the use of groundwater has been mainly driven by the improvement in drilling technology and the invention of the turbine pump in the first-third of the twentieth century. Margat (2008) estimates that groundwater abstractions in 2004 were 800 km^3 yr^{-1}; Shah *et al.* (2007), however, estimate that this amount is more than 1000 km^3 yr^{-1} and its use is on the increase.

For the sake of comparison recent studies on the water footprint and virtual water trade (Aldaya *et al.*, 2009), the total use of green and blue water is estimated as 7000 km^3 yr^{-1}; of this, probably blue water accounts for about 3000 km^3.

1.07.2.5 The Pros and Cons of the Intensive Use of Groundwater

As mentioned in Section 1.07.1, a good number of authors emphasize the problems related to groundwater development. In this chapter, we intend to present an objective appraisal.

Groundwater development produces great economic benefits due mainly to its general resilience to drought, and thus allowing supply to meet demand in a timely fashion. The fact that most groundwater development has been done by private persons, mostly modest farmers, with no, or a small public subsidy, is the best evidence. Some externalities of groundwater development have negative impacts. These externalities are described in Section 1.07.6.1. Nevertheless, in agreement with Llamas and Custodio (2003), in general, many of the negative externalities have been exaggerated and/or could have been corrected or mitigated by good groundwater management.

1.07.2.5.1 The complex meaning of sustainability in groundwater use

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 (Llamas and Custodio, 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.

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 development must be considered with ever-improving technology.

It has been customary – as 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

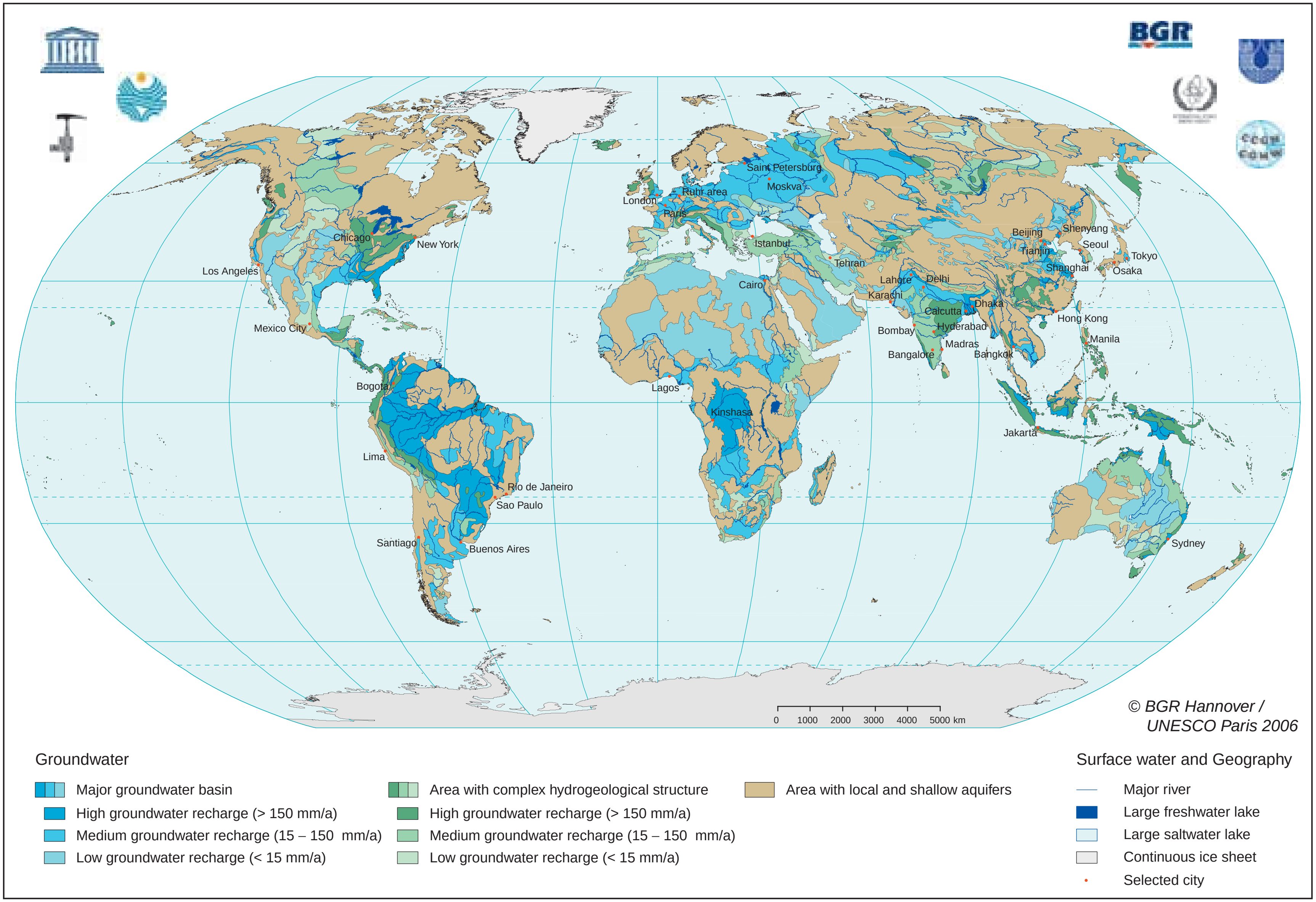

Figure 2 Groundwater resources of the world. From World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP), special edition 2006.

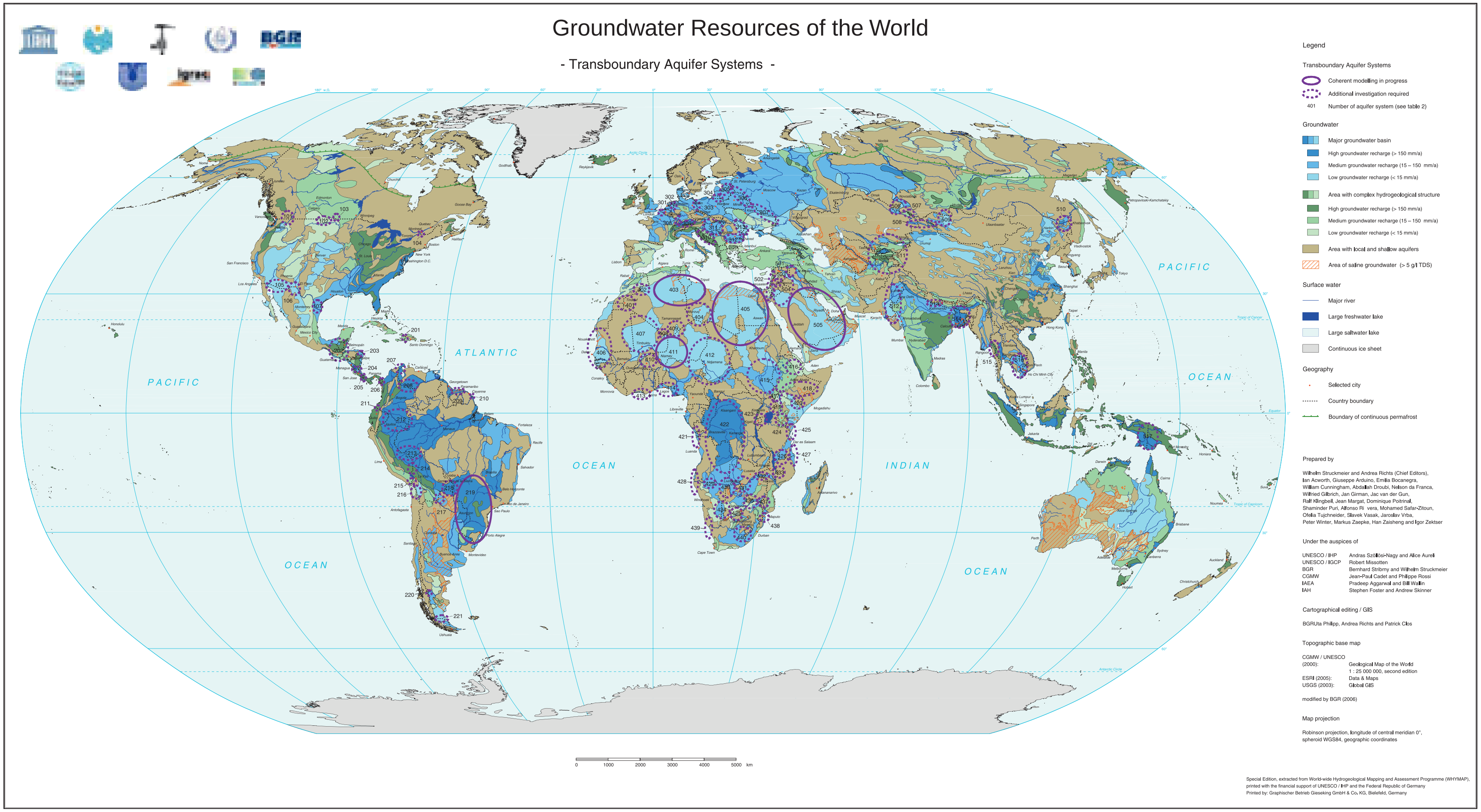

Figure 3 Map on transboundary aquifers of the world. From World-wide Hydrogeological Mapping and Assessment Programme (WHYMAP), special edition 2006.

situation. This is a simplistic approach that might be a long way from the real situation. It often corresponds to a transient state of the aquifer toward a new equilibrium (Custodio, 2002).

Intensive groundwater use frequently depletes the water table. Depletions of the order of 0.5 $m\,yr^{-1}$ are frequent, although rates up to 5–10 $m\,yr^{-1}$ have been reported (Llamas and 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 (Wegerich, 2006). 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 just compensation in terms of water or money to poor farmers.

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

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

In a given aquifer, pumping rates for irrigation may prove to be 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 restraint 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 toward 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 considerations.

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 the 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 in cultural, political aspects, and the socioeconomic situations. In this regard, the *Hydrogeology Journal* theme issue of March 2006 (Llamas *et al.*, 2006) presents the socioeconomic analyses of a number of case studies from all over the world.

Therefore, any study on economic sustainability of groundwater use should take into account the specific regional settings. In 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, while environmental concerns are generally subordinated to human development. This is the case in many small African villages.

1.07.2.5.2 The ethics of pumping nonrenewable groundwater (groundwater mining)

Some arid regions have very small amounts of renewable water resources but huge amounts of fresh groundwater reserves, 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 reserve depletion can be guaranteed for a long period, for example, from 50 to 100 years; (3) the environmental impacts of such groundwater withdrawals are properly assessed and considered clearly less significant than the socioeconomic benefits from groundwater mining; and (4) solutions are envisaged for the time when the groundwater is fully depleted. Selborne (2001), former chairman of the COMEST, agrees with this approach.

In Saudi Arabia, the main aquifers (within the first 300 m of depth) contain huge amounts – a minimum of 2000 km^3 – of fresh fossil water that is 10 000–30 000 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 $km^3\,yr^{-1}$. During a couple of decades, the Saudi government had pumped several $km^3\ yr^{-1}$ of nonrenewable groundwater to grow low-cost crops (mainly cereals), which were heavily subsidized. The official aim of such an activity was to help transform nomadic groups into farmers. 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 $km^3\,yr^{-1}$. Probably, similar situations exist in Libya and Algeria. Other examples of mining groundwater can be found in Llamas and Custodio (2003).

1.07.2.6 The Social Sustainability of Groundwater Management

As previously stated, 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 then, the farmers may have experienced a positive social transition.

Groundwater irrigation has proven to be an excellent catalyst for this social transition of farmers in arid and semiarid regions worldwide (Llamas and Martínez-Santos, 2005; Moench, 2003, 2007). Increased revenues result in, and allow for, a greater degree of social welfare. In addition, farmers are able to provide 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. Therefore, this transition means a reduction of global poverty (Lopez-Gunn and Llamas, 2008).

This social transition, triggered by groundwater together with the implementation of more efficient irrigation technologies, can often result in a sustainable use in the midterm. However, adequate groundwater management and governance remain as important challenges in areas of India, Spain, China, or the southern United States (Shah *et al.*, 2007; Llamas and Custodio, 2003; Foster *et al.*, 2004).

Aquifers constitute an example of common-pool resources, and as in the majority of cases, all actors have direct access (legal or illegal) to groundwater. Therefore, aquifers should typically follow the widely articulated 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 transmissivity and storage-capacity values) where the tragic outcomes outlined by Hardin have taken place causing social or economic disturbances – at least not in the degree of magnitude of those caused by soil waterlogging 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.*, 2007).

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. Although still uncommon, cases of small aquifers that have run out of groundwater have been some times reported verbally to the authors of this chapter.

The reality is that even some poor aquifers, such as the Indian hard-rock aquifers, have played a key role in increasing food production. In India, groundwater-irrigated surface has increased by more than 40 million hectares (ha) during the last few decades (Shah *et al.*, 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 has 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 such areas, pumping data are hardly reliable. Take for instance, California's aquifers, where overdraft estimates range between 1.2 and 2.4 $km^3 yr^{-1}$. Equally, the overdraft in California aquifers has not been adequately analyzed since the 1980s. It is perhaps the lack of willingness to monitor, rather than overdraft *per se* that may constitute the greatest intergenerational threat for groundwater resources.

1.07.3 The Economics of Groundwater Use

It is estimated that more than two-thirds of available freshwater is groundwater, and it is currently the most extracted natural resource in the world. More than half the world's freshwater, for uses like drinking, cooking, and hygiene, comes from groundwater; groundwater irrigates 20% of irrigated agriculture. Groundwater supplies 75–90% of drinking-water supply in European countries, and 95% of the US rural population public-water supply. Aquifers provide natural storage reservoirs with little evaporative loss at little or no cost. Equally, aquifers provide natural transmission of water from the various sources to the point of use. During periods of drought, groundwater provides reliable supplies, compared to surface water, by its use as supplementary irrigation water to surface-water supplies (Howe, 2002). Groundwater is an important economic resource for billions of people, in developed and developing countries. Ninety percent of urban supply in India, and 70% in Mexico are just examples of the socioeconomic importance of this key resource for humans. Figure 4 plots the share of agricultural groundwater use and total groundwater use in total use in 2002 in the Organization for Economic Cooperation and Development (OECD) countries. It shows the importance of both the agricultural sector with groundwater use (countries situated on left) and the percentage of groundwater use over total use (countries on the right).

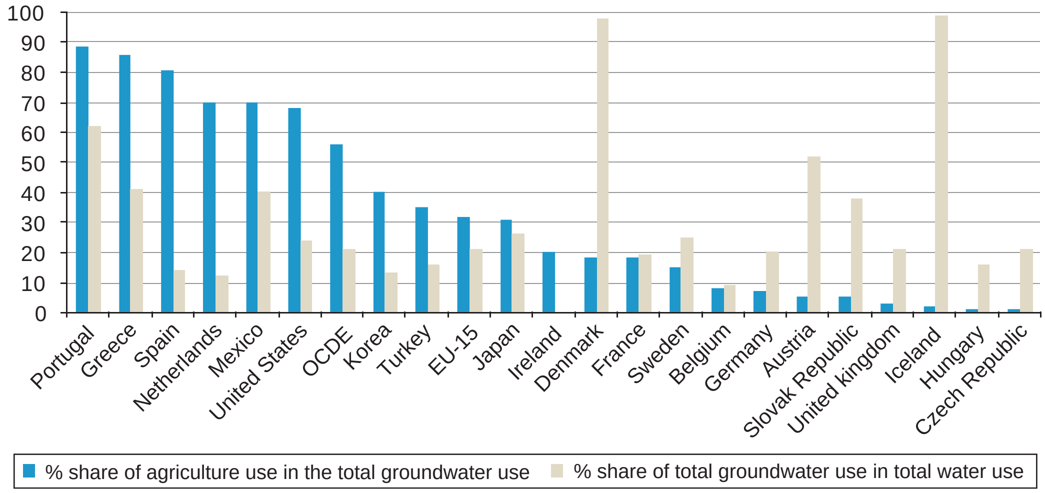

Figure 4 Share of agricultural groundwater use in total groundwater use, and total groundwater use in total water use. From OECD (2008) *Environmental performance of OECD Agriculture since 1990*, Paris, France. Online at: www.oecd.org/agriculture/env/indicators

Rosegrant *et al.* (2002) have estimated that the sustainable yield of groundwater resources in the world would be approximately 861 km^3, down from 925 km^3 as evaluated in the year 1995, with half this amount abstracted in Asia, and 28% in developed countries. It is difficult to put a dollar value to the use of this resource, but considering a conservative figure of US$ 0.25 m^{-3} (including capital, environmental, and resource costs), this generates an annual total value of US$ 231 billion as a preliminary estimation.

The groundwater literature shows that in addition to the direct-use value, groundwater resources also have a significant stabilization value (Tsur and Parker, 1997) in cases where groundwater is conjunctively used with more unreliable surface waters. Estimates of the stabilization value of groundwater resources show that it can be as high as that of direct use. This is because groundwater provides reliability of supply and reduces the probability and severity of water shortages.

In addition to households' water services, groundwater resources are extensively used for food production. With few exceptions, irrigation is the result of uncoordinated efforts of small entrepreneurs and farmers all over the world. These groundwater users have sought to improve their livelihoods investing in private capital and small pumping equipment to improve farm productivity.

1.07.3.1 Groundwater Costs of Abstraction and Groundwater Tariffs

Groundwater unit volume costs increase 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 and US$ 0.30 m^{-3} depending on the country and the aquifer. However, according to Shah *et al.* (2007) the economic cost (value) of groundwater is about US$ 0.20–0.30 m^{-3}). It would be worthwhile to study this aspect worldwide in more detail since values appear 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 the performance of 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) 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 and US$ 1000 $ha^{-1}\,yr^{-1}$.

Despite the difficulties in setting tariffs for groundwater use, a number of countries have these in place. In many cases, tariffs are accompanied by quotas and licenses. In general, developed countries have in place a fixed fee plus a volumetric fee, but these levies are generally not adapted to recharge or movements in the water table. Essentially, this indicates that tariffs on groundwater use are environmental levies but not rationing instruments to manage aquifers. This is because, to ensure sustainable management, tariffs would need to be flexible enough to change according to scarcity costs and all-use externalities – and this – assuming that perfect monitoring and information are economically feasible.

1.07.3.2 Productivity of Groundwater Use

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 ($m^3\ ha^{-1}$), a ratio that increases to between 3 and 10 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) (see Table 1). Thus, it appears relevant and urgent to assess the comparative hydrological and socioeconomic efficiency of surface and groundwater 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.

Many high-value crops are watered with groundwater resources or by combining ground and surface water (Llamas and Martínez-Santos, 2005). For instance, in Table 1, Hernández-Mora *et al.* (2001) show that, in Andalusia, irrigated agriculture using groundwater is economically over 5 times more productive and generates almost 3 times the employment than agriculture using surface water, per unit

Table 1 Comparing ground and surface-water irrigation productivity: Some irrigation economic indicators in Andalusia (Spain)

	Groundwater	*Surface water*	*Total*
Irrigated area (ha)	244 190 (27%)	648 009 (73%)	893 009 (100%)
Average water consumption ($m^{-3}\ ha^{-1}$)	3900	5000	4700
Total production (10^6 €)	2222	2268	4480
Production (€ ha^{-1})	9100	3500	5100
Employment generated (number jobs/100 ha)	23.2	12.6	15.4
EU aid to income (% of production value)	5.6	20.8	13.4
Gross water productivity (€ m^{-3})	2.35	0.70	1.08
Total average water price to farmer (€ m^{-3})	7.2	3.3	3.9

From Hernández-Mora N, Llamas MR, and Martínez-Cortina L (2001) Misconceptions in aquifer over-exploitation. Implications for water policy in southern Europe. In: Dosi C (ed.) *Agricultural Use of Groundwater. Towards Integration between Agricultural Policy and Water Resources Management*, pp. 107–125. Dordrecht: Kluwer.

volume of water used. This difference can be attributed to several causes: the greater control and supply guarantee that groundwater provides, which in turn allows farmers to introduce more efficient irrigation techniques and more profitable crops. Greater dynamism has normally characterized farmers who sought out their own sources of water and have had to bear the full costs of drilling, pumping, and distribution. Higher financial costs to farmers motivate them to look for more profitable crops that will allow them to maximize their return on investments. Surface and groundwater distinctions, therefore, should be taken into account in order to achieve an efficient allocation of water resources.

1.07.3.3 Perverse Subsidies in Water Policy

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 neglect of groundwater problems among water managers and decision makers. Surface water for irrigation is usually given at low or heavily subsidized costs to farmers and this often results in the wasteful use of a valuable resource.

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 through general revenues, instead of advocating a responsible use of groundwater resources. At times, this may lead to social conflicts – such as in the case 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 of the European Union (EU) Water Framework Directive (WFD) 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, in turn, adequate attention to groundwater planning, control, and management would probably follow.

1.07.3.4 Groundwater: From Open Access to Common Pool?

Economics deals with scarcity and the allocation of scarce goods. Groundwater resources until very recently, it could be argued, were not economic goods, because anyone interested in pumping water could do it *ab libitum*. Capital, energy, or time constraints were the only barriers for all potential users of groundwater resources. In this case, however, the economic problem, if any, was related to access to inputs, finance, or labor. Even in cases where the inputs required to pump groundwater are unlimited, deciding on how much water should be pumped may not be an economic problem.

One of the most pressing institutional questions centers on inappropriate legal and administrative structures, which in effect means that groundwater rather than being an open-pool resource becomes an open-access resource which can lead to excessive contemporary and inter-temporal externalities (Howe, 2002) (see Section 1.07.6). As in many other natural resources, the transition from an open access and unlimited resource to an exhaustible and rival one is gradual. It happens by the marginal adhesion of small groundwater users attracted by the benefits that are obtained by those who came earlier. In this slowness and imperceptibility lies a significant part of the difficulties of managing groundwater resources nowadays.

There are a number of political and policy choices to offset the pervasiveness of open access, such as regulatory interventions, market instruments, or information and technical choices. Most often, the effectiveness of policy measures might mean the right mix of policy instruments from an existing portfolio where experience has already been gathered from groundwater management.

For policymakers, there are a range of policy instruments for management (Table 2), with different strengths and weaknesses for groundwater management according to a range of criteria such as effectiveness, economic efficiency, technical efficiency, administrative feasibility, equity, and social or political acceptability (Hellegers and Van Ierland, 2003).

An example of regulatory instruments for environmental protection is the case of the Edwards aquifer, in Texas (USA). The Edwards aquifer is a karstic aquifer, which means that the effects of pumping are quickly transmitted to large areas creating in effect an open-access resource since it operates under the rule of capture, that is, where under Texas groundwater law, landowners can pump without limit (Howe, 2002). Pumping for agricultural and urban purposes has represented 45–50% of the total discharge of the Edwards aquifer for the period from 1934 to 1999. Springs supported several species of fish and amphibians giving the Federal Fish and Wildlife Service the right to intervene to protect these species if the state failed to act. A lawsuit by the Sierra Club, an environmental nongovernmental organization (NGO), under the Endangered Species Act ended in a federal ruling, which meant that the Texas legislature set up the Edwards Aquifer authority in 1996 with extensive powers, including the issuing of permits to regulate groundwater withdrawals. For example, it required pumping limits to protect endangered species. A flow of 150 cubic feet per second must be maintained at the most sensitive springs.

1.07.3.5 Optimal Groundwater Pricing

An optimal groundwater price is a theoretical economic concept, and the solution to a dynamic and stochastic problem. It is dynamic because the optimal price varies with time, and is meant to ensure that pumping rates at any given moment maximize the discounted flow of benefits for an infinite time horizon. As Neher (1990) shows, there is an optimal tax that makes all users of a common pool internalize the (marginal) consequences of their pumping rate so that a socially optimal management use is achieved. Theoretical optimal rates can be obtained to account for irreversible effects – caused by excessive drawdown (Rubio and Fisher, 1997), for situations in which backstop technologies can become operative if pumping becomes too expensive (Gemma and Tsur, 2007), or when surface water and groundwater are conjunctively used (Pongkijvorasin and Roumasset, 2007).

Pongkijvorasin and Roumasset's (2007) main contribution is to combine two problems that have been addressed separately in the literature. One looks at the problem of managing large surface systems with conveyance losses (Roumasset and Chakravorty, cited by Pongkijvorasin and Roumasset, 2007),

Table 2 Portfolio of policy instruments available to manage groundwater quantity and/or quality

Portfolio of groundwater-management tools		*Example*
Standards and regulations	Limit pump capacity	High Plains Conservancy district No 1 outside Lubbock
	Well spacing	e.g., *harim rule* in Islamic law (Middle East)
	Groundwater permits	Indonesia
	Safe-yield criteria	EU Water Framework Directive
	Ban in most critical groundwater areas	For example, sprinkling bans to reduce low value agricultural groundwater abstraction in Holland; Yemen (ban on agricultural wells); and Egypt (ban on new wells)
	Pumping tax, for example, reflect to the individual pumper the negative externalities	Netherlands, France, and parts of Germany have introduced a groundwater-abstraction tax
	Caps on abstraction	Edwards aquifer Texas, (USA)[a], Italy (Perugia province)
	Metering groundwater use	Parts of Spain
	Metering electricity use as groundwater use proxy	China
Market-based instruments (economic incentives)	Groundwater resource fee (money raised earmarked for aquifer management), cost of right (water-resource levy)	Indonesia for industrial water users Holland has a levy under the 1983 Groundwater Act
	Volumetric pricing of groundwater and/or electricity supply, sliding-scale pricing strategy	India and China
	Electricity subsidies	For example, Mexico 1/3 of electricity costs
	Groundwater farms (i.e., purchase of land for associated groundwater rights)	Arizona Spain (Parque Nacional Tablas de Daimiel)
	Issuing tradable permits (leasehold) with or without cap on total abstractions	Spain, for example, for environmental flows
	Water markets (freehold), for example, from rural to urban, from small to large farmers, from low-value to high-value crops, from irrigation to environmental flows	Spain, USA, Australia, Chile Mexico (including energy pricing coupled with water rights)
	Compensation program for third-party effects, for example, tax to area of origin	Contemplated in Texas
	Full cost recovery	EU Water Framework Directive
	Groundwater banks	Trialled in Texas[b]
Administrative planning and education measures	Groundwater zoning, for example, aquifer-vulnerability maps to contamination	United Kingdom, Holland, USA, and Canada Pakistan through informal committees
	Land-use planning	For example, removal of invasive species and replacement with native vegetation in South Africa to help recharge shallow aquifers, India and South Africa studies on impact of forestry (native and plantations) on evaporation and recharge
	Education, for example, agricultural extension service and training	High Plains District Eastern La Mancha aquifer (Spain)
	Political education at senior level on the value of groundwater	e-Water India
	Public awareness campaigns, civil education, for example, value of groundwater	UNESCO
	Name-and-shame list	For example, China water pollution map
	Joint regulation and monitoring	Eastern Mancha aquifer (Spain)
	Participatory groundwater monitoring	India and China
Institutional (incl. information and voluntary measures)	Incentives for private entrepreneurs for example, as franchisees for billing and collecting electricity dues	China
	Self-imposed correlative rights for example, % owned above the aquifer	
	Voluntary agreements (self-regulation), devolved groundwater management	For example, Water Boards in Holland (interest, payment, authority) involved in groundwater-level management
	Groundwater protection codes	UK

(*Continued*)

Table 2 Continued

Portfolio of groundwater-management tools		*Example*
Technological	Use of Geographic Information System (GIS) for monitoring	e.g. Spain and Mexico
	Wastewater-reuse schemes	
	Artificial aquifer recharge enhancement and/or storage	Central Valley (California), Rainwater harvesting (India); well recharge movement
	Improved irrigation technology (for example, irrigation scheduling, micro-irrigation, land leveling)	Israel, Spain, Australia, USA, and Mexico
	Changes in crop type, for example, higher-value crops if possible (i.e., no impact on livelihoods); ban on high water-consumptive crops	Areas in Spain Saudi Arabia

[a]A system of marketable groundwater permits to be issued to all pumpers as a proportion to historical use subject to a total pumping cap. The cap was 450 $mm^3\ yr^{-1}$ which was accepted by all users, urban, agricultural and environmental. In 1998, a groundwater trust was set up to facilitate the trading of permits. In the period 1997–2001 there have been 403 trades with an average size of 235 000 m^3.

[b]For example, under the Irrigation Suspension program, water rights were purchased from 40 farmers representing 4000 ha to supply water to San Antonio. Irrigators were paid $ 98 to $ 1850 ha^{-1} to stop irrigating, with water savings of 20 000 acre feet at a cost of $ 2–3 million paid for by cities, counties, and water companies.

For additional ideas, please see Chevalking S, Knoop L, and Van Steenbergen F (2008) *Ideas for Groundwater Management*. Wageningen, The Netherlands: MetaMeta and IUCN.

and the other looks at the conjunctive use of surface and groundwater. The paper's main accomplishment is to show that, with surface pricing as the only managing instrument, farmers switch from surface to groundwater and vice versa, when groundwater-scarcity rent diminishes, with the irrigation boundary contracting or growing depending on whether groundwater-scarcity rents increase or decrease. The institutional implications of these results are worrying, unless one can think of a much more restricting context in which pumping rights could be effectively enforced, and irrigation districts had nonmobile boundaries. Yet, Rijsberman (2004) quotes work by the International Water Management Institute (IWMI) which shows that groundwater use is largely beyond the possibilities of most water institutions in the developing world for a proper monitoring. Llamas *et al*. (2008) and Shah *et al*. (2007) present a similar general situation.

The large literature on theoretical groundwater pricing yields somewhat impractical policy prescriptions (e.g., Molle and Berkoff (2006)) because of the number of externalities involved in many cases of intensively exploited aquifers (see Llamas and Custodio, 2003). Brown (2000) offers very convincing arguments to explain why optimal pricing has rarely been used to allocate renewable resources such as fisheries or groundwater.

1.07.3.6 Departures from Optimality: Second-Best Solutions

In economics, second-best solutions are those that cannot achieve the results of the first-best optimal solution but are more applicable in practical terms. First-best solutions may be too information demanding or based on a perfect fine-tuning to the specific circumstances. In this section, we review some of the most commonly used second-best (or even third-best) solutions to properly manage groundwater resources. These policy approaches are always implemented to solve one or the other type of the sources of economic inefficiencies. The following are the policies from the less to the more sophisticated: user rights, pumping rights, pumping quotas, water tariffs, and water markets.

Issuing user rights is the simplest way to grant access to an aquifer. The authority may or may not control the pumping capacity and the type of equipment. In intensively exploited aquifers, granting user rights may not be sufficient to deter pumping and, in many situations, the outcome may not ensure that the exploitation is adequate. However, issuing user rights is a prerequisite to consider in any of the policy menus mentioned. In principle, user rights are increasingly required to obtain legal access to tap an aquifer in virtually all contexts in which water is scarce.

The next instrument in the list is granting pumping rights, whereby users are entitled to pump fixed amounts. In principle, the ownership of pumping rights can be associated with private property if those rights cannot be encumbered by new users or forfeited by a public agency. Setting up pumping quotas enables a more flexible instrument, because these can be modulated to the aquifer's recharge. In many cases, pumping rights are combined with water tariffs, but an interesting option would be to modulate tariffs to mimic the optimal price. Perhaps, the most advanced initiatives in the area of groundwater pricing can be found in some European countries, which have seized the opportunity of the EU WFD to implement the principle of full-cost-recovery pricing.

Water markets can be found in multiple formats. In India, for instance, water markets occur as informal exchanges among small farmers (Saleth, 1996). In Australia, water markets are formally established and can facilitate groundwater trading or rights' exchanges. In Spain, the basin authorities have offered farmers permanent buy-outs of water rights, or annual pumping quotas, following public offerings (see Box 1 for examples of water trading).

A prerequisite of all these policies is to have control of (at least) the number of users, and ideally of the pumping yields of all users tapping an aquifer. However, even if control and surveillance can be guaranteed, it does not imply that the aquifer will be sustainably managed. Unfettered water rights can be as damaging to aquifer management as an aquifer that is not controlled. Groundwater management is usually based on rights or licensing, but enforcing compliance with these

Box 1 Water markets and voluntary exchange mechanisms to solve groundwater overdraft. From Garrido A and Llamas MR (2009) Water management in Spain: An example of changing paradigms. In: Dinar A and Albiac J (eds.) *Policy and Strategic Behavior in Water Resource Management*, pp. 125–146. London: Earthscan.

Water banks or exchange centers, as these are called in Spain, received legal recognition in the 1999 Spanish Water Law reform. Not strictly a bank or agency, these centers are hosted, run, and located in the basin agencies themselves. It is widely believed that these centers are a much more efficient medium for promoting water exchanges, for a number of reasons, such as transparency, control, avoidance of third-party effects, and market activity and scope. Yet, the experience so far has been limited to the Júcar, Segura, and Guadiana basins, since these water centers have been primarily used to tackle severe problems of groundwater intensive use.

Since the enactment of the 1985 Water Law, which included special provisions to tackle the problem of overexploited aquifers, there have been at least four major initiatives to manage groundwater resources. In short, these were (1) the declaration of overexploited aquifers and the mandate to enforce regulations and implement management plans; (2) an EU agri-environmental program, only applicable to Aquifer 23 in the Guadiana Basin, with subsidies to farmers who curtail their water consumption; (3) the use of inter-basin transfers, both in the case of the southeast coastal areas and in the Upper Guadiana; and lastly, (4) the Special Upper Guadiana Plan (PEAG, Spanish acronym), and the creation of exchange centers in the Segura, Júcar, and Guadiana basins. Clearly, the first option failed; the second one succeeded, but the financial cost was very high, and the third option failed because the second one was not sustainable.

In the end, the PEAG was approved in 2007 with a total budget for 20 years of €5.5 billion (equivalent to the proposed Ebro transfer) and part of its subprograms are now operational, although under PEAG the basin would reduce to a meager 200 million m^3. Underlying these initiatives, but undermining them too, was the recognition that tens of thousands of users in virtually all basins had no legal rights or concessions to the groundwater resources they had been tapping for years. Any effort to reduce total extractions in the over-drafted hydrogeological units had to be accompanied by the closure of the alegal or illegal uses.

In 2005, it was clear to all managers, analysts, and users that something new had to be given a chance. The option to use buyouts of water rights, permanent or temporary, gave a rationale to the establishment of exchanges centers (*centros de intercambio* in Spanish). We review the different approaches taken in the Jucar and Guadiana. In the Jucar basin, the offer of public purchase (*Oferta pública de adquisición de derechos*, OPA) was targeted at farmers tapping groundwater resources near the Jucar's headwaters. Its objective was to increase the water tables in Castille-La Mancha to ensure that the Júcar flows to the Valencia region increase from historical lows. Farmers were given the option to lease out their rights for 1 year in return for a compensation ranging from 0.13 to 0.19 cents m^{-3}, the variation depending on the distance of the farmer's location to associated wetlands or to the river alluvial plain. The OPA was launched in two rounds, the first with disappointing results in terms of farmers' response, while the second had more success. The purchased waters served the unique purpose of increasing the flows, enabling more use downstream in Valencia. However, the OPA did not have any specific beneficiaries downstream, other than to increase flows. The OPAs of the Guadiana followed a completely different approach and were meant to address serious problems of overdraft in the Upper Guadiana. As stated before, the OPA formed part of the more ambitious program of aquifer recovery, the PEAG. The Guadiana's OPA made offers to purchase permanent water rights to groundwater, paying farmers €6000–10 000 ha^{-1} of irrigated land. Note that, since these farmers had seen their allotments reduced in preceding years, what the Guadiana basin was truly purchasing from the farmers was about 1500–2500 $m^3\,ha^{-1}$, effectively €2–4 m^{-3}. The Guadiana basin agency has the objective of purchasing the water rights of 50 000 ha^{-1} of irrigated land, and is budgeting €500 million for the whole plan. A marked difference from the Jucar's OPA is that the Guadiana exchange center will transfer part of these rights to other farmers (growing vegetables) and to the autonomous community of Castille-La Mancha. The Guadiana basin will grant less rights than it has purchased, allocating the difference to wetlands and to increasing the piezometric levels of the aquifers.

rights remains a major challenge for adequate groundwater management. For example, there is wide experience with water markets in the USA; according to Howe (2002), what water markets do best is to generate information on values for more rational, better-informed water allocation – for example, the sale or lease of water rights to off-site buyers such as cities. In Arizona, the government had acquired 200 000 ha of land by 1990 for the associated groundwater rights. These water farms or water ranches average about 12 150 ha and are valued at US$15 million, and expected to supply 15 000 acre feet of groundwater per year for 100 years. In Colorado, Front Range water rights in 1990 sold for US$ 1000–4000 per acre foot (Colby, 1990 in Wagner, 2005).

In systems where groundwater rights have been incorporated into the general water-rights system, groundwater rights can be bought and sold, transferred to other locations, or transformed into surface rights (e.g., tributary groundwater–groundwater that is intimately connected with surface water). In Texas, groundwater was purchased to secure water for urban centers such as Houston, San Antonio, and El Paso. For example, an old mining right from the Alcoa-Sandown mine was sold for US$ 688 per acre foot annually. The city of Amarillo also bought groundwater for US$ 679 ha^{-1} for groundwater rights from 28 350 ha of lands, when the land itself sells for US$ 494 (Gillinland, 2004 in Wagner, 2005). The El Paso Water Utility purchased more than 19 000 ha of ranchland to pump 15 000 acre feet by 2010 (Texas Center for Policy Studies in Wagner, 2005). Lucrative groundwater leases with at least four private water ranches on over 200 000 ha have been formed to sell or lease a significant amount of water to off-site users, principally cities. Another example is the Irrigation Suspension Program, where water rights were purchased from 40 farmers representing 4000 ha to supply water to San Antonio. Irrigators were paid US$ 98–1850 ha^{-1} not to irrigate, with water savings of 20 000 acre feet at a cost of US$ 2–3 million paid for by cities, counties, and water companies (Wagner, 2005). Nevertheless, there is a range of issues that has to be considered in water marketing. Over-entitlement occurs when the sum of all legally defined rights are greater than 100% of the system's potential. Overuse occurs when the quantity of water abstracted is greater than the system's potential to supply. Sleeper or dozer licenses are legal entitlements that are not used at present but are legal (e.g., UK sleeper licenses). One major reason why some people might distrust markets is the fear that markets might fail to deal with issues of distributional equity, fairness, public concern, and community interest.

1.07.3.7 Internalizing the Value of Environmental Services Provided by Groundwater

Water can be framed on current discussions on ecosystem functions from environmental services. Ecosystem functions refer to system properties and processes. Services represent the benefits that society derives, directly or indirectly, from ecosystem functions. A summary of the authors' evaluation of annual flows of water-related ecosystems at the world scale is presented.

Humans avail many types of services from water-related ecosystems in addition to water supply. Note, for example, that 1 ha of wetlands can generate almost US$ 4200 yr^{-1} in waste-treatment services (Costanza and de Groot, 1997). While this evaluation was certainly preliminary at the time it was produced, it conveys a clear idea about the costs and damages that water scarcity can provoke. The mere recognition of many of the identified services valuable for society has huge implications for drought-policy design and implementation. Chief among this is the fact that many of these services have public-nature features, which means that they are nonrival and nonexclusive goods. As scientists have learned to identify and value them, water policy must take into account and ensure that decisions are a compromise between both productive and nonproductive services (National Research Council, 2004).

The Millennium Ecosystem Assessment undertaken in 2005 classified the goods and services provided by natural resources as provisioning, regulating, supporting, and cultural services. In this context, Bergkamp and Cross (2007) discuss the high-value ecosystems supported by groundwater. The total economic value (TEV) of groundwater resources is the sum of groundwater resources: use and non-use value, based on direct values, indirect values, option, and existence values. A number of methods have been developed by environmental and ecological economists to value these goods and services using a range of environmental techniques such as contingent valuation method (willingness to pay and willingness to accept), choice modeling, production-function approaches, surrogate markets, costs-based approaches, and stated preference. These methodologies are addressed in one of the chapters of this volume. This is a way of internalizing the value of groundwater services and also the economic value of groundwater externalities. This can help decision making to evaluate the costs of action and costs of inaction. It gives a clearer signal of whether it is better or not to opt for preventative policies when the full remediation costs of polluted groundwater are accounted for, that is, measure the potential benefits (or damages) of a range of effects. In 1996, the US Department of Defense invested in 75 pump-and-treat systems to remediate contaminated sites estimated at US$ 500 000 per site. Equally, a calculation on the externality costs of over-abstraction in the Queretaro aquifer (Mexico) between 1970 and 1996 included: the increased pumping costs due to drop in piezometric levels estimated at US$ 6 million; the loss of water quality for public water supply at US$ 26 million; and damage to urban infrastructure due to land subsidence at US$ 26 million (6 million as private cost and 20 million as costs to taxpayers). Moreover, it is relevant to consider impacts on other policy sectors like the costs for public health due to the mobilization of naturally occurring arsenic through deep wells in Bangladesh, which is estimated to affect 30–35 million people (WHO, 2001).

Opportunity costs are the foregone benefits that could have been generated if resource was allocated to the next-best use if water is not allocated to its highest use value and, in fact, opportunity costs may be greater than the value generated by next-best use. In this case, the economy is subjected to inefficient and suboptimal groundwater allocation, although this may be justified in equity or sociopolitical terms. Therefore, it is equally important to properly include the positive services provided by groundwater.

In terms of equity, Acharya and Barbier (2000) analyze losses to farmers from reduced groundwater recharge. On average, farmers could lose US$ 413 ha^{-1} if the groundwater benefits are not accounted for, that is, evaluating the system-wide benefits associated with groundwater use.

The increased recognition of the benefits associated with groundwater use is reflected, for example, in the growing aquifer-recharge movement. In Texas, aquifer recharge through open-space protection and cooperative groundwater allocation is a new paradigm in water management (Wagner, 2005), based on valuing the products and services that a functioning system provides. In India, meanwhile, the so-called decentralized recharge movement was a spontaneous response to groundwater depletion to help water tables rebound to predevelopment levels at the end of the monsoon season in pockets of intensive use. This is an example of contrasts between popular hydrogeology and formal hydrogeology; for example, scientists argue that hard-rock areas have too little storage and advocate recharge; meanwhile, the prolific growth of recharge structures is based on the value people attach to a check-dam even if their wells provide only 1000 m^3 which – although small – is crucial for life-saving irrigation in times of delayed rain. Thus, rainwater harvesting can be used to recharge groundwater via recharge ponds, based on the main sources of recharge: rain, and infiltration from riverbeds and from the floodplain. Equally, in Australia and the USA, sand dams are used to make artificial shallow aquifers in streambeds to reduce evaporation of stored waters. The growth in the number of sand dams could substantially increase to compensate for potential climate variability and change making use of groundwaters' buffering service (see Section 1.07.6.2.1). Failing to account for the opportunity costs of groundwater and surface/groundwater linkage often result in suboptimal outcomes. Groundwater recharge is one of the most important environmental functions brought about by wetlands. For example, households in rural Nigeria rely on groundwater for drinking and cooking, and in the arid north, particularly during drought, it often has the added advantage of its higher quality (Table 3).

1.07.4 Regulatory Frameworks for Groundwater Multilevel Governance

One of the most obvious examples of the Cinderella status of groundwater in global water resources is reflected in the evolution of regulatory frameworks. Due to its silent (and relatively recent) rapid growth, groundwater traditionally had little or no regulation (i.e., as exemplified in the rule of capture in Texas), part of mining law, or of private-property rights (tied to land). This lack of prominence and the lack of concern over its management and state of preservation have historically been reflected in the law. Therefore, groundwater

Table 3 Valuing groundwater goods and services

Total economic value of groundwater	*Environmental goods and services*	*Definition*	*Example*
Direct value	Provisioning service	Drinking water supply	Two billion people rely on groundwater directly for drinking water
	For example, storage and retention		More than 50% of cities with population of more than 10 million rely on or make significant use of groundwater
		Agriculture	Forty percent of world's food relies heavily on groundwater
			Land irrigated from aquifers has increased 113 times between 1990 and 1990. Aquifer supplies more than half the world's irrigated land
		Industrial	For example, manufacturing processes and geothermal and cooling systems
Indirect value	Regulating services	Water regulation;	Groundwater stores and releases water, sustains river flows, springs, and wetlands
		Water purification and waste treatment	Through microbial degradation of organic compounds and potential human pathogens, microbiological and some chemical contaminants removed, retarded, or fragmented
		Erosion and flood control	For example, by absorbing run off
		Climate regulation	Primary buffer against climate variability and spatial variability of droughts
			Potential innovation as future use for anthropogenic carbon sequestration in the ground
Option value and existence value	Supporting services	Necessary for the production of all other ecosystems services	For example, groundwater recharge and discharge
	Cultural services	Non-material benefits people obtain from ecosystem services	Spiritual enrichment, cognitive development, religious value, and symbolism

From Bergkamp G and Cross K (2007) Groundwater and ecosystem services: Options for their sustainable use. In: Ragone S, de la Hera A, Hernandez-Mora N, Bergkamp G, and McKay J (eds.) *Global Importance of Groundwater in the 21st Century: The International Symposium in Groundwater Sustainability*, pp. 233–246. Alicante, Spain, 24–27 January 2006. Westerville, OH: National Groundwater Association Press.

was legally structured as one more facet of the right of ownership for a specific area of land. Starting out from that premise, the various laws gave shape to the depth of that right and regulated how it would fit in with the rights held by owners of adjacent pieces of land. All of the above emerged from an eminently private perspective imbued with the wealth of duties and rights conferred by ownership rights.

Groundwater doctrine in Texas is based on the rule of capture, an English common-law approach based on absolute ownership, where landowners can pump without limit, as long as water is put to beneficial use, which allows unrestricted pumping by competing groundwater users as long as it is not wasted, and whereby property rights are not defined (Wagner, 2005). This is an example of one of the few natural resources in the USA not regulated by a central agency. The activities of 88 water districts in Texas are unusual because they have been based exclusively on a voluntary approach controlling wastage of water, recharge, enhancement, and water-conservation education rather than controlling abstractions. For nearly 100 years, the rule of capture has survived attempts to regulate groundwater use. Although government oversight and technical assistance are vital, a carefully crafted free-market system based on private rights to a communal resource becomes increasingly important. A bottom-up process created the State Water Plan of 2002, which incorporated regional water plans' gradual increase in the security of mining rights from open access to other systems.

1.07.4.1 Diversity in Groundwater Regulatory Regimes

Regimes with a civil-law tradition, inherited from the principles of Roman law, are clear exponents of this and not very far from them are those grouped under the parameters of common law. Under common-law regimes, the landowners were the right holders of groundwater, flowing under their properties, which could be harnessed (Embid Irujo, 2002).

From the legal viewpoint, legislation on aquifers presents two main issues of concern: first, ownership and second, transferability or flexibility with ownership rights. The first one relates to whether groundwater resources should be public or private property. Ownership of groundwater resources shows a high level of diversity from completely private (e.g., in Texas USA), groundwater from the Ogallala aquifer is mainly private (Peck, 2007), to state-owned resources, such as in the case of Mexico, to plural legal systems, as in parts of Africa, and community based, such as in Bolivia. Legal provisions may confer ownership of groundwater directly on public authorities, as part of the public domain (Morocco, Italy, Spain, Zimbabwe, Israel, some US States, Jamaica, Mexico, Argentina, Australia, the Lebanon, Jordan, and Syria), give the authorities preferential rights in groundwater (South Africa and Uganda), or make groundwater the common heritage of the nation and place conditions on its use (France). Particularly, in Muslim countries, the applicable legal regime is intertwined with principles related to religious beliefs which result in the classification of water as public in itself with cases of private appropriation being seen as exceptional (Caponera and Nanni, 2007). Whichever route is taken, the result is very similar: governmental authorities give themselves powers over groundwater with the aim and effect to implement public policies that they lay down.

The progressive importance of groundwater in the definition of water resources in various countries has engendered the implementation of legal reforms that protect public intervention (Hodgson, 2006). When groundwater is public, the concept that is generally used by the rule makers is the permit, license, authorization, concession, or a similar instrument. 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. In all of these cases, a private party, individual, or community is granted the right to use a certain amount of groundwater. This right is subject to certain conditions relating to time or use. The right may or may not be granted according to whether it is consistent with the status of the resource and with the parameters of the planning regulations on water resources that must govern its contents. Those same premises must be used to determine the period for which the right is granted and the amount that may be extracted. It is also necessary for the law to outline the cases in which this right can be altered, restricted, or even eliminated as a result of damage to the aquifer, possible droughts, water-supply needs to the population, or similar events, or principles such as reasonable and beneficial use. A legal regime for groundwater should ideally consider some of these aspects:

- approval of compulsory legal norms for all groundwater users;
- determination of the legal rules and principles to be applied in the management of groundwater, including its relationship with surface water;
- legal parameters to define groundwater as a resource;
- institutional regime applicable to groundwater;
- specification and regime for uses of groundwater available for all citizens without being subject to specific control;
- determination of the rights on water (transitional rules in the event of amendments to the law; concession rules; registration processes; contents of the right – volume of water, term, conditions, and termination – transfer of rights; and dispute-resolution mechanisms); and
- rules on the protection of groundwater and measures to adopt if needed (control of the pollution of groundwater – rules on discharge and authorization; use restrictions; and prohibition on use).

1.07.4.1.1 The controversy over private, public, or community groundwater rights

Evidence indicates that ownership *per se* (public, private, or common) does not guarantee or pre-empt sound management. The importance does not lie in what name is given to the legal title but rather in the contents given to that title. The emphasis is placed on the aim to be achieved. Preferences on ownership are societal choices, which are subject to change and flux; the underpinning question is not ownership but whether management is according to some predefined *a priori* objectives, which in any case are themselves subject to constant negotiation and renegotiation as part of a normal political process. 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 centralized management of groundwater resources is not automatically the solution to promote solidarity in groundwater use as a common good because a key element is the internalization, by often thousands or hundreds of individual users, on the need for collective action. Groundwater management sometimes can successfully be devolved to stakeholders of the aquifer, in self-governance arrangements under the supervision of the corresponding water authority. Stakeholders' participation has greater chances of success if it emerges bottom -up and is supported top-down. The practical application of a hybrid (public and private) system is exemplified by a few countries in the world where a range of systems coexist: one is the US, where states like Colorado, Arizona, Texas, and California exhibit a range of ownership rights to groundwater; and the other is Spain with a particularly interesting example of a mixed system. Wells drilled after 1 January 1986 require governmental permission, while those operational before 1986 remain private. Private groundwater may remain so for 50 years (provided 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 ignore a significant share of existing wells, and the registry or inventory is therefore incomplete. A key ingredient is the need for a strong political willingness to apply the laws. It seems clear that a reliable inventory of groundwater rights is desirable in order to ensure adequate management.

The second issue 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 markets and banks (discussed in the previous section) is perhaps subordinated to the first in terms of importance, even if significant informal markets already exist in some places (Mukherji, 2006). It cannot be ignored, however, that in other territories, the inseparable link between water, land, and private property has been maintained. The states of California and Texas or countries such as Chile and India are examples of this. These cases have maintained the private ownership of water and in many cases applied the doctrine of prior appropriation, although this is subject, depending on the territory and circumstances, to specific measures of administrative or court intervention, linked, for example, to the principle of reasonable use. It is also possible

Box 2 Groundwater-use rights in China. By Simon Howarth, based in Gansu, under the UK Department for International Development (DFID)-funded Water Resources Demand Management Assistance Project.

The Shiyang River Basin in Gansu province in Northwestern China is an area of severe water shortage, where groundwater abstraction greatly exceeds recharge. A package of measures, including greater delivery of surface water and restrictions on the use of surface water, is being introduced.

A key element in this process is the allocation of water rights to individual households. These are based on land allocations and household size (to take account of domestic use and livestock as well as agricultural demands). Both land and water are owned by the state in China, but user rights have been granted to individuals. Land rights have been granted since the 1980s and further reforms are in progress. Water rights have been formalized since 2007, when individual household water-rights certificates were issued (via village committees or WUAs). The rights are calculated to be sufficient for the locally recommended cropping pattern, and are being reduced each year (e.g., from 7200 to 6615 to 6435 $m^3 ha^{-1}$ in one typical irrigation district) as recommendations are revised and farmer skills in water savings are developed. Awareness and capacity-building programs are being run simultaneously so that farmers can protect their livelihoods while coping with less water.

Wells were developed by villages and are owned by them, but the amount of water that can be pumped from them is regulated by the state through a system of permits. Well permits are now being reissued to suit the new water rights, and electronic controls (IC cards) are being installed at all wells. These will limit the amount that can be pumped from the well to the annual total permitted for that well. These cards are held by the well operator who is responsible for ensuring that each household receives water in accordance with their individual rights. These systems are new, rely on both sophisticated technology and complex administrative systems, and have been introduced rapidly (in over 10 000 wells in 1 year). Not surprisingly, some teething difficulties have been encountered, but there is a very strong political will to solve these problems.

Allocation of water rights is intended to enable trading of rights, although this does not yet happen on a formal basis in this area of China. It will be subject to certain restrictions – for example, the right will be salable at a maximum of three times the water-resources fee, which is small when compared to both the value of water and the cost of pumping. There is a large and growing requirement for water for industrial development, which is a more valuable use of water, but there is a competing requirement for food security – these competing demands cannot be managed purely by market measures but will require government control as well.

to outline mechanisms for exchanging water rights in the context of what has come to be called the water market (Chile, South Africa, Mexico, Spain, the UK, Australia, and the US).

The use of water-market institutions for groundwater has its detractors who point to the risks involved. In our view, however, those risks do not necessarily warrant ruling out the option completely. Bringing flexibility to the allocation of resources and allowing them to be exchanged are not in themselves misguided concepts. The usefulness of water markets is usually associated with cases of multiple supply and demand sources, with transparent exchange mechanisms and the appropriate transportation networks that make them feasible (Melgarejo and Molina, 2005). The key lies in controlling their use and making them subject parameters of sustainability and protection (Box 2).

1.07.4.2 Implementation and Enforcement of Groundwater Legislation

In the context of groundwater management, rules on the ground are crucial, for example, those related to time, well location and spacing, technology, or groundwater-abstraction quotas. In addition, another factor is the interaction between formal groundwater law and its operation on the ground. More attention is being paid increasingly to the implementability of regulation, since the problem with most groundwater legislation lies in its implementation and enforceability.

For example, South Africa established an implementation team with the task of anticipating what the water domestic bill would require, with close interaction between the drafting and implementation teams to identify possible implementation problems before enactment. In the case of groundwater, it would be useful to develop implementation tools such as guidelines, procedures, information systems, user manuals, and organizational arrangements. Another option is to opt for framework laws, which specify general guidelines but leave implementation to detailed regulations as used in Uruguay. Implementation requires time, and needs political support at the highest level since strong economic and political interests are usually affected by allocating or reallocating groundwater resources. As Garduño (2003) states that implementable legislation is one that the government is able to administer and enforce and water users have the ability to comply with. Experience shows the education of stakeholders and widespread presence of groundwater-user associations is crucial for an adequate participatory bottom-up management approach.

One of the main problems in groundwater governance is lack of enforcement in some cases of relatively sophisticated laws, such as in Spain. As stated earlier, institutions encompass not only rules in norm but also rules in use or institutional arrangements. In effect, the implementation and enforcement of groundwater laws have to be legitimized and supported by society (social norms). The involvement of groundwater users in groundwater-management regimes is a necessary (although not sufficient) condition for successful enforcement regimes.

In traditional societies, social networks were denser and therefore transaction costs lower, whereas modern societies require complex institutional structures that constrain and regulate interactions among groundwater users. Groundwater users possess detailed local knowledge on water use, and these communities can apply for sanctions unavailable through formal institutions. For example, name and shame can resolve conflicts at the local level in a manner customized to local circumstances, which reduces transaction costs, which in turn are critical for economic performance. In fact, in a study undertaken in Spain, groundwater users had a clear perception of the kind of behavior that should be penalized and how sometimes sanctions devised by farmers do not mirror sanctions designed by higher-level authorities (Lopez-Gunn, 2003). This can be rooted in different perceptions of equity and fairness. For example, farmers in an aquifer in Spain would prefer to be sanctioned in the following irrigation season with water as a penalty, in lieu for the same amount of water that farmers abstract over their quota in the previous irrigation season, instead of the current (formal) sanctions of a monetary penalty.

Thus, groundwater users can reduce the transaction costs of enforcement and devise adequate sanctions. However, it should not be forgotten that authorities in most cases ultimately hold this legal responsibility to protect public goods. Higher-level authorities will often have to be imaginative with monitoring and sanctioning regimes. Many Asian administrations lack the capacity to perform complex tasks, for example, urban groundwater management with joint monitoring of industrial groundwater abstraction and wastewater discharges. A feasible alternative tried in Indonesia was to select a random sample and thoroughly monitor these users. In cases of noncompliance, the weight of the law should be applied and widely publicized in the media; as capacity grows, the sample could be enlarged. Limited administrative capacity is a key constraint to groundwater management and revenue-raising fees can be re-invested toward capacity programs.

1.07.4.3 Multilevel Regulatory Frameworks

The section above described and discussed briefly some of the main challenges for national groundwater law. It is increasingly recognized, however, that national groundwater law is only part of the regulatory framework. Other levels (both conceptual and in terms of scale) have to be taken into account: first, international conventions currently being negotiated, for example, for transboundary aquifers or the rise in the human right to water; second, a pragmatic approach on the advantages and limitations of legislation and litigation; and third, a consideration of the legal principles that have to underpin legal norms and an evolution in our understanding of how laws will be drafted in the twenty-first century.

First, in relation to international conventions, there are two conventions that are applicable to groundwater: the first relates to transboundary aquifers and the second refers to the International Convention on Human Rights (1948) and its new impetus to recognize a human right to water (or HRW). Until only a few years ago, international law did not pay too much attention to groundwater. This state of affairs has changed, aided by the Convention on the Law of the Non-Navigational Uses of International Watercourses (1997) (Eckstein, 2004). This Convention, yet to be ratified, only partially covered transboundary groundwater, that is, those connected to rivers, and thus left many aquifers uncovered. As a result of this situation, in 2008, the International Law Commission delivered to the United Nations General Assembly, draft articles for the law on transboundary aquifers. After reaffirming the protective and environmental approach to the use of groundwater, they ratified the application of the principle of fair use (1997) and of sensible damage. They also outlined measures for the following: first, cooperation between states; second, the regular exchange of data and information; third, the promotion of bilateral and regional agreements; and fourth, measures for the protection and preservation of ecosystems, and the prevention, reduction, and control of pollution. Along these lines, they provided that where appropriate, a shared management mechanism will be established.

Claims for the right to water to become a fundamental right, and thus protected, are increasing. This is probably highly applicable to groundwater since in many countries public water supply (to which the HRW is addressed) is supplied largely by groundwater. This is the case, for example, in Africa, the continent lagging most behind in the Millennium Development Goals. In relation to lack of access to water and sanitation by 2015, Africa is the continent most off target where groundwater is the daily source of drinking water for more than 75% of the population The first reference in this respect is to be found in articles 11 and 12 of the International Covenant on Economic, Social, and Cultural Rights of 19 December 1966. While not expressly mentioning the right to water, its wording has led the United Nations Committee on Economic, Social, and Cultural Rights (2002) to define the HRW as one which entitles everyone to sufficient, safe, acceptable, physically accessible, and affordable water for personal and domestic uses, and even links this right to the International Bill of Human Rights (1948). This reference to the right to water has been kept in recent documents such as the Plan of Implementation of the World Summit on Sustainable Development (2002), the Charter of Water of the Senegal River (Mali *et al*., 2002), or the Third World Water Forum Ministerial Declaration (2003).

Second, there are advantages and disadvantages to a pure regulatory approach. Recognized limitations include symptoms such as the existence of rigid overly bureaucratic administrative procedures, the large number of authorities involved in taking decisions on groundwater, scarcity of technical and human resources to enforce compliance with legislative requirements, the often-absent citizens' participation in decision-making processes on deliberation and decision making, or the confrontation of interests among the various government departments. These are clear examples of what we could call organization sickness. Legal proceedings that are prolonged, costly, hard to enforce, or construed poorly with practical needs of water management make it problematic for courts to be able to solve groundwater conflicts. Crucial and fundamental advantages to regulatory processes remain, such as its role as leverage and recourse for aggrieved third parties in court. This is why it is crucial in the case of groundwater to facilitate legal literacy or legal empowerment improving the capacity of communities to know and use the law – training in techniques such as interest-based negotiation, mediation, and facilitation.

Third, the step from regulation by rulemaking process to negotiated rulemaking can never replace the public decision-making process, with the participation of all interested parties, or generate inequality. A series of legal principles have to be embodied in formal groundwater regulation, leaving more freedom or flexibility in terms of the implementation and enforcement (Table 4).

1.07.5 Institutional Aspects of Groundwater Management

The problem of groundwater over-use has often been portrayed by the tragedy of the commons, that is, Hardin's seminal essay in 1968 (Hardin, 1968) which describes how the

Table 4 Legal principles applicable to groundwater legislation and its implementation

Legal principles	*Rationale and justification*	*How*
Effectiveness and efficacy	Efficacy of water management must be sought, by implementing or furthering measures	Adapting organization and competent authorities to conform to the natural characteristics of the resource – normally identified as a drainage basin Fostering the participation of users and interested third parties which has already been identified as a mechanism to secure acceptance and implementation of the agreed measures. Encouraging planning related to the allocation of resources or water-quality protection or restriction measures, rules on improvements and irrigation transformations, guidelines on recharge and aquifer protection.
Cooperation	Cooperation between authorities as fundamental (Declaration on Groundwater in the Mediterranean, 2006)[a]	Cooperation, either through procedures or by agreeing to specific conventions, must enable more effective, allow the views of each of the players with responsibilities in the area to be known, avoid subsequent defects in the implementation of agreements and, in short, allow views to be joined to find the best solution.
Participation and subsidiarity	Aarhus Convention (1998)[b]	Environmental governance that is transparent, legitimate, and efficient. Public authorities, as the necessary guardians of correct application of the legal framework, may confer an especially important role on user associations directly involved in the management of, for example, groundwater resources. There has already been a certain amount of international experience in this area in countries such as Argentina, Colombia, Spain, the US, Indonesia, Mexico, Nepal, the Philippines, Sri Lanka, or Tunisia. Besides, it acquires greater importance in relation to groundwater as it is a way of surmounting the management difficulties caused by having multiple users.
Sustainability and precautionary	Rio and Johannesburg Summits[c]	The implementation of sustainable development must pervade decisions on territorial and urban planning and the performance of specific projects, the approval of new protection rules, to end, cease or modify granted rights to groundwater and, especially, the economic development and growth initiatives in every country.
Common responsibility	Commission on Sustainable Development, United Nations Economic and Social Council (2008)[d]	Groundwater is a common good and therefore the responsibility for its protection and correct management belongs to everyone.
User and polluter pays principle		To determine the obligation to repair and replace the resource base to their original state. In addition, it will be absolutely necessary to establish the strict liability regime in these cases, notwithstanding any potential exceptions linked to the state of technology or the grant of approvals.
Solidarity	Levels of solidarity in groundwater management	• *Intergenerational solidarity*. Future generations must be considered when adopting initiatives. • *International solidarity*. Not all countries have the same difficulties. Ranging from the actual exchange of water to the transmission of technology and knowledge. An example is the Johannesburg Declaration on Sustainable Development of 2002. • *Regional solidarity*. The areas within a state must seek points of consensus and foster instruments of cooperation in the rational and sustainable use of groundwater. It will undoubtedly be fundamental for this task to be able to plan and study the circumstances of each specific case, but it is important to take as reference the need to share and join forces in searching for the balance sought by all.

[a]Málaga-Marrakech Declaration on Groundwater in the Mediterranean, 2006. (This Declaration is the result from two international congresses organized in 2006, AQUAinMED'06 – Málaga – and GIRE3D – Marrakech).
[b]The United Nations Economic Commission for Europe Convention on access to information, public participation in decision making, and access to justice in environmental matters, Aarhus (Denmark), on 25 June 1998.
[c]Johannesburg Declaration on Sustainable Development (World Summit on Sustainable Development, United Nations, 2002).
[d]Commission on Sustainable Development, Report on the sixteenth session May 2007 and 2008 (Economic and Social Council, United Nations).
Author: D. Sanz.

rational actions of individual actors, in our case groundwater users, lead to the demise of all, that is, aquifer over-use. This is because groundwater, which is a classic example of a common-pool resource, is defined by two characteristics: the resource is largely rival and nonexcludable. These common-pool resources exist at different scales from transboundary to regional or small local aquifers. The works of Ostrom (1990) and other institutionalists have demonstrated that this case underestimated the capacity of the users to self-regulate their actions, that is, to develop rules in norm and rules in use to prevent aquifer overuse. The groundwater silent revolution described earlier in the chapter has however outpaced the capacity to develop institutions suitable for good groundwater governance in terms of resilience, while maintaining a level of flexibility and adaptability to cope with a high degree of change.

1.07.5.1 Groundwater Institutions: Mapping Groundwater Institutional Design

A number of conditions have been well documented in the literature for the successful management of common-pool resources. These factors are summarized in Box 3 (Schlager and Lopez-Gunn, 2006) in relation to groundwater.

1.07.5.1.1 Boundary definition

The first tenet of institutional theory refers to boundaries. This refers on the one hand to natural boundaries and on the other to institutional (property right) boundaries. In the first case, the definition of natural aquifer boundaries for management purposes has the added complication that groundwater aquifers do not necessarily coincide with surface-water systems. In addition, groundwater suffers from the same problem that surface water had traditionally experienced, lack of overlap between administrative and natural boundaries (i.e., problem of fit), that is, the boundaries of for example, regional administration do not coincide with river-basin boundaries, with the added twist that surface basins and aquifers often do not coincide, which further increases the complexity. An interesting example is currently pursued under the EU WFD, which has adopted a twin-track approach of managing water according to river basins while simultaneously mapping groundwater bodies, while setting the objective to achieve good status for all water bodies in the EU (surface as well as groundwater) by 2015.

According to Howe (2002), assigning well-defined groundwater property rights, for example, through pumping permits (discussed earlier) enhances the value of water, which creates incentives to use water more effectively or to transfer rights and/or use to third parties who are willing to pay for pumping rights. Therefore, the most complex challenge for water laws is the administration of water rights, that is, the granting of licenses, concessions, permits, and other legal deeds for the abstraction of groundwater, and for the discharge of waste water directly or indirectly into the aquifer. Groundwater, in particular, offers additional problems because of the following: first, the potentially large and often heterogeneous number of users, and second, the boom in use which has often overwhelmed administrations. In Spain, 20 years after the 1985 Water Law, the registration of groundwater rights was required (1988), but the administration has still not finished the process; or in places such as Mexico an ecological price has been effectively been paid for the process of registering 330 000 water rights by 2003, by over-allocating groundwater resources. The new 2002 Water Law in China established the need to obtain groundwater permits. Yet, the issuing of water permits in China by counties is proceeding very slowly, and there is lack of consistency between authorized abstractions via permits and groundwater-resource availability (Foster *et al*., 2004).

Furthermore, growing experience in the process of assigning groundwater property rights has shown that it is crucial to take context into account when assigning groundwater rights, for example, in South Africa, where plural legislative frameworks (formal and customary) coexist. These plural, often dual legal systems have important implications for the registration of groundwater property rights, due to overlapping legal orders. The diversity and flexibility of customary laws, principles, and practices may be intentionally or

Box 3 Ostrom's institutional design principles applied to groundwater institutions. Reproduced by Lopez-Gunn E from Ostrom E (1990) *Governing the Commons: The Evolution of Self-Governing Irrigation Systems*. Cambridge: Cambridge University Press; Schlager E and Lopez-Gunn E (2006) Collective systems for water management: Is the tragedy of the commons a myth? In: Rogers P, Llamas MR, and Martínez-Cortina L (eds.) *Water Crisis: Myth or Reality?*, pp. 43–60. London: Taylor and Francis; and Cleaver F and Franks T (2005) *How Institutions Elude Design: River Basin Management and Sustainable Livelihoods*. BCID research paper 12, ICID Conference, London.

- *Clearly defined boundaries*. Both the boundaries of the aquifer and the individuals or households with groundwater rights from the aquifer are clearly defined. This principle refers both to the physical boundary of the aquifer and a clear identification of groundwater rights (legal boundary on groundwater).
- *Collective choice agreements*. A clearly defined groundwater-user group or community should be involved in groundwater management.
- *Appropriation rules*. Operational rules in relation to time, location, technology, or groundwater-abstraction units should include the groundwater users affected by these rules and should be included in decision-making processes to modify these appropriation rules.
- *Monitoring*. Monitors who actively audit physical conditions and behavior are accountable to groundwater users and/or are groundwater users themselves.
- *Graduated sanctions*. Sanctions are devised for noncompliance with collective rules (operational rules). Groundwater users who violate operational rules are likely to receive graduated sanctions by other groundwater users, by officials accountable to these groundwater users, or by both. These sanctions have to be applied consistently, impersonally, and rapidly.
- *Conflict-resolution mechanisms*. Groundwater users and officials have access to low-cost local arenas to resolve conflict among users or between users and officials. Conflict-resolution mechanisms should be clear, accessible, and quick.
- *Legitimacy*. The legitimacy of groundwater users to organize and set up their own institutional arrangements is not challenged by external government authorities.
- *Nested enterprises*. Local groundwater institutions are nested within other levels of decision making, in multiple layers, which facilitate governance (in terms of consistent operational rules, monitoring, and enforcement and conflict resolution).

unintentionally replaced by new water laws, and uniform rigid principles and requirements. Legal frameworks empower if these recognize rights of existing water-user communities, and enable legal recourse if rights are harmed. Plural groundwater property-rights systems ideally have to be based on the principles of good governance: transparency, accountability, and the rule of law. There is also a risk in idealizing customary groundwater rights, which might not necessarily, for example, be gender neutral.

1.07.5.1.2 The role of groundwater-user associations

Decentralization of groundwater-resource management is coherent with the creation of collective institutions like groundwater-user associations that can be directly involved in groundwater management. There is a range, nevertheless, on the degree of management devolution to groundwater-user groups, for example, market co-production, co-management, or regulated autonomy. In the late 1990s, decentralization was a consequence of rolling back the state, and transferring management directly to users – participatory-irrigation management (PIM; or irrigation-management transfer) since the dominant use of groundwater globally is agriculture. This is part of the wider trend in PIM (Merrey *et al.*, 2007). In the case of groundwater, PIM has interesting twists and turns because at least two types of groundwater-irrigation systems can be identified: first, the case of collective wells which are managed as very small surface-water systems, and second, and most common, individual farmers exploiting their well for productive agriculture and/or livelihoods. The creation of water-user groups and PIM would be similar to surface water in the first case, and would face similar limitations as those recently put forward for surface water, that is to say, that this is no panacea and it is suitable in some cases but not necessarily in all cases. These water-users associations (WUAs) are much smaller than WUAs for surface irrigation: this makes it simpler to organize them but it is also less important for them to be formal organizations. Informal groups are generally adequate for managing irrigation from individual wells, even when managed by groups of up to 50 farmers, such as in China. The second case is a true case of collective action because individual users have to be persuaded externally (top-down) or realize (internally) that the benefits of self-organization are higher than the costs, and that free riding on the collective action of others is now penalized either through formal sanctions or through informal, social norms. The objective in this case is regulation of the aquifer (i.e., the source of water) rather than equitable management of the distribution of water from the source.

The case of PIM in groundwater is fascinating because there is evidence from groundwater-user associations that have been both created top-down and others which have emerged bottom-up, spontaneously. This is the case of Spain, where *Comunidades de Aguas Subterraneas* – which is in effect, part of the water authority and instigated by the administration, and which manages groundwater as part of the public domain – coexists with *Comunidades de Usuarios de Aguas Privadas*, where private groundwater-user groups have been created through user initiative. More research is needed on delivery of management outcomes; what is already evident is that the scale of these groundwater-user groups is large, managing aquifers which can cover areas from 7000 km^2 to 300 km^2, and where success is mixed in terms of sustainable aquifer management. In China, groundwater management has gradually become more decentralized, and bottom up, with increased stakeholder participation at all levels, and closer interaction between users at the local level and the responsible authority, the Water Resource Bureau, normally designated at county level for rural areas and district level for urban municipalities, while some groundwater-user associations have also been established (Foster *et al.*, 2004).

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 availability of groundwater to users. For example, in Mexico, in the early 1990s, due to intensive groundwater use in the central and northern part, many groups started to emerge concerned with the problem of intensive groundwater use and negative externalities: for example, the spontaneous creation of the *Grupo del Agua in the Comarca Lagunera* (1991) and the *Grupo del Agua of Santo Domingo* valley a year later (1992). Other groups appeared in other areas. Initially, there was lack of clarity on the regulatory structure of these groups and their financing, which meant there was little support from the federal level. Initially, the Mexican Federal Government did not legitimize these spontaneous water-user groups until the mid-1990s, when these groups reorganized themselves as *Comites Tecnicos de Aguas Subterraneas* or COTAS, starting in the Queretaro valley, and then spreading to other aquifers in the central and northern part of Mexico. In the state of Guanajuato, local authorities encouraged the formation of COTAS in all aquifers in the state, supporting them financially (Escolero and Martinez, 2007). Meanwhile in the USA, local landowner associations in Texas have been experimenting with the feasibility of self-monitoring and regulation under local groundwater districts, which would set pumping limits and well placement based on hydrologic models, to deliver public goods such as open-space protection and aquifer recharge through cooperative landowners associations (Wagner, 2005).

In India there is evidence of the spontaneous creation of WUAs, through what Shah (2005) calls *swayambhoo* (self-creating), involving entrepreneurial efforts, which are normally present since most groundwater users are by definition small-scale entrepreneurs. It is estimated that over a quarter of Indian irrigated areas operate through this kind of spontaneous creation of informal water markets (Shah, 2005). The challenge is when *swayambhoo* institutions have to be scaled up, whether motivation can shift to longer term, and collective self-interest, then, can also start to internalize externalities (Box 4).

1.07.5.2 An Institutional Audit of Groundwater Institutions

Added research and experience have however highlighted new dimensions to the institutional framework analyzed above (Cleaver and Franks, 2005; Cleaver and Franks, 2008). The so-called post-institutionalist turn has added some caveats and

Box 4 WUAs for groundwater management in China. By Simon Howarth (UK DFID-funded Water Resources Demand Management Assistance Project.

Water-users associations (WUAs) are being set up in each village in the Shiyang River Basin, an arid internal river basin in Gansu Province of Northwestern China. They are being promoted by the government to assist in the management of groundwater, but with a primary focus on achieving water savings. Existing tube-well management arrangements, by local production groups (subdivisions of villages) supported by water-management stations (WMSs) (government) at township level, are believed to be effective and equitable, but insufficiently focused on reducing total water use – with the result that groundwater levels are dropping at 50–100 cm yr^{-1}, making agriculture unsustainable. These WUAs thus have different objectives to WUAs set up elsewhere in the world, which are required to improve management of large surface canal flows and hence ensure greater equity of water distribution.

Each village (or WUA) typically includes 20–50 tube-wells (each serving 5–20 ha, farmed by 10–50 households) which are managed by production groups (water-user groups). The tasks of the village-level WUA include assistance to the WMS in many of the new groundwater-management procedures, such as issuance of household water-rights certificates, enforcement of permits, and collection of fees – all of which are aimed at reducing the amount of water that farmers use. These are onerous requirements and thus the WUA are repaid part of the water-resource fees collected in order to cover a small salary for directors and vice-directors and some administrative costs – in recognition of the role that WUAs play in water-resources management. This formal process of paying staff from part of the newly introduced water-resources fee is important for ensuring that the WUAs are effective and sustainable.

In addition to these responsibilities for assisting the government, WUAs also have a small role in water management which includes improving maintenance; reducing conflicts; planning, implementing, and monitoring water distribution; monitoring groundwater levels; and ensuring effective communication between WMS, WUA, and farmers. Much of this work is done by well-established informal means by production groups, but the WUA coordinates between production groups and provides services at a higher level – such as employing a maintenance technician who is available to all groups, linking groups to government-sponsored training programs, and assisting in contracts with crop-grower associations, seed suppliers, and markets.

These WUAs are intended to be independent, autonomous, democratic, village-level organizations, but for practical reasons, the staff are often largely drawn from existing village committees (these are elected, but all candidates are required to be vetted and approved in advance). On paper, it is a strong system, but it is newly established and not yet fully effective. Many questions remain unconfirmed, including sustainability of financial arrangements, ability to deliver a positive service to farmers, and the willingness of farmers to accept the restrictions on water use.

Further work on WUAs will require a combination of administrative measures at provincial, municipal, and county levels, and capacity building among WUAs. This capacity building will in turn require awareness-raising at the various levels of government, where there is typically greater faith in top-down controls (such as IC cards) or infrastructural improvements (canal lining) than there is in local institutional methods for water savings. Nevertheless, early indications are that the strong commitment to water savings by the government will ensure that WUAs will be effective, but that their role and responsibilities will be modified and simplified as they are implemented.

new dimensions to a strict application of Ostrom's institutionalist framework. The main criticisms are that it is does not provide a causal analysis for the processes underlying these design principles. In particular, the areas that are increasingly perceived as fundamental to sound groundwater governance are: first, the key role of social capital and higher-level authorities; and second, the relevant role of political leadership and acknowledging the politics and vested interests of groundwater use, which are played out in the prioritization of groundwater use among competing users; and third, the potential problem of corruption as a symptom of a malfunctioning groundwater systems and the antidote of transparency and participatory groundwater management.

1.07.5.2.1 Higher-level authorities: Supporting, legitimizing, and leading

The relevance of higher-level authorities comes to the fore as an essential supporting element for effective institutions and the development of organizational capacity since both authority structures and social norms (e.g., collective action by users) have to support and underpin the functioning of design principles.

Higher-level authorities are key as facilitators for local groundwater management and for the vertical integration between the different spatial scales (farm level, aquifer, and regions, national, and international scales). For example, it appears that cross-scale linkages exist in China where there is a provision for transboundary issues across provinces, and also indirect leadership, as professional guidance from higher-level authorities without any hierarchal subordination. County government can issue groundwater regulations within its boundaries, in agreement with provincial and national legislation (Foster *et al.*, 2004).

Higher-level authorities are increasingly perceived as a necessary condition to support local institutional arrangements. One of the most important roles for higher-level authorities is either to provide leadership or to facilitate leadership. In many cases, leadership is actually in the form of legitimizing or supporting local leaders. These local leaders in turn can drastically reduce the transaction costs of institutional change. In India, for example, the common aspect of all successful tank institutions was a leader or a leadership compact, which could sway the community and thus drastically reduce the transaction costs of "enforcing institutional arrangement that would either not work in their absence nor survive them" (Shah, 2005, p. 17).

1.07.5.2.2 Transparency and participatory groundwater management

This chapter starts from the tenet that there is no global physical groundwater crisis; rather, there is a crisis of groundwater governance. Governance in this context is defined as the interplay of actors (public, private, and civic) to promote societal goals and the production of collective goods. One of the key basic assumptions of effective functional groundwater management is transparency and participation by all groundwater users in the decision-making process in line with the Aarhus Convention on Public Participation (UNECE, 1998).

The problem of corruption often damages those most vulnerable, weakening the rule of law, and fostering social norms that systematically prioritize private gain over social well-being. Corruption according to Transparency International is about breaking socially established expectations of appropriate behavior (Stalgren, 2006). As stated earlier, groundwater has some inherent characteristics that should make it less prone to corruption. In the case of groundwater, the timescale and size of investment is normally smaller than in the case of surface-water projects. Evidence of corruption in the case of groundwater tends to refer to drilling concessions, bribing meter readers, distorted site selection for boreholes, for example, for those with more political or economic influence; bribery to obtain drilling permits or to cover up excessive abstraction, to obtain preferential treatment for services or repairs, and also to falsify meter readings (Transparency International, 2008).

Advances are constantly made to facilitate transparency, accountability, and decentralization in groundwater management and use, for example, in the use of technology (Calera *et al.*, 1999). Three measures are considered crucial in the case of effective groundwater management. First, reduce the complexity in regulation, licensing, and control; this is to prevent a weak and ineffective legal system which can encourage a clientelistic patronage system. Second, facilitate and incentivize so-called participatory monitoring. As stated early, transparency, monitoring, and sanctioning are part of healthy groundwater institutional arrangements. Robust groundwater institutions can benefit from advances in participatory geographical information systems, that is, use of technology jointly by groundwater users and regulators to increase transparency in water use and allocation. A good example is currently being implemented in the Mancha region in Spain, where satellite information is being used directly by farmers through an irrigation advisory service, which integrates real-time data to help farmers improve water use by different crops, while optimizing production (Calera *et al.*, 1999). Third, encourage transparent access to data on groundwater use, licensing, and subsidies. This can be strengthened by partial decentralization to water users, to involve them in decision making, which would decrease the transaction costs of obtaining good-quality information while increasing the level of information available (**Box 5**).

In summary, good, symmetric information equally accessible to both users and the regulator is crucial to facilitate cooperation among aquifer stakeholders. This information ideally has to be externally audited and contrasted, to allow for advocacy and disclosure of illicit behavior. Often, easy access to good and reliable data on abstractions, water quality, and aquifer water levels is a prerequisite to succeed in groundwater management. Current information technology can help 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 easy access to water data to the general public. This partly comes from a shift in mentality that strengthens accountability of public authorities downward to users and civil society.

1.07.6 The Complex Concept of Groundwater Sustainability and Future Management Issues

An economic, efficient use of an aquifer would imply maximizing the present value of the resource in the case of the Ogallala, in Texas, where abstractions are much greater than natural recharge. It was discussed earlier in Section 1.07.2.5 that this exemplifies the complexities in defining what is meant by sustainable groundwater management. The exhaustible nature of the resource would raise the issue of appropriate long-term economic and demographic development of the region. The availability of open-access inexhaustible resources such as groundwater often invites gold-rush patterns of excessive fast exploitation and maladapted patterns of infrastructure and social development, that is, so-called boom towns (Howe, 2002). Economic efficiency in a renewable aquifer may imply drawing down the aquifer during droughts and allowing its recharge in periods of good surface flow. However, ecological dimension of sustainability used to equate recharge equal to abstractions is what some authors consider the renewable yield. Nevertheless, the EU WFD introduces a more complex concept, the achievement of good ecological health of aquatic ecosystems, which depends on the available yield. This new concept, not fully applied yet, may imply significantly lower amount of groundwater allowed abstraction than the renewable yield.

Literature, such as Moench (2003) and Shah *et al.* (2007), and examples in Indonesia, China, USA (Ogallala), Spain, and Mexico, seem to indicate that *de facto* development (e.g., in terms of agricultural productivity) is prioritized over longer-term ecological groundwater sustainability. In Indonesia, regulation of groundwater is perceived to be at cross-purposes with industrial growth. In China, pure economic growth is

Box 5 Participatory groundwater monitoring in China. By Simon Howarth, based on Gansu under the UK DFID-funded Water Resources Demand Management Assistance Project.

Simple monitoring by villages of the volumes of water abstracted and of the groundwater level is valuable for developing an understanding of groundwater. This has three classes of benefit: promoting awareness of groundwater, which is commonly less well understood than surface water; this can profitably be incorporated into school curricula so that children become aware of water issues:

- Enabling WUAs to manage their resource better, and understand why restrictions are being introduced.
- Providing data to supplement formal data-collection programs by government hydrology bureaus.
- Involving communities increases ownership of the concepts and reduces asymmetry of information. The information can easily be published on village notice boards.

seen as a central part of development policy, in the policymakers' mindset toward pure economic accumulation. In Mexico, continued overdraft in Hermosillo is driven by problems of reconciling economic efficiency and ecological sustainability (e.g., problem of saltwater intrusion), and where huge economic returns derived from groundwater in terms of income create an incentive to search for additional water resources through surface-water transfer (Escolero and Martinez, 2007). This is similar to the case in Southeast of Spain, in the Murcia and Almeria regions, where the intensive use of aquifers for highly productive agriculture started to drive national water policy to transfer water to this area, because of the political difficulty of controlling this intensive but highly profitable intensive groundwater use (Llamas and Martínez-Santos, 2005; Llamas and Martínez-Cortina, 2009).

The strength of negative externalities depends partly on aquifer characteristics (e.g., transmissivity storage), spacing of wells, and connection to surface water. These questions over preferred criteria as against competing uses go to the heart of the meaning of groundwater sustainability and to what extent this is feasible or, indeed, it is perceived as feasible or possible due to the institutional path dependencies of choices made in the past.

1.07.6.1 Groundwater Management Externalities

In groundwater, externalities are the rule rather than the exception. The real issue is not the elimination of externalities (usually physically impossible) but rather, whether the impacts on third parties are excessive according to certain criteria. The relevant policy question is whether these externalities are considered excessive and for which criteria they are used or prioritized: economic efficiency, groundwater sustainability, or social equity. In the EU, according to the WFD, the goal is to restore the ecosystems to a good ecological status unless the cost of this recovery is economically or socially very difficult. In this case, member states have to report in detail to the European Commission on the extenuating circumstance to ask for derogations. This is a process currently underway, but it appears that countries are anticipating the difficulty of complying with the WFD by 2015.

Here, we summarize five indicators of typical problems of intensively used aquifers, but it is important to mention that these are sometimes used inadequately (Table 5).

1.07.6.1.1 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 to excessive abstraction of groundwater in relation to average natural recharge. Other causes may be responsible, such as return flows 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 (Custodio, 2002). For instance, the groundwater-quality degradation in many Central and Northern European countries is related to intensive rainfed 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. Moreover, in this case, the relevance of saline-water

Table 5 Typology of groundwater externalities

Type of externality	*Externality*	*Explanation*
Environmental	Affected ecosystems	Damage to ecosystems or surface-water features dependent on discharge from aquifers; spring-flow reduction
Socioeconomic	Pumping costs externality	Increase in pumping costs due to drop in aquifer levels, these costs can be fixed or marginal costs that one user imposes on another when pumping lower from a water level, external costs can be reduced by selecting a better well location
	Potential loss of agricultural land	Due to salinization or marine intrusion
	Groundwater quality externalities	Water quality varies with depth (normally more saline with more depth) and also location specific, for example, aquifer located in coastal areas and islands (e.g., saltwater intrusion), the spread of low-quality water within an aquifer
		Water pollution due to intensive agriculture, for example, with nitrates and/or pesticides
	Land subsidence	Decrease in pore-water pressure, related to amount of groundwater withdrawn
	Aquifer compaction	Aquifer compaction with possible resultant reduction in aquifer storage capacity
	Social externalities	For example, when small farmers cannot adjust to the drop in aquifer levels
Option and intertemporal externalities	Increased scarcity value	Increased opportunity cost due to an increase in scarcity value due to intensive use
	Buffer value of a groundwater stock	Reduction to buffer value provided by groundwater against drought
	Intertemporal externalities	Diminished economic activity in the area, reduced water availability for other water-right holders, and reduced land-use options for future inhabitants

intrusion depends not only on the amount of the abstraction in relation to the natural groundwater recharge, but also on well-field location and design, and 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. It appears, for example, that the last half-century seawater intrusion has been well controlled in the coastal plains of Orange County (California) and Israel.

1.07.6.1.2 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, and others. In Bangkok (Thailand), parts of the city were sinking at a rate of 10 cm yr^{-1}, with an increased risk of flooding and damage to roads and buildings.

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. There are a number of well-known examples of land subsidence due to intensive groundwater use. 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. In Tianjin city (China), excessive abstraction of deep groundwater caused a land subsidence of up to 3.0 m (Foster *et al.*, 2004). In Texas, Galveston and adjacent counties have experienced subsidence due to the long-term drop in aquifer levels (Wagner, 2005). Meanwhile, land surfaces in parts of central Arizona have fallen by 20 m in the last 20 years (Howe, 2002).

1.07.6.1.3 Interference with surface water and ecological impacts

There are potential conflicts due to groundwater pumping and its interaction with surface waters and riparian habitat. For example, if there is no source of capture, a well will continue to withdraw water from storage until, either the aquifer is depleted, or the drawdown exceeds the well depth. The groundwater pumped from an aquifer is derived from a decrease in storage in the aquifer, a reduction in previous discharge from the aquifer, an increase in the recharge, or a combination of these changes. Capture may be defined as the increase in recharge plus the decrease in discharge. Examples of capture are: (1) an increase in groundwater recharge from losing streams (or increased infiltration); (2) a decrease in groundwater discharge to gaining streams (or interception of baseflow); and (3) the reduction in the component of evapotranspiration that is derived from the saturated zone. If we restrict the groundwater pumping to the capture, there will no longer be a decrease in storage. Restricting the groundwater withdrawals to what may be captured is a definition of safe yield or sustainable yield for the aquifer. Nevertheless, the definition of safe yield is controversial for some authors. Groundwater mining, that is, when water is abstracted mainly from storage (as discussed in Sections 1.07.2.5 and 1.07.2.6) may also be considered a safe yield, which can be valid under certain conditions. This is because sustainability has to consider different aspects, including economic, ecological, and social, and the real-life difficulties of implementing the concept of sustainability.

Most river systems have a hydrology that is simple in concept but complex in detail. 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 serious water-table depletion (~ 30–40 m). The most alarming consequences of the water-level drop were 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 $Mm^3\,yr^{-1}$ (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 (Llamas and Martínez-Cortina, 2009).

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, especially in the 27 countries of the EU because of the requirements of the WFD. A famous case is the Tablas de Daimiel National Park, a Ramsar site, whose main source of water used to be aquifer discharge before intensive irrigation made the area a recharge area rather than a natural outflow for the aquifer (**Figures 5** and **6**).

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, and 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

Figure 5 The Tablas de Daimiel National Park, October 2008. Photo courtesy: Pedro Zorrilla).

Figure 6 The Tablas de Daimiel National Park, October 2008. (Photo courtesy: Pedro Zorrilla).

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 programs often ignore the need to simulate the natural hydrologic regime of the wetlands, that is, restore not only its form but also its hydrological functions (Bergkamp and Cross, 2007). 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 and Garrido, 2007; Garrido and Llamas, 2009).

1.07.6.2 Groundwater: Future Risks and Opportunities for Management

1.07.6.2.1 Groundwater and climate change

The latest report of the IPCC by Bates *et al.* (2008) only marginally addresses the role groundwater can play in the adaptation or mitigation of the potential negative effects of climate change. The report says "There is a need to improve understanding and modeling of climate changes related to the hydrological cycle at scales relevant to decision making. Information about the water related impacts of climate change is inadequate – especially with respect to water quality, aquatic ecosystems and *groundwater* (added emphasis) – including their socio-economic dimensions" (p. 4).

A detailed analysis of this topic is outside of the scope of this chapter. However, it seems that the role of groundwater development will increase significantly if the pessimistic predictions of the IPCC reports for the arid and semiarid areas become true. These pessimistic forecasts are mainly related to the increase in evaporation rates, due to the increase in temperature, and to the higher drought frequency. As it is shown in this chapter, the evaporation of groundwater from the aquifers is usually irrelevant and one important property of most groundwater reservoirs or aquifers is their resilience to dry spells. The UK Groundwater Forum, for example, studied potential scenarios for groundwater as a result of climate change, and some of these scenarios pointed to a long-term decline in aquifer storage, increased frequency, and severity of groundwater-related floods, mobilization of pollutants due to seasonally high water tables, and saline intrusion due to sea-level rise (Bergkamp and Cross, 2007). However, these predictions have to be contrasted with others across the world, with different climatic regimes.

The Edwards aquifer is one of the largest freshwater aquifers in the USA with a total area of 15 640 km^2, and a primary source of water (agricultural and municipal) for southern Texas (Loaiciga, 2003). It has been identified as one of the areas most vulnerable to complex, nonlinear climate feedbacks, and where potentially aquifer-exploitation strategies must be adapted to climate variability. In fact, when climate and groundwater-use changes are considered together, the role of groundwater use over climate prevails, that is, changes in groundwater use due to population growth and changes in land use or economic preferences may cause more profound aquifer impacts than those associated with global warming. For example, climate change in San Marcos springs could increase spring flow relative to the base condition by 17%, while the groundwater use alone in the year 2050 can reduce springwater flow by 22%, that is, groundwater use dominates over climate change. Therefore, the primary threat to the Edwards aquifer comes from the rise in groundwater use associated with predicted growth not from climate change. The latter in fact would increase spring flow in the study area (Loaiciga, 2003).

There is also increased understanding that the vegetation response to climate change could either increase or decrease recharge. Climate change in fact could increase aquifer recharge according to recent simulation models, although highly dependent on geological settings (Green *et al.*, 2007). In study areas characterized by sandy top soils and large interconnected aquifers, groundwater levels rose significantly. In Australia, simulations of twice the existing CO_2 led to significant changes in the rate of groundwater recharge in Mediterranean and subtropical climates. Water recharged from 34% slower to 119% faster in the Mediterranean climate and from 74% to 500% faster in the subtropical climate. Opportunity for decrease exists but the general trend is toward increase in recharge (Green *et al.*, 2007).

In the context of groundwater and climate change, it is important to note the spatial and timescales of aquifer and climate systems. First, aquifers often operate in scales of much less than 10^6 km^2 and in a great majority of cases, groundwater basin encloses areas of 10^4 km^2, while global climate models (GCMs) operate on 200 km × 200 km (4.10^4 km^2) and regional climate models (RCMs) with resolutions of the order of 20 km × 20 km (Loaiciga, 2003); therefore, the scales do not necessarily match up. Second, the nature of medium- and long-term climate predictions and the contrast between flood-impact studies with temporal scale from minutes to days, and drought impact studies precipitation and temperature temporal scale from days to years depending on inter- and intra-seasonal variation. These uncertainties in both space and time make predictions, in terms of climate change and variability, difficult; what is clear is that in this context, aquifers have the natural capacity to act as climate regulators, that is, buffering capacity for drought and floods.

1.07.6.2.2 Future management issues

There are a number of future management issues that become apparent and whose importance is increasing. One of the main issues is the joint use of surface and groundwater and the linkages between water quality and water quantity. There are good examples across the world of successful joint management of surface and groundwater that play to the strengths and weaknesses of both. For example, the case of Israel, and the case of the cities such as Barcelona (Spain) and Phoenix (Arizona), which rely on groundwater supplies as a strategic resource in times of drought. However, there are also examples on lack of joint management or in fact disjointed management, that is, when poor groundwater management leads to surface-water transfers to compensate. This is the case, for example, of lobbies pushing for surface-water transfers or the authorities pushed to find additional water supplies due to groundwater-quality problems.

For example, both in London and in the coastal metropolitan area in Barcelona, there is a problem with aquifer rebound, and these polluted groundwater resources signify that it is easier to invest on large desalination plants to augment supply, since the costs of cleaning polluted groundwater are prohibitive. Meanwhile, in both Spain and Mexico, pressure builds in areas where aquifers are intensively used to bring surface-water supplies. The city of Hermosillo (Mexico) is heavily dependent on groundwater for its level of productivity and the residents of the area have been lobbying the Mexican government for a large water transfer that would bring water from the State of Sinaloa 485 km away (*Plan Hidráulico del Noroeste*). As groundwater storage continued to fall, the rising shadow (marginal price) value for groundwater rose. This shadow value can indicate what would be the optimum timing for the water transfer to occur, which would be when the values of the transferred water are lower (US\$ 0.0222 m^{-3}) than the shadow groundwater value price (US\$ 0.0224 m^{-3}). This highlights that the ideal time to build the project would be in the 29th year. This indicates that if the water project was built at the current costs of groundwater abstraction, it would have been built prematurely (Howe, 2002). This, however, is only if one applies economic-efficiency criteria. If other criteria (such as environmental sustainability) were used, this would call for a much quicker solution (e.g., due to the external costs of saltwater intrusion). In Spain, lack of groundwater management in the southern Mediterranean coastal belt, triggered in large, the conflict to divert water from the Ebro river in the north to help compensate for rapidly depleting aquifers (Llamas and Martínez Santos, 2005). Water agencies tend to build projects far in advance of their justifiable need on pure economic terms (Howe, 2002), and often fail to capitalize on the synergy between effective joint surface and groundwater use, which by definition implies the management of both.

Restrictions on groundwater allocations are a direct loss attributed to decision makers and thus unpopular, whereas a loss of income due to over-abstraction is a probabilistic loss. Therefore, it is politically rational for decision makers to prefer users to continue pumping than to take the (unpopular) decision to cut allocations and instead opt for the politically more popular water transfers. There are very few systems of explicit conjunctive management. Until the 1940s, one main reason was the lack of understanding of hydrogeological knowledge and therefore the poorly developed model of surface and groundwater interaction. There are recent examples of regulatory innovations to deal with groundwater due to a much clearer understanding and a capacity to play to the strengths of surface and groundwater joint use – for example, in Colorado, where tributatory groundwater rights have been incorporated into the prior appropriation (priority) doctrine of water law, which in theory could preclude conjunctive management since groundwater tends to be junior rights compared to surface senior water rights (Howe, 2002).

1.07.6.2.3 Groundwater: Issues of fit and political windows of opportunity

There is increasing evidence of the institutional diversity of groundwater user groups, from landowners associations, local landowner cooperatives, natural resource cooperatives, and water districts in Texas, to tube-well cooperatives in India, to agricultural transformation societies, and both public and private user communities in Spain. There is also some evidence that spikes in groundwater scarcity can trigger organization of these groundwater-user groups and in fact provide a window of opportunity for collective action, for example, drought can act as a motivator for self-organization or increased competition for groundwater resources among users. Drought intensifies conflicts and yet stimulates short-term and long-term efforts to modify rules and procedures for regulating rights.

Scarcity value encourages the spontaneous creation of cooperative groups as groundwater becomes scarcer and groundwater economic value raises the cooperative model of groundwater pumping. Increasingly, it is appreciated that issues such as droughts rather than perceived as short-term crises are in fact also an opportunity for institutional change and adaptation. These are windows of opportunity for political action and social change since most stakeholders are receptive to the need for effective responses – that is, they provide opportunities for institutional innovation. Strategically, choices can be made on the value of groundwater resources and prioritization of use, for example, for domestic water supply while at the same time providing incentives for economic transition.

In addition, there is increased recognition on the importance of context and that there are no ideal aquifer-management regimes; rather governance arrangement. In particular groundwater basins are highly individualized, there is no single best-practice model for groundwater management; rather there are context-specific, multiple management scenarios which have to be negotiated. Institutional solutions that are viable in a particular context have to be framed within the inherent limitations of scientific knowledge, and centered on core objectives rather than specific groundwater parameters (Moench, 2007). That is, focus on livelihoods and environmental values rather than sustainable yield, which by itself is increasingly a contested concept (Llamas and Garrido, 2007). Responses have to be suitable for specific socioecological context rather than politically correct integrated management, which sometimes can be too rigid or overtly focused on technical ideals. Management in groundwater has to be pragmatic because timescales in the case of groundwater vary, on the one hand between the resource itself, which has an in-built lag, and requires a long-term perspective, and groundwater users themselves who often operate on a much shorter timeframe, normally driven by economic development. These two (long and short-term timescales) somehow have to be synchronized. The stabilization of the North China plain aquifer will be a long-term process when one considers that in 1988 the Hai river basin exceeded recharge by some 8800 $Mm^3 yr^{-1}$, and an average recharge deficit of 40–90 $mm yr^{-1}$ (Foster *et al.*, 2004).

As discussed earlier in the chapter, at times it might be rational to use an aquifer intensively due to the associated socioeconomic and generational changes, which in time might decouple livelihoods from groundwater dependence, for example, through education or a more diversified economy.

Issues of spatial scale and fit as raised earlier are relevant since often human institutions do not match groundwater boundaries. In the case of groundwater, in many cases, it is the individual, micro-level which drives groundwater use as the aggregate demand of thousands of groundwater users. To this, one has to add the high levels of uncertainty, which are an integral part of groundwater management, possibly magnified due to climate variability and change. For groundwater institutions, these limitations are inherent rather than situational (Moench, 2007).

1.07.7 Conclusion

Suggestions or recommendations to achieve sustainable and ethical groundwater management have been presented in many conferences. The Alicante Declaration (Ragone and Llamas, 2006) is one of the recent ones. We include here what we consider relevant aspects:

1. There is no doubt that agriculture is the main blue and green water consumer. The virtual water-trade analysis

seems to show that in many countries the motto 'more crops and jobs per drop' is changing to 'more cash and nature per drop'.

2. Usually hydrological and economic productivity of groundwater irrigation is significantly greater than the corresponding productivities of surface-water irrigation. Detailed analyses on this aspect in different climates and countries should be done to confirm or reject these preliminary data.
3. The spectacular increase in groundwater use that has occurred in the last five or six decades can be classified as a silent revolution because it has taken place with scarce planning and control by governmental agencies. This is the main cause of some observed negative impacts, which could be avoided or mitigated with adequate groundwater management.
4. It is extremely difficult to provide a general guide to good groundwater management, 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.
5. 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.
6. 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.
7. Appropriate groundwater management requires a significant degree of trust among stakeholders. This implies that groundwater data should be transparent and widely available (e.g., via the Internet). In addition, the system should be able to punish those who act against the general interest.

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