CHAPTER 14

Intensive groundwater development: A water cycle transformation, a social revolution, a management challenge

Emilio Custodio

Royal Academy of Sciences of Spain; Department of Geo-Engineering and Foundation International Centre for Groundwater Hydrology, Technical University of Catalonia (UPC, Barcelona, Spain)

ABSTRACT: Groundwater is the slow path of the water cycle. It is generally associated to a very large water storage relative to recharge/discharge annual flows, which means generally a long average water turnover time, quite delayed hydraulic responses and very retarded chemical water composition changes, especially for large aquifer systems. This behaviour is often beyond the normal human temporal experience. Groundwater development needs adequate drilling and pumping technology, as well as relatively cheap and easy-to-obtain energy. This has not been possible until mid the 20th century. Before that time most aquifers were close to natural conditions and groundwater use was mainly from winning natural outflows. Between the 1930s and the 1950s an exponential groundwater development took place in some countries, mostly in arid and semi-arid areas. In many developing countries this happened between the 1970s and 1980s, or later. This has produced and is producing large economic and social benefits with only very few exceptions. However, intensive groundwater development modifies groundwater flow in aquifer systems, as well as the relationships with surface water. The consequences are groundwater level drawdown, discharge decrease to rivers, springs and wetlands, chemical changes – which is an important issue and a future growing challenge–, and also economic, environmental and social costs. Also, aquifer development is generally associated to a rather long transient evolution that may involve progressive water level drawdown and increasing costs, up to a new steady situation. This should be compensated by benefits from socio-economic development, as is in most cases, with only a few exceptions, but attention is needed to assure this is in this way and will continue to be. Intensive aquifer development has been produced mostly by individual and small groups, especially farmers, often without public funding. This is like a social *silent revolution*. Since groundwater is a limited resource, in order to avoid the problems associated to unrestricted access, management is needed to move towards sustainable development. The complexity of dealing with a very large number of stakeholders over an extended territory needs a combination of government and public management institutions, regulations and means, and stakeholders' involvement and co-responsibility. This is a current challenge due to short experience, and the need to create knowledge, data, and awareness on the need to manage a valuable and essential common asset. Collective stakeholders' institutions, tailored to the characteristics of each local situation, seem an effective component. Sustainable use is possible, although under different economic and social conditions as those existing when development started, and inside integrated water resources management plans, agreed by all interested parts.

Keywords: *groundwater, intensive development, management, collective institutions, silent revolution*

1 GROUNDWATER: THE SMOOTHER OF THE WATER CYCLE

Groundwater, which is an essential branch of the Earth's water cycle, is still poorly known by a large part of many water professionals, the population, and the media. It often suffers from knowledge errors and deviated principles, or *hydromyths* (Custodio, 2003; Custodio & Llamas, Insert 1. Key groundwater characteristics.

- Essential part of the Earth's water cycle
- Large storage to flow ratio
- Long turnover times: 10s to 1000s of years
- Recharge and storage distributed over the territory
- Closely linked to surface water
- Delayed response: 10s to 1000s of years
- Important role in natural processes and environmental services to humans
- Key source for human water needs through:
  - Tapping natural outflows
  - Using groundwater-sustained vegetation and fauna
  - Pumping and drainage

1997). Groundwater is not directly perceived or recognized by lay people, although it shows up as springs and stream base flow and as contributions to permanent lakes and wetlands.

Groundwater is associated with a large water storage in the pores, fissures and voids of the terrain. It flows slowly from recharge (inflow) areas to discharge (outflow) areas. In recharge areas, often extensive ones, rain, snowmelt, runoff and losing streams – besides anthropic-generated irrigation return flows and leakages – infiltrate and increase water storage in the ground. Discharge areas can be both diffuse and concentrated, and they appear in a small part of the territory as springs, along streams, at the sea and lakes coasts, as more or less permanent wetland areas and lagoons, and as shallow water tables. Discharge means a depletion of storage (reserves) that is continuously or discontinuously compensated by recharge. The large water storage smoothes out recharge variability – which may be almost constant for deep water tables – and produces a discharge that is much less variable than recharge.

Average renewal time of water in aquifers is typically from several years in small, highly permeable formations, up to many millennia in large ones; especially in deep, confined aquifer systems (see Insert 1). This means a slow and delayed aquifer response to external actions (extractions, land use modifications, surface water alteration, climate and global changes) that is beyond the common experience of human beings, which is at the scale of daily to monthly, at most a few years scale.

What has been commented above refers to water flow and storage, but it is also true for water chemical composition, a key issue as well, whose changes may be even slower and more complex. Salinity and chemical composition is the result of the evaporative concentration of rainfall diffuse recharge, interaction with soil gas and reaction with ground materials. The event related and seasonal surface water chemical composition variability, to which people are used to, for groundwater is highly smoothed out and it can even disappear. However at the outflow point, independent of whether it is natural or artificial, seasonal and interannual, the mixing of variable groundwaters with different origins and characteristics is in fact possible, which may be indirectly related to seasonality.

Poor hydrodynamical and physico-chemical knowledge by humans has not been a deterrent to groundwater development; the main deterrents so far have been available technology and energy sources to extract the water. However, development without knowledge that is good-enough on groundwater systems has often led to serious interference problems with Nature and with other groundwater users, other water resources, and even with land surface conditions. There are serious possible water quality problems. The current and common poor management of aquifers, and the associated water quantity and quality problems, and increasing costs, that are being observed in many areas of the world can be explained by the multiple developers, who often have adequate technology for obtaining groundwater but poor knowledge of the resource, compounded by a water administration institution, that often is unprepared, unstaffed and uninterested. Groundwater problems are often highlighted by the media, without analysing the actual causes. However, groundwater is a key, cheap and reliable freshwater resource (Burke & Moench, 2000; Custodio, 2005b; Bocanegra *et al.*, 2005), which has been and will continue to be essential to the local economy and for social development. This is rarely mentioned. Serious aquifer development failures are rare and local, mostly reflecting very extreme situations of lack of water resources (e.g. Sana'a in Yemen) or serious contamination. In water scarce areas brackish groundwater is currently becoming a water resource through modern membrane technology desalinization, provided the residual brines produced can be safely disposed, and the cost can be afforded.

2 GROUNDWATER AND AQUIFERS

Groundwater is held in porous and fissured geological formations that are called aquifers when water can be abstracted at rates that allow supplying local needs, or when there are measurable discharge flows to rivers, lakes, coastal areas and wetlands. When water can be only abstracted with small rates, the geological formation is called an aquitard. An aquifer system consists of aquifers and aquitards that may exchange quite large groundwater quantities due to their large contact areas. Aquifers and aquifer systems exchange water with surface water: rivers, lakes, the sea and wetlands, with other groundwater systems, feeding springs, wetlands and river baseflows.

Groundwater is not subjected to significant evaporation to the atmosphere by solar radiation, except for shallow water tables in arid and semi-arid areas, or when transpired by phreatophyte plants.

In what follows surface areas will be expressed in km^2 (10^6 m^2) and in ha (hectares, $10^4 m^2$), and water volumes in hm^3 (million cubic meters, 10^6 m^3) and in km^3 (cubic kilometers, 10^9 m^3). Time is generally given in years (yr).

Aquifer characteristics and circumstances are highly variable. Their size vary from very local, a few km^2, to very large aquifers, of continental size, often across regional and national boundaries. 1 m^2 of land may contain free-water depths from a few up to some tens and even a few hundreds of meters, depending on aquifer thickness and porosity, although only a fraction (0.1 to 0.3) can be extracted due to capillary retention, and at least some meters of saturated thickness has to be left to allow well functioning. Thus, the large figures of aquifer reserves given in many reports may be misleading and they should be changed to usable reserves under specified conditions (well depth, economic cost, water quality degradation with depth or in some areas of the aquifer system, . . .). Renewable resources may vary from almost zero (in very arid lands) up to more than 0.5 m/yr (0.5 m^3/m^2/yr) in rainy areas with slightly retentive soils and poor vegetation cover.

World aquifers have been mapped in WHYMAP (2004) at the 1:50,000 scale, with an associated Geographical Information System (GIS) for downscaled details. The large transboundary aquifers have been mapped in WHYMAP (2006) and IGRAC (2009).

Table 1 shows a selection of the world's largest aquifer systems. Some have quite important renewable resources, at least on part of the territory (see Box 1 for the Guaraní aquifer system). Others are in arid areas and -under current climatic conditions- their renewable resources are very small, but contain huge developable water reserves that have accumulated for millennia.

Small aquifers are also important, since they may provide key local water resources. Besides they may be ecologically significant and provide a manageable flow and storage reserve that may be very important for dealing with seasonality and short-term inter-annual fluctuations, especially when integrated into the water resource system. An example are the small, highly permeable, largely river-recharged aquifers of the Lower Llobregat (about 120 km^2), that are key pieces for the urban and industrial water supply of the Barcelona area (Catalonia, Spain) (see Box 2). Examples like these are very numerous around the world. They have a special significance in densely populated coastal areas, often highly developed for tourism, and with important intensive agricultural developments around (Custodio, 2010; Bocanegra *et al.*, 2010). Many of them, after initial stages of deterioration, are moving towards sustainable development through management, as explained later on.

Table 1. Some of the largest aquifer systems of the world (data derived from WHYMAP, 2006; Foster & Loucks, 2006; Margat, 2008; IGRAC, 2009; UNESCO, 2007; other sources). Uncertain extent if bracketed.

Aquifer/Aquifer system	Type	Countries	Extension (km^2)
Northern Great Plains	C	Canada, USA (N)	[500,000]
Ogallala (High Plains)	B	USA (central)	450,000
Gulf Coast Plains	C	USA, Mexico	1,150,000
W Amazonia (Solimões – Alter do Chão)	A/B	Brazil, (Peru, Bolivia, Ecuador)	[950,000]
Yrendá – Toba – Tarijeño	B	Paraguay, Argentina, Bolivia	[500,000]
Guaraní	A	Brazil, Paraguay, Argentina, Uruguay	1,200,000
La Pampa	C	Argentina (central)	[200,000]
NW Sahara + Murzuk	A	Algeria, Libya, Tunisia, Niger	1,500,000
Senegal – Mauritanian Basin	A/B	Mauritania, Senegal, Gambia, Guinea-Bissau	300,000
Nubian Sandstones	A	Chad, Egypt, Libya, Sudan	2,200,000
Iullemeden – Irhaser	B	Mali, Niger, Nigeria, Algeria	635,000
Chad Basin	A/B	Niger, Nigeria, Chad, Cameroon	1,900,000
Northern Kalahari	B	Angola, Botswana, Namibia, Zambia, Zimbabwe	[700,000]
Karoo Basin	B	South Africa	600,000
Arabian Platform	C	Iraq, Jordan, Saudi Arabia, Syria, Yemen, Bahrain, Kuwait, Oman, Qatar	>2,000,000
Central Europe Lowland Plains	C	From the Netherlands to Russia	[3,000,000]
Central Asia	C	Kazakhstan, Kyrgyzstan, Uzbekistan, Tajikistan	660,000
Indus Plain	B	Pakistan	320,000
Ganges – Brahmaputra Plain	B	Bangladesh, India	600,000
New Guinea	B/C	Indonesia, Papua New Guinea	870,000
Great Artesian Basin	A	Australia	1,700,000

Types:
A: Largely confined, outcropping at the boundaries
B: More or less continuous, largely outcropping aquifer
C: Compound of a series of smaller aquifers

Box 1. The Guaraní aquifer, South America

The Guaraní aquifer is part of the 1,600,000 km^2 Paraná sedimentary basin. It covers an area recently evaluated to have 1,200,000 km^2 (Rebouças & Amore, 2002; Kemper *et al.*, 2003), mostly in Brazil (70%), and extending into Argentina (19%), Paraguay (6%), and Uruguay (5%). The aquifer crops out over 13% of its surface area, mostly in Brazil, and contains freshwater. It is recharged directly through rain infiltration, and indirectly through leakage from upper formations: $20 + 140 = 160$ km^3/yr of freshwater.

The much larger confined area (70%) contains most of the freshwater reserves, although their quality degrades progressively, and presents salinity, sulphate and fluoride excesses due to the very slow flow rate. The aquifer thickness goes from almost nil to more than 800 m toward the southern and southwestern areas, with an average value of 250 m. The confining beds include the huge Paraná basalt lava flows –an aquitard yielding moderate quantities of groundwater – and the Bauru aquifer. Depths to the Guaraní aquifer varies from a few metres to up to 1,800 m. Water reserves are about 45,000 km^3, but only a small fraction is sustainably developable. The area containing warm water, mostly related to their depth and very slow flow, is assumed to be close to 400,000 km^2, about 30,000 km^2 of them with an expected temperature of more than 60°C, up to 70°C. Warm water is currently mined in Argentina and Uruguay for spas, mostly as brackish to saline water (Tujchneider *et al*., 2007).

Freshwater development from the Guaraní aquifer is currently intensive in some areas of Brazil (e.g. São Paulo and Curitiba), with local cumulative drawdowns up to 120 m. A GEF (United Nations Global Environmental Facility) project has been carried out recently (2004–2008) by the World Bank, to advance towards the management of this huge transboundary groundwater reserve through improved, shared knowledge, and means for technical, administrative and political coordination, fostering international and national entities to be involved in the job.

This is an attempt to try to deal with possible future problems at the time that existing regional and local problems are addressed, including the important general economic and social components.

Box 2. Managed small aquifers: the Lower Llobregat aquifers (Barcelona, Catalonia, Spain).

The Lower Llobregat aquifer system, close to Barcelona (Catalonia, Spain), is a small, about 120 km^2, river valley filled with gravels that continues into a delta formation formed by an Upper aquifer and a Deep aquifer separated by an aquitard (Custodio, 2008). The Deep aquifer opens to the sea bottom at about 4 km offshore, at about 120 m depth. Groundwater dynamic storage, mostly in the valley, is up to about 200 km^3. Currently, recharge is largely from infiltration from the Llobregat river, canal irrigated areas, and inflow from the mountain sides. There is intensive agriculture, largely supplied through surface water canals, and partly by using groundwater. The large urban and industrial areas of the metropolitan area of Barcelona are partly on the aquifer. Groundwater use started late in the 19th century through wells pumped with steam engines for urban supply, and many flowing wells in the delta for town and rural supply, and later on for industrial use. Intensive industrial use started in the 1920s and especially in the 1940s, peaking in the 1970s, jointly with urban supply, up to 130 hm^3/yr. After this moment, extraction has been decreasing down to the current 60 hm^3/yr. This is due to management efforts (Box 16), as well as a changing industrial pattern, which has evolved from high water demanding factories to less water demanding ones. Extraction for supply to the Barcelona area in the 1960s changed from continuous to complementary, and during droughts and emergencies, when local and imported treated river water was made available. The small groundwater reserve relative to annual extraction was a concern in dry summers and drought periods, so the Barcelona's Water Supply Company started enhanced river infiltration in 1948, and occasional artificial recharge of treated river water through wells in 1969.

The intensive aquifer development produced low groundwater levels in the whole Deep aquifer, below sea level, starting a serious seawater intrusion, first detected in 1965. Many salinized wells were abandoned but others continued to be operated for industrial cooling, thus helping to slow the seawater intrusion process. The current extraction decrease and the increased artificial recharge are improving the situation. Starting in 2007 an injection well barrier of deeply treated (including reverse osmosis) municipal waste water is operating to successfully control and redress seawater intrusion (Niñerola *et al*., 2009). Increased artificial water recharge through infiltration basins in the river valley is also under way. Currently, groundwater levels are rather high, available storage for droughts and emergencies has been increased, and groundwater quality is improving.

Upstream from this aquifer system there are two small, rather isolated, gravel-filled river tracts, the *Cubeta d'Abrera* and the *Cubeta de Sant Andreu de la Barca*. Currently they supply industrial settlements and provide water to the towns around. Groundwater resources depend heavily on river water infiltration and may suffer reserve exhaustion at the end of the summer season. Exhausted reserves recover when river flow increases. These aquifers are used as 15 to 20 hm^3 water reservoirs due to their high transmissivity. Management includes artificial recharge of river water through basins.

Small aquifers may be key pieces and their use can be made sustainable through management. There are noticeable costs involved in management but benefits compensate for these costs.

3 GROUNDWATER DEVELOPMENT: HISTORICAL EVOLUTION AND INTENSIVE USE

Groundwater has been traditionally developed from its natural discharge by tapping springs or deriving stream baseflow, or by excavating shallow wells in high water-table areas and using manual or simple mechanical pumping devices. At most this development had a small influence in natural groundwater flow and on its chemical composition. Only in arid areas have humans devised other more sophisticated groundwater winning methods such as water galleries –the well known *khanats* (or other denominations like *foggaras*, *viajes de agua*, galleries), in Persia, Yemen, North Africa, the eastern Iberian Peninsula, and the Spanish archipelagos– or deep excavated wells. The Bible mentions some in the eastern Mediterranean area. All of them were costly and slow to construct, expected to endure for generations. In some cases these were complemented with works to increase aquifer recharge by retaining storm flow in creeks by means of transversal works, or by deriving them to flat areas to favour infiltration. Examples can be found in the Middle East, the Atlas, eastern Canary Islands, and the Iberian Peninsula. Even in these cases, aquifer conditions remained close to natural.

Important changes did not appear until the mid 18th century, when steam-driven pumps were used to dewater mines, as done in England and Wales. In the 19th century this technology was applied for town and factory water supply in some urban and industrial areas by means of quite expensive, large diameter, hand or mechanically excavated wells, down to at least a few meters below the water table, or penetrating through low permeability confining beds. In these shaft-wells, water-proof chambers to hold the bulky piston pumping machinery were installed and operated by means of steam engines. Some are preserved as museums.

In the mid 19th century, small diameter, cased deep-bore technology was made available in Europe, partly inspired by old methods developed in China. This allowed the construction of flowing wells under favourable hydrogeological conditions. A first success was the Rue de Grenelle well in Paris, in 1841. This technology rapidly expanded to other places, with variable success, and helped to solve acute town water-supply problems. Prat de Llobregat, near Barcelona, is one of the examples; late in the 19th century this was a water-supply revolution for the village and farmhouses, and later on fostered an important industrial development.

In Madrid, the attempts to drill flowing wells in the mid second part of the 19th century failed due to an erroneous hydrological conceptual model that was assumed to be similar to that of Paris. After Llamas (1983), this failure discouraged the centralized public Spanish administration to consider groundwater as a reliable water resource. The consequence was that groundwater was not taken into account in government-financed projects for more than a century. This was in spite of the success in other areas of Spain, which were mostly promoted through private funding.

Many flowing wells decreased or soon ceased to flow due to what is now a well-known hydrodynamical evolution of confined aquifers. Flowing wells were substituted by pumping from drilled wells once the first mechanical means were available. Development was accelerated, following progress in hydrogeological science (de Vries, 2007). Groundwater abstraction was made possible through the submergible centrifugal pump technology. This went on in parallel with easy and relatively cheap energy availability by means of internal combustion engines coupled to electricity generators, and afterwards through the electricity network, as is currently the case, except in remote locations or in poorly developed areas.

The combination of easily available drilling technology, pumping machinery, and energy, led to a rapid expansion of groundwater development in many areas of the world, often exponentially at the early stages (Shah *et al.*, 2007). This is what happened in many aquifers and is what currently happens in many developing countries.

Intensive groundwater development means a water extraction that significantly modifies aquifer natural flow (Llamas & Custodio, 2003; Sahuquillo *et al.*, 2004; Custodio *et al.*, 2005; Llamas & Garrido, 2007). This situation comes from small early developments. Then, the benefits derived from groundwater development encourage accelerated development. Overexploitation, and other similar designations, are often used, but they are poorly defined concepts, corrupted by careless use – alike to what happened with the concept of sustainability–, often with poor understanding of hydrological processes and putting the accent on negative aspects (Custodio, 2002; Hernández-Mora *et al.*, 2001; Collin & Margat, 1993), thus downplaying the often quite important, associated benefits of aquifer development, and its role on the assumed world water crisis (Mukherji, 2006).

The starting time of intensive aquifer development vary according to the area. This may be as early as the 1910s in central Australia, the 1920s and 1930s in the arid southwestern USA (Texas, Arizona, California) and in Long Island (New York), and also in the volcanic Canary Islands by means of deep shaft-wells and long water galleries. In Europe this happened largely in the 1940s in industrial areas of northern France, Belgium, Germany, western England, and Catalonia and Valencia in eastern Spain, and later on in northern Italy, and in the 1960s and the 1970s in intensively irrigated agricultural and tourist areas along the Mediterranean Sea coast. In Mexico and Brazil intensive development started in the 1950s. Large areas are now under intensive aquifer use in developing countries. Some of the most important ones are in India, northern China, Pakistan and Indonesia (Shah *et al.*, 2000; 2003; Ragone *et al.*, 2007; Margat, 2008). Very large quantities of groundwater are currently extracted in some of these areas as shown in Table 2. The evolution in a few countries is shown in Figure 1.

4 CONSEQUENCES OF LOCAL WATER-CYCLE MODIFICATION THROUGH AQUIFER INTENSIVE DEVELOPMENT

The consequences of the modification of the local water-cycle through intensive aquifer development can be summarized by considering the different involved aspects (Custodio & Cardoso da Silva, 2008; Custodio, 2001a) (see Insert 2), aside from the economic and social implications, which are explained in the next section.

4.1 *Effects on hydrodynamics and water quantity*

Aquifer development has two main aspects: a) winning groundwater flow on its way from recharge to discharge areas; b) depleting groundwater storage. Both of them are closely related and simultaneous. The consequence is water level drawdown, first around the wells and later on over progressively larger areas. Initially groundwater reserves are preferentially used and later on the behaviour evolves toward decreasing aquifer natural discharges (Figure 2). This is a transient process that may last years to centuries, depending on aquifer size and hydraulic characteristics. In many cases the evolution is toward a new steady state if development does not change; then what is abstracted is detracted from natural discharge, discounting possible enhanced natural recharge or artificial recharge.

In extreme situations, when water extraction exceeds recharge, groundwater reserves are progressively depleted. This situation is known as groundwater mining. Examples are given in Box 3 (Ogallala aquifer), Box 4 (Columbia River Basalts), Box 5 (Hermosillo aquifer), and Box 6 (Canary Islands). Groundwater mining is possible due to the large water reserves of aquifers. This is often a common situation in arid and semiarid lands (Foster & Loucks, 2006), where the extracted water is mostly for irrigation. Groundwater mining may be the consequence of unplanned intensive aquifer development, but may be an accepted transient situation, as in the Ogallala aquifer and in south-eastern Spain (Box 7), or a wanted development as in Libya (Box 8) and Saudi Arabia. Some

Table 2. Some examples of aquifer depletion of large aquifers (data modified from Brown, 2002; Foster *et al.*, 2005; other diverse sources).

	Water-table depletion		Use km^3/yr					
Aquifer	m/yr	m (a)	Total	Exc. (b)	Main use	Evolution (c)	Results	Notes
USA (as a whole)		>12	>100		I, U	TM, M	Δ cost, LS	(1)
Ogallala (USA)	up to 3	80	36	10	I	TM	Δ cost, IA	Box 8
Columbia River Basalts (USA)	up to 0.5	>200	–	–	I, U	TM	Δ cost	Box 4
Guanajuato (Mexico)	2–3	–	–	–	I, U	TM	Δ cost, LS	Box 15
Hermosillo (Mexico)	–	>100	0.5	0.05	I	TM	Δ cost, S	Box 5
Sana'a (Yemen)	7	–	0.27	0.22	I, U	U	Δ cost, Ex	(2)
Qatar				–	I, U	TM	S	(3)
Chenaram Plain (NW Iran)	3 up to 8	–	> 50	–	I, U	U	Δ cost	(4)
Indus Plain (India, Pakistan)	–	–	> 50	10	I	U	Diverse	(5)
India (as a whole)	up to 1–3	–	280	30	I	SD, U	Δ cost	(6)
Ganges-Brahmaputra Plains (India, Banglad.)	–	–	> 100	50		SD, TM	Δ cost	
N Plain (China)	0.5–3	35	>100	–	I	SD	Δ cost, IA	(7)
Great Artesian Basin (Australia)	–	80	>100	50	cattle	TM	Less flow	(8)
SE Spain	up to 10	250	0.8	0.5	I	U, TM	Δ cost, S	(9) Box 7
Canary Islands (Spain)	up to 10	300	0.25	0.1	I, U	TM	Δ cost, IA, S	(10) Box 2

Notes:

(1) Country as a whole. Excess extraction in California, Arizona, New Mexico, Texas, Kansas, areas in the southeast, east coast, northwest.

(2) Small but important aquifer. Urban reserves estimated to last some years (NWRA, 2009).

(3) Small area; mostly freshwater lens depletion from 1984. Saline water below.

(4) Seasonal problems.

(5) Start in 1960. Some million wells.

(6) Many states. In some areas extraction rate may double recharge. About 30 million wells (including paddle pumps); they were 11 million in 1960.

(7) About 3.5 million tube-wells.

(8) Flowing wells starting in the 1880s; flows dwindling. About 60% of recharge.

(9) Small carbonate aquifers being depleted. In the whole Spain there are officially 0.5 million wells but other estimations are up to 2 million, including springs for supply (Custodio *et al.*, 2009a).

(10) The three main islands: Gran Canaria, Tenerife and La Palma (Custodio & Cabrera, 2002; 2008).

(a) Total water-table depletion in the more seriously affected areas

(b) Excess refers to storage depletion. This may be the transient hydrodynamic evolution towards a new steady state when extraction is less than recharge (both uncertain), or permanent depletion, or a mix of them. Often this is unclear when there are not enough monitoring and serious studies

(c) SD = starting development; TM = towards management; M = managed; U = uncertain

Main use: I = irrigation; U = urban

Results: Δcost = increasing water cost; IA = irrigation abandonment; LS = land subsidence; S = increasing salinity; Ex = exhaustion and serious local supply problems.

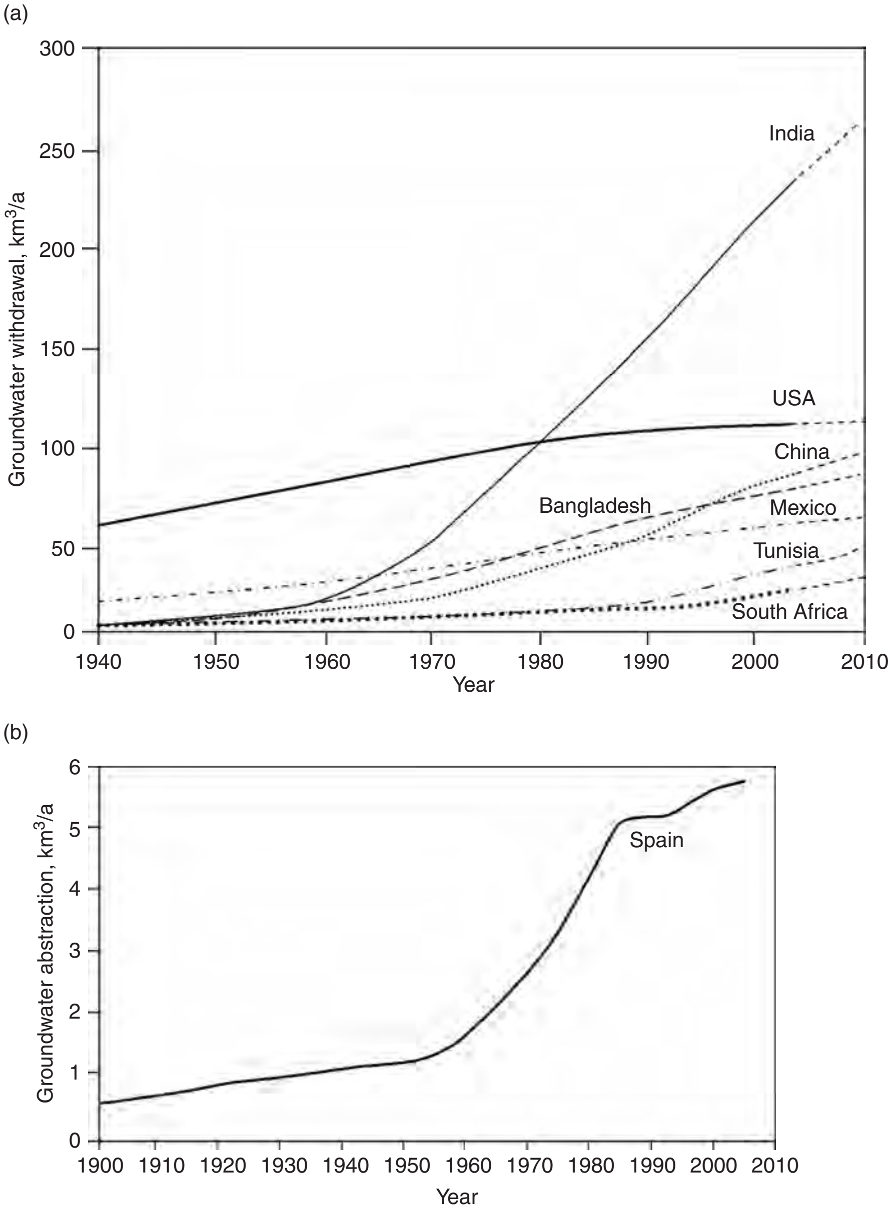


Figure 1. Development of groundwater withdrawal in selected countries.
A) In countries evolving towards stabilization (USA, Mexico) and countries still on the early stages of accelerated development (India, China, Tunisia) (modified from Shah, 2005).
B) Development in Spain since early the 20th century with the accelerated development initiated in the 1950s and the current trend towards stabilization from the 1980s (modified from MIMAM, 2000).

Insert 2. Main consequences of groundwater (intensive) development.

Drawbacks:
- On water quantity (progressive, slow appearance):
  - groundwater level drawdown and storage decrease
  - discharges to springs, rivers and wetlands decrease
  - reduction of phreatophyte and riparian vegetation areas
- On water quality (progressive, slow appearance):
  - penetration of poor quality water, including marine intrusion
  - solutes from the ground (direct, hydrolysis, redox changes)
- On ecological values: decrease of Nature services to humans
- On land surface: subsidence and collapses
- On economic aspects: increasing costs (extraction, water quality treatment)

Benefits:
- Increased freshwater availability
- Taming water resources variability
- Resilience to droughts and catastrophic events
- General low cost (even if progressively increasing)
- Availability over large areas (shorter water transport lines)

examples are included in Table 2. In the large Nubian Aquifer System there is also groundwater mining (Box 9).

Piezometric level drawdown results in a modification of aquifer-river relationships by decreasing and even stopping river baseflow, in which case the stream converts from draining the aquifer to a temporary or permanently recharging situation if there are ephemeral or allochtonous flows (Sophocleous, 2002; 2010). The same can be said for lakes and wetlands (Custodio, 2000a; 2001b). The effect may often be quite clear as spring-flow decreases and even dries out. Lake level may be lowered and groundwater contribution may be lessened with respect to surface water inflow. Groundwater-dependant wetlands tend to reduce their size. This may be conspicuous in semi-arid and arid areas, in which the vegetation cover evolves toward sparse, deep-rooted plants, or just disappear.

In coastal aquifers the marine water-freshwater relationships are modified due to the freshwater head changes relative to seawater level. The result is often a landward salt water wedge penetration into the ground, often a complex situation. Also relationships with already existing saline and brackish water in the aquifer may be changed, often slowly decreasing the depth of these water bodies. Below pumping wells and drainage structures (ditches, drains) the freshwater head decreases and this favours brackish and saline water upconing. This may also affect nearby extraction works, which may be accompanied by a serious saline water disposal problem (Custodio, 2005a).

Wells are often constructed to yield as much groundwater as possible for a given penetration into the aquifer, thus connecting different aquifer layers through the well bore. Consequently the well yields a mixture of water from different depths, with different recharge areas, transit time, and chemical characteristics. The mixing pattern varies with discharge, time, well construction and local aquifer properties.

4.2 *Effects on water chemical composition and quality*

These effects are often less conspicuous and may appear long delayed, but they are by no means less important. They may be the result of water mixing in the abstraction work when different aquifer layers are penetrated and interconnected, even allowing the inflow of brackish or saline water

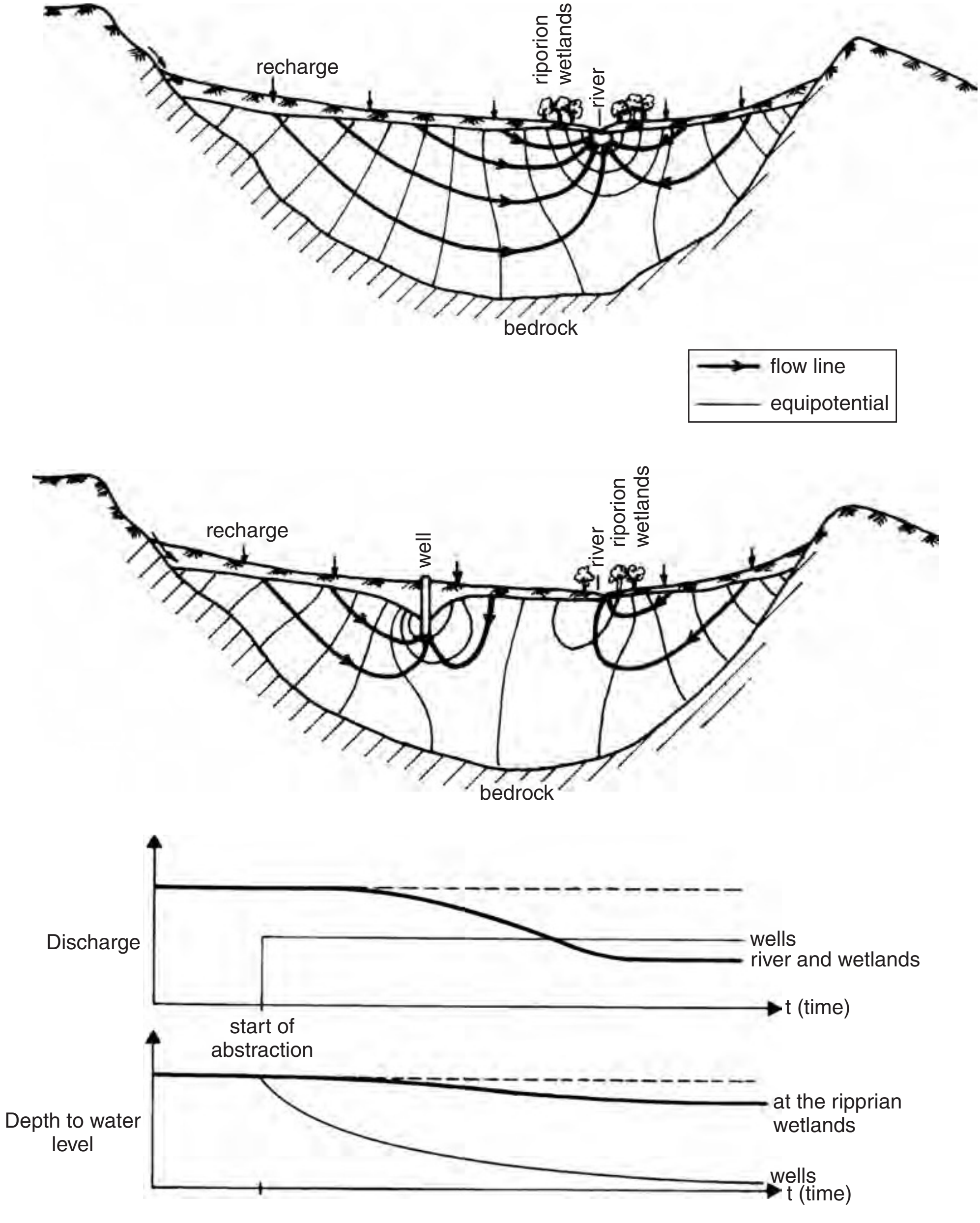


Figure 2. Schematic representation of the groundwater withdrawal effect.
a) Natural situation in a sedimentary basin recharged by rainfall infiltration and main discharge into a river and through the associated riparian vegetation.
b) Long-term effect of intensive groundwater development, in which a generalized water-table drawdown is produced in order to concentrate a large fraction of recharge in to the well area, thus reducing discharge into the river and riparian vegetation area.
c) Schematic evolution of river and riparian wetlands discharge, and of groundwater level at the wells and the riparian wetlands; the time scale may vary from months to centuries depending on aquifer hydraulic characteristics and size. In this case only a fraction of recharge is withdrawn and in the long-term a new steady situation is possible.

already in the aquifer, or the result of development-induced seawater intrusion, and/or upconing. Water-table lowering may induce surface water recharge having a different chemical composition or polluted, and the down-leaching of wastes, fertilizers, agrochemicals, leakage from pipes and tanks, … or may allow the displacement of groundwater in nearby or overimposed aquifers and aquitards (Custodio, 2007).

Box 3. Aquifer intensive development: The Ogallala aquifer, USA.

The Ogallala aquifer is a large unconfined aquifer (450,000 km^2) extending over large, semi-arid areas of the High Plains of Texas and Kansas, and also South Dakota, Wyoming, Nebraska, Colorado, Oklahoma and New Mexico, in Central USA. Saturated thickness is from less than 15 m up to 300 m in some areas in Nebraska. Depth to the water table is 30 to 200 m. The aquifer is intensively exploited, mainly for irrigation, since late in the 19th century, but mostly since the 1950s, when pumping reached up to the current level of about 26 km^3/yr (Dennehy, 2000; McGuire, 2007). The result is a continuous water-table drawdown in Texas and Kansas since average recharge is about 5 to 10 mm/yr and extraction in Kansas was about 110 mm/yr in 1990 and 90 mm/yr in 2000. A total depletion of about 320 km^3 has been produced, out of the 3,600 km^3 remaining storage, although such a large figure is misleading because it assumes that the aquifer can be completely desaturated as a whole, which is not practically feasible, and only a fraction can be extracted. The result is water cost increase and important depletion of groundwater reserves in some areas. In Kansas, in the period 1991–2001 drawdown in critical areas has been 6 m, or 0.6 m/yr, and the saturated thickness has been reduced from 21 to 15 m. Exploitable reserves are reckoned to last about 10 years in some areas, about 25 years or more in other areas, assuming no action is undertaken [http://www.kgs.ku.edu/HighPlains/atlas/]. Reaction is variable according to the State, from little action in Texas to decrease extractions in Kansas. The Kansas Water Plan goals are aimed at stopping or sensibly decreasing water-table drawdown by 2020, and restoring the flow of some streams to natural conditions. This means reducing extractions, even purchasing rights and lands by state agencies, and changing from irrigated to rain-fed agriculture. Problems are important but known in advance, and may be afforded through the richess created by previous and outgoing groundwater depletion, by means of innovative management approaches. The creation of an interstate groundwater commission for the High Plains aquifer is a possibility (Sophocleous, 2010).

This shows how after a long period of depletion there is action for sustainable use.

Box 4. Intensive groundwater development: The Columbia River Basalts aquifer, USA.

The Columbia River Basalt Group is the northern part of the 370,000 km^2 Columbia Lava Plateau of flood basalts with interbedded sediments. The Columbia Basalt Group underlies an area, more than 164,000 km^2, in the States of (western) Idaho, Oregon and Washington (USA), and contains more than 17.4 km^3 of mostly freshwater. The formation consists of more than 300 extensive continental tholeiitic flood-basalt flows, in total some hundred metres thick, up to 3,200 m (Eaton *et al.*, 2009). The N-S Cascade Range, parallel to the Pacific Ocean coast, divides the area in two: the western side is more humid and rather well recharged; the eastern side is semi-arid and poorly recharged, generally less than 50 mm/yr. Groundwater development has been intensive since the 1960s, especially in the eastern side, mostly for agricultural irrigation. In some areas there are up to 7 deep wells per km^2. In Willamette Valley it is reported that there are about 100,000 wells, growing at a rate of 3,000 to 4,000 per year. Groundwater level drawdown of up to 0.5 m/yr is accompanied not only by increased pumping costs (the depth to water level increased from 20 m in 1960 down to 40 m in 2000 in Willamette Valley area) but also a progressive well yield decrease.

Some Groundwater Management Areas have been created to deal with problems and the possible loss of jobs, and in some areas ASR (Aquifer Storage and Recovery) practices have started for urban area supply (Eaton *et al.*, 2009) and for some large agricultural establishments, through injection of treated-to-potable quality impounded surface water, when it is available. The economic analysis shows that ASR technology is affordable.

When effects of intensive use are detrimental, action starts to make aquifer use sustainable.

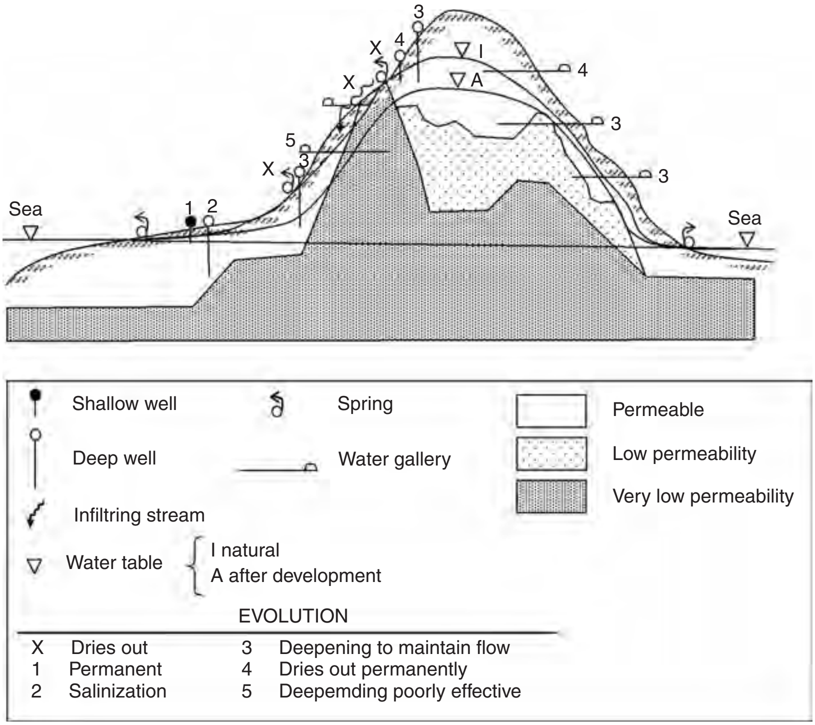
Box 5. Intensive groundwater use: The Hermosillo coastal aquifer, Mexico.

The Hermosillo coastal aquifer underlays a 3,200 km^2 area, Sonora State, northwestern Mexico. This and the close-by Guaymas area, hold important irrigated agricultural areas, the basket of Mexico. These Miocene coastal aquifers, with an open, long shore front, are 150 to 500 m, up to 800 m, thick, although the lower part may be confined by a coastal clay layer up to 400 m thick near the shore but thinning out at about 40 km inland. In Hermosillo, starting about 1947, the groundwater development was exponential. Around 1967 extraction was estimated at 1,200 hm^3/yr (Rangel-Medina *et al.*, 2005; Moreno Vázquez, 2006). Current groundwater level drawdown in the central areas is up to 135 m below the natural situation, which means up to 65 m below sea level. Studies showed growing salinization problems in some areas about 30 km inland from the coast (Steinich *et al.*, 1998), about 27 km^2 with up to 16 g/L salinity, and a progressive water cost increase. Farmers did not pay much attention to government agencies warnings and continued to be largely unorganized to confront the situation. Groundwater exploitation was predicted to fail in about 25 years according to models. Some agreement permitted reducing extractions and to move inland some of the close-to-the-coast salinized wells. Current extraction is about 550 hm^3/yr out of 350 hm^3/yr of recharge, including 70 hm^3/yr infiltrated from surface water (canals and storage reservoirs) and about 100 hm^3/yr of aquifer water substituted by seawater or saline water, mostly upflowing from the deep aquifer layers (Rangel Medina *et al.*, 2005; Szynkiewicz *et al.*, 2008). This means 200 hm^3 of freshwater storage depletion. This has to be compared with an average rainfall recharge of 100 hm^3/yr. However, the aquifer, as well as the smaller Guaymas aquifer, continues to supply water, complemented with surface water from the Hermosillo dam and water taken from close-by aquifers, thus permitting to move towards sustainable use of these important water resources, at a cost, while sustaining the important current economic development.

This shows the resilience of a large aquifer to be exhausted, thus allowing time for awareness on the common asset to be protected.

Box 6. Intensive groundwater development: The Canary Islands, Spain.

The Canary Islands is a volcanic archipelago in the eastern Atlantic Ocean, facing the Sahara region. It consists of seven main islands, 250 to 2,000 km^2 of surface area, with altitudes up to 3,700 m, one of the highest in Europe, although the easternmost islands, the oldest and most eroded ones, are only 650 to 850 m high. Gran Canaria, Tenerife and La Palma are the most populated islands, with important economic activities that include important tourist establishments and large irrigated areas since the 16th century although fully developed after the 1930s. The low and medium altitude areas, especially at the southern slopes, are arid to semi-arid, but the highlands receive up to 1,000 mm/yr. Groundwater is obtained by tapping springs (if still flowing), drilling deep wells and excavating long water galleries (Custodio & Cabrera, 2002), to penetrate into the low permeability, although with vertical fissures, volcanic core formations (Custodio & Cabrera, 2008). Exploitation of this type of volcanic islands, with high water table gradients, is subject to hydrodynamic effects that -in many areas- produce a continuous water-table lowering, which in some cases may exceed 300 m, even when abstraction is less than recharge since outflow into the sea continues to be relatively important due to hydrodynamic conditions. Further problems are local seawater intrusion in some coastal aquifers, and quite important nitrate pollution derived mainly from agriculture. The Figure is a cartoon to show hydrogeological conditions in a volcanic-core island, as inspired in Gran Canaria (after Custodio & Cabrera, 2002). It shows how the progressive water-table lowering has a moderate effect in reducing outflow into the sea in part of the coastal areas, but may dramatically affect springs, wells and water galleries in mid and high altitudes.



Some recent groundwater balances, derived from the island's Water Plans, are:

Island	Surface area	Recharge	Coastal outflow	Seawater inflow	Extraction	Irrigation return flows	Water storage decrease	Current average draw-dawn rate m/yr
	km^2	hm^3/yr						
Gran Canaria	1,500	100	40	5	80	15	30	0.5 – (0–2)
Tenerife	2,000	280	270	0	190	30	150	1.2 – (0–4)

Surface water resources are small, only 8% of total resources in Gran Canaria, the most favourable due to outcropping low permeability old volcanics, even if it has the world's largest density of large dams (higher than 15 m), but with rather small storage capacity due to the land stepness. Up to 25 hm^3/yr of desalinated water is made available in the eastern islands. There is an increasing treated waste water use for agricultural use in some areas, in some cases after reducing salinity through reverse osmosis. In Tenerife and La Palma, high altitude, long water galleries dominate. They yield continuously, so water produced in low demand seasons is wasted. To cope with this wastage of reserves, temporal storage reservoirs have been constructed, partly publicly sponsored. Besides, bulk-heads have been build-up recently in galleries to stop flow, but this needs favourable geological conditions to resist the very high differential pressures that may develop, up to tens of atmospheres.

Governmental and stakeholder actions are helping to reduce groundwater exploitation and decrease drawdown, and even redressing it to avoid current high water extraction costs. An important goal is preserving groundwater for high and medium altitude uses, where desalinated and reused water is not available or too costly. There is some management success in Gran Canaria where groundwater producers and users are being organized for self-control. Groundwater stakeholders have a quite numerous representation in the *Consejo Insular de Aguas* (Island Water Board) that allows them to influence decisions.

The policy is toward preserving aquifers for sustainable uses in critical areas for the economy, and for land and landscape conservation, while providing alternative water resources for urban supply at low altitude areas. But during the 20th century development was unsustainable, mining reserves.

Box 7. Groundwater reserve depletion: Small aquifers in southeastern Spain.

In the Alacant/Alicante, Murcia, and Almeria provinces, in southeastern Spain, climate is semi-arid but conditions for intensive cultivation of highly valued crops are excellent. Only small river basins and limestone aquifers exist since the high rangeland is close to the coast and tectonic disturbance of geological formations is high. Aquifers have been intensively exploited since the 1960s, and continue to be, in spite of the high cumulative groundwater level drawdown, as well as salinization in some cases. This is due to the high profitability of special cash crops that have a sure and lucrative market in Europe. In coastal areas, brackish groundwater is being desalted by reverse osmosis. Besides, seawater desalination plants have been made available, but the water price is currently higher than the direct cost of continuing to exhaust groundwater reserves, for which opportunity and environmental costs are not considered. Away from the coast, reserves are exhausted rapidly, waiting for importation of water resources from other areas, as in the Vinalopó area (Alacant/Alicante), where storage depletion since 1980 is currently about 120 to 150 hm^3/yr, and a water transfer is in an advanced stage of completion. Some figures by areas that include several of these small, quite isolated, thick aquifers, after data in diverse official sources (e.g. DGOH, ITGE,), are:

	Reserves in 1995, km^3			Exploitation, hm^3/yr		
Area	Used(1)	Remaining	Usable	Renewable	Reserves	Years to depletion
Almeria	0.8	1.1	0.7	50(2)	50(2)	15 (10–75)
Murcia Highlands	2	10	7 to 11	200	125 to 300	60 (10–800)
Campo de Cartagena	–	–	1–2	50	90	20 (10–40)
Alacant / Alicante	1	7	6 to 11	30	150	160 (10–200)

(1) Period 1980–1995

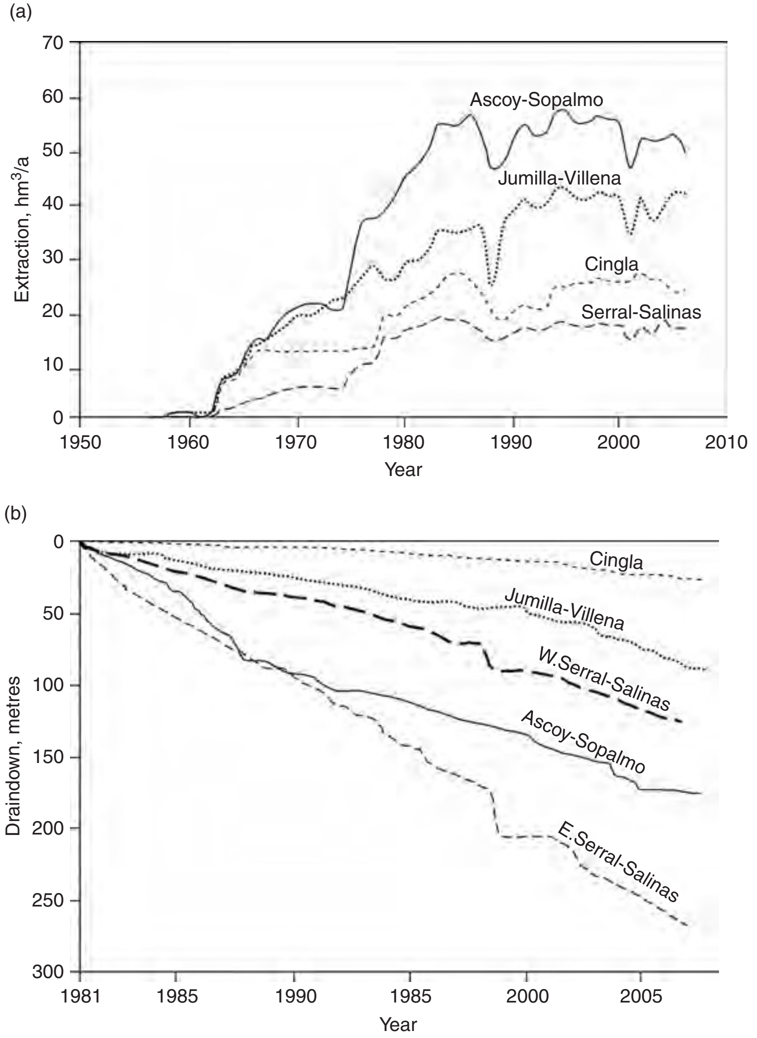
(2) Current figures of exploitation in the whole province are about 160 hm^3/yr, which correspond to the Campo de Dalías-Sierra de Gádor aquifer system.

For some of the Murcia Highlands small aquifers (Molina *et al.*, 2009):

Aquifer	R	B	ΔS	Δh	Rate
Cingla	13	30	17	25	1.3
Jumilla-Villena	13	46	31	115	3.5
Ascoy-Sopalmo	2	52	50	190	4.5
Serral-Salinas	5	18	13	130–290	4.9–10.5

R = estimated recharge rate, hm^3/yr; B = pumpage rate, hm^3/yr; ΔS = decrease rate of aquifer water storage, hm^3/yr; Δh = estimated total drawdown (m), from natural situation; Rate = current drawdown rate, m/yr

The groundwater level evolution is shown in the Figure, in which: a) shows the evolution of extractions in hm^3/yr; and b) the groundwater level drawdown referred to the situation in October 1980, when exploitation was already developed. Extraction is well above recharge. Even if pumpage is stopped, recovery will need many decades.



Box 8. Groundwater mining: The Great Man-Made River, Libya.

Libya is an arid country in which most of the population and economic activities are in the north, along the Mediterranean Sea coast. The southern area is a desert but holds one of the largest world's fresh groundwater reserves in several extensive aquifers. The most important are:

Aquifer	Emplacement	Surface area in Lybia (km^2)	Maximum thickness (m)	Water reserves (km^3)(4)
Kufra(1)	SE	350,000	2,000	20,000
Sirt(2)	Center-NE	300,000	1,000	10,000
Murzuk and Hammada(3)	SW	350,000	500	4,800

(1)It is part of the Nubian Sandstone Aquifer System

(2) They extend to the E and the SW

(3) They are in the western Sahara aquifer system (more than 1,000,000 km^2)

(4) Only a fraction is developable

A large project to extract deep groundwater (down to 1,000 m) from these aquifers was launched in 1984, to be conveyed to the north: 80% is to irrigate 150,000 ha, and 20% for urban and industrial areas. The project budget was 20×10^9 €, yielding water at a cost of about 0.10 €/m^3, which was assumed cheaper than alternative water sources, mostly seawater desalination (Zidan, 2007; Loucks, 2004; Salem, 2005a; 2005b; Gijsberg & Loucks, 1999), although some evaluations did not consider investments already carried out. The project has been developed over 25 years, in four stages, to convey 6.5 hm^3/day (2.3 km^3/yr) of water extracted by means of more than 1,300 wells, deeper than 500 m. There are 4,000 km of pipes in four large systems across the country, from south to north, and along the Mediterranean Sea coast, Benghazi and Tripoli being the main destinations, where local aquifers are overused (Salem, 2005b).

After numerical modelling was carried out, the environmental impact in the exploited areas was assumed small (Abdelrham *et al.*, 2008), but the effect on other areas, especially in confined sectors, seems poorly known. In the receiving areas important social changes (increased prices, more food availability, but increased wasteful use of water) and environmental changes (climate improvement, less local pressure on local aquifers, but increased pollution due to fertizers and pesticides, . . .) have been or will be produced.

This is an example of planned massive use of groundwater reserves, having both supporters and detractors. The project may produce large social benefits if correctly carried out with a long-term perspective, provided means to compensate current and future negative impacts are applied and then put aside.

Box 9. Groundwater mining: The Nubian Sandstone Aquifer System.

The Nubian Sandstone aquifer extends over more than 2,000,000 km^2, in eastern Libya, Egypt, northeastern Chad and northern Sudan. It is probably the largest of the world's fossil water aquifers. The area is arid, except in the SE, where recharge is significant. The aquifer system consists of a series of vertically and/or laterally related aquifers. In the southern part it crops or subcrops out, the rest being mostly a confined aquifer. Water is generally fresh but in some deep areas may contain saline water. Groundwater flows south to north where outflows from deep layers through discontinuities have created large evaporation areas with salt deposits. Results derived from a CEDARE/IFAD study of the area carried out early in the 2000s (Salem & Pallas, 2004), show:

	Area (km^2)	Freshwater storage (km^3)	Recoverable freshwater (km^3)	Extraction (hm^3/yr)
Nubian (1)	2,176,000	373,000		600
Pre-Nubian (2)	920,000	169,000		1,600
Total	3,096,000	542,000	15,000	2,200

(1) Nubian system: Paleozoic to Mesozoic sandstones
(2) Post-Nubian system: Miocene

Present annually extracted volume is a tiny fraction of recoverable freshwater reserves. Most of extracted water is for large irrigated agricultural areas around traditional oasis in Egypt and in Libya (Kufra aquifer), about 70 hm^3/yr to the Big Man-Made River (Box 8) to the branch heading toward the Benghazi area.

This development has actual and potential important impacts on lakes and oases. In some cases natural outflow may be substituted by pumped wells, with a progressively increasing cost. Dried up areas are sources on moving sands that increase dune fields, as in Chad, where people are forced to migrate. Soil salinization and contamination by fertilizers is an added problem. In confined areas, the groundwater head depressed areas may extend over distances of several tens of km. In the Egyptian oasis of Kharga, deep wells between 1960 and 1998 have produced a groundwater drawdown up to 60 m. Although in some cases development seems relatively safe in the short- and medium-term, long-term consequences need to be further assessed, taking into account the sustainability of current developments due to increasing extraction costs and the capacity to transfer part of the economic benefits to future generations.

The policy of resettlement of poor farmers from the Nile Valley – to relieve pressure for land – to the Nubian aquifer-sustained oases has to be compatible with the falling groundwater levels and increasing energy costs. Also, the use of valuable fossil groundwater resources, subsidized as regards infrastructure and energy costs, for not very competitive agriculture near Mediterranean areas is an issue, blurred by policies heavily influenced by politics.

Water-table drawdown desaturates formerly water saturated ground zones, thus allowing oxygen penetration. This favours mineral and organic matter oxidation. The increase in CO_2 enhances mineral hydrolysis. Reduced metals may be oxidized and dissolved, although metals are often re-precipitated afterwards as insoluble oxides and oxy-hydroxides, but not always, as may happen for arsenic (As) (Hering *et al.*, 2009), a current serious health concern. Also sorbed ammonia in the ground is often oxidized to nitrate and dissolved. Fluctuating water-table produces an alternatively saturated and desaturated ground zone in which chemical reactions are enhanced, especially redox ones.

In some agricultural areas, irrigation with imported water has raised the water table up to shallow depths from which evapoconcentration takes place, thus precipitating salts and producing soil salinization, and even alkalinization when sodium (Na) is abundant. This may reduce crop yield dramatically or may lead to barren areas. Groundwater exploitation may help to alleviate or prevent this situation by lowering the water table (Box 10).

Box 10. Groundwater extraction to control soil salinization: The Indus Plain, Pakistan.

The Indus Plain is an arid, large area, with about 13 million ha under irrigation, supplied by 43 large surface water canals from the Indus river basin, 15 of them with a flow of up to 280 to 600 m^3/s. The large, mostly unconfined aquifer below, contains about 350 to 500 km^3 of fresh to brackish water. The unsaturated thickness was initially up to 70 m in the interfluves. Irrigation started before 1910 and excess irrigation water has been recharging the aquifer and increasing groundwater levels, up to close to the land surface in many areas. This has damaged crops and salinized the soil through evaporation. In order to correct this by artificially lowering the water table, a project to drill and pump 32,000 wells was prepared by the Government, with the goal to pump up to 70 km^3 of water per year, which is about half the contributed surface water. The Government of Pakistan halted the project when farmers begun to carry out the task by themselves, combining the use of surface with extracted groundwater. Part of pumped water was intended to export excess salinity through disposal into the canals in the lower area. In large areas, below the freshwater lens there is brackish to salty groundwater of natural origin. Avoiding salinity increase of pumped water is quite a difficult task; scavenger wells could be needed (Stoner & Bakiewicz, 1993), which is quite a complex technology.

This is a case in which groundwater exploitation is useful to alleviate problems created by surface water use, but at a cost, and with technical problems in some areas to deal with current and future salinity problems in flat areas with difficult surface drainage, if canal salinization affects downflow users.

4.3 *Ecological effects*

The value and ecological diversity of many wetlands depends on sustained water availability to define and sustain the hydroperiod and its fluctuations. Wetlands provide important services to humans that may dwindle and even disappear by intensive groundwater development.

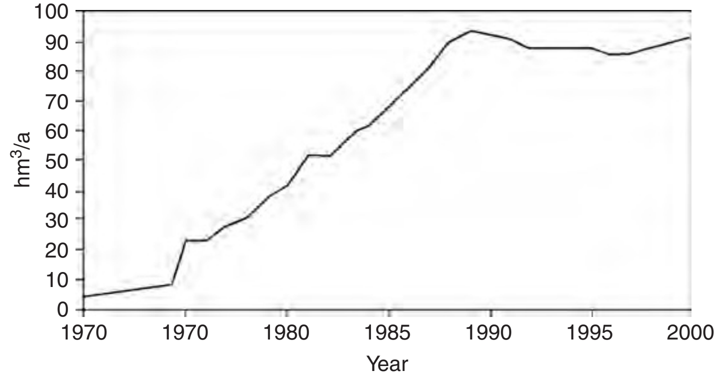
Groundwater is important to sustain springs and river baseflow as well groundwater-dependant wetlands, both freewater ones or shallow water tables attainable by vegetation (crypto-wetlands). Groundwater development may reduce – even dry out – wetlands, and increase the depth to the water table. This means ecological changes that may be compounded by important chemical changes. Box 11 refers to the wetlands of the Doñana area, in southwestern Spain, an area at risk. Box 12 shows a more acute situation in central-southern Spain, in which groundwater flow to wetlands ceased some time ago.

Box 11. Impact on wetlands: The Doñana aquifer system, southwestern Spain.

The Doñana area, in southwestern Spain, over the Provinces of Huelva and Sevilla, holds the largest wetland area of western Europe, a Ramsar Convention wetland. The area currently contains about 1,700 km^2 of surface-water fed marshes, bounded by 1,200 km^2 of sandy lands, partly with a recent eolian sand cover. This area is quite well recharged (Custodio *et al.*, 2009b) and sustains groundwater discharges to some permanent streams, the coastal area, and the contact fringe (ecotone) between the sands and the marshes, besides several hundreds of small lagoons all over the territory, from recharge to discharge areas. All of them are crucial for local fauna, especially during the dry season, and sustain important vegetation areas.

The area, a largely uninhabited one due to poor conditions for human settlement, has been subject to several kinds of groundwater development. The first one, from late the 1940s and mainly in the next two decades, was the introduction of planted eucalyptus forests that increased groundwater evapotranspiration over large areas. In the early 1970s a large irrigation project based on local groundwater extracted from the sands was initiated in areas close to the ecotones. At the same time a Biological Reserve and a National Park were created as a result of the growing Nature conservation awareness. Thus, a confrontation between development and preservation took place, with the result of the halt in new developments, except in the westernmost area. Currently, nature preservation and existing groundwater-demanding developments try to live together. The Park has been enlarged with new protection areas, with some agricultural land purchases and pressure to reduce irrigated areas for rice cultivation, a highly water consuming crop. Agriculture in the area is economically important. In the 1990s a large part of the eucalyptus forest was eradicated.

Groundwater abstraction leveled after a fast growing period. The Figure shows groundwater exploitation, except for the westernmost sector, with an initial accelerated development and a later stabilization, even before the irrigation plan was completed due to pressure to not damage ecosystems further.



The consequence of groundwater development has been water-table drawdown, which is ecologically significant in many areas even if small, since they affect lagoons, mostly in recharge areas, and phreatophytes, and flowing wells used to water cattle and fauna along the ecotone. As numerical modeling shows, the time that it takes for the groundwater level and discharges to evolve from an initial value to half way towards the final steady state is about 20 years. This means that changes produced late in the 1970s are still evolving; depletion will continue for some time even if current extraction situation go on hold. An improvement was obtained after the eradication of the eucalyptus forest. Conspicuous seasonal and annual recharge changes can be observed, with periods in which it seems that Nature recovers the predevelopment aspect, but in reality it is not so, since the time between recovery events is increasingly longer. Agriculture and human activities are also a source of groundwater pollution which is poorly known, with current problems of nitrate build-up in some areas. This will affect ecological values in the future. Some effects seem to be already appearing (Manzano *et al.*, 2009a; 2009b). A part of the ecotone and a series of lagoons are seriously damaged but other parts of the ecotone and many lagoons survive, although with deteriorating health.

The current policy is towards management and water quantity and quality restoration, compatible with maintaining a reasonable groundwater development, reducing groundwater extraction and the use of agrochemicals, and purchasing critical agricultural areas.

Attempts to create governmental entities, further to the Park administration, have been largely unsuccessful since local people have been slow to understand the benefits of Nature protection and the importance of preserving their own groundwater resources. They have only been marginally involved in decisions and up to know have not been able to create representative associations, in part due to a lack of leadership. However this is partly compensated by quite a good level of monitoring of some variables, and good scientific hydrogeological studies.

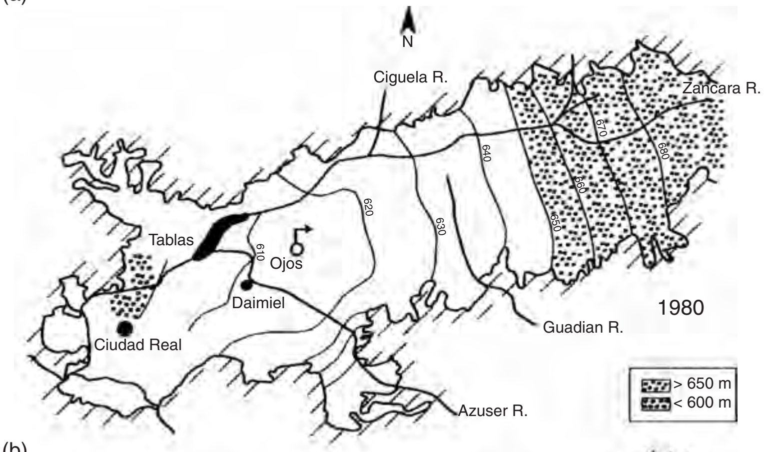
The area has the potential to be correctly managed for a sustainable ecological and human situation, where groundwater is a key component. Efforts are under way.

Box 12. Impact on wetlands: The Upper Guadiana Basin, southern-central Spain.

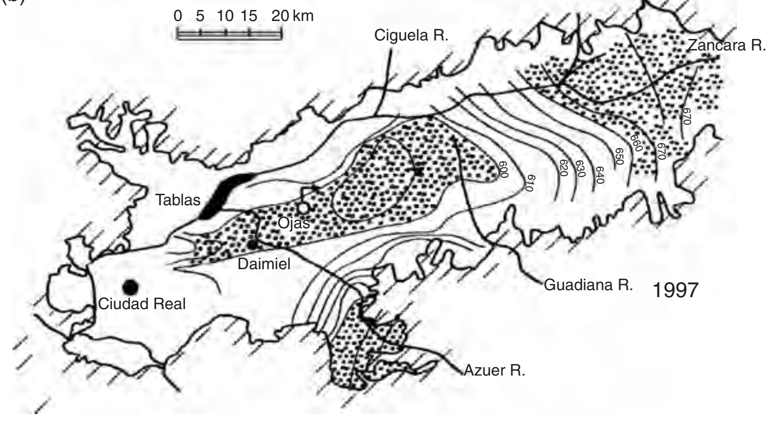
The Upper Guadiana Basin, in southern-central Spain, about 16,000 km^2, is a rather flat platform with a poorly defined drainage network due to good soil permeability and high transmissivity of the water-table aquifer. Total usable water storage is about 3,000 hm^3. It is a semi-arid area with an average recharge less than 30 mm/yr, including streamflow infiltration (Martínez-Cortina, 2003; Bromley *et al.*, 2001). The area was well known for a large spring (*Ojos del Guadiana*) at the basin lower boundary, and for being an important Ramsar Convention wetland (*Las Tablas de Daimiel*). This and other minor wetland areas covered about 2,000 km^2. Wetlands depend partially on surface water but groundwater was the essential component for the hydroperiod.

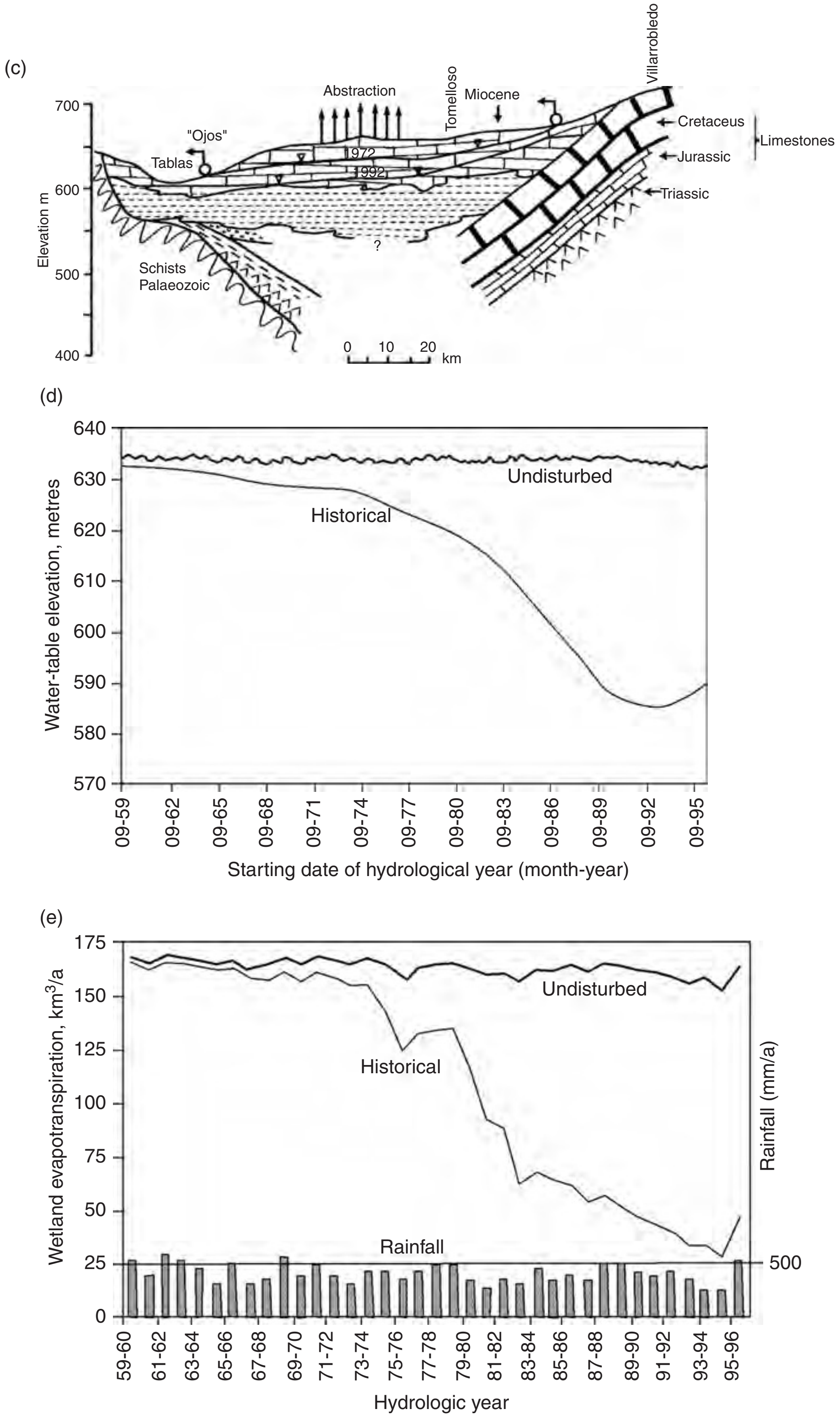
This extensive rain-fed agricultural area started irrigation with local groundwater in the 1970s, with a fast expansion during the 1980s, with 130 km^2 of irrigated lands, using about 575 hm^3/yr of groundwater. This dramatically improved the local economy. However the rate of abstraction exceeded the estimated 415 hm^3/yr of recharge. The consequence has been the progressive lowering of the water table, down to 40 m in some areas, which means drying out the *Ojos del Guadiana* and many of the wetlands to the point that currently they depend only on surface water and occasionally on imported water to try to maintain artificially the hydroperiod in part of the area. Moreover, drained out peatlands started spontaneous ignition in dry periods. The Figures show: the water-table map evolution (a, b) with a cross-section (c); and the numerical model simulated evolution of water-table elevation (d), and the smoothened out wetland evapotranspiration rate (e). The actual (historical) evolution is shown together with what would be the undisturbed aquifer conditions. The slight decreasing trend of the undisturbed situation is due to a series of dry years in the 1980s and 1990s (modified from Martínez Cortina & Cruces, 2005).

(a)



(b)




(c)
Villarrobledo
Tomelloso
Abstraction
Miocene
"Ojos"
Tablas
1972
1992
?
Cretaceus
Jurassic
Triassic
Limestones
Schists
Palaeozoic
Elevation m
700
600
500
400
0
10
20
km
(d)
Water-table elevation, metres
640
630
620
610
600
590
580
570
Undisturbed
Historical
09-59
09-62
09-65
09-68
09-71
09-74
09-77
09-80
09-83
09-86
09-89
09-92
09-95
Starting date of hydrological year (month-year)
(e)
Wetland evapotranspiration, km³/a
175
150
125
100
75
50
25
0
Undisturbed
Historical
Rainfall
Rainfall (mm/a)
500
59-60
61-62
63-64
65-66
67-68
69-70
71-72
73-74
75-76
77-78
79-80
81-82
83-84
85-86
87-88
89-90
91-92
93-94
95-96
Hydrologic year

The water balance is (in rounded up figures):

	Inflow (Recharge), hm^3/yr			Outflow (Discharge), hm^3/yr				
	Rain	Streams	Total	Wetland evapotranspiration	Pumping	To rivers	Total	$\Delta S^{(1)}$
~1950	455	140	595	170	60	365	595	0
~1974	425	120	545	145	160	320	625	−80
~1990	330	115	445	45	540	85	670	−225

(1) ΔS = water storage change (hm^3/yr)

The cumulated storage depletion due to extraction around 1990 is 3,500 hm^3, of which 1,000 hm^3 are due to natural causes related to the two long dry spells in the 1980s and 1990s (Martínez-Cortina & Cruces, 2005), and the remaining 2,500 hm^3 to the effect of exploitation.

Action undertaken to further try to control non-authorized new wells – a difficult task due to the large area, unstaffed water administration and the delayed creation of operative Groundwater Users Associations – was to give incentives for closing wells. There is some success but it will not solve the short- and mid-term problem. Even stopping all the extractions the system will not recover in more than a decade, and this is socially a highly difficult task. A politically and administratively difficult alternative is declassifying the area as a Ramsar Convention wetland and habilitating an equivalent surface of new protected wetlands in other not far-away areas, but at that moment this will have a high economic and social cost too. As in any other situations, a win-win solution has to be negotiated between social and ecological interests. A further constraint is to comply with the European Water Framework Directive (WFD, 2000), which is compulsory for all member States. It compels meeting good aquifer status by 2015, or at most obtain a negotiated extension to 2021 or 2027. Exceptions due to disproportionate economic and social burden is a highly debated issue (Görlach & Pielen, 2007), since this may imply economic advantages of some European Union countries with respect the others.

Ecological impacts have to be considered with the social component (Deb Roy & Shah, 2003) to put them in real perspective as the man as the final receiver of Nature benefits.

4.4 *Effects on land conditions*

A main result of groundwater head lowering, which means a pore water pressure decrease, is enhanced compaction of soft, recent, unconsolidated sediments. This results in land surface subsidence. Subsidence may be more or less homogeneous over large areas or present conspicuous spatial variations in heterogeneous sedimentary formations. This may produce deep cracks and faults that may disturb roads and railways, and break down pipes and sewers. Subsidence may be a worrying situation that favours flooding in flat areas and coastal plains, mostly recent sedimentary basins and deltas, as in Tokyo, Bangkok and Venice, or the coastline may retreat, as in the Llobregat delta, Catalonia, Spain. Subsidence of several meters is well known in the Central Valley of California, in Arizona, and in areas of Mexico such as the Capital and in Guanajuato State.

In karstified areas, underground cavities may form or be enlarged due to rock dissolution and internal erosion, especially where groundwater flow has been increased. In relatively shallow formations, land collapses may be a landscape feature, such as sinkholes and dolines. The frequency of these events may increase when the water table is lowered. This is well known in Florida, in shallow carbonates (Galloway *et al.*, 2001), and around Zaragoza, Spain, in gypsum-rich sediments.

Insert 3. Economic and social issues of groundwater development.

- Groundwater development involves benefits and costs: direct to the exploiter and indirect to other users and the Society.
- The cost of groundwater in the terrain is not nil; consider opportunity and environmental costs.
- The effects of development may be long delayed; decide how to value the future.
- Groundwater manifestations have social intangible values by themselves.
- Evaluations involve ethical aspects, informed by moral principles.
- Management is needed: governmental and by Society.
- Benefits are in most cases greater than costs.
- Sustainable use of aquifers is possible, generally at a cost less than no action.
- Groundwater is often the cheapest alternative when full cost is considered.
- Groundwater is a key piece for integrated water resources management.
- Groundwater management has to be linked with land use and energy policies.

4.5 *Effects in urban areas*

Groundwater is an important asset for many urban areas. It is often the main or the only source of freshwater. When feasible, wells are inside or around the urban area. Their exploitation may produce important water-table drawdown. Natural recharge may be drastically reduced, but it is usually replaced by water distribution and sewage network losses, and return flows from unsewered areas and green areas and orchards. Often the consequence is groundwater quality degradation, seawater intrusion in coastal areas, and in some cases, important land subsidence. Besides, soil dewatering in formerly shallow water-table areas allows to construct underground facilities (tunnels, building basements, parkings, . . .) in drained soils. Sooner or later these wells are abandoned and moved to peripheral areas or substituted by imported water. Then, the water-table recovers in the cities, even up to a position higher than the initial one. Then serious inundation problems may appear in underground structures, and instability and corrosion in some building basements may occur. Examples can be found in many places, like London, Mar del Plata (Argentina), Milan and Barcelona (Chilton, 1997; 1999). In Barcelona the problem is partly dealt with by pumping groundwater again, for municipal uses and also in some cases for drinking water after costly, advanced treatment.

5 ECONOMIC AND SOCIAL ISSUES

Economic and social issues are important aspects of groundwater development and use, as briefly shown in Insert 3. Problems related to groundwater development are common to any other natural resource development, although with different shades and timing. They have to be evaluated considering costs and benefits, not only from the point of view of an individual developer or a group of developers, but also from a social and environmental point of view. This last aspect of indirect costs has been, and often is neglected, while it is an essential part of the socio-economic analysis.

Often direct benefits and costs are the only ones considered in economic analyses, including taxation and subsidies. Under this point of view, groundwater development problems appear mostly as increased energy costs for pumping due to incremental water level lowering, and also due to early replacement or refitting of pumping machinery, energy transport lines, and wells. This may affect extractors if water is a significant part of production costs, but not so much when water is a small fraction, as for highly valued crops (Figure 3) or water supply to relatively rich urban and tourist areas. There are also direct costs related to water quality changes, mostly salinity increase, and the

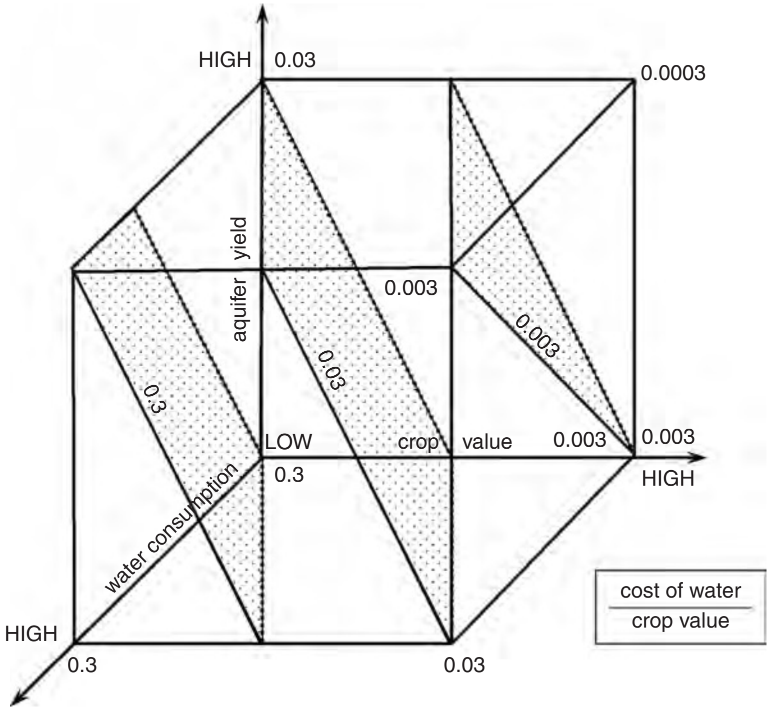


Figure 3. Simplified representation of indicative direct cost of irrigation with groundwater relative to crop value, depending on aquifer yield (low-high), crop water consumption (low-high) and crop value (low-high). The shaded planes are the surface of equal ratio, as indicated.

need for further water treatment to deal with increasing hardness, appearance of soluble iron (Fe) and/or manganese (Mn), arsenic (As), or fluoride (F). They are taken into account as an external burden for producing drinking or industrial water, but may not be taken into account for irrigation uses when crop yields need more water in order to avoid soil salinization, or early problems in irrigation devices appear. Some of these costs show up quite delayed, and this explains why these costs are often non considered in water cost computations. A correct economic evaluation should take them into account.

Also indirect costs and benefits have to be considered from a social point of view. These indirect costs are due to environmental impairment, to the effect of groundwater use on neighbours and downstream surface water users through decreased spring flow, river baseflow, and wetland area, and to land subsidence. If these costs are not internalized, some other must pay for these, or Society as a whole, now or in the future. There are also indirect benefits from exploitation-induced drawdown, such as increased aquifer recharge (if this is not damaging others), decrease of drainage efforts in underground infrastructures (tunnels, cellars, underground parking lots, . . .) and for keeping the water table low in order to avoid soil salinization due to direct evaporation.

As a general rule, water cost increases when groundwater development progresses, with magnitude and relevance depending on the case, although these costs appear gradually. In theory, this should not be a serious drawback since the effects can be anticipated and compensated if aquifer behaviour is taken into account from the beginning through management. Negative aspects are mostly the result of poor understanding and lack of developer awareness, and also poverty. Groundwater is cheaper at the early stages and becomes more expensive when benefits from development increase. Part of these benefits should be reserved to compensate for increased direct costs, and also for indirect costs, currently and in the future. However, this is not an easy task.

It needs institutions and awareness with a mid- to long-term perspective, but it can be done, and this has to be duly and realistically explained and made known; otherwise groundwater detractors have arguments to discourage groundwater use and send doomsday forecasts on aquifer use. Aquifers need protection, conservation, and restoration measures when damaged in their quantity and/or quality. This has a cost, which has to be accepted and supported by users although it is difficult in poor areas, and may need technical, economic and social support from richer areas.

In cost evaluation, the value of water in the aquifer is often considered nil. This is not true since the consequences of groundwater development, including environmental protection and restoration, if not paid by direct users, has to be paid by others or by Society in general. The evaluation of indirect costs – including intangible costs if there is some way to express them in monetary values – is neither an easy task, nor there is a well-established way to compensate Society and Nature. Taxation is a possibility, but how to put aside and apply the collected funds is also a complex issue. This highly depends on local legislation and political orientation, and need popular support.

Some countries like the Netherlands, Denmark, France and parts of Germany have introduced taxes for groundwater abstraction. Abstraction taxes or charges appear as more relevant for quantitative management of groundwater protection, e.g. leakage reduction, and only indirectly for the protection of groundwater quality (Görlach *et al.*, 2007). In the Netherlands levies may include costs involved in bank filtration and artificial recharge. In Germany, revenues from groundwater taxation are earmarked for improvements in municipal sewage treatment.

Timing is an important issue since effects may be long delayed. They may exceed normal political behaviour and even pass from one human generation to the next, and even beyond. This makes economic, social and environmental compensations and transfers a tricky affair. Really, the current generation is supporting the diseconomies from one or two human generations ago, when groundwater intensive extraction began. In the same way, the current generation is affecting the next ones, besides itself.

In the same way that current technology allows to deal with inherited diseconomies and afford increased costs, since the current generation is richer than the preceding ones – although this is not always true worldwide – it may be assumed that the coming generations will be under similar circumstances. But there are limits, both in technology and in the resource itself when water use is intensive. This is a poorly known and inexperienced field. Then, some caution is needed, although not leading to a paralysis that may over-increase the burden to current human generations and consequently affect future ones.

Economists try to consider delayed effects through the discount rate, but there are very different points of view on the long-term discount rate value that should be applied. This discount rate does not coincide with the financial interest and discount rates applied at a given moment by banks. It reflects what people and economists think in a given moment about how the future should be valued (Broome, 2008). A small discount rate favours future generations and gives preference to long-lasting infrastructures and resource conservation. A large discount rate favours the present generation and gives preference to short-term, non-lasting solutions, thus giving more weight to future generations capacity to develop improved technology, in a richer society. But science and technology development needs time and resources (López-Gunn & Llamas, 2008; Quevauviller, 2008), and may have limits.

Existing experience on socio-economic issues and sustainability of aquifer use is short and often poorly documented. Then, extrapolation towards the future is highly uncertain. This future has to be analyzed through different scenarios in which social perceptions of welfare, environment, solidarity in space and time, and ethics play an important role (Custodio, 2000b; 2009; Llamas, 2004; 2009; Llamas & Martínez-Cortina, 2009; Llamas *et al.*, 2009). This perception is also evolving and is different according to social groups and political systems, and also with background religious beliefs that consider humans have the duty of using natural resources properly, to improve living conditions of other persons, and to preserve the environment, but this is not the supreme value since humanity will transcend present life (Benedictus XVI, 2009).

6 A SILENT SOCIAL REVOLUTION FROM THE BOTTOM

Important surface water development generally need large economic investments that can only be carried out by governments, big enterprises or conglomerates of numerous, often rich persons and entities. This is not the most frequent case for groundwater development since it can be afforded at the local level, by individuals or small groups, often farmers, using 20th century technology. Economic resources often come from their savings or through relatively small loans (Llamas *et al.*, 2006).

This makes an enormous difference between surface and ground-water. Surface water development, which often involves large water works, is mostly from the top-down. Surface water is often managed by specialized teams, and users have to be organized into participative bodies in order to have access to water. In many areas of the world surface water is often in the public domain.

Instead, most groundwater developments, especially for irrigation and farming uses, are initiatives from the bottom, by a large number of mostly unrelated developers, often lacking a sufficient aquifer knowledge about the effects they produce and the effects in turn that they receive from other developers. This has to be combined with the circumstance that groundwater often has been, or still is, administratively a private affair, compounded with the difficulty of having to deal with a large number of unorganized owners and right holders. The result has been, and still often is, that public water administration is not interested in these affairs. Circumstances are changing fast in many areas due to already felt effects of intensive groundwater development, mostly on surface water, the environment, and recognized existing water rights (Llamas *et al.*, 2006).

Groundwater development, especially by farmers, but also for small town and rural water supply, has been growing almost exponentially, as already commented, at least in the initial stages. This may be viewed as a social *silent revolution* from the bottom (Fornés *et al.*, 2005; Llamas, 2007; Llamas & Martínez-Santos, 2005; 2006), mostly outside governmental plans and without using public funds. *Silent* refers to the almost imperceptible mode under which groundwater development is produced. *Revolution* reflects a conspicuous change in water availability, and the consequences in population health, and mostly in food production and farmers' income. This implies that developers and users pay the abstracted full direct water cost – with only some exceptions, as the subsidised energy cost in some states of India – and also common taxes. Instead surface water developments often pay only for operation and maintenance costs, sometimes with subsidies – wicked subsidies in many cases (Myers & Kent, 1998) – and tax exemptions, where the amortization costs of investments are not fully considered or even not accounted for at all.

As in most revolutions, some inconvenient issues crop up – perhaps some serious concerns in some areas – that have to be tamed and controlled in order to converge to a sustainable situation. But this sustainable situation is not easy to define, is the subject of different opinions and has to be established for a large area, even at world scale, in a wide social framework (Rogers *et al.*, 2006; Llamas *et al.*, 2007).

7 MANAGEMENT ISSUES AND CHALLENGES

Groundwater is one of the available water resources in a given region, varying from the most important in arid areas, mostly for irrigation, to only a convenient, safe and cheap commodity in wet areas, where it is used mostly for drinking water. They vary from fully renewable to non-renewable fossil reserve, depending on aquifer circumstances, recharge rate, and exploitation intensity. Management is needed to get a sustainable use and to preserve the benefits of its intensive development at the time the negative effects are bounded and compensated. This is a challenge (Insert 4). However, groundwater management is a sectorial aspect inside a wider framework, in which the conspicuous differential characteristics of groundwater have to be considered.

Insert 4. Management issues and challenges for groundwater.

- Groundwater is a kind of *common pool good.*
- Unrestricted use may lead to a *tragedy of the commons* situation.
- Management is needed for quantity and quality sustainability.
- Groundwater should be evaluated in the framework of whole water resources and land use.
- Management should be carried out by the joint action of government authorities, groundwater users and stakeholders, as well as civil society.
- Management means knowledge, monitoring, institutions from the top and from the bottom, legislation, co-responsibility and co-operation.
- Collective bodies appear as efficient tools for aquifer management and governance.

Water management is the set of activities, decisions, rules and means used by institutions that have capacity to carry out their job. It needs enough human and economic means, good knowledge and data, both in space and time, and a framework of accepted and respected rules. The institutions and organizations have to accomplish goals, such as providing water of adequate quantity and quality for human needs, preserving the environment and making sustainable and environmentally admissible the extraction of water resources. They may be from the government and public water administration, or from the stakeholders, and preferably by a well equilibrated and effective combination of them. All this should be placed inside the larger-scope framework of other goals such as land use and energy management, within the restrictions set by social constraints and ethics. Local management in a relatively small territory has to consider the links with other territories, even across political borders. This is provided by more general institutions, up to those contributing a worldwide, wide-scope perspective, such as water and food security, and virtual water trade as a means to compensate for water availability and cost heterogeneities.

In the case of groundwater, the often large number of developers – and also stakeholders – is a management challenge, since the starting point should be to raise a collective conscience that the aquifer is a common asset that needs to be managed. This is often a difficult task that needs many years, perhaps the passing of a full human generation. This cannot be simply imposed from the top since then they may be often rejected at the bottom, thus raising confrontation. Policies and undertakings should be adequately tailored to solve local problems.

Bottom-up pressure for management may be induced by careful action, involving some groundwater developers from the beginning, to act as seeds to drag other developers. This needs a well organized information and education effort at the local level, often with the initial help of government funds. Developers accept self control when they see that their water source – their income – is at risk of becoming a *tragedy of the commons* (Hardin, 1968; Nordhaus, 1994) – the situation in which access to the good is unbounded, thus leading to depletion–, and also when they trust experts and data. Identifying common interests and common threads is a key step to start action, as well as considering local administrative circumstances (see Box 13).

Box 13. Aquifer management: California and Arizona, USA.

Large urban and agricultural areas of California and Arizona (USA) depend on groundwater. They also receive surface water, if available, and imported water. Then, there is integrated water management in which the aquifers play a key role both as a source of water and by providing regulation through their large storage. In some areas the aquifer also provides water to large urban areas and to local supply wells. In some areas of California, drawdown is compensated through artificial recharge, and seawater intrusion is controlled through barriers of injection wells, in some cases with the help of saline water pumping barriers. This is the case of Los Angeles County, Santa Clara Valley and Orange County, through Water Districts (Box 14). This started late in the 1950s. In the 1970s, pilot tests and projects with treated sewage water were initiated. In Orange County injection of highly treated sewage water into the aquifer started in 1977 with the construction of a facility that included reverse osmosis desalinization. The reclaimed water was mixed with groundwater, to be injected into the 23 wells of the Coastal Barrier Project. This facility was the precursor of a recently completed much larger plant which uses only municipal effluent water treated through reverse osmosis to be injected in the seawater intrusion control hydraulic barrier. Also, both Orange County and Los Angeles County use reclaimed and imported water to replenish their aquifers by using water-spreading facilities located in Santa Ana, Rio Hondo and San Gabriel Rivers.

In Arizona, the Water Plan includes attaining sustainable use of aquifers by regulating excess exploitation. The 1980 Groundwater Management Act mandates the condition of safe yield to be attained by the year 2025. In the Phoenix metropolitan area the decline of groundwater of its underlying Salt River Basin aquifer is controlled by limiting the annual pumping volume of each well. Management is carried out by the Salt River Project and the Central Arizona Project through integrated use of local surface water from the reservoirs in the Salt and Verde Rivers and imported Colorado River water. The aquifer provides storage for artificially recharged water in basins by means of deep wells and unsaturated zone wells. Besides, highly treated urban waste water is recharged into the aquifer for later use in agriculture and recreation areas.

Management goals may include actions to preserve aquifers from a quantitative and qualitative point of view, including the damage derived from land use changes, new large constructions, and expanding urban areas. Insert 5 shows some main threads. It is not rare that management means reducing abstraction and integrating other water resources, and even carrying out artificial recharge (Harou & Lund, 2008). Aquifer system management in an integrated water resources framework has been and is being carried out in the Llobregat's Lower Valley and delta, at the southwestern boundary of Barcelona (Catalonia, northeastern Spain) by the Water Authority, with the cooperation of the Groundwater Users Association, as commented in Box 2.

Insert 5. Threads to groundwater sustainable use.

- Contamination from agriculture, livestock, urban and industrial sources.
- Unawareness of contamination risk due to its slow pace, which may translate into highly delayed recognition and policies.
- Contamination may affect large volumes.
- Quality degradation and related surface water degradation. It is often independent of groundwater development, but depends on land use and other human activities.
- Decreased recharge by land use changes and civil and mining dewatering.
- Winning cost becoming too high to sustain uses.
- Costly, very difficult, long-lasting restoration, if feasible at all.
- Poor knowledge and management.
- Poverty.
- Corrupt political behaviour.

The European Water Framework Directive (WFD, 2000) and the daughter Groundwater Directive (GWD, 2006) are key legal pieces for the European Union. Although these Directives are environmentally oriented, they impinge on groundwater quantity and quality management. Members have incorporated them into the country's water legislation, following the subsidiarity principle (Sahuquillo *et al.*, 2009; Molinero *et al.*, 2008). The subsidiarity principle means that public administration has to be carried out at the closest level to people and entities, and exceptionally at higher levels if the lower ones cannot carry out the job.

8 COLLECTIVE BODIES AS AN EFFECTIVE TOOL FOR AQUIFER MANAGEMENT AND GOVERNANCE

Groundwater management deals with numerous developers and stakeholders distributed all over the territory. This poses quite a large difficulty for management organizations whose officials are often not able to master the area, have no access to many sites and need an enormous monitoring effort. This may be carried out more easily and effectively by local people as corresponsible aquifer developers. These developers should have a voice in water management decisions in the Water Authority, share duties and receive funds, or at least a part of what they are paying as general and specific taxes.

Since the numerous stakeholders cannot participate individually, stakeholders need to be effectively represented in the water management body through agreed representatives. This means that users should be associated to be adequate represented. They should carry out their duties with their own economic resources, but also with funds transferred from the government to do specific tasks. Furthermore they should have a technical staff, a financial system, legal support, and a jury to punish deviations. Membership should be compulsory, or at least decisions adopted by a majority should bind other users.

Experience of these collective management bodies of stakeholders – or strictly the groundwater developers – is still small and recent, but there are encouraging examples in some countries such as USA, Spain, Mexico and India, with different contents and structure according to local circumstances. Collective groundwater management (Hernández Mora & Llamas, 2001; Schlager & López-Gunn, 2006) seems a necessary step toward groundwater management and governance, at least until worldwide experience develops. How to carry them out depends highly on local legal frameworks and habits. See Boxes 14 through 16 for experiences under very different circumstances. The existence of groundwater markets, even if imperfect and gray, may be first steps toward management, as in India (Shah, 1993), the Canary Islands and Eastern Spain, once the strict monitoring goals are overcome.

Box 14. Groundwater management institutions: California and Arizona, USA.

In California, landowners have the right to extract as much groundwater as can be put to beneficial use. The State cannot directly manage groundwater according to the California State Water Code. Thus, groundwater management programs have been developed including public (municipalities and counties) and private entity initiatives, in order to solve existing local problems. Agencies, adjudications and districts under special legislation have been created to allow users to manage groundwater inside their boundaries. Currently there are 12 districts. Some counties have a long tradition (Orange since 1933; Monterrey Peninsula since 1947; and Santa Clara Valley since 1951), and others are recent (Lassen since 1993) and still developing. Orange and Santa Clara Valley Water Districts rely on surface water and imported water, and can levy pump taxes to regulate groundwater extraction, but they do not have authority to regulate groundwater extraction by ordinance (WRD, 1996). Tasks vary from agency to agency, from monitoring to limiting extractions, including water imports to alleviate nitrate pollution and seawater intrusion problems, or to agree in exporting groundwater to other areas. After WRD (1996), an average 5 year time is currently needed from the start of the district steering group until the operative district board officially meets.

Orange and Santa Clara Valley Water Districts general policy is to transfer agricultural water to urban areas. They have carried out and operated aquifer recharge facilities in which imported water, and in some areas highly-treated municipal waste waters, are up-graded to drinking water standards, and then stored underground. This is carried out to control and mitigate seawater intrusion problems, and for water storage. The Orange County Groundwater Replenishment System Project, with a cost of US$ 485 million, went on line in January 2008, after almost 30 years of studies, tests and demonstration facilities.

The Los Angeles County Water Replenishment District has a long experience in operating artificial recharge facilities and seawater intrusion barriers since the 1960s, in order to improve conditions in the Central and West Coast basins.

Similar entities exist in other areas, including artificial recharge for temporal storage (the ASR, Aquifer Storage Recovery. An example is the Salt River Project (SRP), Phoenix area, Arizona (Lluria, 2005). Groundwater management by this Water District has been effective in reducing groundwater mining, partly by reducing irrigated area, but also through a better management of local and imported water. This is part of the Arizona Department of Water Resources Plan, which will last until 2025.

The goal of water management activities is to sustain the essential role of aquifers for local water supply and water distribution to users, and for temporal storage, as part of an integrated water resources management plan that, in some cases, may receive external water, as is the case in southern California and Arizona. The cost is rather high, but water demand can generally afford this, given the good economic productivity of water. In the mid- to long-term, management is cheaper than no action.

Box 15. Collective groundwater management: The COTAS of Mexico.

The central region of Mexico has a large population, well established irrigated agriculture, and important industrial developments. Groundwater is crucial for supply in the 192,000 km^2, high altitude, partially closed basin on the Lerma-Chapala river basin, in a semi-arid environment. It extends over five states that include the Federal District of Mexico and the State of Guanajuato to the north. There are about 100 aquifers that are considered overdrafted. The result at the local level is groundwater level drawdown, increasing water exploitation costs that are threatening some important agricultural developments, and land subsidence, as well as decreasing surface area of the large, relatively shallow Chapala Lake.

The *Comisión Nacional del Agua* (CNA, National Water Commission) is the federal government agency responsible for water management. It has been unable to deal effectively with problems. In order to foster better groundwater management at the local level, with more involvement of stakeholders, the CNA promoted and supported civil society organizations called COTAS (*Comités Técnicos de Aguas Subterráneas*; Technical Groundwater Committees) in 1992, with the goal of helping to address local groundwater resource management.

In the case of the State of Guanajuato, groundwater extraction exceeds local and seasonal recharge in 26 out of the 38 significant aquifers. Around 26,000 wells extract about 14 km^3/yr, while recharge is only 13 km^3/yr. Groundwater level depletion rate can be up to 2 to 3 m/yr. Groundwater supplies almost the whole urban and industrial needs, and about 60% of irrigation water demand. In Guanajuato, the COTAS have been developed more in depth. The State Government launched a complementary programme to confront groundwater resources problems. Each individual COTAS was given an office, three staff members, a vehicle, groundwater monitoring equipment and computer facilities, plus technical and juridical support. Total investment during the period 1998–2003 was about US$ 4 million; a second stage is now ongoing. The COTAS governing board is formed exclusively by groundwater users. The operational staff has to implement a yearly agreed work programme with the *Comité Estatal de Aguas de Guanajuato* (Guanajuato State Water Committee). Fund allocation could be retained if a COTAS does not comply with performance indicators. Groundwater resource management must rely on local social agreements as much as possible, to implement adaptive measures based on best-available scientific understanding. The potential activities envisaged by Guanajuato State, to be undertaken by the COTAS are (Foster *et al.*, 2004):

- Capacity building in support of groundwater management plans implementation.
- Promotion of management-related projects to solve specific water problems.

- Support to the federal government in groundwater rights administration.
- Improve public awareness of groundwater management needs.
- Assist well users in administrative requirements and improving efficiency.
- Achieve financial sustainability from members and public and private partners.
- Enhance recharge.
- Indemnify well owners that agree to close down their wells.
- Improving aquifer knowledge.

Some preliminary economic studies have shown that the cost associated to reducing extractions, improving groundwater use efficiency, and enhancing recharge is less that no action. After Foster *et al.* (2004), experience shows that up to the present, the smaller municipalities have shown more willingness in supporting the COTAS than the bigger ones. It is still too early to evaluate results and see if COTAS may survive without basic public funding. A few can be considered successful and many others do not since there is not enough support from stakeholders for what they consider a suspicious public administration initiative. However, the COTAS are a notable leap forward to attain aquifer sustainable use after the problems derived from the early development stages. Their full success needs to also consider groundwater quality, since nitrates are increasing in many areas. However, this has to be developed in the future.

The COTAS are an interesting local solution to address groundwater problems in any case, even when extraction is less than recharge. However, COTAS have to carefully avoid promoting further development or selling technology to users.

Box 16. Groundwater users associations: Experience in Spain.

Eastern and Central Spain is semi-arid but with excellent conditions for human settlements and highly productive agriculture. Communal water regulating infrastructures and rules to share and distribute water flows exist from the Middle Ages, so there is a long tradition for community action. In Valencia, a farmer's jury solves irrigators complaints on the spot; it meets once a week, at least since 700 years ago.

The development of groundwater for irrigation by means of pumped wells started late in the 19th century and mostly in mid the 20th century. In some cases this was to contribute water to irrigators' communities, although the development was often carried out by individuals, or small groups sharing expenses. This led to a rather uncontrolled aquifer development, with scarce public regulation since after the 1879 Water Act this was considered a private affair (Garrido & Llamas, 2009). Groundwater development was, and is, an important boost to water supply, industry, and especially agriculture, with clear private and social benefits, although with the drawbacks associated to intensive development. Something similar happened in the volcanic Canary Islands (Box 6), where the rather expensive groundwater mining prompted the creation of societies by shares to confront costs of construction and for the periodical refitting needed to keep yields.

To try to cope with groundwater intensive development, preserve the benefits and correct drawbacks, groundwater was declared a public domain in the 1985 Water Act. This means that new groundwater developers need a concession from the corresponding Water Authority. Already existing groundwater users were given the option to exchange their rights for a concession, or to remain just as they were. However, for *overexploited* aquifers (after the Water Act terminology) there is the possibility of a formal declaration by the Water Authority, which means that all groundwater users must adapt to norms, reduce extractions, and constitute an association.

Groundwater users associations are publicly recognized entities for collective management of aquifers, with regulations inspired in the tradition of surface water communities. The Water Act encouraged their formation. Currently there are more than 1,400 groundwater users associations registered, and hundreds of others organized as private corporations. But these are mostly for sharing water and manage irrigation networks (Hernández-Mora & Llamas, 2001), and so they cannot be considered as true institutions for the collective management of aquifers, except a few ones, as commented below.

The top-down creation of groundwater users associations (CUAS), even the compulsory ones in the areas declared as *overexploited*, have being largely a failure (Aragonés, 1995). But the good example of the Llobregat's association commented below, and the need to solve problems, has favoured bottom-up initiatives after making known to users the aquifer functioning, the current situation, and the benefits from collective action to try to solve existing problems, as well as the possibility to get public funding to complement their own financial resources. Promotion and assistance have come mostly from the Spanish Association of Groundwater Users, a private entity supported by the already formed CUAS. Some CUAS (Vall d'Uixó, Mancha Oriental, Lomas de Úbeda, Poniente Almeriense), besides those of the Llobregat, have been successful in reducing groundwater abstraction and improving water use efficiency in irrigated fields. Currently 12 groundwater users associations have been formed and are active, or are close to start. A fast expansion is foreseen. Each association is tailored to the specific situation of their area. They are dominated by irrigation interests.

An important success are the CUAS that exist in the small but important Llobregat's Lower Valley and delta aquifer system (Box 2). The detailed hydrogeological studies carried out from the 1960s by the Public Water Administration were make known to groundwater users, who decided to cope with existing and foreseeable problems. As a consequence, in 1975 a CUAS was created (CUADLL), well before groundwater was declared a public domain (Galofré, 2000; Codina, 2004), in an area in which aquifer management was already being carried out. Currently the CUADLL is a public entity supported by their members, with a technical staff capable of carrying out studies and monitoring. Currently it receives funds from the Water Authority by means of contracts and assignments to carry out specific jobs. It has been effective in abstraction control, including water drainage from large underground infrastructures, in controlling sand quarrying, in the virtual cease of waste disposal, and in promoting corrective action, as well as in reducing total groundwater abstraction and protecting associates' groundwater rights.

The success of the CUADLL prompted the creation in 1982 of a CUAS in the Cubeta of Sant Andreu de la Barca, and another in 2008 in the Cubeta of Abrera (Box 2).

A distinctive characteristic of these three CUASs is the dominance of urban supply and industrial groundwater users, while in the others dominate farmers, except in Vall d'Uixó, where there is a mix.

After Hernández-Mora & Llamas (2001), some common keys for the CUAS success are the understanding of the aquifer and the problems, an observation network and easy access to data, the ability to articulate common goals, and the capacity to establish mutually accepted rules regarding resource access and use. A good complement is long-term view of water resources and the environmental implications. The CUAS's area of influence should be large enough to be able to articulate effective solutions to existing problems, although the ability to agree on common goals is increasingly difficult the larger the area is and when more than one administrative or political jurisdiction is involved. The participation of users or stakeholders with economic means and technical know-how (large water suppliers, industrial complexes, important farmers groups) facilitates the creation and effective operation of CUAS, besides the collaboration of the Water Administration technical staff. Trusted leaders that understand the problems and are able to communicate, to organize and motivate others to cooperate are important. Existing social capital and tradition for creating representative civil associations are important too. An important issue is the attitude of the Water Authority towards the users, and the mutual relationships, which are not always easy due to personal attitudes or conflicting goals. A frequent complaint of existing groundwater users is their small weight in the Water Authority governing boards, generally dominated by surface water representatives and officials, except in the Canary Islands, where they dominate.

9 COMMENTS ON CLIMATE AND GLOBAL CHANGE ON GROUNDWATER RESOURCES

Groundwater resources depend essentially on rainfall recharge processes in the upper layers of the land, besides surface water infiltration, which may be increasingly important the drier the area is. Climate, and consequently rainfall and other recharge variables, have been changing along the Earth's history, and more significantly for groundwater, in the last thousands of years, including the recent 16th century to early 18th century small ice age in Europe, although less noticeable in other areas (Mann *et al.*, 2009). Climate will change in the future as a combination of the poorly known natural trend and the anthropic atmospheric changes, which are also uncertain. Besides, there are important land changes such as big forest fires, forest destruction and efforts for afforestation, expansion and reduction of agriculture, expanding urban areas, . . . All of them contribute to global change, whose effects on precipitation recharge mechanisms and stream flow is still not well known. Results of modeling by using established climatic change scenarios predict that recharge will increase in some areas and aquifers, mostly in mid and high latitudes, and will decrease in other areas, mostly at low latitude and around the Mediterranean Sea. Some significant changes seem to show out already in some basins, but the causes are not well defined and probably these are mostly due to land cover and use changes.

Actually, large aquifers contain a large proportion of groundwater recharged in the distant past, some -but not always- in pluvial epochs during the Pleistocene (thousands of years ago). Anthropic effects are important and may have both decreased and enhanced recharge. In the Murray River Basin, in southern Australia, and in other areas of central USA (Scanlon *et al.*, 2009), the transformation of native forest into grassland in mid the 20th century has notably increased local recharge. This is not a blessing because it has accelerated the downward movement of large bodies of climatically-generated saline water in the unsaturated zone toward the underlaying aquifer, thus currently enhancing salinity problems downstream. Something similar happened probably in semiarid areas of Spain in old times (about the 17th century in the Monegros, in the northeastern area) with an impact not recorded, but probably explaining some rather saline springs and streams. The effect last until the saline body is depleted, although this may last decades to centuries.

10 CONCLUSIONS

Groundwater is an important part of the hydrological cycle, with quite different behaviour with respect to other components. In most cases this has clear advantages to obtain fresh groundwater in adequate quantities and with small temporal changes, and also to improve integrated water resources availability and management. But intensive groundwater development has also drawbacks, most of which can be known and anticipated, provided there are enough studies and monitoring, and these can be compensated. One of the most serious future drawbacks is groundwater quality deterioration, and these are only partly due to groundwater development, and depend on land use. Impacts on surface water are also important.

Social and private benefits from groundwater development are in most cases quite large and thus they may compensate drawbacks, except in a few, local situations, in spite of alarming news on groundwater level drawdown, reserves depletion and quality impairment. Many of them are the result of the hydrodynamic evolution in the mid- and long-term, and the associated water cost increase can be progressively dealt with the economic and social benefits obtained from the development, even in cases in which there is groundwater mining. But caution is needed in order to arrive at a new, hydraulical and social sustainable situation. Often groundwater is the cheapest local water resource, and in cases where it is not, it is often due to hidden subsidies or unaccounted costs for other sources.

However, almost unrestricted access to groundwater resources and lack of development rules, carried out by persons and entities not aware of aquifer properties, characteristics, quality constraints, and mutual interrelationships, has often led, and is leading, to problems, sometimes serious ones, but still with large reserves left and environmental damage that can be reversed, at least partly. To deal with this, and save what is a common asset, groundwater management, jointly with the whole water resources, land use and energy management is needed. This takes time, perhaps more than one or two human generations, but is achievable with a combination of public administration efforts and groundwater stakeholder involvement and co-responsibility. This last aspect can be developed through representative water users associations. Experience is still scarce but will probably grow fast, if knowledge is made available, there is political will, civil organizations are involved, and users recognize there is a common asset and heritage to be managed, defended, and make available to future generations, under ethical and moral principles. A mid- and long-term view is always needed, within a time framework which depends on aquifer size, relevance to Society, and environmental values at stake, considering both water quantity and quality issues.

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