Chapter 15
The Role of Groundwater During Drought

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Abstract Groundwater drought is a natural hazard that develops when groundwater systems are affected by drought, first groundwater recharge and later groundwater levels and groundwater discharge, that decreases. The origin of drought is a deficit in rain precipitation and that takes place in all the elements that comprise the hydrological cycle (flow in the rivers, soil humidity and groundwater). Depending on the deficit and duration of the drought this may affect all segments or not. This chapter analyses how drought influences and affects groundwater, which depends not only on the rain deficit but on some other parameters such as the physical properties of the aquifer, type of porous rock, aquifer dimensions and thickness of the unsaturated zone. Hydrological drought can be analysed using hydro-geological features and parameters such as piezometer levels, natural recharge or base flow. The usefulness of some indexes is presented here. The related concepts of water scarcity, overexploitation and groundwater mining are explained. This chapter reviews the importance and dependence of the different countries of the Mediterranean Basin on groundwater.

Background

Although there are many books dedicated to analysing droughts, not so many are focused on the groundwater system. In Tallaksen and van Lanen (2004), all the concepts related to hydrological droughts are reviewed, including all the segments of the hydrological cycle, flow generating processes, best estimation methods to describe and analyse drought periods, drought indicators and modelling. A whole chapter is dedicated to the human influences and the type of measurements that can be implemented to cope with drought phenomena. Peters et al. (2005) and Peters et al. (2006), analyse the performance of a groundwater drought in terms

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of reliability, resilience and vulnerability. New performance indicators that consider the relationship between drought frequency and severity are proposed. Propagation of droughts in the groundwater system, taking into consideration the spatial distribution is analysed for the Pang Catchment (UK), using modelled time series of recharge and hydraulic head.

Groundwater is an important issue in the Mediterranean Basin. The role of groundwater in the Mediterranean countries has recently been reviewed in MGR (2007) and in particular because drought situation and water scarcity are very frequent. The delayed or on some occasions inexistent influence of droughts on the groundwater system, makes this last one an ideal source of freshwater supply to alleviate and mitigate drought effects as has been pointed out by many authors. (Pulido, 1991). In Spain the Basin Drought Plans for each one of the riverbasins have recently been approved.

Groundwater and Drought

Groundwater in the Mediterranean Basin

The Mediterranean region with its 23 countries with a coastline, extends over an area of 8.5 million Km^2. The population is around 454 millions from the Mediterranean population the 33% is concentrated in these coastal regions and during the summer season the population increases substantially. The enormous extension implies a great variability not only on climatology and geology but in socio-economic and technological conditions too. The length of the coastline is 46,000 km, with 19,000 km belonging to islands. This long coastline must be remarked as groundwater salinisation problems are quite frequent.

Rainfall has an irregular distribution ranging as a mean from 1000 mm/year in the northern countries to values of 400 mm/year in the southern countries. Evapotranspiration values are very irregular too. Frequent situations of hydric stress are created by the combination of low precipitation and high evapotranspiration values, especially in the south. As a result, rivers are frequently ephemeral, hydrological regimes are hyperannual and recharge values to the aquifers very small (or even inexistent on the last decades), especially in those countries located in the Middle East and north of Africa. Aquifer behaviour is conditioned by these facts and creates important problems in relation to groundwater management especially in dry periods. Besides, for many countries, groundwater resources are the most important or even the only source of fresh water. A bad aquifer management may create serious harm not only in the present but for the future generations.

According to CWD (2006) and MGR (2007), in the Mediterranean region there are ten countries with a total population of around 100 million, with an availability of water less than 1000 m^3 per person and per year. Regarding this group of countries it is noteworthy that there are seven with a total population of 65 millions, Israel, Jordan, Malta, Tunisia, Algeria, Libya and West Bank and Gaza, in which the resources are less than 500 m^3 per person and per year. Of the total water resources for the Mediterranean countries, equal to 1,197 km^3/year, 317 km^3/year (26.5%) are groundwaters, and only 75.6 km^3/year are renewable groundwater resources (MGR, 2007).

Table 15.1 summarises the situation of different countries concerning groundwater use. There two sources of information in relation to those data, Margat (2004), and more recent data in CWD (2006), but only available for a small group of countries. The analysis is difficult because data from the first report sometimes are quite different from data from the second one.

Table 15.1 Main characteristics of groundwater in the different countries of the Mediterranean Basin. Data from Margat (2004) and CWD (2006)

COUNTRY	EXT (10^3 km^2)	POP. (10^6 in.)	TWR (km^3/y)	TGR (km^3/y)	GW% (%)	TGA (km^3/y)	NRA (km^3/y)
Spain	505.4	43.4	111.50	29.9	26.8	4.82	0.7
France	551.5	60.7	189.50	100	52.8	6.10	
Italy	301.3	57.5	191.30	43	22.5	10.40	
Malta	0.3	0.4	0.06	0.027	45.0	0.02	0.02
Slovenia	20.3	2	31.87	13.5	42.4	0.28	
Croatia	56.5	4.4	71.40	11	15.4	0.42	
Bosnia-Herzeg.	51.2	3.9	37.50	6	16.0	0.30	
Serbia-Monten.	102.2	8.2	208.50	3	1.4	1.00	
FYR Macedonia			6.40	1	15.6	0.20	
Albania	28.8	3.1	41.70	6.2	14.9	0.63	
Greece	132	11.1	74.25	10.3	13.9	3.56	
Turkey	783.6	72.6	231.70	69	29.8	6.00	
Cyprus	9.3	0.8	0.78	0.41	52.6	0.29	0.04
Syria	185.2	19	26.26	5.4	20.6	1.80	
Lebanon	10.4	3.6	4.80	3.2	66.7	0.40	
Israel	22.1	6.9	1.67	1	64.1	0.90	0.19
Gaza Strip	..	3.6	0.06	0.056	100.0	0.13	
West Bank			0.75	0.68	90.7	0.17	0.03
Egypt	1001.5	74	58.30	2.3	3.9	5.40	0.00
Libya	1759.5	5.9	0.82	0.5	61.0	0.65	3.63
Tunisia	163.6	10	4.57	1.55	33.9	1.40	0.18
Algeria	2381.7	32.9	19.00	7	36.8	3.5	0.41
Morocco	446.6	30.2	29.00	10	34.5	2.63	
Jordan	88.8	5.4					

EXT: Extension; POP: Population (2005); TWR Total water resources; TGR: Total groundwater resources; GW%: Groundwater as % of TWR; TGA: Total groundwater abstractions; NGA: Non-renewable groundwater abstractions

According to Messaoud (2006) in CWD (2006), Algeria, with 30% percent of its territory being desert, has 19 km^3/year of total water resources. Of this amount, 7 km^3/year are groundwater. Surface water resources are concentrated in the northern part. Groundwater abstractions are equal to 1.7 km^3/year in the south of the country, (which is the Sahara Desert), and 1.8 km^3/year in the north, the country has been under a serious drought over the past 25 years that has reduced the total resources to 10 km^3/year.

In Tunisia total resources are 4.57 km^3/year and groundwater resources are about the 50% of this amount.1.55 km^3/year of the groundwater resources are stored in shallow aquifers, which according to Hamzha (2006) in CWD (2006) are completely overexploited. The rest isstored in deep formations.

In the case of Cyprus, according to Margat (2004), more than 50% of the total resources is groundwater. According to Artemis (2006), in CWD (2006), groundwater abstractions are equal to 290 Mm^3/year, (110 Mm^3/year according to Margat, 2004). The insular condition of the country together with the excessive groundwater abstractions, are creating an unsustainable situation due to saline intrusion. Besides this, precipitation has decreased by 15% in the last thirty five years (see Artemis, 2006, in CWD, 2006).

Groundwater abstraction in many aquifers in countries such as Spain, Israel, Palestine, Malta and Cyprus, are exceeding the recharge rates. Some other countries such as Tunisia, Algeria, and Libya are managing fossil aquifers following a mining strategy, because recharge is almost zero. This aspect is reviewed later in this chapter.

By way of summary it can be said that groundwater is a very important issue in the Mediterranean basin, especially because it represents a high percentage of the total water resources. In some regions it is the single source of fresh water and due to the fact that precipitation, as in the case of Cyprus, has been reduced dramatically in some countries. Nevertheless, is necessary to refine current knowledge on the hydro-geological behaviour of aquifers and to develop specific strategies to manage groundwater use, especially in those countries where groundwater is a non renewable resource and where aquifers are shared between nations, such as the case of the Nubian Sandstone Aquifer (in Egypt) that will be mentioned later.

Response to the Hydro-Geological Systems to Drought

Groundwater and surface water belong to the same and unique "Cycle of Water". Whenever there is a deficit in rainfall precipitation, a deficit in recharge occurs, the water table is depleted and groundwater discharge through rivers and springs decreases or stops. Although this is true, it is not always a climatological drought that triggers a hydrological drought, especially if the groundwater system is considered. The response of an aquifer to drought is strongly dependent on the type of aquifer, hydraulic parameters (transmissivity, storage and specific yield), recharge, and depth of the saturated zone, flow paths and the size of the aquifer.

Aquifers with thick, deep unsaturated zones and large catchments are not affected by short drought periods, or even if they are, the aquifer response is subdued and delayed in time. This fact gives groundwater an opportunity as a source of fresh water during periods of scarcity and has conditioned the fact that the more valuable crops are irrigated frequently with groundwater or in mixed systems (Llamas, 2004).

The Influence of the Type of Aquifer

Basically there are two major types of aquifer, those with intergranular porosity and those with porous formations during a solution process. In the first type water is contained in pores between the grains of a detrital rock or sediment. In the second type, the so-called carstified aquifers, water is contained in the secondary porosity of the rock, produced during a process of carstification. Behaviour and drought management has to be completely different in one or in other.

Detrital aquifers are formed mainly by sands, clays, silts and conglomerates. Frequently these types of aquifer are formed by none consolidated and recent sediments, such as those coming from alluvial plains or alluvial fan depositional environments and for this reason, are frequently non confined aquifers. In the Tagus Basin in Spain both types of aquifer are represented.

Aquifers in the Tagus River Basin

The Tagus basin (see Fig. 15.1) is a large sedimentary depression flanked by ranges. Aquifers at the head of the basin are formed mainly by cretaceous and Jurassic limestones (brick symbol in Fig. 15.1); while a detrital tertiary and very thick aquifer is developed around the Madrid Basin (dot symbol in Fig. 15.1). The tertiary aquifer, "Tertiary Aquifer of the Tagus River Basin", extends over a surface area of 5,600 Km^2 and is considered to be more an aquitard than a real aquifer. It is formed mainly by interbedded clays and sands. Aquifer thickness is around 3,000 m in the very centre of the basin. The huge thickness, the big size and the 40 m deep unsaturated zone (on watershed) make this aquifer not sensitive to rainfall deficit.

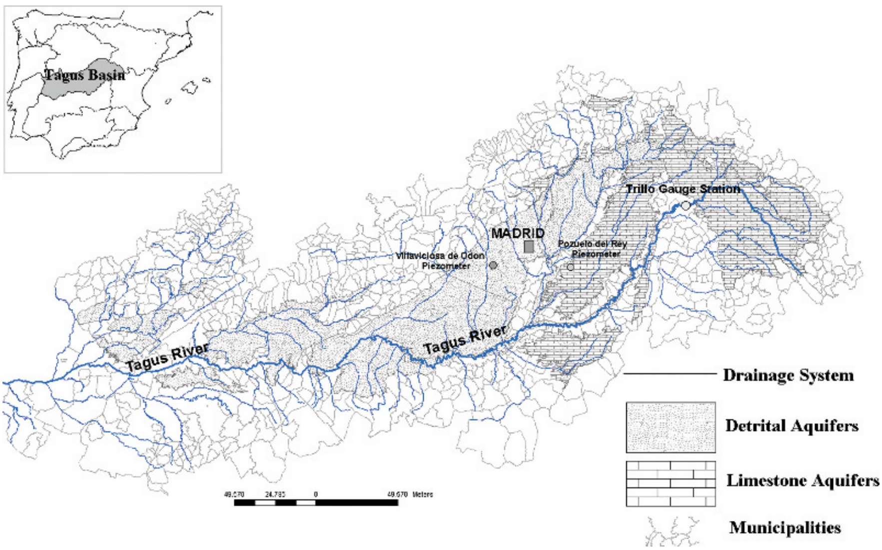

Fig. 15.1 General Tagus River Basin situation. Aquifers and locations mentioned in the text

Typical transmissivity given by different authors ranges from 10 to 100 m^2/day, but according to recent pumping tests carried out by the Basin Water Authority in 2006, this value only occasionally exceeds 40 m^2/day. Although the hydraulic parameters are not very good from a hydrogeological point of view, the huge sediment thickness makes this aquifer quite interesting for drinking and irrigation water supply purposes.

According to the conceptual model that was proposed by Llamas and López Vera (1975) (see Fig. 15.2), under natural conditions, recharge (around 40 mm/year) came mainly from rain infiltration and the discharge occurred through underground drainage towards the main rivers. Nowadays, discharge is produced mainly by pumping, especially in dry periods, and although it is not clearly demonstrated is very likely that the rivers are now effluents rather than influents.

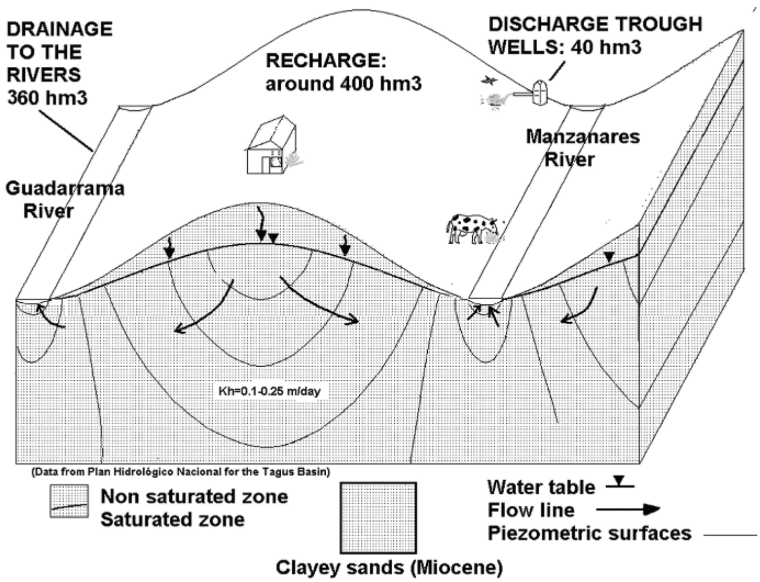

Fig. 15.2 Conceptual Model for the Tertiary, detrital aquifer of the Tagus River Basin, for almost an unperturbed situation

The thick unsaturated zone makes a drop of water take a period of up to a hundred years to travel across the unsaturated zone. The effects of climatological droughts are attenuated or even imperceptible (Casado, 1998). This kind of aquifer is affected more by drought due to the increase in pumping rather than the effects of the drought itself. The delay response of the aquifer to the yearly recharge, drought or even discharge offers an opportunity to manage the water supply whenever there is a lack of surface water.

The public company, Canal de Isabel II, manages the Madrid System water supply and uses the aquifer as a strategic source of water supply during dry years. Moreover, to supply the almost 6,000,000 million inhabitants of the city of Madrid, groundwater is pumped from this aquifer in drought periods (more or less one every four years) to help urban water surface supply. In fact, recently in 2005, from March 2005 to March 2006, one of the most dry years in the last thirty years, around 50 Mm^3 has been pumped.

Groundwater Drought Analysis

Drought is a complex phenomenon and it is necessary to decide, when analysing drought propagation over the groundwater system, which are the relevant parameters or characteristics that are suitable to describe it. It must be pointed out that are many ways of describing a drought; different ways may lead to different conclusions, and results are conditioned by the availability of data (recharge, discharge and piezometric records). Long time series are needed and frequently they are not available, especially when looking into the groundwater system.

Indices are threshold levels of time series below which a groundwater system is regarded to be under a drought. For some authors an index, that is a single value, is not much more useful than raw data for decision making (cfr. Hayes, 2006). Although an index helps to define when a drought is established there are some other questions that need to be answered: which is the start, the end, the total duration and the severity of the drought (Rees et al., 2004), spatial distribution or occurrence probability, or even the vulnerability of the system. Groundwater drought analysis is not frequently included in drought analysis; and non-specific indices have been derived. Usually it is possible to analyse base flow to rivers and piezometric or even recharge records in the same way as other hydrological data are considered. Some examples are presented.

The Recession Curve of the Hydrograph

Rees et al. (2004) describe the calculations and procedures to develop flow duration curves, (from which the low percentiles are selected), base flow separation techniques from which is possible to calculate “base flow indices”, and the classical analysis of recession curves of the hydrograph that can be plotted.

As an example the situation in the Trillo gauge station (E-3005) over the Tagus River (see the situation in Fig. 15.1) is presented in this epigraph. Trillo is located upstream, in the head of the Tagus River. The river at this point drains 1,000 km^2 of calcareous aquifers and 90% of the discharge is base flow (DGOH, 1998). There is a significant difference in seasonal flow discharge. Winter discharge may be more than ten times that of summer discharge.

Discharge at this point is relevant because there is a nuclear power plant that needs 1.5 m^3/s for normal operations. The year 2005 was a very dry year and it was necessary to predict how groundwater discharge was going to evolve under a very long dry period. It was necessary to asses for how long the necessary flow for the plant would be guaranteed.

In order to analyse the different dry periods in the historical records, flow duration curves were prepared on a monthly basis (see Fig. 15.3). Figure 15.4 shows the hydrograph on a monthly basis from 1955 to 2005. The percentile 90 was used to choose droughts in the record (grey coloured line). This line represents the flow that was surpassed in 90% of the months of the 73 years. Seven major drought events were analysed and the correspondent recession periods were studied. Dry periods are marked on the graph. It can be seen that 2005 was the worst year in whole period studied. It is a remarkable aspect to mention that for some reason, discharge is lower from the 80 s onwards, the peaks are smaller and less frequent.

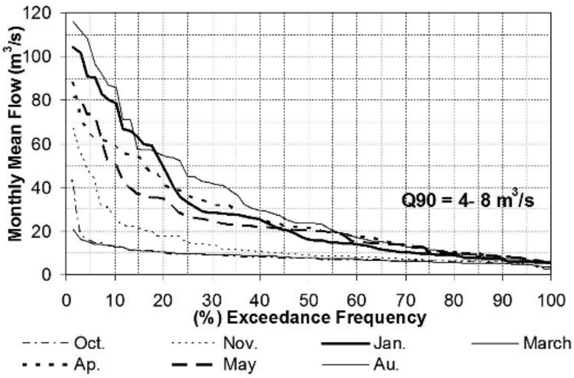

Fig. 15.3 Flow duration curves, made on a monthly basis for a historical serie of 73 years. To avoid a mesh of lines, only have been represented 7 months

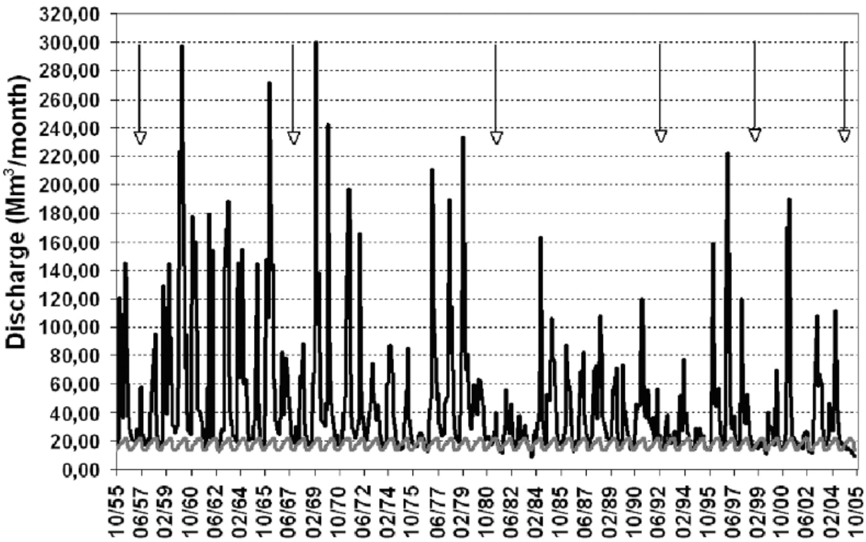

Fig. 15.4 Historical discharge in Trillo gauge station E-3005, from 1955 to 2005. Q90 is also shown in grey. Major drought events are marked with an arrow

It is well known that groundwater discharge to rivers follows (15.1) an exponential law (Custodio and Llamas, 1983, p.392),

$$q = q^{\circ} * e^{-\alpha t}, \tag{15.1}$$

Where q is discharge, q° is the initial discharge when the recession begins, α is a parameter that depends on aquifer transmissivity and specific yield. Plotted on a logarithmic base, the recession flow period can be drawn as a straight line (see Fig. 15.5). Once Alfa is known it is possible to calculate the volume that will be drained along a period of time "t". In Fig. 15.6 it can be seen how the aquifer would continue to drain enough water for a period of 300 days without any rainfall.

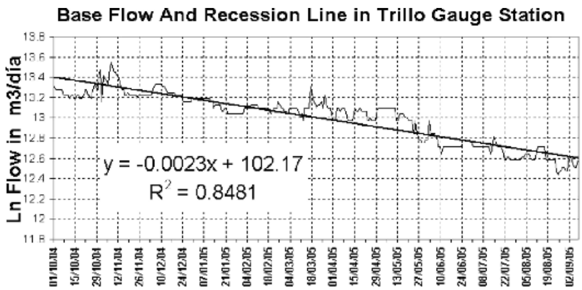

Fig. 15.5 Recession lines for the flow in Trillo along the hydrological year 2004/05 and the adjusted linear function

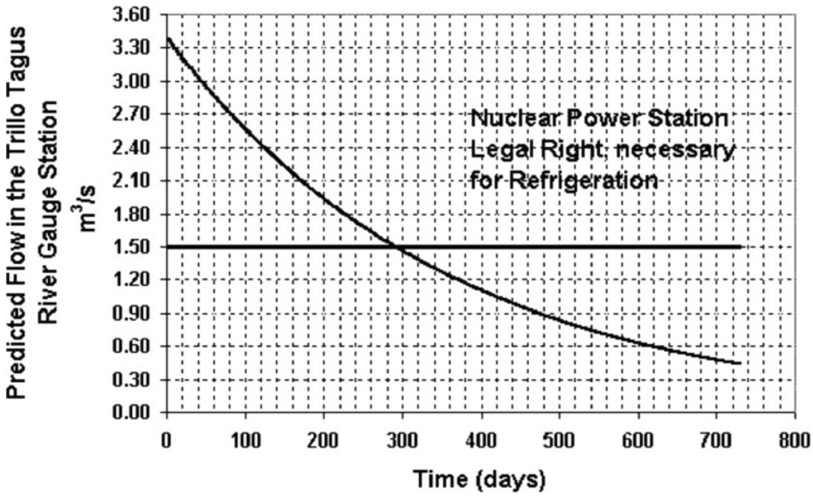

Fig. 15.6 Predicted base flow in Trillo, from a initial flow of 3.5 m^3/s

Piezometric State Index

A different type of index that has been used to define a drought in any element of a hydrological system is the "State Index" (Pi) (see CHJ, 2005). This kind of index could be used for piezometric levels. This index considers media, maximum and minimum values of a historical trend and is calculated according to the expressions:

$$(a)Pi = \left[\frac{1}{2}\right]\left[\frac{Vi - Vmin}{Vmean - Vmin}\right] \quad (b)Pi = \left[\frac{1}{2}\right]\left[\frac{Vi - Vmean}{Vmax - Vmean} + 1\right]$$

When Vi$<$V Mean When Vi $\geq$ Mean

Where, Vmean: Mean of the historical record, Vmax: Maximum value of the historical record, Vmin: Minimum value of the historical record

This index gives an idea of how a single measure is related to the mean, maximum, and minimum values of the historical record. The index varies from 0 to 1. Normal situation is from 1 to 0.5. Caution from 0.5 to 0.3, danger from 0.3 to 0.15 and below 0.15 to 0 is the historical minimum. This approach seems to be suitable for some aquifers but has no meaning at all in others.

Groundwater levels are measured through piezometers. These are small-diameter cased wells, screened just at the depth of interest.

We present two examples of two piezometers located (see Fig. 15.1) in the Tagus Basin. One is located in the Tertiary Aquifer and the other is situated on a limestone aquifer. Results obtained are completely different in each case. In both cases the piezometer state index has been calculated.

Figure 15.7 shows a piezometer record from the aquifer of Madrid in Villaviciosa de Odón. As it was mentioned previously, this aquifer with a thick unsaturated zone is more sensitive to exploitation than to droughts. The record further reflects the intensive pumping that began in the 1992 drought, rather than the drought itself. From 1992 until now the aquifer is continuously under a historical minimum. It is clear than in an aquifer like this, this kind of index is not at all useful. The graph is continuously showing exploitation but not drought.

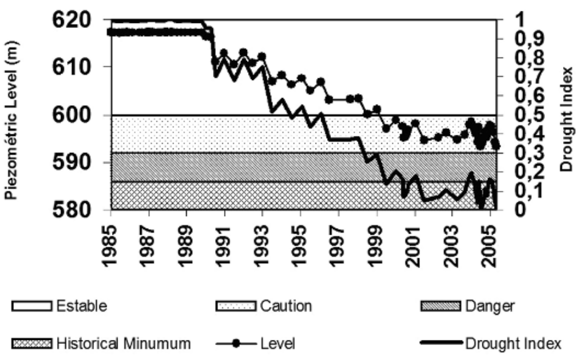

Fig. 15.7 Piezometric record and piezometric index for a piezometer in the tertiary Detritical Aquifer of the Tagus Basin

Figure 15.8 presents the same kind of graph for a piezometer located at the head of the Tagus Basin in a limestone aquifer. Carstified phreatic aquifers, with high transmissivity, tend to have a quick response in a climatic event, high precipitation or a drought period. They are more sensitive to periods of low recharge. The very dry period in Spain from 1992 to 1995, is clearly marked. On this kind of aquifer, drought periods are well identified on piezometer records and the state index seems to be suitable.

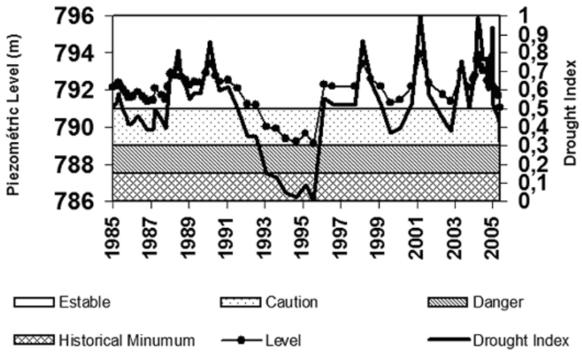

Fig. 15.8 Piezometric record and piezometric index for a piezometer located in Pozuelo del Rey on a limestone aquifer in the Tagus Basin

Natural Recharge

A very important concept related to the hydrological drought in an aquifer is the concept of "natural recharge". Lerner et al. 1990 defined this concept as "the downward flow reaching the water table, forming addition to the groundwater reservoir". Recharge is not a constant but a variable, although the complexity of the measurement makes many managers consider it as a fixed figure. Recharge is a variable both in space and time. The immediate factor responsible for a groundwater drought is the decreasing recharge rate that may follow, a low soil humidity subsequent to a low precipitation period. It is possible to study drought periods on recharge records. Although the main problem related to this is the enormous difficulty to measure this parameter, it is possible to conduct recharge studies, using different kinds of technique.

As an example, some recharge calculations were done in Albacete (Spain) using borehole tensiometric techniques, during 1996, cfr. Casado (1996), see Fig. 15.9. The graph shows hydraulic gradient, unsaturated hydraulic conductivity and recharge, which is the product of both. These calculations were made at the bottom of a 300 cm profile. A negative flux means downward flow, while a positive flux means upward flow. Precipitation was 413 mm, distributed in six or seven major events. Results show how recharge ranged from 0.4 mm/day to less than zero (this is negative recharge or evaporation). The recharge on this experimental site was estimated to be around 50 mm for this specific year.

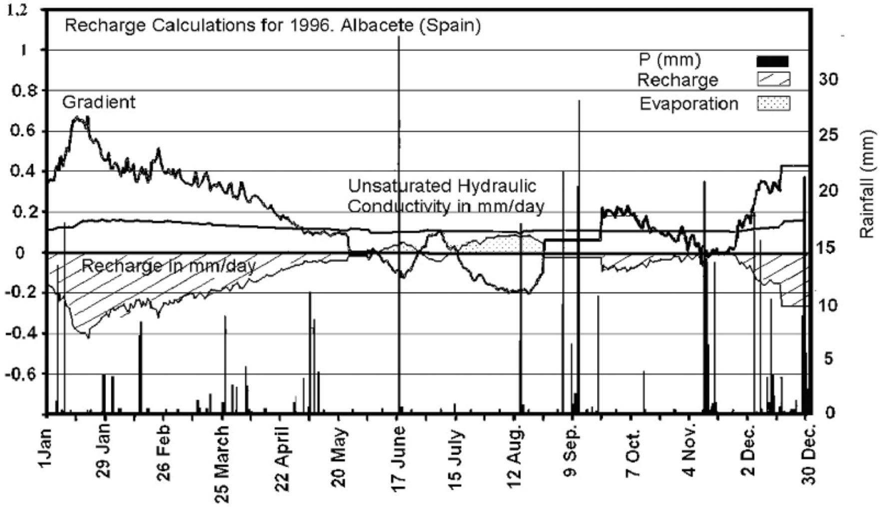

Fig. 15.9 Recharge measurements for the Aquifer Mancha Oriental (Albacete, Spain)

Some Groundwater Drought Related Concepts: Overexploitation, Water Scarcity and Groundwater Mining

Overexploitation

It is usually considered that an aquifer that experiments negative effects as a result of water abstraction is overexploited, or in other words, that the recharge rate is less than the pumping rate. This term has been specifically defined in the Spanish Water Act (1985) as the consequence of an aquifer exploitation to values higher or very close to the mean annual renewable resources of the aquifer or when the quality of the aquifer seriously deteriorates as a result of the exploitation. Custodio (2002) concludes that the negative effects observed on an aquifer (drawdown, worsening of water quality, decrease in discharge rate to springs and rivers, change in the river-aquifer relationship, dry up of wetlands) do not necessary imply that water abstraction are exceeding recharge rates. An increase in the abstraction rate or even a decrease in the recharge rate creates a transient situation inside the aquifer, that modifies the water head and that gradually stabilises when the aquifer discharge changes to compensate the change undergone. The transient period depends upon storage, transmissivity and aquifer dimensions.

The question to answer is to what extent can a region's groundwater resources be exploited without unduly compromising the principle of sustainable development? (cfr. Ponce, 2006). According to this author, a good definition of "Sustainable development" is the development that meets the needs of the present without compromising the ability of future generations to meet their own needs. In Foster and Louck (2003) the situation is analysed of some aquifers in the Mediterranean that are being used following a mining strategy policy, although it is recognized that further analysis and studies are required, this ground water is the driving force of the economy of vast regions.

Groundwater Scarcity

Groundwater abstraction without planning may initiate a hydrological drought or even a permanent situation of water scarcity. The case of the upper Guadiana Basin and Aquifer 23 in Spain is a good example. The Mancha Occidental Aquifer (aquifer 23), is a calcareous carstified shallow aquifer that extends over 5,500 Km^2. Flat topography, interactions between shallow limestone aquifer and rivers, gave rise to many riverine wetlands (see Figs 15.10 and 15.11), like "Las Tablas de Daimiel". Natural recharge was calculated to be from 200 to 500 Mm^3/year, depending on the yearly rainfall. Discharge from the wetlands was mainly by evapotranspiration.

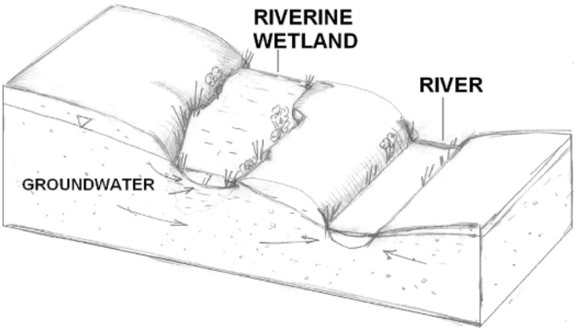

Fig. 15.10 A riverine wetland, relation between the river and the groundwater feed wetland

Due to changes in the aquifer land use from dry-farming to irrigation farming, irrigated land increased from 200 km^2 in the 70 s to 1300 km^2 in the 80 s, leading the region to a situation of permanent water scarcity. The irrigated farming was done mainly under private initiative and groundwater irrigation fed systems. In twenty years an amount of 3,000 Mm^3 was pumped from the aquifer, with a peak of 600 Mm^3 in 1988. Piezometric levels (see Fig. 15.10) decreased from 20 to 50 m in many places, the result being that many wetlands disappeared (like "Los Ojos del Guadiana") and some others were seriously damaged as is the case of Las Tablas de Daimiel, which was already a National Park. The discharge of the aquifer no longer takes place by evapotranspiration. It seems that this figure has been reduced by 150 Mm^3/year, (cfr. Cruces et al., 1997).

The total surface area of wetlands was around 10,000 ha in 1970, and nowadays is more or less 2000 ha (cfr. De la Hera, 2003, p.172).

Groundwater Mining

Groundwater systems without recent recharge are quite common in the Mediterranean basin. Drought facts are irrelevant for such type of unit but groundwater use is crucial for the survival and socioeconomic development of such countries.

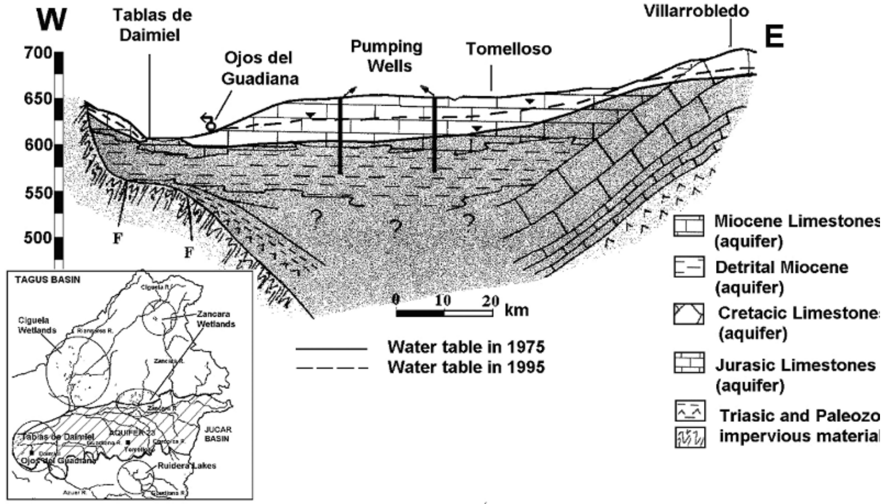

Fig. 15.11 Cross section of the Aquifer Mancha Occidental System. Mod. From García and Llamas (1994)

Groundwater management in this kind of aquifer implies "mining of the aquifer storage reserves" (cfr. Foster and Loucks, 2006), and should be undertaken following some specific strategies, legal strategies (developing legal groundwater codes, preparing groundwater abstraction right systems, that treat the aquifer as public property, full participation of users, or concern campaigns) and the use of some key management tools such as improving knowledge, or developing numerical models that help to asses the mining strategies. One of the most important groundwater basins in the world is the "Nubian Sandstones Basin" (cfr. Bakhbakhi, 2006) that extends through Egypt, Libya, Sudan and Chad.

This is a complex system with confined and unconfined units. Total storage is around 520,000 km^3. Water quality is variable and the salinity ranges from 500 ppm to hyper saline water. Groundwater exploitation has increased steadily since the 60 s, from this time 40,000 Mm^3 have been pumped and as a result general groundwater drawdown has been 60 m. Traditional wells and springs have been replaced by deep boreholes.

Another similar example of the same situation is the North Western Sahara Aquifer System that extends over 1,000 km^2 in Algeria, Libya and Tunisia. Natural recharge is around 1 mm/year and groundwater is used through 8800 wells, springs and boreholes (6,500 in Algeria, 1,200 in Tunisia and 1,110 in Libya).

Drought Effects on Groundwater

Some of the negative effects of drought on groundwater have already been explained. Drought may have a direct influence on the groundwater system, decreasing the recharge rate so the water table is depleted, but usually the immediate effect of a dry period in many aquifers is a result of pumping.

According to Bachmat (1999), analysing the 1999 drought period in Israel, the effects of drought on groundwater were mainly two: 1) The shortage on the recharge rate 2) The second was the drastic increase in groundwater pumping. Other relevant effects were the lack of fresh water for artificial recharge and the increase in salinization of the wells.

Coastal Aquifers

An important issue that should be taken in account is that whenever groundwater is pumped on a coastal aquifer in hydraulic connexion with the sea, the created gradients may induce the entrance of saline water in the aquifer. Fresh and saline water are mixed in a more or less thick zone called "zone of saline encroachment" (cfr. Fetter, 1994, p.368). Saline water as is denser than fresh water penetrates the costal zone below the fresh water and the contact between them can be sharp or may be enlarged in a thick mixture area, in which salt concentration decrease towards the continent. The shape and thickness of this mixture zone is dependant upon aquifer type, geometry and parameters, seashore and tidal conditions. Any increase in the pumping rate will make the intrusion to penetrate deeper on the continent. This evolution is called "aquifer salinization". On phreatic aquifers, the intrusion propagates slowly and is possible to foresee on time if proper indicators are used, while on confined aquifer, intrusion is fast and difficult to be monitored. It is not possible to avoid a certain degree of salinization whenever a coastal aquifer in relation to the sea is pumped and this fact has to be keep in mind in order to make a good management.

Piezometric networks in coastal aquifers should monitor piezometric levels and some chemical indicators (Cfr. Custodio and Llamas, 1983), such as chloride concentration, relation between rMg^{+2}/rCa^{+2} and $rCl^{-}/r(CO_3H^{-})$. In general an increase in the chloride content or in the relation, rMg^{+2} rCa^{+2}, is a good index of saline encroachment. The relation $rCl^{-}/r(CO_3H^{-})$ is about 0.1 to 5 in continental waters and from 20 to 50 in the sea.

Groundwater Measurements

The delay or inexistent effect of dry periods in the underground part of the hydrological cycle makes groundwater a source of fresh water available whenever there is a lack of surface water.

Techniques like drilling the so called "drought" wells are widely used. In Spain in the 2005, the Jucar Basin Water Authority successfully drilled thirty "SOS wells". In the 1992 drought the Spanish Government undertook a series of groundwater-based measures to increase water resources. According to Santafé (1996), the central government drilled a total amount of 268 wells, with a total abstraction capacity of 16,266 l/s.

Another technique is the artificial recharge of aquifers. In periods of surface water surplus, aquifers can be used as an additional element of the system infiltrating water through wells or ponds. Although the techniques required are complicated and not applicable always and everywhere, this technique is being used very successfully in Israel or in some parts of Spain as in the Aquifer of Los Arenales in Segovia.

It is necessary to improve:

– The level of knowledge. Usually managers invest most of the budget in surface water studies, while little effort is made on hydrogeological research. This research should be conducted during normal climatological periods in order to be prepared for a situation of drought stress.
– The integrated management of ground and surface water. The combined use of surface and groundwater has been carried out successfully in many places all around the world, but requires specific models that consider groundwater too.

The Integrated Management of Ground and Surface Water

The integrated management of ground and surface water, considering both quality and quantity, is essential for the general interest of the users and inhabitants of the territory, whose resources should be considered jointly to acquire the best water use and to achieve a sustainable use of the water. The general goals should be to reach the good ecological status of the water body, to satisfy all the water demands, to find an equilibrium between the regional and sectorial development, increasing and protecting the quality of the water resources, in equilibrium and harmony with the environment and other natural resources. The main objectives mentioned previously are sometimes complementary goals while others are alternatives. In practice, uses and water demands, infrastructures, water reservoirs, aquifers, and the exploitation rules of the system together comprise a whole system and for these reasons the general rules of analysing systems can be applied.

In the case of hydraulic systems, there are highly developed techniques for their analysis. Some systems can present difficulties, due to the complexity of characterizing certain elements, as the aquifers, or in the case when it's necessary to coordinate many exploitation rules.

It is necessary to respect the principles mentioned previously in order to maximize the resources. The first task that should be accomplished is to establish the geographical territory of each system and afterwards to define the different elements that constitute the whole system.

On one hand aquifers are part of the natural elements that constitute the system, just as rivers, lakes and wetlands that together are the natural resources of the system under a natural regime. The natural cyclical behaviour is different in all of them due to the cyclical period of time of each. Because of these differences between them it is necessary to simplify the system in order to treat all of them together.

On the other hand it is necessary to characterize hydraulic infrastructures (reservoirs, channels, water tanks, impulsions, conductions) that together with the rules of exploitation derived from the existing water demands, make it possible to establish available total resources.

The models chosen in each situation to simulate the system and prepare the water balances, will be imposed by the relative weight of the different system elements and their relation with the water demands.

When the weight of the surface resources is higher in the system than groundwater resources the models are usually made on a monthly basis. In some other situations the monthly basis is also used but then is necessary to use additional specific models to simulate groundwater flow.

Water supply to demand must be characterized through the following parameters:

- Volume of water supplies on a yearly basis and with temporal distribution. Quality conditions that will be required.
- Degree of guarantee for the different uses.
- The net consumption or the part of the water supply that will not return to the system
- The annual volume of the return, and its temporal distribution. The envisaged quality, before any treatment is done.

The way in which demands are satisfied from aquifers and reservoirs are the exploitation rules and are dependent on the resources, (amount, temporal distribution, aquifers, pipes, and other infrastructures. Experiences and models show that for each system there are some specific rules that are the most adequate to reach an optimum.

Results, for example, show that in a system the first uptake of water should be done in such points where if water is not taken will run off out of the system. In the cases of the aquifers, if there is a calcareous aquifer and a detrital aquifer, is convenient to pump water first from the carstified aquifer and second from the detrital aquifer.

Nevertheless, water management and exploitation involves not only technical, physical, ecological, and quality aspects, but social, economic and political criteria too.

Exploitation system analysis is a task that has to be done during the planning processes and consists of an analytical study that helps the manager in the decision-making process and to identify and select alternatives from a great number of variables in the system.

It has to be done with a logical and systematic approach, in which hypothesis, objectives, and criteria are clearly defined in order to help the manager to improve the knowledge on the aquifers, reservoirs, demands, exploitation rules, behaviour of the system and interconnections between subsystems.

A systems analysis procedure should be accomplished following these steps:

- Problem definition
- System identification and acquirement of data
- Definition of goals and time steps
- Quantitative and quality measures

- Alternatives
- Evaluation and selection of the best alternatives
- Checking, update and feedback.

A system is conditioned by multiple technical, economic, and legal factors that are self-limiting. Non-consideration of this fact may lead the manager to idealistic solutions that are far from reality. Some authors do not consider legal aspects, water property rights, or even use conditions before analysing system solutions to the system exploitation problem. This situation makes it quite difficult to integrate certain systems, such as the aquifers, on the general exploitation systems.

Another factor to be considered in a whole exploitation system is that there may be many actors involved in water management: Central state agents, usually the decision and law makers and the users, public or private, (some of them individuals, others water users communities). There are also local and regional administrations that take part in the construction, financing, exploitation and management of infrastructures. The principle of cost recovery is not regulated on a homogeneous basis so the result is that the application creates some results contrary to an efficient water use.

In Spain a new water act was implemented on 1985, this law meant a change in the previous trends. One of the main achievements of this regulation is that it declared water as a public good, the previous law stated that groundwater was private. This law established the so-called "Libro del Registro" in which all the waters rights should be included. As there were some legal groundwater rights previous to the 1985 law, a section called "Catálogo de Aguas Privadas" were included, which includes private groundwater rights.

Considering the aquifers in the system, analysis may be conducted in many ways, but all of them have a certain degree of difficulties; some of them require a long time, others a longer period of time and more human and economic resources: The present difficulties are:

A better knowledge of the content of the records, or "Libro del Registro", in order to analyse what the total recognized legal volume of groundwater is necessary. Not many researchers have conducted this analysis, and some the results of the works undertaken to date are sometimes unrealistic.

It is necessary to evaluate the effects of groundwater exploitation, using technical and economic data, in order to evaluate what the effect of implementing a new and different groundwater abstraction regime would be. This new regime would obtain different benefits and would affect new beneficiaries, different from those of the past. In any case, affections to existing rights will have to be considered, as well as the costs of modifying or eliminating the current ones.

Parameters that are most commonly used to measure reliability and performance of a system are guaranty, vulnerability and resilience (Cfr. Hashimoto et al., 1982). Guaranty gives an indicator of the frequency of the failures that a system can suffer. Traditionally this concept applied to the hydraulic resources exploitation systems, refers to the measure of the ability of those systems to satisfy demands in a certain period of time.

In recent years many different ways have been suggested to calculate this parameter. None of them are universally accepted. In Spain, a good example are the different criteria used on the different Hydrological Basins' Plans or in the Libro Blanco del Agua (cfr. MMA, 2000). So the criteria used to measure guaranty are basic for the system analysis procedure.

Vulnerability is an index of the seriousness of the failures. Resilience is an indicator of the duration of the failures.

A good management policy will try to minimize resilience and vulnerability and will try to maximize guaranty. If resourses are scarce in relation to demands, not all the parameters can be optimized, so if one of them improves the others become worse.

An conservative operation policy will try to diminish the vulnerability of the system reducing guaranty, and will increase the resilience of the system with small failures. A risky policy is the one that by increasing the temporal guaranty will reduce the resilience thus increasing vulnerability.

Conclusions

1. Although groundwater and surface water take part in the same and unique "Cycle of Water" and a deficit in precipitation may produce a groundwater drought, the delayed and attenuated response that the groundwater system has, makes aquifers a very good source of fresh water during drought periods.
2. Groundwater is very important in most of the Mediterranean countries, being almost the only source of fresh water supply for some places like deserts or countries like Palestine.
3. Aquifer exploitation under a sustainability management condition requires an improvement in investments and knowledge. Monitoring networks need to be implemented, to control both quantity (piezometers and gauged springs) and quality. The current recharge rates need to be better estimated.
4. It is necessary to include the groundwater system in the basin's drought plans. The same type of analysis that is usually conducted to study hydrological drought can be applied to historical groundwater data, such as piezometer records, spring flows, base flow, and recharge rate records.
5. Drought affects different aquifer types in different ways. Selecting drought indices related to the groundwater systems should be done carefully. Aquifers with a thick unsaturated zone may not be affected by dry conditions at all. On the contrary, carstified shallow aquifers may respond quickly to a drought. In this type of aquifer, a selected piezometer could be a good tool to monitor drought.
6. There are many aquifer systems in the Mediterranean basin that do not recharge at all, or recharge is very small. These hydrogeological units are considered to be "fossil aquifers". Management of these aquifers needs to define what sustainable development is in each case. Sustainability does not necessary imply

water abstractions equal to the recharge rates. For some basins and countries a mining strategy may be adequate, although it is recognized that stronger efforts are necessary to understand the natural systems better, to improve regulations, to improve user coordination, to ensure coordinated management between the countries affected.

7. The main effects of a rainfall deficit in aquifers are: Replenishment of the groundwater table, diminishing of spring flows, increase in water salinity. The effects of drought in detritical aquifers with thick unsaturated zones may be simply an increase in the pumping rate.
8. Groundwater is a strategic resource of freshwater during dry periods. Drought wells, artificial recharge and mixed supply ground and surface water are alternatives to be implemented on drought management protocols.
9. The integrated management of ground and surface water, considering both quality and quantity is necessary in hydraulic system analysis. Uses and water demands, infrastructures, water reservoirs, aquifers, and the exploitation rules of the system together make up a whole system. General rules that include aquifers as one more element of the system can be applied.
10. The analysis of the system taking into account the aquifers may be conducted in many ways, but all of them have difficulties, including the following:

    – Gaining better knowledge of the content of groundwater being used legally, considering both the spatial and temporal distribution.
    – What is the real volume of groundwater used.
    – It is necessary to evaluate the effects of groundwater exploitation, technical and economic data, in order to evaluate what the effect of implementing a new and different groundwater abstraction regime would be.

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