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CHAPTER 8
Drought as a catalyser of intensive groundwater use

J.A. López-Geta [(1)] & J.A. de la Orden [(2)]
Geological Survey of Spain (IGME), Madrid, Spain
[(1)] *lopez.geta@igme.es*
[(2)] *ja.delaorden@igme.es*

ABSTRACT: Drought is a climatic phenomenon that occurs all over the world with sometimes catastrophic effects on the populations affected. The lack of water caused by drought may lead not only to great economic loss but also to health risks, and so drought must be approached by the international community as a matter of the greatest concern. This chapter, after briefly examining the main concepts related to drought and the different types of effects that may occur, highlights the need to develop reaction plans to situations of drought. An analysis is made, and examples given, of the fundamental role played by groundwater during such periods. Indeed, groundwater often becomes a vital water source to alleviate the problems that arise during drought. A number of measures to optimise the use of groundwater is proposed. The opposite effect, namely the role played by drought in triggering the intensive use of groundwater, is also discussed. This aspect is significant because the extraction of groundwater frequently continues as a backup source of water after the actual drought has ended.

1 INTRODUCTION

Today, water is one of the assets most highly valued by society. This is reflected by the constantly increasing demand, by all sectors of society, for a water supply that is sufficient both in quality and quantity. In the industrialised countries, most households receive a water supply that is enough for domestic needs. When the supply is interrupted, reduced or worsened there is an immediate response from those affected, demanding a rapid solution to the problem. Such problems can be due, among other reasons, to drought.

Basically, a drought is a water scarcity situation, although water scarcity does not necessarily imply the existence of drought. Some arid or semi-arid countries have a chronic scarcity of water. Such is the case of Israel (Shamir 1993), where non-conventional sources of supply are used to supplement the traditional water supply. Another revealing example of the fact of water scarcity even when there is no climatic drought is to be seen in China (World Resources Institute 2000). This is a country that periodically undergoes sudden variations in monthly and annual levels of precipitation. Of the 640 largest cities in China, 300 (47%) at present have water supply problems, while in 100 cities (16%), the scarcity is severe.

In other countries, the scarcity of water is not chronic, but rather is due to irregular rainfall. This is the case of India, where in 1999 and 2000 drought affected various states, including Rajasthan, Gujarat and Andhra Pradesh, inhabited by 15% of the population of the country, some 130 million people (UNICEF 2000).

In Central America, the drought caused by *El Niño*, which particularly affects Guatemala, Honduras, Nicaragua and El Salvador, threatens a population of over 1.5 million people and has caused economic losses in the agricultural and industrial sectors of over 230 million €.

In the near future the scarcity of water will become a worldwide problem; demand is rising fast (between 1990 and 1995, global consumption rose by 600%) but resources are not being made available at the same rate, while quality is also a serious problem (World Resources Institute 2000).

2 DROUGHT AND ITS EFFECTS

There is no universally accepted definition of drought, nor are there any objective indicators of when a period of drought begins and finishes. In this respect, scientists have proposed various definitions, on the general understanding that a drought is a period during which precipitation is below normal, which originates problems or undesirable effects in relation to water resources. Various types of drought may be defined (Navarro 1991, USGS 1993, NDMC 1995, Hayes 1999, Llamas 1999), including meteorological, hydrologic, agricultural and socio-economic.

A *meteorological drought* is defined as a reduction in precipitation with respect to normal values over a certain period of time. The threshold that determines the degree of diminution beyond which drought is considered to exist must be defined. This type of drought is the easiest to measure, because it is only necessary to measure precipitation levels during a specified period. This definition is specific for each location, as the distribution of precipitation varies greatly from one area to another.

A *hydrologic drought* is associated with the effects of the scarcity of precipitation on surface and groundwater resources. These effects include the diminution in the amount of water available for normal use, and can be evaluated by recording streamflow, the quantity of water stored in reservoirs and the fall in water levels in aquifers.

There is a lag between the meteorological and the hydrologic forms of drought, as the fall in precipitation is not immediately reflected in the water supply systems.

It should be noted that sometimes the effects of a drought are almost imperceptible at groundwater level, due to the high water regulation capacity of some aquifers.

Although the climate is a decisive factor in the appearance of a hydrologic drought, it may also arise as a result of human activities.

An *agricultural drought* occurs when the fall in precipitation levels makes it impossible for a given crop to get the humidity necessary for normal growth. This humidity deficit in the soil impedes crop development and can even lead to total crop failure. This type of drought is the prototypical one recognised throughout history; cases have been recorded since the dawn of civilisation, and even in the Bible.

An agricultural drought varies depending on the crop affected and on its stage of development. The effects of agricultural drought take longer to become apparent than those of a meteorological drought.

The *socio-economic drought* reflects the direct impact of a water scarcity on the human population. This situation arises when, as a result of the drought, the availability of certain goods of economic value, such as water itself, agricultural products and hydroelectric power is reduced. This type of drought is determined by social factors and varies over time (Wilhite *et al.* 2000, as cited in Llamas *et al.* 2001).

Finally, there also exists (or could exist) a legal concept of drought, defined by legislation. In Spain, the Water Act, passed in 2001, does not establish a definition of drought, but confers the Government wide powers in situations termed "extraordinary drought conditions". This imprecision has allowed different water authorities, in their River Basin Hydrologic Plans, to define drought according to their own criteria. One such definition is that of a situation in which stored and available water resources, plus foreseeable supplies for different periods with a degree of probability estimated on the basis of historical time series, do not completely meet water demand (similar to hydrologic drought); another considers a period of drought to begin when, over a period of two consecutive months, recorded precipitation is below 60% of mean values for these months, and to end when recorded precipitation during one month is equal to or above the mean.

As can be seen, not even for legal purposes is there unanimity regarding what a drought is. Thus, planning what measures to take in such circumstances is greatly complicated.

Just as there is no single definition of drought, neither there is a single indicator by which to measure it and evaluate its effects. Although the declaration or otherwise of a state of drought is ultimately a political question (Llamas *et al.* 2001), the use of drought indexes that are recognised to be based on objective criteria is a highly useful tool for managers in such situations.

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With these considerations in mind, the international scientific community has developed a series of indexes that attempt to measure and quantify states of drought. The most important are: the indexes of standardised precipitation (SPI), Palmer drought severity (PDSI), crop moisture (CMI), surface water supply (SWSI) and reclamation drought (RDI); also used are the percent of normal precipitation, deciles and tree rings.

Margat (1998) defined an index to characterise the effects of drought on groundwater as the semi-emptying period of the aquifer, i.e. the time during which the aquifer loses half of the previously stored volume of water. On the basis of this definition, the greater the inertia of an aquifer, the lower is its vulnerability to drought.

2.1 *The effects of drought*

Drought produces wide-ranging, complex impacts on different socio-economic sectors and geographic areas, which are sometimes far from the region that directly suffers the problem. It has to be remembered that water is the basis for the production of numerous goods and services, and that the main consequence of a drought is a scarcity of water. The severity of this can be such that some authors (Pagney 1994) have described drought as the climatic catastrophe that is most to be feared.

These impacts produced by drought may directly affect different economic, social and environmental goods. Such is the case of the reduction in agricultural production and woodland growth, a rise in the risk of forest fires, damage to ecosystems and wild-life, and a diminution in the amount of water available for human use.

As a consequence of these impacts, others may appear, for example reduced income in the agricultural sector, a rise in unemployment, higher food prices and a fall in taxation income, progressive erosion of the soil and the loss of plant cover, among others (NDMC 1995).

2.1.1 *Socio-economic effects of drought*

The effects of a drought are reflected as the scarcity of water for habitual uses, urban supply, industry, and agriculture. Supply problems generally produce economic problems, together with widespread dissatisfaction, particularly in industrialised countries, where a reliable supply of water is considered to be a basic necessity. Drought may even generate social conflict between users, affecting either different regions within a country or various countries. Today, such a situation exists between Israel and the Palestinian community (Shamir 1993)

Drought can also cause severe economic damage. For example in Palma de Mallorca (Balearic Islands, Spain) during the drought between 1992 and 1995, water for urban supply had to be shipped in by tankers, which from June 1995 to December 1997 transported a volume of 20,500 m^3/d from the mainland, at a cost of over 2 €/m^3.

Drought affects the agricultural sector not only in terms of output, but also in terms of the economic losses caused. The possible lower quality of agricultural produce could lead to its being rejected in the market, and to difficulty in establishing a long-term production strategy. Sometimes the farmer is obliged to change to less profitable crops. According to data supplied by Corominas (2000), in Andalusia (Spain) during the 17 irrigation seasons between 1982 and 1998, the water obtained from surface resources was less than 65% of normal levels on 7 occasions; during these dry years, the negative impact on crops was high or very high. The Guadalquivir Irrigation Federation evaluated the economic losses caused during the 1991 to 1996 drought (based on estimated shortfalls in harvests) as totalling 3,400 million € (Plataforma del Guadalquivir 1999).

A similar situation happened in the state of North Dakota, USA, when crop production losses caused by the 1988 drought were up to 70% for wheat and 60% for barley (Aakra *et al.* 1988).

2.1.2 *Effects of drought on the environment*

Drought produces multiple effects on the environment. The most important are related to the ecosystems that depend on water provided by rainfall or by the natural discharge from aquifers (Custodio 2001). When this water supply diminishes or disappears entirely, then extremely high rates of mortality are suffered by plant and animal species (González Bernáldez 1988); there is a loss of biomass in woodlands and forests, with

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subsequent negative effects on the food chain, and sometimes whole animal communities disappear (García & Varela 1995).

The Fuente de Piedra lagoon in Andalusia, Spain, is a good example (ITGE 1998). This lagoon takes water from rainfall and too from the underground discharge of the aquifer over which it is located.

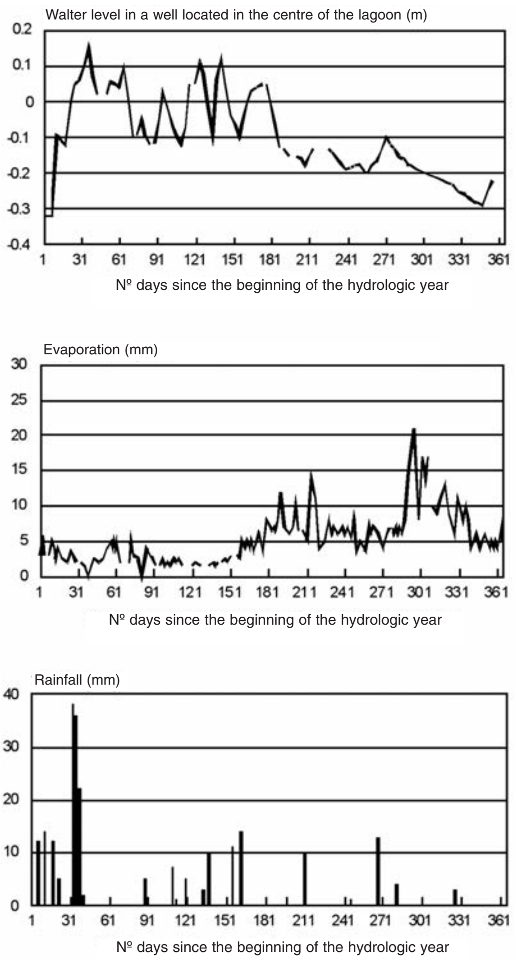

Figure 1. Evolution of the water level in the Fuente de Piedra lagoon during a dry year, in relation to evaporation and rainfall.

Figure 1 shows the evolution of the water table in the lagoon during a dry hydrologic year, as a consequence of variations in levels of precipitation and evaporation. The same variation can also be seen in Figure 2, which illustrates a monitoring piezometer located in the vicinity of the lagoon.

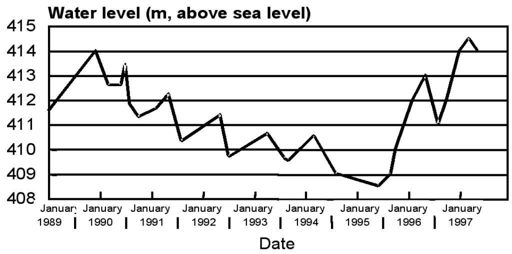

Figure 2. Piezometer response to drought in Fuente de Piedra lagoon.

Groundwater also reflects the negative effects of drought, sometimes directly as lower volumes of recharge to the aquifers, and sometimes indirectly, as an increase in the volume of water pumped out. Various other effects have been noted, such as reductions in the water volumes drained by the springs, falls in phreatic levels and possible subsidence (Fig. 3). There may also be an advance of the saline interface in the coastal aquifers, and a general worsening of water quality.

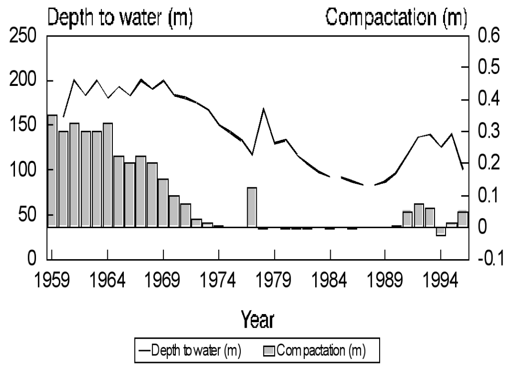

Figure 3. Subsidence related to groundwater depth. 1977 and 1987-1994 are drought periods (USGS 2001).

2.1.3 *Legal and legislative effects of drought*

Public concern about the problems of drought often stimulates legislation aimed at alleviating its harmful effects. In general, the legislative measures adopted regulate the use made of available water resources and establish obligatory priorities. The state of Colorado, USA, has enacted the Colorado River Law, which establishes priorities for water use. Similar legislation was applied in Spain during the 1992 to 1995 drought, when the *Confederacion Hidrográfica* of the Guadalquivir river (the water authority) gave priority to urban supply, reducing water availability to 450,000 ha of agricultural land.

This type of measure is usually accompanied by various complementary rules intended to provide economic compensation for those affected by drought, either in the form of cash indemnities or in the form of tax advantages.

The concept of the water bank is of special importance in legal measures to combat drought. This system was developed in California during the 1986 to 1993 drought. The State proposed that farmers who were entitled to use water to irrigate their crops should sell it to the Government so that it could be distributed for urban and industrial use. The agricultural land, meanwhile, would not be cultivated. A similar legal figure exists in the state of Colorado (McDonnell *et al.* 1995), in the form of *Interruptable supply contracts*. During droughts, farmers with water rights who temporarily cede their water for urban supply are paid by the state for these transfers. In Spain, the recent amendment to the Water Act enables the creation of similar water banks.

Where other situations arise, different legislative possibilities have been employed. The state statutes of Florida, USA, enable the water management authority (South Florida Water Management District) to establish a drought action plan (State of Florida 1991, as cited in Ahn 2000). Under this plan, rigid norms may be applied to restrict the use of groundwater, depending on the severity of the drought.

In the European Union, the most important norm, by which drought is recognized as a state of scarcity, is the Water Directive (2000/60/EC). In South Africa, the 1998 National Water Act was intended to ensure the protection, management and control of national water resources, considering, among other aspects, the appropriate reaction to periods of drought.

2.2 *Drought management and the need for planning*

In some countries, drought is a common occurrence within the normal climatic cycle. Then, it should not be treated as exceptional, but planned for, taking into account the climatic, economic and social conditions of the country. Thus, actions taken with regard to drought should be weighted more towards avoidance of its negative consequences than attempting to remedy an unforeseen crisis. Nevertheless, it is quite common for droughts to be treated as if they were extraordinary phenomena, and thus no plans exist, *a priori*, to counter the negative effects of drought. Consequently, the measures taken normally give rise to greater expense and lesser efficiency than if preventive measures had been taken, as such emergency measures rarely correspond to long-term planning criteria (Llamas *et al.* 2001). What normally happens is that costly hydrologic infrastructure works, such as canals, wells and dams, are constructed. Then, after the drought has finished, such facilities are underutilised. This is what has often happened in Spain, where policy decisions concerning drought management have been taken after the crisis is recognised. A series of measures have been legally established and adopted, mainly aimed at alleviating the negative effects of the drought, but the implantation of a comprehensive planning system has never been considered. The consequence of this has sometimes been to make drought management much more difficult.

In this type of situation, the best response is advance planning, as is routinely performed in countries such as Australia and the USA (Wilhite *et al.* 2001). In the latter country, the National Drought Mitigation Centre is charged with the task of assisting the population and institutions to develop and implement measures to reduce the vulnerability of society to drought, and to stress the need for preparation and risk management rather than crisis management.

The European Union has recently created a European Regional Working Group on Drought, one of whose main aims is to elaborate a Europe-wide strategy to combat the harmful effects of drought (ICID 1998).

In Spain, the first signs of planning for drought were observed between 1992 and 1995, with the development of the *Metadrought Plan* (Santafé 2000). Subsequently, the National Hydrologic Plan, passed in 2000, required water-management bodies, within a period of two years, to draw up special plans for action against drought. This law also obliges the public administrations responsible for urban water supply for populations of over 200,000 inhabitants to create an Emergency Plan for drought.

In many studies of drought and its consequences, the use of groundwater as a possible solution is not considered. Nevertheless, it could

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play a crucial role in terms of optimising and ensuring water supplies. The use of groundwater during periods of drought is in general considerably more efficient and less expensive than the construction of large structures for surface storage. It is true, however, that the use of groundwater often meets the opposition of small groups of consumers of surface water, because groundwater extraction constitutes an extra expense for their activities (Llamas *et al.* 2001) while the regulation and distribution of surface water is normally state-funded and so the cost for the consumer is well below the real level. Nevertheless, the policy of using groundwater is, for society as a whole, the more rational solution. Moreover, the integration of groundwater into systems for the exploitation of water resources, known as conjunctive use, reduces the overall vulnerability of such systems to droughts, by enabling an alternative source to be used when the supply of surface water is inadequate (Sahuquillo 1983, López-Geta & Murillo 1996, Castaño *et al.* 2000).

An example of a successful conjunctive use scheme is the one developed in California (Burke & Moench 2000), where its in the Central Valley water system enabled a significant increase in the water supply to different users. An analytical tool, WEAP (Water Evaluation and Planning System), was developed to facilitate the implementation of this system. Results showed that water deliveries to the State Water Project, one of the most important water users in the state, were enhanced, especially during drought years (Fig. 4).

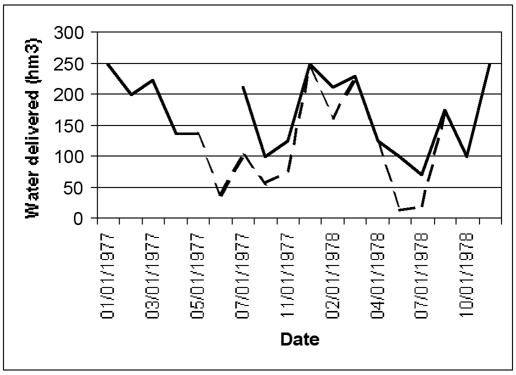

Figure 4. WEAP model results in Central Valley, CA (USA) during the drought year 1977. The solid line represents water deliveries to the State Water Project with conjunctive use; dashed line without conjunctive use (Burke & Moench 2000).

Sometimes artificial recharge is applied in a conjunctive use system in order to recharge and store water in aquifers, where the aquifers hydrodynamic conditions permit. Thus, water surpluses accumulated during periods of abundant precipitation can be used subsequently, during dry periods (Custodio *et al.* 1979, Lluria & Fisk 1994, Llamas *et al.* 1996, De la Orden *et al.* 2000, ITGE-DPA 2000, Sahuquillo 2000).

3 THE USE OF GROUNDWATER DURING PERIODS OF DROUGHT

3.1 *Introduction*

Drought is both a catalyzer and a trigger of the use of groundwater. Effectively, during drought periods, almost everyone turns to look at them, that are seen as almost the perfect solution, providing abundant quantity and acceptable water quality, when such groundwater exists in sufficient quantity and quality (Foster 1991, Lloyd 1991). Today, groundwater is widely considered by the international scientific and technical community to be a strategic element to be exploited in extreme situations, one of which is the existence of drought (Custodio 2000).

Aquifers present specific characteristics that are highly beneficial during periods of drought. Firstly, their great capacity for hyperannual regulation and the fact that slowly-accumulated reserves can be exploited during a drought (López-Geta 2000). Moreover, they are less affected by prolonged periods of drought, due to their functioning as an inertial system that is capable of delaying the discharge of water previously infiltrated, both in a natural or in an artificial way. The source of recharge to the aquifer is mainly rainfall, but less influential sources also exist.

The influence of drought on the intensive use of groundwater is not only limited to the periods when extra water supplies are needed; it also acts to spur on initiatives to exploit previously under-utilized underground resources. The use of groundwater, then becomes permanently integrated into the normal water supply network, and not just a temporary support during a period of drought.

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3.2 *Some examples of the use of groundwater*

Worldwide, there have been many cases in which the extraction of groundwater during a period of drought has greatly mitigated its negative effects on the population. A paradigmatic case is that of California, USA where, during the 1987 to 1992 drought, the contribution of groundwater to the total water volume supplied increased from 30% to 40%. In Greece, during the 1987 to 1993 drought, 110 Mm^3 were extracted from aquifers to supply Athens (Koutsoyiannis & Mimikou 1996).

Spain, with large arid and semi-arid zones, is a country that is frequently affected by drought. The semi-arid characteristics of the country are shown in Figures 5, 6. Figure 5 shows urban water demand, expressed as a percentage of average annual runoff. It can be seen that in wide areas of the country the ratio between urban water demand and average annual runoff is greater than 100%, and on the Mediterranean coast it exceeds 200%.

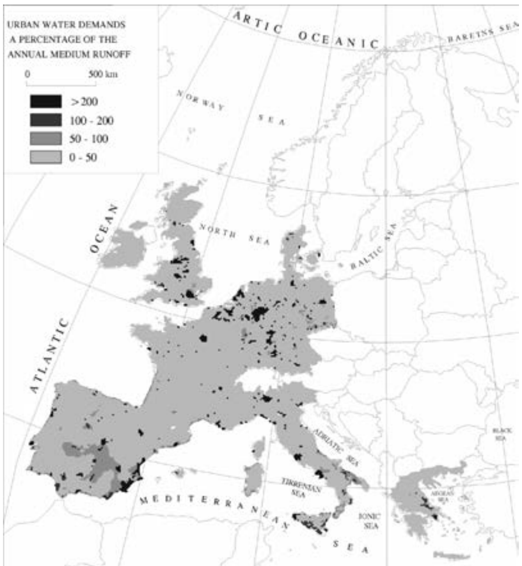

Figure 5. Urban water demand as a percentage of the annual average runoff (MIMAM 2001).

Figure 6 shows the 90% percentile of the freshwater flow available, i.e. the fresh water available 90% of the time. We can see that most of the land surface in Spain has only 25 mm of fresh water available 90% of the time, *versus* corresponding values of 250 mm for Northern Italy and the 100 mm or more in large areas of France and Great Britain.

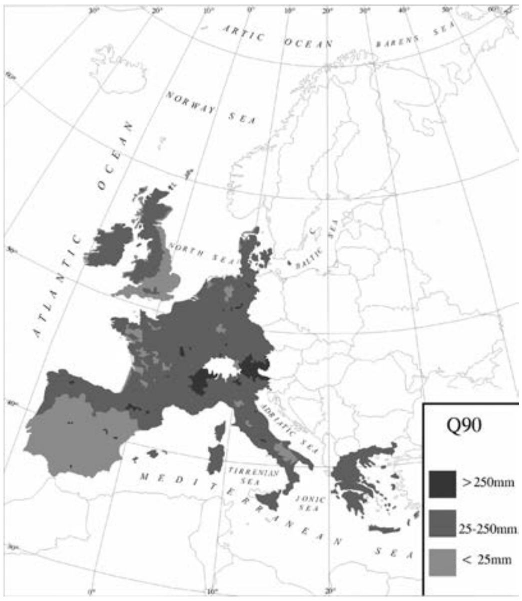

Figure 6. 90 percentile of fresh water available (mm) (MIMAM 2001).

One of the most significant effects of this is the resulting low volume of water supplied to surface water regulation systems. In extreme circumstances, like droughts, surface water reserves are almost exhausted and demand cannot be met. An example of this can be seen in Figure 7, which shows how, as a consequence of the 1992 to 1995 drought, reserves in the Guadalete river basin (Southwest Spain) fell to 2.3% of total capacity. An even more extreme situation occurred in the Barbate river basin

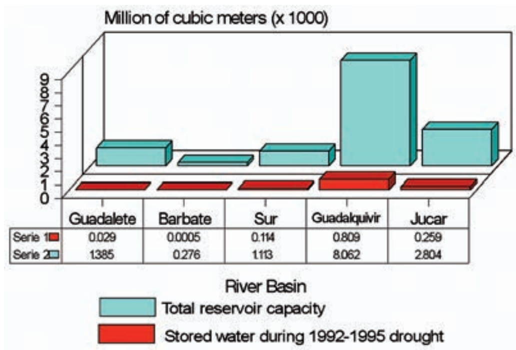

Figure 7. Stored water *vs*. total capacity of the reservoirs in some Spanish water basins.

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(Southwest Spain), where reserves fell to 0.19% of total capacity. As a result, virtually the entire population (some 724,000 people) in this region suffered water restrictions that on occasion reached 24 hours per day for 3 months.

Faced with such an extreme drought situation, the solution adopted was to exploit the aquifers in the area, and transport water using existing canalisation systems from the wells to urban centres, using the conjunctive use optimisation scheme illustrated in Figure 8.

This policy enabled a volume of 23 Mm^3/yr to be supplied (Martín Machuca 1999). A significant proportion of this volume was extracted from the Sierra de las Cabras aquifer. Water levels in this aquifer, as shown in Figure 9, fell initially, but after a period of normal rainfall returned to the initial level. This is proof of the capability of the aquifer to supply volumes of water that exceed renewable resources for a limited period of time, in order to satisfy immediate demand, and to recover a normal equilibrium within a relatively short period.

This type of response to a drought has been applied in different cases during recent years, usually with acceptable results for cities where the water supply is obtained exclusively from surface reservoirs, since those that use only groundwater or conjunctive use systems do not suffer the effects of drought with the same intensity. Representative cases include the following:

- In the region of Madrid, the exploitation of the detritic aquifer by means of a series of drillings enables a volume of 4 m^3/s to be extracted (Domínguez 2000). This system is brought into action when surface-water availability is insufficient, and makes up about 10% of total water consumption in the region, about 500 Mm^3/yr. This use of groundwater has been integrated into the normal water supply system.
- In Barcelona, the Llobregat aquifer is used during periods of drought as a strategic resource, and pumping is intensive until the aquifer is almost empty. Thus, drought in this area is countered and the city has not had to undergo water restrictions. Once the drought has finished and the climate in the area has returned to normal, the aquifer quickly recovers its former water levels.
- Other cities and regions in Andalusia, such as Granada, Jaén, Málaga and the Costa del Sol were totally dependent on groundwater during the 1992 to 1995 drought. More than 18,000 m were drilled, and the water flows gauged were up to 5,000 L/s (Figs. 10, 11). Similarly, in the region of Murcia, over 70 wells were drilled, and these extracted a total volume of 124 Mm^3/yr, while in the Valencia region, a pumping infrastructure was established to supply 6,500 L/s (MIMAM 2000). This system required the drilling of 1,253 wells.

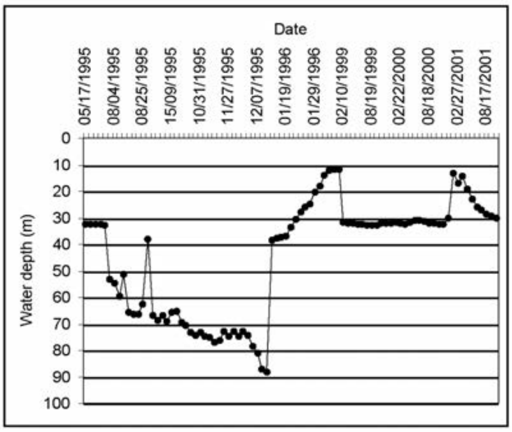

Figure 9. Water level in the Sierra de las Cabras aquifer (Cadiz, Spain). Note the low levels during 1995 drought.

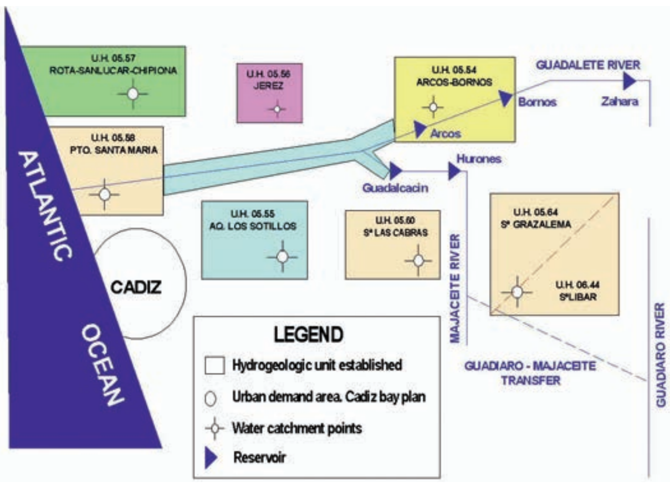

Figure 8. Conjunctive use scheme for the Cadiz bay area water supply.

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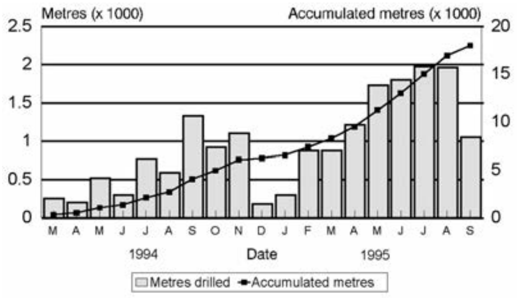

Figure 10. Borehole metres drilled during the 1994-95 drought for the Costa del Sol (Málaga province, Spain) supply.

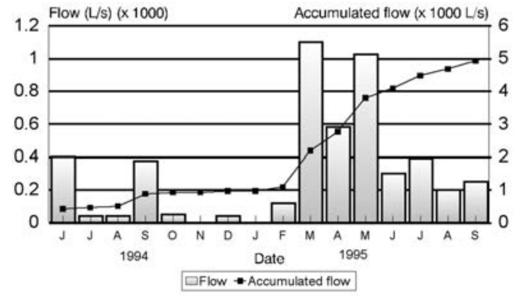

Figure 11. Total flow gauged in the new boreholes drilled during the 1994-95 drought in the Spanish Costa del Sol, (Málaga province) located in the south of Spain.

4 MEASURES TAKEN TO COMBAT DROUGHT

The link between drought and social, economic and environmental disasters is an obvious one, made apparent every time a prolonged absence of rainfall occurs. The phenomenon occurs not only in countries generally considered to be arid or semi-arid, but also in others that depend exclusively on surface resources, with a hydrologic infrastructure that is designed for high levels of precipitation with no great oscillations. In the latter case, when an extraordinary drought occurs, the necessary structures to guarantee the availability of water are lacking.

In such a situation, it is well known that the mechanisms to combat the harmful effects of drought are not put into effect until the necessity for action is known by the public (informed usually, but not only, by the media). Every time a prolonged period of drought occurs, the same debate is held, as to whether it is desirable or not to expand the available infrastructure for surface water storage. Studies have shown (López Geta 2000) that in many situations this is not the ideal solution. To date, however, the decision to expand such storage facilities has always been taken, despite the frequently negative consequences for the environment.

If surface storage is not the solution, then what is? The answer, in principle, is simple, and one that most specialists agree upon: precautionary measures should be adopted, ranging from the timely prediction of periods of drought, to the creation of strategic infrastructure, to the implementation of measures to improve the efficiency of water use and to encourage water conservation. Nevertheless, such a bundle of measures will also fail if they are not integrated into an overall water planning strategy.

4.1 *Measures adopted*

Short term solutions are adopted, on the one hand, by private initiative, obliged to react to counter the economic losses produced by a lack of water, and on the other hand, by the State, which in such circumstances promotes a series of activities, not previously foreseen, that are urgently needed. The implementation of these measures requires the participation of human, technical and financial resources. A problem frequently encountered is that such resources are not available in sufficient quantity and the expenditure is not foreseen in the country's budget.

The aim of private enterprise is usually to obtain water resources to replace or complement normal supplies. For this purpose, new drilling activity is often undertaken, which may give rise to a proliferation of wells, frequently created with unsuitable technology and largely ignoring the relevant legislation. The costs of these measures are normally borne by those directly responsible.

Public administrations act in a similar way with regard to the technical resources employed to obtain greater quantities of water. Additionally, however, they offer other means of assistance, especially financial, by means of subsidies and tax reductions. These incentives are supported by a legal framework and are justified by the exceptionality and urgency of the situation. Some examples of such cases are described in previous sections.

This kind of reaction to a drought situation has certain consequences on the environment: it affects aquatic and terrestrial ecosystems, alters the quality of groundwater and can lead to overpumping, among other results. With regard to socio-economic indicators, there may be restrictions in water supply, reduced harvests and industrial production, lower *per capita* income, etc. Some of these consequences are difficult to evaluate, but in all such cases can be considered serious. Additionally, a negative factor remains after the immediate adverse situation has disappeared, namely the abandonment of the recently created installations. In addition to the financial cost, this has potential harmful effects on the aquifer, if the drilling was badly carried out, or if the design and construction were not appropriate. In many cases, this leads to interconnection between aquifers, which are of different physico-chemical composition, and sometimes contaminated by nitrates, pesticides, etc.

4.2 *Conceptual models*

In general terms, two types of conceptual models can be defined, the choice of which depends on the exceptionality of using groundwater to respond to a particular level of demand during a particular period of time. One such exceptional case is when a region suffers a period of drought.

The technical basis of the two models is the same: the existence of aquifers and their proximity to centres of demand, the possibility of regulating water resources by means of drilling, and an acceptable physico-chemical composition of the water for the use required. The difference between the two models lies in the way they are applied.

Application of the conventional model, that of non-exceptionality, is appropriate when groundwater is the only or the most favourable alternative source of supply. In this model, the conjunctive use of surface water and groundwater plays a fundamental role. This is the model that is adopted in most countries, where groundwater comprises a significant proportion of total water.

Application of the model of exceptionality (emergency) or of extreme necessity (drought), should respond to the preventive or strategic character required by such special situations. Implementation of this model requires:

a) The availability of a catalogue of aquifers with a priority reservation for this type of situation, specifying:
   - Their location with respect to the demand centres previously identified as vulnerable to such situations.
   - The water resources available and the plan for their exploitation.
   - The storage capacity of the aquifers, their reserves and plans for exploitation.
   - The evolution over time of the aquifers, determined by a monitoring system.
   - The wellhead protection areas around each aquifer (López-Geta *et al*. 1991, EPA 1993, López-Geta *et al*. 1996, Lallemand-Barrès & Roux 1999, Martínez & García 2001a, b).

b) The availability of infrastructure to enable the exploitation of groundwater resources (wells, channels, storage tanks, etc.) and the development of a maintenance plan for such installations so that they are permanently available to operate at full capacity.

c) The existence of a legal framework to support such activities.

5 FINAL CONSIDERATIONS

The effects of drought on human activity are the reduction in the availability of water for normal uses and are reflected in many sectors, including social, economic and environmental. The impact of drought is almost always a negative one, and minimising such an impact is one of the greatest challenges facing present-day societies.

Society in general, and public administrations in particular, take rapid action to combat the lack of water arising from drought conditions, although sometimes the measures adopted are not completely effective. Thus, legislation is approved to reorganise and redistribute available water supplies, tax benefits are granted to the hardest-hit sectors and the construction of new infrastructure to obtain water resources is enabled. In the adoption of such measures, the media play a key role, as they exert significant pressure on public bodies by denouncing the lack of foresight in hydrologic policy to overcome the temporary emergency of a drought.

To alleviate the effects of drought, it is necessary to possess suitable mechanisms to supplement water deficiencies in supply systems, whether they are for urban populations, for irrigation, or for other purposes. The most effective policy is that of adequate prior planning, including a set of measures to be taken to reduce the adverse effects of drought. Such a planning procedure may contain various possibilities for the management of water resources, and one of the most efficient is the exploitation of groundwater supplies.

Aquifers present ideal characteristics for use as sources of supply during periods of drought. They possess a large storage capacity, much greater than that of surface reservoirs; they function as inertial systems that are capable of delaying the outlet of previously recharged water, both that acquired in the short term during a rainy year and that entering over the long term, during the centuries in which natural recharge has increased the levels of reserves. Another important factor is that aquifers are less vulnerable to contamination than surface waters; the transportation mechanisms of solutes in the groundwater are much slower.

On many occasions and in many countries groundwater has been exploited during periods of drought to meet a demand for water that would otherwise remain unsatisfied. The US Army Corps of Engineers concluded that the use of groundwater is the most useful tool available to counter the negative effects of drought.

The case of Spain provides a useful model to explain how such measures may be implemented. This country suffers cyclic long-lasting periods of drought and has frequently resorted to groundwater to reduce its negative effects.

With respect to the future, it is evident that water planning policies need to be established in all countries. Such policies should include specific plans to react to periods of drought, in which hydrologic policy is oriented more towards prevention than towards remedy. These preventive plans must give high priority to the utilisation of groundwater.

Nevertheless, in reality very few initiatives that correspond to a preconceived plan have been taken in response to a drought-caused water scarcity. Rather, the general attitude is one of improvisation, due to the lack of previously adopted prevention mechanisms. Therefore:

- To avoid the failure of many urgent activities, often caused by ignorance of the hydrogeological characteristics of the aquifers and the amount of available groundwater, it is necessary to obtain detailed, exact knowledge of the physical medium. It is impossible to acquire this knowledge in the short term, when the drought is present; the necessary studies must be addressed beforehand.
- The need to make water resources available to meet demand has led to sometimes uncontrolled well drilling. This has produced overpumping from some aquifers and a deterioration of groundwater quality. To avoid such effects, there must be specific drought-action plans, including the construction of infrastructure to obtain the water needed that can be put into use when necessary. In this way, improvised remedies may be avoided.

  The urgent need to drill new wells means that in many cases this activity is carried out without taking into account existing legislation. Those responsible are, on the one hand, the promoter of the work, who seeks to resolve an immediate problem, and on the other hand, the water administration, which is required in a very short period to decide upon a very large number of applications for water use. Moreover, there is a lack of suitable legislation to regulate such circumstances. Therefore, what is most necessary is for the procedure to be made more efficient by the approval of appropriate legislation and by the availability of sufficient qualified manpower to enforce it.

  The above-described uncontrolled activities sometimes may cause severe problems to nearby wells, a degradation of water quality and a lowering of water levels. As a result, extraction costs rise and, in the case of coastal aquifers, there may occur marine saltwater intrusion. To reduce these negative effects, wellhead protection areas must be established, together with exploitation rules to limit the zones from which water may or may not be extracted and to control the construction characteristics of the wells that are drilled (isolated sectors, foundations, etc.), as well as their depth and spatial distribution.
- During periods of drought, there is a great demand for drilling equipment, which means that sometimes machinery that is technically obsolete is pressed into service, possibly operated by relatively unskilled

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workers in the design, control and drilling of wells. In such circumstances, the project becomes much more costly, sometimes up to three times the optimum cost. This inefficiency would not occur if there existed suitable co-ordination between the demand for water resources and their supply, under any given hydrologic situation.

- A frequent occurrence is the abandonment of extraction and distribution infrastructure once the immediately urgent situation has been alleviated. This constitutes a waste in financial terms that has negative effects on the whole society, as usually public funds are employed in such cases. Moreover, the abandoned wells become potential points of groundwater contamination. The best way to avoid such problems is by prior planning and by establishing suitable maintenance programmes of the installations, so that they are permanently available to operate at full capacity. The costs of such maintenance should not impede its performance. A generally-shared opinion at present is that such expenses should be considered an additional cost involved in the water supply service and incorporated into the price of water. Nevertheless, public administrations could use tax benefits to provide an incentive to those responsible for applying such measures.

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