

The anthropogenic impact on Mediterranean karst aquifers: cases of some Spanish aquifers

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Abstract Mediterranean karstic aquifers are a major source of water supply for drinking water and agricultural use. In semiarid areas, the risk of causing an intensive exploitation is high, leading to degradation processes of water quality, not only due to limited agricultural activities developed on the karstic rocks—being generally poorly developed soils—but to the presence of deep evaporates which can be mobilised, or because of being coastal aquifers where seawater intrusion can progress rapidly. Moreover, karstic massifs constitute often positive reliefs that can generate barriers for civil works, more and more saved by building sophisticated tunnels; such works can affect the quantity and quality of the waters from the karst. Five examples of human impacts on some karst aquifers in SE of Spain are shown in this paper, three of them with impacts on water quality and the other two correspond to the impact of tunnels in high-speed trains drilling below the water table.

Keywords Low storage · Intensive exploitation · Increasing salinity · Tunnels

Introduction

Karstic aquifers are excellent groundwater reservoirs due to their high permeability and excellent water quality. They

support approximately 25 % of the water demand of the world's population (Kollarits et al. 2006). However, karstified carbonate aquifers are particularly vulnerable to pollution from point and diffuse sources, which allow rapid infiltration and transport of dissolved substances along highly permeable conduits. Frequently, the ingress of pollutants is favoured by the absence of any clayey soil layer to act as a protective barrier against the passage of contaminants, and for this reason, karst groundwater is more readily polluted—and over shorter time periods—than non-karstic groundwater (Kaçaroğlu 1999). The impact of natural and/or anthropogenic phenomena on water quality can be differentiated by means of a combination of hydrochemical and isotope studies (Pu et al. 2014). Moreover, some other anthropogenic actions on the karst aquifers are going to be related not only to water quality but also to quantity. Both aspects will be taken into account in this paper.

Regards to groundwater pollution, nitrate is possibly the most widespread groundwater contaminant in the world. Karstic aquifers and their associated spring systems are particularly vulnerable to nitrate contamination (Tulipano and Fidelibus 1995; Panno et al. 2001; Li et al. 2010; El Gaouzi et al. 2013). Therefore, the determination of the source of the nitrate in groundwater is an important first step in the process of improving groundwater quality. Then, the concentrations of nitrate and total organic carbon (TOC) can be used as natural tracers of infiltration in this type of aquifer (Pulido-Bosch et al. 2000; Mudarra et al. 2014).

Another source of pollution is wastewater (Katz et al. 2009; Schmidt et al. 2013). Different substances have been proposed as wastewater indicators, including inorganic anions such as nitrate, chloride or boron (Vengosh and Keren 1996; Panno et al. 2006) and organic substances or

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microorganisms such as *Escherichia coli* (Heinz et al. 2009). Moreover, since chloride is not removed by common wastewater treatment processes, it can be used as an indicator of both treated and untreated wastewater. Due to the usual absence of surface streams in karst environments, the injection of partially treated sewage is applied as a method for wastewater disposal (Foster 2008; Einsiedl and Radke 2010). It was assumed that this method is very effective to dispose of wastewater because of the high dilution of contaminants in karst groundwater systems. However, the improved understanding of the hydrogeology of karst systems provides some evidence that this assumption does not hold true (Einsiedl et al. 2010).

By the other hand, the exploitation of karstic aquifers is the main cause of modification of their flow systems, affecting both the quality and volume of outflows via springs (Bicalho et al. 2012). By simulating different scenarios of karst groundwater exploitation, with adequate knowledge of hydrogeological conditions, a realistic basis for future optimal controlling of outflow regime of karst groundwater can be created (Jemcov 2014).

A special case of impact on karstic aquifer dynamics is a result of civil works (Parise et al. 2008). Construction of a tunnel can have various impacts on groundwater: the host aquifer can be affected due to the new drainage route for groundwater created by the tunnel; nearby aquifers can be affected by the development of a new groundwater flow pattern. Other impacts may include infiltration of wastewater from the tunnel into the host aquifer, or impacts on surface water bodies linked to the aquifer (Raposo et al. 2010). To avoid such drawbacks, detailed environmental impact studies are required prior to the execution of civil projects, in addition to monitoring during and after construction works (Kitterod et al. 2000; Molinero et al. 2002; Yang et al. 2009).

In the Mediterranean Basin, karstic aquifers are especially important, providing water to approximately 50 % of the population (Daher et al. 2011). Several of the largest karst springs in the world discharge in Mediterranean countries, where carbonate rocks form a large proportion of the outcrop geology (Bakalowicz et al. 2008). The need to draw up vulnerability maps of these aquifers was recognised (Andreo et al. 2009; Marín et al. 2012).

There have been numerous studies of the impacts of anthropogenic activity on karstic systems in the Mediterranean arc. For instance, in the peninsula of Italy the subsidence in the Apulia karst is a relatively widespread hazard (Delle Rose and Parise 2002). In cases where gypsum is the predominant rock, karstic processes can be much faster; changes in groundwater flow brought about by anthropogenic activity can increase dissolution and promote the development of collapse sinkholes which, in turn, affect man-made structures (Fidelibus et al. 2011).

Karstic systems are also widespread in the Balkans region. Here, endemic pathologies have been linked to the anthropogenic chemical pollution of groundwater supplies (Long et al. 2012). Balkan endemic nephropathy (BEN) is a kidney disease that affects people living in Bosnia, Croatia, Serbia and Montenegro, Bulgaria and Romania (Tatu et al. 1998). The results show biogeochemical differences between BEN and non-BEN villages. However, these differences are not fully understood. More work needs to be done on water quality in the Balkans to address not only historical health issues (e.g. BEN), but also new environmental health issues (Long et al. 2003). Moreover, human activity in this region is also having marked impacts on the karst environment (Parise et al. 2004), including ground subsidence in some places (Milanovic 2002).

Elsewhere, in the arid and semiarid regions of the Mediterranean Basin, the main impact on karstic aquifers is that of overexploitation. The peculiar climatic conditions (low precipitation and high evapotranspiration), together with the changing demographic and economic characteristics (increasing immigration, agriculture and tourism), have led to high water demand in a region where water is scarce, and a high rate of discharge of polluting substances. The result is increased exploitation of groundwater resources, which in turn, are at high risk to pollution. The situation is particularly notorious in south-eastern Spain, where the majority of water resources are supplied from groundwater.

In coastal aquifers, problems arise from seawater intrusion. For example, the seawater intrusion identified on the southern coast of mainland Spain and on the Balearic Islands is difficult to resolve (Garing et al. 2013). Similar problems have been identified in Italy (e.g. Capo Caccia, Sardinia; Palermo region; Murgia and Salento coastal fringe; Barrocu 2003; Cotecchia et al. 2005). In Greece and Croatia, coastal and submarine springs are common, but their increased exploitation could be the reason why many of them are showing signs of marine intrusion into the aquifers (e.g. Istria, South Parnasos, Crete Island; Lambrakis, 1998). In South Turkey, despite the underexploited conditions, the Ovacik plain is showing signs of marine intrusion associated with underground karstic channels open to the sea (Elkhatib and Günay 1993). The effects of seawater intrusion in these plains are generally seasonal in character. A significant amount of the seawater is notably reduced by winter precipitation. The effects of the seawater become observable again toward the end of summer months. Seawater intrusion in these coastal plains has increased drastically during the last decade (Günay 2003). In France at least, no large areas of Mediterranean coastal aquifers are so far affected by salt-water intrusion as a result of human impact (Dörfliger 2003).

This paper presents a number of case studies from the karstic massifs of the south-eastern Iberian Peninsula (Fig. 1), where various anthropogenic activities have substantially modified the quality and/or quantity of water resources. The cases correspond to: (1) overexploitation caused by pumped abstraction and deterioration in water quality (Sierra de Crevillente and Sierra del Cid aquifers in Alicante province); (2) marine intrusion and agricultural pollution (Sierra de Gádor, Almería province); (3) impact on groundwater flow pattern due to the excavation of a tunnel through the karst (Sierra de Archidona and Sierra de Abdalajís, Málaga province). The common factor in all these carbonate systems is that their groundwater supports the local and regional economy, which means they are of strategic importance for future development in these areas.

Cid aquifer

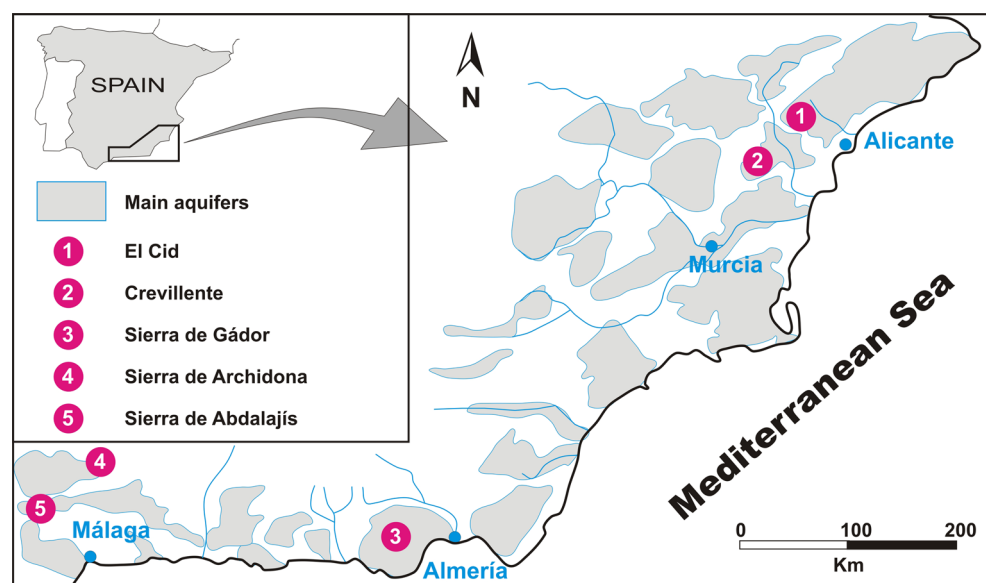
The Cid aquifer is located in the central part of Alicante province (Fig. 1), extending over a little more than 30 km². This aquifer belongs to the Prebetic domain of the Betic Cordillera. It comprises mainly Cretaceous limestone with intercalations of marl. The series is more than 400 m thick. Its impermeable base consists of more than 300 m Lower Cretaceous marl. It is completely isolated from other aquifer formations by marl and Keuper evaporite and clay. Average annual rainfall is around 400 mm, while the average annual temperature is 14.5 °C. The mean water resources of this aquifer are estimated to be between 2.5 and 3 hm³/year (Andreu 1997).

As in other aquifers of this region, an intense exploitation began in the 1960s, when a spectacular transformation

in the agricultural landscape occurred, from the traditional non-irrigated croplands to irrigated ones over the space of just a few years. Approximately 21,000 ha, which overlies the Cid aquifer, was converted. Due to the scarcity of surface water resources, groundwater provided the resource needed for the new crops. The profitability of the new crops was high and easily able to offset the investment needed to construct the boreholes, pumping stations and irrigation canals. In addition, the legislative situation at that time declared that the groundwater belonged to those who harvested it, and so there was a marked increase in the number of wells and boreholes tapping the aquifer. Because many of the aquifers in this region are small and have limited inflows due to the semiarid climate, a large proportion suffered from overexploitation.

Although the Cid aquifer was tapped before 1968, the intensive exploitation began between 1968 and 1972. The elevated yields from almost all of the boreholes in this aquifer and the acceptable water quality detonated a boom in well construction. Soon, more than thirty boreholes were taking an estimated 10 hm³/year. The evolution curve of the piezometric level in the Cid aquifer clearly reflects the different phases of exploitation (Fig. 2a). The first phase was effectively water mining; it lasted until 1983–85 and over this period water levels fell continuously. In certain years, like 1976 and 1977, levels fell more than 30 m. Overall, about 150 m of the aquifer was desaturated. This falling trend was inverted in the mid-1980s and water levels recovered due to the abandonment of the majority of the boreholes. The rate of filling was favoured by an anomalous period of high rainfall during the second half of the 1980s. This new dynamic led to a recovery of water levels of more than 100 m in little more than 5 years, with

Fig. 1 Main aquifers in SE of Spain locating the studied karstic aquifers



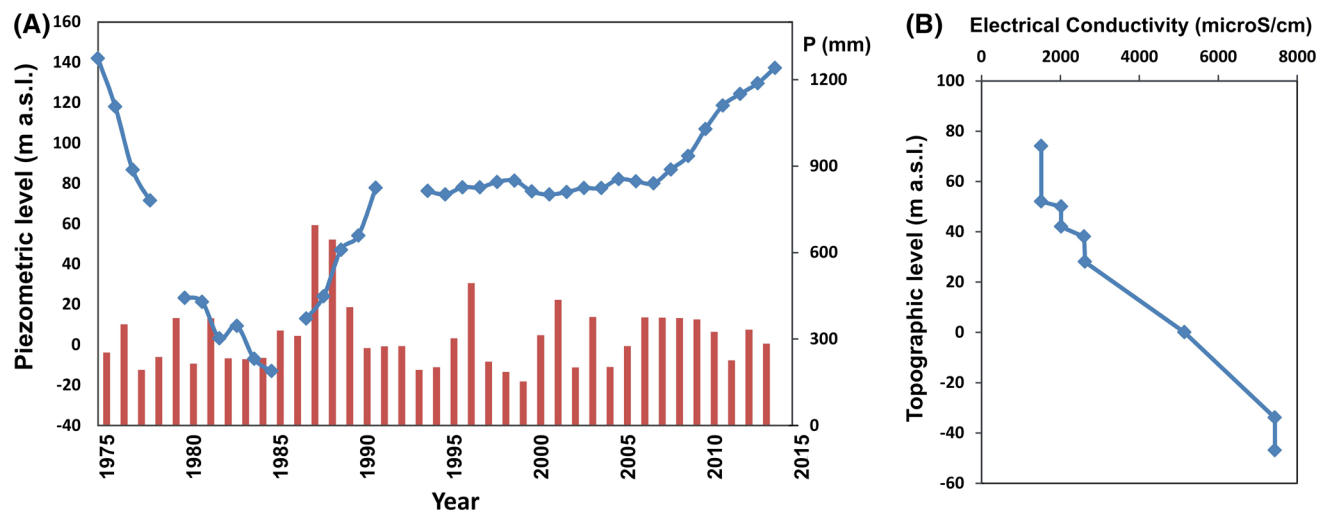


Fig. 2 a Temporal evolution of piezometric level in Cid aquifer, together annual rainfall. b Electrical conductivity log in Cid aquifer

relative rises of almost 20 m/year. After this, the recovery rate slowed and there was a period of relative stability. In recent years, a further recovery has occurred.

Though the overexploitation induced deterioration in water quality, it is difficult to establish how groundwater quality changed as exploitation of the aquifer progressed because there are no data on the initial, pre-abstraction characteristics of the groundwater. As in other aquifers, the earliest chemical analyses date back to when the aquifers were already overexploited. However, a number of chemical analyses do show that, initially, the water had a mixed chloride type, despite the fact that the aquifer lies in carbonate rocks. Over time, there was a clear evolution towards a sodium chloride type and, therefore, towards characteristics that resemble more closely some of the saline springs found in the Triassic terrains.

More recently, two studies on the Cid aquifer provided full data on the saturated zone (Pulido-Bosch et al. 1998; Andreu et al. 2010). In broad terms, water in the top 40 m had an electrical conductivity between 1,500 and 2,600 $\mu\text{S}/\text{cm}$ (Fig. 2b). Below this was a wide band of gradually increasing electric conductivity. At the bottom of the boreholes the water was more mineralized, with conductivity of slightly more than 7,000 $\mu\text{S}/\text{cm}$. Hydrogeochemical zoning seems to be evident to a greater or lesser extent and explains the change in water quality that occurred as overexploitation of the aquifer progressed (Andreu et al. 2010).

The Cid aquifer is one of the most spectacular cases of overexploitation of Mediterranean aquifers, whereby groundwater resources were exhausted in less than two decades. This exhaustion was not a physical exhaustion, but a fall in quality to below the minimum acceptable for use.

Crevillente aquifer

The Crevillente aquifer is located in Alicante province (Fig. 1). It covers an area of approximately 140 km^2 . Geologically, this aquifer forms part of the Betic Cordillera. It is formed by a sequence of carbonate deposits more than 500 m thick. These include dolomite and limestone dating from the Lower Liassic to the end of the Jurassic. As Cid aquifer, this is situated in a semiarid area, being the average annual rainfall 330 mm, while the average annual temperature is 16 °C. Recharge to the aquifer comes solely from effective precipitation over the permeable outcrops, which equates to a surface area of 74 km^2 ; inflow is estimated to comprise between 6 and 10 hm^3/year (Pulido-Bosch et al. 1995; Andreu 1997). Only the outflows via the pumped abstractions are still active in the aquifer. In recent years, the mean abstraction has been between 5 and 7 hm^3/year .

Intense exploitation of this aquifer began in the 1960s, when a private company decided to tap its waters by drilling a gallery in the SW sector of the aquifer. It is estimated that water from the aquifer is mainly used for the irrigation of approximately 9,000 ha, dedicated principally to the cultivation of table grapes and, in smaller measure, other fruits and market garden vegetables.

The first abstractions were made in this aquifer, after drilling the so-called “Swiss Gallery”. The gallery drilled through the impermeable Keuper clay–gypsum to reach the carbonate. Vertical boreholes were drilled to reach the floor of the gallery and used to pump water out of the aquifer. Other boreholes were also drilled in the SE sector of the aquifer. Intensive exploitation began in 1963 and abstractions increased enormously over time. By 1970, pumped abstractions approached 19 hm^3 ; a decade later, in 1980,

they had reached 28.6 hm³. Since then, the consequences of overexploitation, such as loss of yield from the boreholes, began to be felt and many boreholes had to be abandoned. Pumped abstractions have gradually declined since.

The intensity of abstractions, along with the scarce recharge, has caused significant dewatering of the aquifer, which could be defined as water mining. The persistence of this situation over several decades has unleashed a series of phenomena, the most relevant being the pronounced fall of piezometric levels, deterioration in water quality and loss of yield, together with abandonment of boreholes (Pulido-Bosch 1985; Custodio 2002).

Piezometric changes affected both of the pumped sectors of the aquifer, leading to a continuous fall in water levels until 1988 (Fig. 3). In 1979 and 1983, the fall in water level approached 30 m. Until 1983, a similar behaviour of water level was observed throughout the aquifer. After that moment, although measurement frequency is not equal in both sectors, it is possible to establish that the behaviour of the SE and SW sectors began to differ slightly. While the drop in levels intensified in the SE sector, it slowed in the SW (Swiss Gallery) sector. This piezometric phenomenon was thought to be due to a possible disconnection or, at least, a reduction in the hydraulic communication between the two ends of the Sierra de Crevillente. Accordingly, the greatest fall in water level has occurred in the south-eastern sector, where the piezometric level now lies 55 m below sea level. In total, a band of more than 300 m depth of the aquifer has been depleted. Dating from about a decade ago, variations in piezometric level have been modest and so, currently, the SE sector of the aquifer can be considered to have reached a phase of certain stability. In the south-western sector, following the differentiation in piezometric

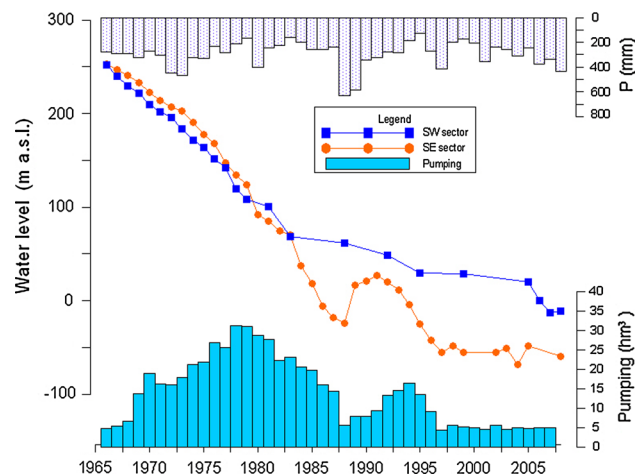


Fig. 3 Piezometric evolution (m a.s.l.) in the main sectors of pumping in Crevillente aquifer. Pumping rate (hm³) and precipitation (mm) are shown in the figure

behaviour, the continuous drop in level has been maintained, although at as much reduced rate. The cumulative depletion in this part of the aquifer is estimated to be around 230 m.

The deteriorating water quality is probably the most serious of the impacts on this aquifer because the water is now unsuitable for irrigation and so many of the boreholes have been abandoned. Nevertheless, not every sector of the aquifer has undergone mineralization. It appears that the water chemistry acquired is related to the geology and the presence of evaporites (Pulido-Bosch et al. 1995; Andreu et al. 2008). Thus, the greatest mineralization has occurred where saline deposits occur nearby or at depth.

The greatest deterioration in water quality has occurred in the SE of the aquifer. The original physico-chemistry (prior to exploitation) is not known exactly, since analytical data are available only from 1978. Nevertheless, there is a possible close correlation between the behaviour of electrical conductivity and piezometry. As the water level fell, the conductivity of the pumped water increased. This increased mineralization was due mainly to enrichment in sodium and chloride. Figure 4 shows how chloride concentrations have changed over time in three boreholes in SE sector. Only one of these (T-15) remains active, while the other two were abandoned when the chloride concentrations exceeded 1 g/L.

Another aspect related to the continuing overexploitation is the rising cost of pumped abstractions. Obviously, the marked fall in piezometric level means that the water must be lifted over a greater height, which incurs a rise in energy costs. Many boreholes were deepened after their initial yields fell. Another increased cost comes from the pumping equipment itself, which becomes more costly as the lift height increases, and because the corresponding maintenance costs are much higher. Though an economic

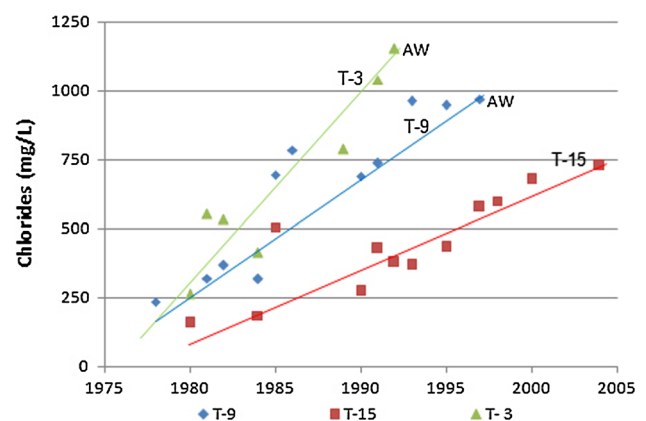


Fig. 4 Chlorides evolution in different wells of the SE sector. It can see the tendency line in each well, which show us the velocity of the quality lost. AW abandoned well

study has never been done regarding the increasing costs of exploitation, there are references to the increased price of water as the piezometric level falls (Pulido-Bosch 1985; Andreu 1997).

Sierra de Gádor

The province of Almería depends on groundwater, as exemplified by the karstic macrosystem of Sierra de Gádor. The total surface area of this coastal mountain chain is close to 700 km². Geologically, it belongs to the Internal Zone of the Betic Cordillera. There are two tectonic units in the area. Both consist of phyllite at the base and Middle–Upper Triassic dolomite at the upper part of the series. The carbonate series is approximately 1,000 m thick in one of the units but much thinner in the other, normally less than 100 m. The carbonate of both units is highly permeable. The semiarid character of the area arises due to the combination of a lack of precipitation (290 mm), strong insolation (around 2,900 h/year), inter-annual variability in precipitation (22–35 %) and high potential evaporation. The average annual temperature is 19 °C.

This aquifer system is currently exploited to irrigate some 20,000 ha of highly profitable early-season greenhouse crops, located on the emerged coastal platform of Campo de Dalías, which is in hydraulic connection to Sierra de Gádor (Fig. 5). In addition, it supplies more than 200,000 people with drinking water and more than double this number during the summer months. The intense exploitation of the Sierra de Gádor is reflected in the aquifer units in various ways, including a fall in piezometric level, deterioration in water quality and seawater intrusion (Pulido Bosch et al. 2005; Molina et al. 2002, 2003).

Pumped abstractions are the most important factor explaining the change in how this hydrogeological system functions. Annual pumping began to be evaluated by IGME (Spanish Geological Survey) at the beginning of the 1970s, and there has been continuous monitoring since 1980/81 (Fig. 6). The piezometric data reflect large irregularities; indeed, whilst some piezometers register a continuous fall, others show a smooth rise in water level. This is attributed to the abandonment of some boreholes and the drilling of new ones at other locations.

Under natural regime, this large aquifer had its principal discharge in its eastern sector, where groundwater discharges formed the largest component in the water balance (Díaz-Puga et al. 2011). The intensive exploitation that began in the 1970s practically eliminated all freshwater discharges. The hydrodynamic situation clearly shows the flow inversion that has taken place in the area that has hydraulic connection to the sea—with clear evidence of marine intrusion coming from the SE (Daniele et al. 2013). Most of the water from the carbonate aquifer has a Mg–Ca–HCO₃ type. The Durov diagram for samples taken in the eastern zone shows a gradation of groundwater from Ca–HCO₃ to Na–Cl type, with a clear trend towards seawater composition (Fig. 7). Recent pumping figures indicate that some 120 hm³/year are currently taken from the carbonate formations.

Nitrates are frequently used as an indicator of agricultural pollution. The nitrate ion was used in this aquifer as a tracer, to define and clarify whether the water from a particular borehole is derived from a deep, superficial or intermediate formation (Pulido-Bosch et al. 2000). To identify the effect of agricultural contamination in this area, data from 1996 have been compared to data taken since 2002 (Fig. 8). The plot of nitrate concentrations vs. total dissolved solids shows that water from deep carbonate formations have been affected by anthropogenic activity.

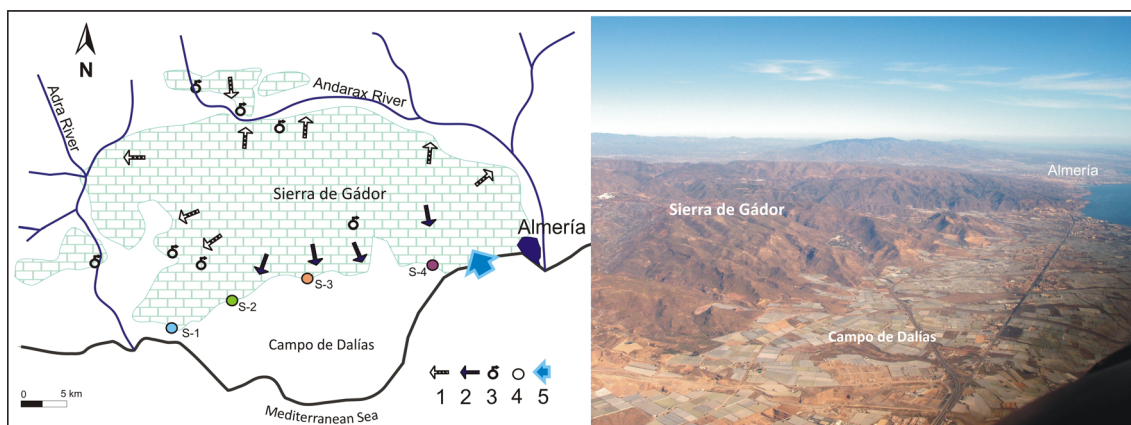


Fig. 5 Hydrogeological scheme of Sierra de Gádor (Almería). 1 Groundwater flow, 2 groundwater flow towards deep carbonate aquifer of Campo de Dalías, 3 main springs, 4 boreholes, 5 marine influence

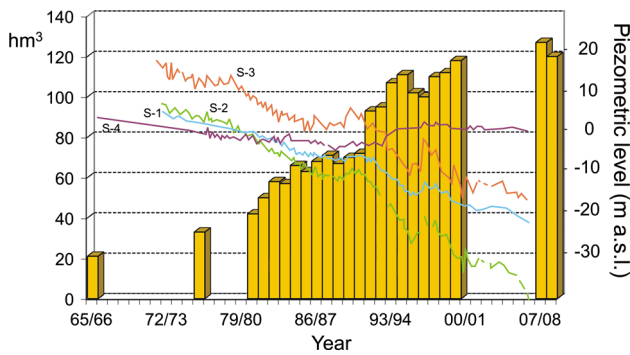


Fig. 6 Annual pumping of groundwater (hm^3) from carbonate aquifer and evolution of water level in Sierra de Gádor (see Fig. 5; data from IGME 2003)

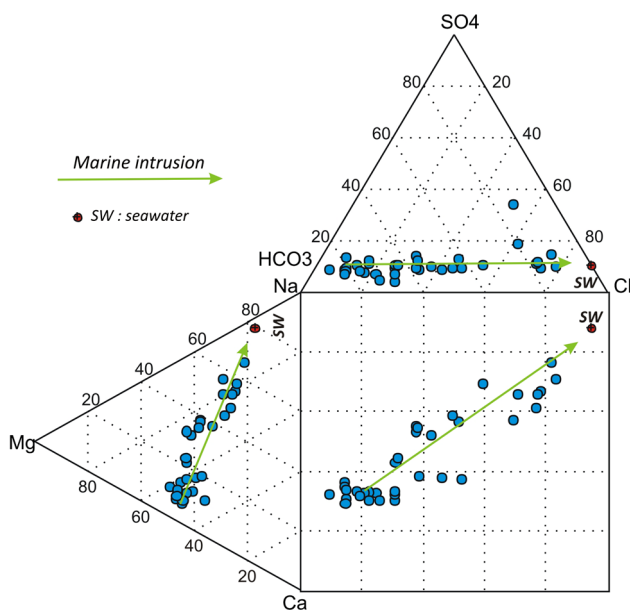


Fig. 7 Durov diagram showing general chemical character of groundwater in the eastern sector of Sierra de Gádor (% of meq/L)

The entire area is exploited for agricultural use, driven by the high profitability of cropping under plastic in this semiarid climate. The overexploitation of the aquifers has unbalanced the natural regime, markedly changing the interconnections between the aquifers. The elevated nitrate concentrations are probably due to a flow of water contaminated by agricultural activities, from the central part to the zones where groundwater levels have been depressed by overexploitation.

Archidona tunnel

The presence of aquifers or aquitards of notorious volume poses a significant problem to civil works involving tunnelling, markedly increasing excavation costs (Day 2004;

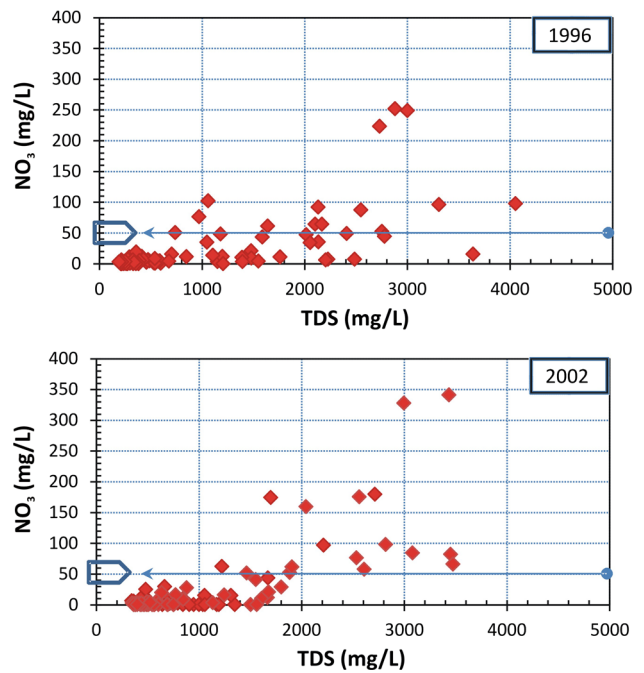


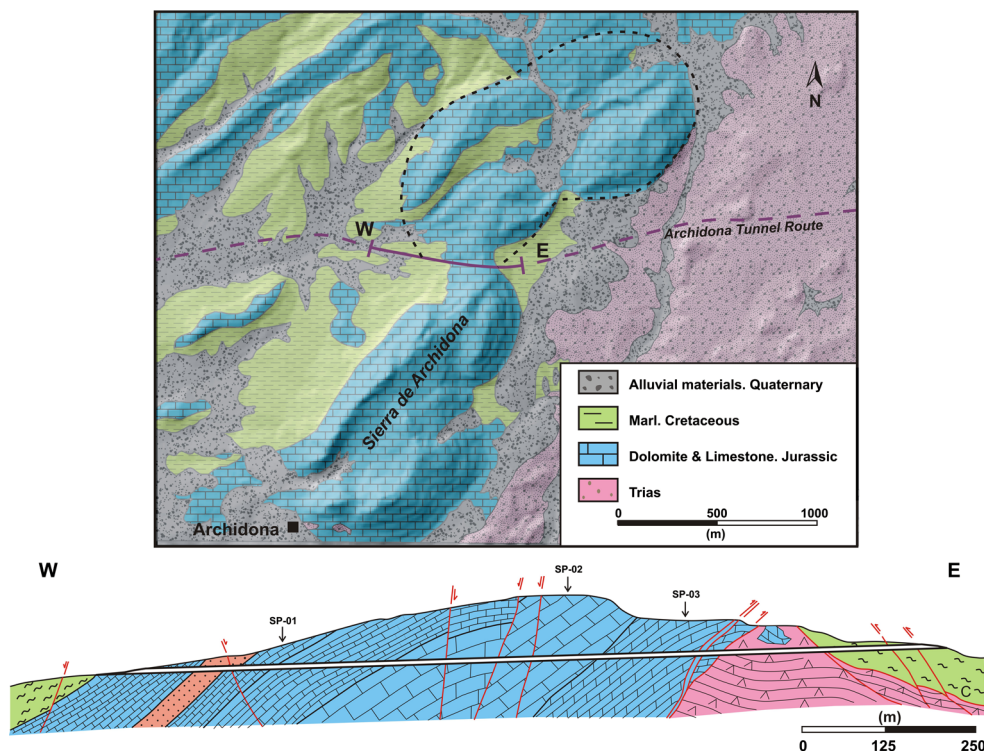
Fig. 8 Relationship between total dissolved solids (TDS, in mg/L) vs. NO_3^- (mg/L) in Sierra de Gádor. Nitrate levels in drinking water: 50 mg/L

Chiocchini and Castaldi 2011). On top of technical difficulties, tunnelling can alter the hydrodynamics of an aquifer, generating environmental and/or social problems (Sjolander-Lindqvist 2005; Gisbert et al. 2009; Vincenzi et al. 2009).

The high-velocity train line in Málaga province involved a tunnelled section through northern end of the carbonate massif of the Sierra de Archidona (Fig. 9). This massif, belonged to the External Zone of Betic Cordillera, is composed of Jurassic dolomite and limestone and Cretaceous marl. Average annual rainfall is around 500 mm, while the average annual temperature is 15 °C. The tunnel was planned so that the train line would be practically always lying above the saturated zone. Before tunnelling work began, a number of boreholes were drilled to determine the geological and hydrogeological characteristics of the massif (Sola and Pulido-Bosch 2014). Three of these bores, SP-01, SP-02 and SP-03, aligned along the tunnel route (Fig. 9), were equipped with divers to take continuous measurements of variations in piezometric level. In addition, a flow metre was introduced to measure drainage.

Piezometric measurements recorded the precise position of the phreatic surface over the period October 2008–October 2011. Its position was clearly controlled by precipitation. As tunnelling work began, the phreatic surface lay beneath the level of the inverted vault at its lowest point (western mouth of the tunnel). The intense precipitation that fell in 2009 and 2010 provoked a rise in water level to

Fig. 9 Hydrogeological map and geological cross-section of the Archidona tunnel route

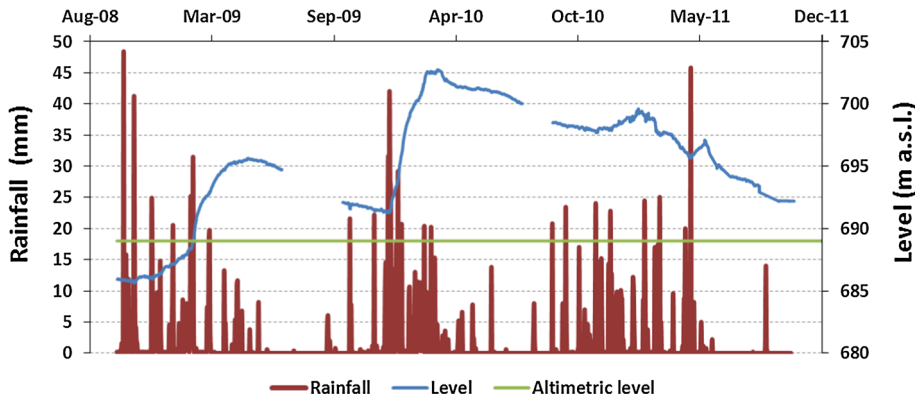


20 m above the inverted vault at this point. In turn, the rising trend has marked by annual cycles, with peak levels in winter and spring and lower levels in summer, with a certain delay between the rainfall event and the corresponding water table rise (Fig. 10).

Analysis of autocorrelogram establishes the correlation of a series with itself. An autocorrelogram that falls slowly indicates the system is inertial, with scarce development of karst and a barely hierarchical flow pattern (Jiménez and Andreo 2012). The memory effect of the system was defined by Mangin (1981) as the time lag, k (days) for $r = 0.1–0.2$. In our case, the time lag for the water level data was 140 days, while there was a memory effect of 65 days for the discharge rate (Fig. 11a). In turn, the crossed correlation function shows the relationship

between the inflow and outflow series, and represents the response of the aquifer (Mangin and Pulido-Bosch 1983; Padilla and Pulido-Bosch 1995; Padilla et al. 1994; Larocque et al. 1998). The delay, i.e. the time between the action of the input variable and its effect on the output variable, determines the velocity of transference in the system. Thus, the crossed correlation quantifies the statistical dependence and the time lag between precipitation and piezometric height and between precipitation and flow volume, over the study period. The analysis of precipitation-piezometric level indicates a delay between 60 and 80 days, and for the precipitation flow, between 80 and 100 days (Fig. 11b). A comparison with published values for nearby karst areas indicates similar time lags (Jiménez et al. 2004; Jiménez and Andreo 2012).

Fig. 10 Comparison between rainfall and evolution of groundwater level measured in SP-01 during the period of study. The final height of the inverted vault of the tunnel is indicated



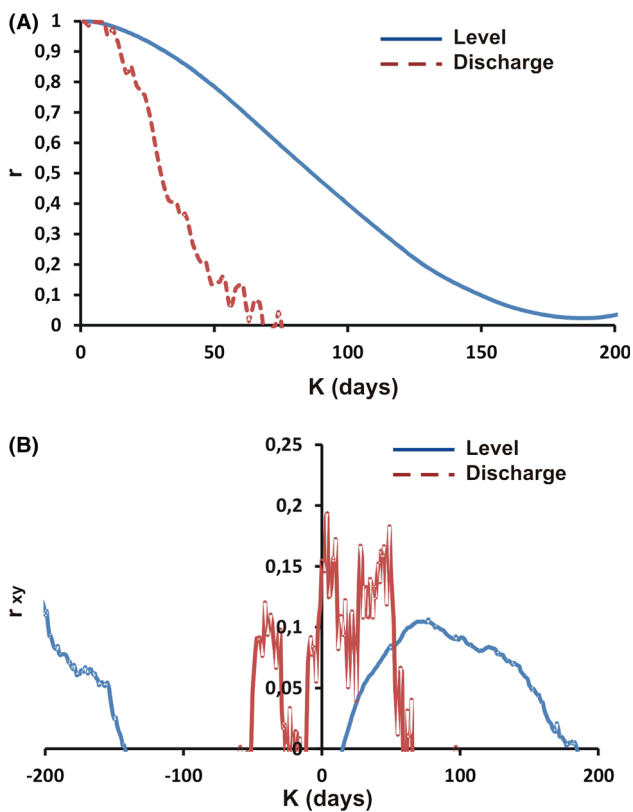
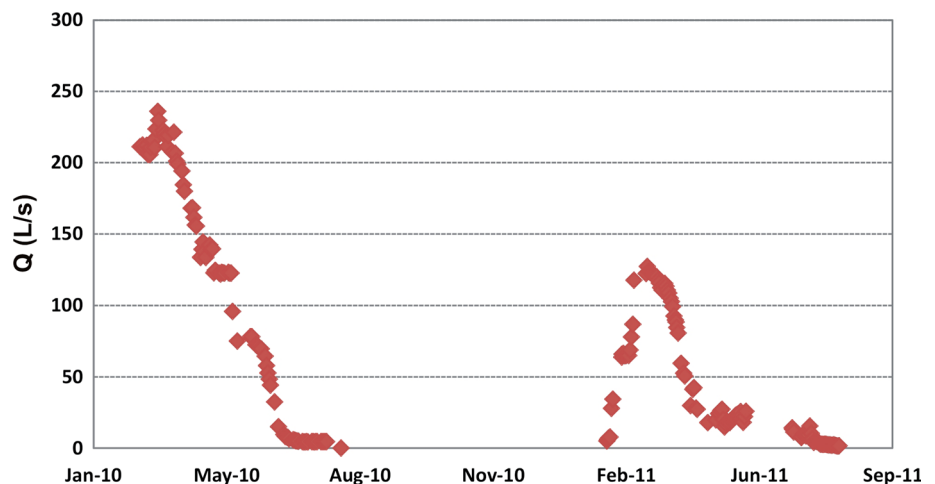


Fig. 11 a Correlograms of groundwater level in borehole SP-01 and discharge drained by the Archidona tunnel. b Cross-correlograms rainfall-groundwater level in SP-01, and rainfall-discharge drained by the Archidona tunnel

When the phreatic level in the tunnel lay above the level of the inverted vault, the western tunnel mouth became an artificial drainage point for the aquifer. The outflows for 2010 and 2011 yield flow curves with similar falling slopes (Fig. 12). The peak drained flow, 230 L/s, was recorded in March 2010. After this moment, there was a gradual decrease in flow until it completely dried up in August. In

Fig. 12 Discharge of groundwater drained by the Archidona tunnel



February 2011, drainage increased rapidly, reaching its peak of 135 L/s in March.

The exhaustion (depletion) coefficient calculated as $2.3\text{--}3.2 \times 10^{-2} \text{ day}^{-1}$ is quite close to values obtained in karst massifs situated a few kilometres away (Mudarra and Andreo 2011).

As with so many other underground civil works, this tunnel provides a privileged observation point of the interior of a karstic aquifer. Despite the apparent scarcity of karstic features, the production from the boreholes was very high. This confirms the well-proven fact that the storage in the aquifer is low (rarely exceeding 2 % effective porosity), but the capacitive elements confer high productivity at the intake works. The marked delay of the system in response to precipitation is explained by the complex geometry of the carbonate blocks.

Abdalajís tunnel

Another example of engineering and environmental difficulties generated by tunnelling through a carbonate massif is the case of Abdalajís, also in Málaga province (Fig. 1).

The total outcrop area is about 21 km². This massif is composed of Jurassic carbonate, compartmentalised into tectonic sheets. Within the Abdalajís hydrogeological system, several aquifers or subunits can be distinguished. Mean annual precipitation in the region oscillates between 440 and 670 mm, and highlights the slight pluviometric contrast within the area. The average annual temperature is 16.5 °C. Global average groundwater resources are estimated to be 6–7 hm³/year, and are drained by springs. The aquifer subunits correspond in many cases to tectonic units, which occur over the entire system. Three subunits are differentiated; from south to north, they are: Huma Unit, Capilla Unit and Abdalajís Unit (Fig. 13), each drained by a number of springs. The analysis of piezometric levels evolution in

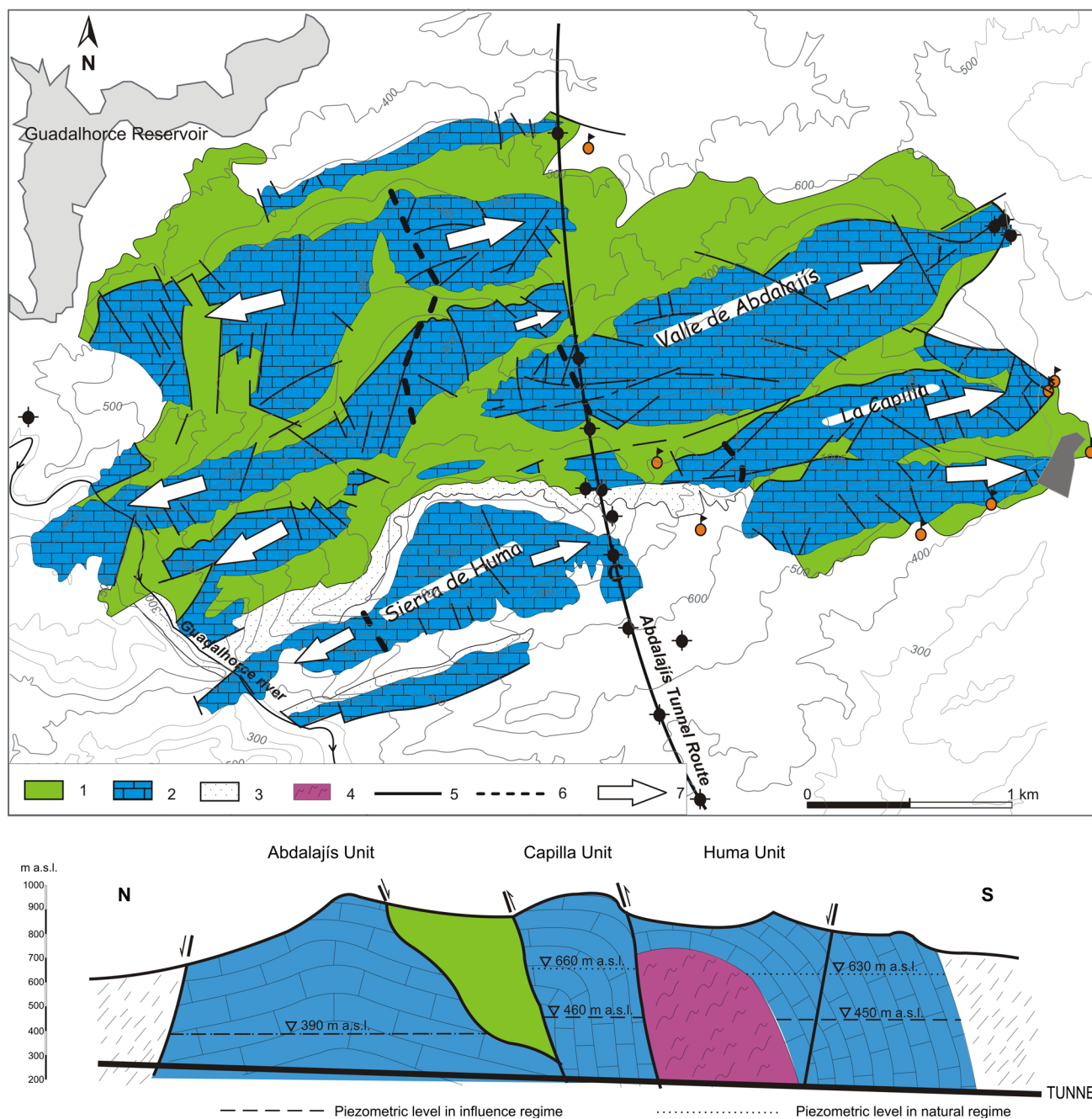


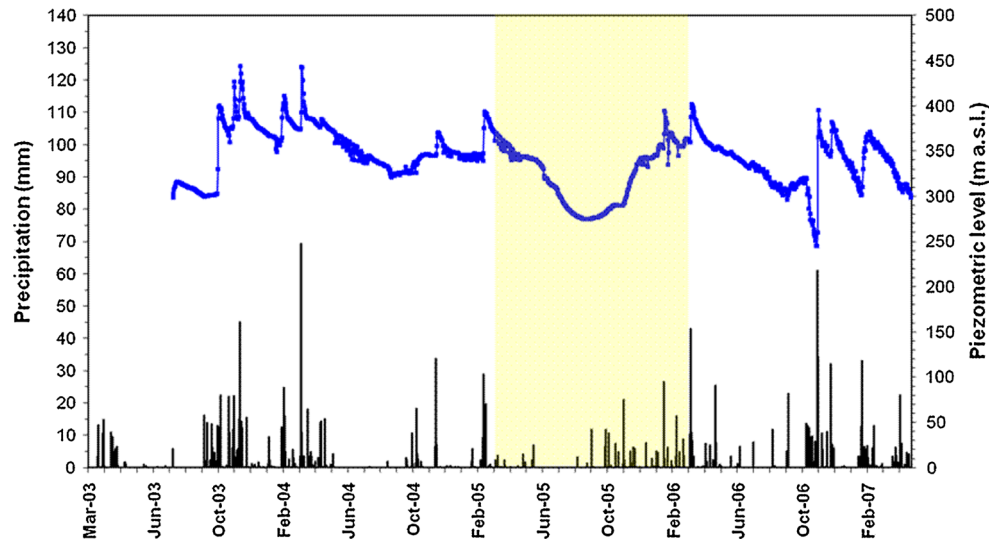
Fig. 13 Hydrogeological map and scheme of the Abdalajís aquifer. 1 Cretaceous marl, 2 Jurassic carbonate, 3 undifferentiated impermeable deposits, 4 triassic clay and gypsum, 5 route of the tunnel, 6 groundwater watershed, 7 groundwater flow

piezometers and from spring discharges revealed the inter-connection existing between these units. The memory effect found in the flow record of the springs shows a relative delay in the evacuation of flow from all the springs (from 57 to 141 days), and a variable moment as regards the time that the springs run dry (16–40 days) (Gisbert et al. 2009). The memory of these systems is moderate or high in comparison to certain heavily karstified French aquifers such as Badget (13 days) and Aliou (5 days) (Mangin 1984), or more

regulated aquifers, such as El Torcal in Antequera (Spain; 72 days) (Padilla and Pulido-Bosch 1995).

Whilst the Abdalajís tunnel was being drilled, some groundwater drained through the mouth of the tunnel, but it was not until March 2005 that a notable increase in flow rate occurred. After this moment, the discharge of every spring suddenly dropped, an effect accentuated by the lack of rainfall (barely 25 mm between April and September 2005). The springs situated at higher elevations dried up

Fig. 14 Piezometric evolution of Abdalajís Unit. Precipitation is shown as a bar chart. In yellow, period of massive water discharge in the tunnel



over the summer months, whilst lower springs maintained their base flow—although the flow fell as low as 1–2 L/s, it never disappeared completely.

The piezometric level in the Huma Unit peaked in the autumn of 2003 and the beginning of 2004. During this period, variations in water level and precipitation were coherent, since the piezometer is located in a recharge zone. However, in May 2005, the level fell by 180 m. The piezometric level in the Capilla Unit was constant during 2003 and 2004, lying at over 600 m a.s.l. It fell by 200 m during tunnelling works (Fig. 13). The Abdalajís Unit reflects the seasonal rise and fall in response to precipitation, as well as daily cycles resulting from the pumping of water to supply the town of Valle de Abdalajís. During tunnelling works, water in this unit fell various tens of metres (Fig. 14).

The event of March 2005 caused a large inrush of mud and water that invaded the tunnel with an estimated instantaneous flow of more than 600 L/s. This coincided with the tunnel penetrating the carbonate rocks of the Huma Unit. The drilling intercepted a fault zone in this unit, possibly containing large conduits, which suddenly dewatered and produced the drop in the water table. The total volume of water drained from the tunnel during 2005 was at least 3.26 hm³.

Final considerations

The singular examples described illustrate the main anthropogenic practices that can threaten Mediterranean karstic aquifers. In the semiarid regions of the Mediterranean, due to water scarcity these impacts are magnified because of the intensive exploitation of groundwater resources; this is associated with deterioration in quality

and possibly with the compartmentalization of the aquifer system, when the geological structure is complex.

The classical literature on karstic aquifers identifies them as being highly vulnerable to pollution and possessing little self-purification capacity (Leibundgut 1998; Ravbar and Goldscheider 2009). The case studies presented here indicate that these aquifers are the main source of drinking water supply throughout the Mediterranean. It is possible that their vulnerability can be buffered as karstic massifs correspond to upland areas. This means that the recharge is favoured, since precipitation is greater than in the corresponding valleys; in addition there are fewer point sources of pollution in these scarcely populated mountain regions.

In addition, the tendency of karst formations to possess elevated transmissivities means that the abstractions are especially high yielding. The downside is that the storage coefficient of these aquifers tends to be much lower than those with intergranular porosity; this means that smaller outcrops will have very limited groundwater reserves and consequently a very short service life during periods of drought or high demand (Aguilera and Murillo 2009).

The execution of civil works in the massifs, whether for road or rail construction or other tunnels, requires that especially sophisticated protective and mitigation measures are put in place if the aquifer is used for human water supply, since the risk of impacting the groundwater supply is so high.

Last, the characteristics of these aquifers mean that their exploitation in coastal areas is especially delicate. Karstic springs close to the coastline are highly vulnerable to salinization, even when—as frequently happens—the spring is well above sea level. Examples of salinization include Sierra de Mustalla, Valencia and Alicante in Spain; Almiros and many other springs in Greece; Port-Miou, in

France—where one gallery has never pumped fresh water; and many other cases in the former Yugoslavia (Potié and Ricour 1974; Pulido-Bosch 1999; Maramathas et al. 2003; Fleury et al. 2007).

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