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SPECIAL ISSUE

Environmental and hydrogeological problems in karstic terrains crossed by tunnels: a case study

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Abstract The construction of one of the high-speed railway tunnels between Malaga and Córdoba (South Spain) beneath the Abdalajís mountains occasioned a series of hydrogeological problems with geotechnical and environmental impacts. The double tunnel, 7,300 m in length, runs south to north across several lines of small, calcareous mountains that have a highly complex structure. Beneath the Jurassic limestones lie Triassic clays and evaporites. Overlying the limestones is an essentially marly and limestone-marl Cretaceous series, which culminates with Miocene marls containing some organic matter. These mountains have generated springs that are used for urban water supply and irrigation, as well as drinking fountains in the surrounding villages. The initial water level in the aquifer series varied from 400 to 650 m above sea level. After drilling approximately 2,900 m, and intercepting a fracture zone within the carbonate rocks, a sudden water eruption occurred that reached a peak flow of 800 L/s. After a short while, spring discharges dried up, leading to a public protest. In this paper, we describe the geological and hydrogeological settings, the development of the aquifer as the drilling operation proceeded, the measures adopted and the responses subsequent to completion of the tunnel, including the effect of rainfall on the recovery of water levels. Lastly, a generalized estimate is made of how the system functions, and a forecast is made for recovery of its equilibrium.

Keywords Tunnel · Karstic aquifer · Spring · Water level

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Introduction

For underground mining and civil engineering works that take place below the level of the water table, the intrusion of water can pose real problems. The more heterogeneous the physical environment is, the greater the risks. Karstic aquifers are among the most problematical (Parise and Gunn 2007), because although many stretches drain easily and can be worked without difficulty, other localized stretches (which are very difficult to identify beforehand), can be subject to sudden and rather violent invasion by water. Such sectors usually correspond to large fractures that provide preferential flow paths for the water (Worthington et al. 2000; Kiraly 2003; Bakalowicz 2005; Casagrande et al. 2005). Sometimes the fluid drainage and pore pressure variations after tunnel construction causes as well consolidation of fractures that may result in vertical settlements above the tunnel (Zangerl et al. 2003). The impact on the engineering works is obviously immediate, causing delays and requiring considerable intensification of the safety precautions in place (Milanovic 2004; Kolimbas 2005).

However, the impact on the natural and human environments is also important to consider, since the interception of flow lines by engineering works can lead to the rapid drying up of springs draining the karstic massif, and consequent public outcry. On the other hand, if the sealing is adequate, there is a rapid return to the initial conditions. These properties are a consequence of the structure that is described by the conceptual model of a karstic aquifer (Drogue 1980; Pulido-Bosch and Castillo 1984). This model normally consists of a capacitive element comprising the blocks that occupy the majority of the karst massif, but which have a mean storage coefficient that is normally less than 0.005; in addition, there is a transmissive element formed by fractures and karstic conduits, which are the means by which the system can be drained rapidly. Together these elements usually have a mean storage coefficient of less than 0.01. In such circumstances, once the tunnel has been sealed, 2 or 3 years is sufficient for the water to recover to the pre-project levels, though this is a function of rainfall and the size of the drained system.

This article describes the events that happened while two tunnels were being excavated for the high-speed rail link between Malaga and Cordoba in the south of Spain. Drilling of the tunnel began in November 2003, in a stretch that runs approximately north–south through the Sierras del Valle de Abdalajís (Malaga, southern Spain), a mountain landscape dominated by limestone (Fig. 1). Drilling began at the southern end at an elevation of nearly 290 m, and ended at close to 400 m a.s.l., in the middle of March 2006.

The main aim of the study reported here was to identify what happened and determine what actions would enable the original conditions of the system to be promptly re-established. In addition, a hydrogeological characterisation of a small karstic aquifer system with a highly complex geology has been carried out.

Hydrogeological setting

General description

From a hydrogeological point of view the tunnel, along its route from north to south, crosses the hydrogeological unit of the Valley of Abdalajís (ITGE 1998). This unit is composed of Jurassic carbonate aquifers, compartmentalized into tectonic sheets. Global average groundwater resources are estimated to be 6–7 hm^3/year, and are drained by springs. The hydrogeological unit is bound to the north by impermeable Tertiary flysch deposits and to the south by impermeable Tertiary deposits from the Lower Miocene; the eastern boundary is defined by a large regional fracture (which also puts the limestone sheets into contact with more impermeable Tertiary deposits). Finally, to the west, the unit is bound by the river Guadalhorce, the lowest drainage level of the whole system (Fig. 1).

Various boreholes tap the village of Valle de Abdalajís for water supply, and to a lesser extent, for irrigation and other water uses.

Hydrogeological characteristics and hydraulic parameters

The object of this study is the karstic aquifer in the Jurassic carbonates of the Abdalajís mountains, and those tectonic

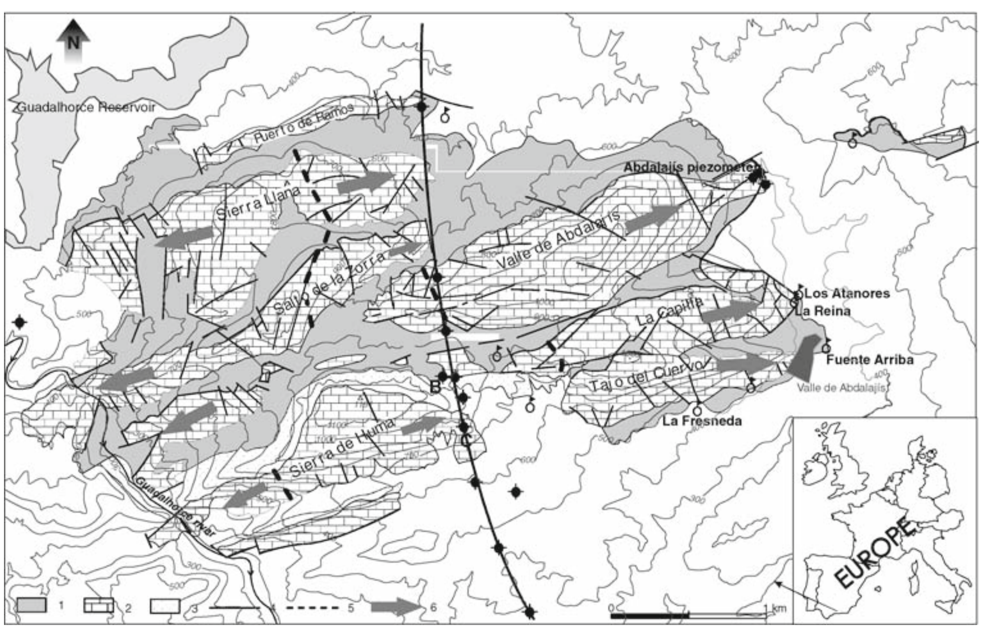

Fig. 1 Location and hydrogeological map of the study area. *1* Cretaceous marls, *2* Jurassic carbonates, *3* Triassic clays, *4* route of the tunnel, *5* groundwater watershed, *6* groundwater flow

slices within the aquifer crossed by the tunnel. The outcrop area of these deposits is some 21 km^2. In general, the behavior of carbonate aquifers is due to fracturing and fissuration, as well as to the strong karstification; the matrix porosity, or porosity of the carbonate rock matrix—microfissuration and intercrystalline—is generally very low.

The shortfall of water supply to the Valle de Abdalajís municipality during autumn 2005 led to the drilling of emergency boreholes. Pumping tests in a borehole in December 2005 provided useful data for obtaining values for the aquifer parameters in this sector. Interpretation of these tests, not exempt from problems because of the typical barriers at the edge of an aquifer boundary, indicated transmissivity values (*T*) of $3.5\ 10^{-3}$ m^2/s and storage coefficients (*S*) of 8×10^{-3}. *T* is relatively high, given the location of the borehole in the eastern discharge zone of the Abdalajís tectonic sheets, the most-strongly karstified sector.

Moreover, three surface reservoirs supply the city of Malaga. The impact of one of these, Guadalhorce (Fig. 1), is a question to be considered: this reservoir has a very high salinity as a result of the inflow from the Meliones spring (brines). The mean top water level of the reservoir is approximately 351 m (GEOCISA 2001, unpublished data), which indicates that there may be contamination of the groundwater contained on the tectonic sheets further to the west. With respect to the eastern sheets, and given the lack of connection with this sector and its greater hydraulic potentials, it seems unlikely that it is contaminated by water from the reservoir.

Aquifer units

The groundwater sampling points (wells, piezometers and springs) are concentrated at the eastern and western sector of the aquifer, as a result of the orography of the terrain; characterized by the presence of marked differences in altitude between the central part of the mountain range and its two extremes, which means that the main springs occur at the lower elevations. In addition, the abrupt relief does not favor the drilling of boreholes and wells over the greater part of the central sector of the Sierra.

Within the hydrogeological unit or general system various subunits or aquifers can be distinguished. These subunits correspond in many cases to the tectonic sheets, and are shared over the entire system. The following four subunits (of sheets or groups of sheets) have been distinguished from south to north with the associated aquifer point:

- Sierra de Huma (2.72 km^2): piezometer C;
- Tajo del Cuervo–La Capilla (3.73 km^2): piezometer B, and springs of Los Atanores, Fuente Arriba, La Reina and La Fresneda;
- Valle de Abdalajís (4.75 km^2): Abdalajís monitoring piezometer;
- Salto de la Zorra–Sierra Llana–Puerto de Ramos ($3.58 + 4.33 + 0.53$ km^2).

The limits of these units are shown in Fig. 1. In terms of the hydrogeological connection between the various limestone sheets, the earliest available reports indicate a lack of connection between them. Nevertheless, analysis of piezometric levels evolution in piezometers and discharge of springs, as well as a revision of the geological and hydrogeological characters carried out in this study allowed to know in detail the interconnection between these units. This study focuses on those tectonic sheets crossed by the tunnel. For this reason, the aquifer units situated further to the north and north-east (Salto de la Zorra, Sierra Llana and Puerto Ramos) were not analyzed; the tunnel had little or null impact on the users of the groundwater there.

The sub-units located to the south-east (Tajo del Cuervo and La Capilla) form a single aquifer unit, approximately 4.7 km^2 in extent (3.73 km^2 in the eastern sector). Both units disappear toward the west and one of them (Tajo del Cuervo) is transformed into the Huma Unit.

The Huma Unit outcrops in the south-western part of the system and covers an area of 2.72 km^2; it is isolated from the other units and has limited hydrogeological connection with adjacent units. This unit has a relatively well-developed Triassic base, which separates it, together with its tectonic features, from the Tajo del Cuervo Unit to the east. This was the first unit penetrated in its entirety by the tunnel, and the first to be dewatered by means of the highly developed faults that are present at depth within the carbonate formation.

The last large unit of interest in this study is the Abdalajís Unit, situated to the north-east of the hydrogeological system, and covering 4.75 km^2. Though its general structure is a gentle, symmetrical anticline, in detail it is structurally very complex, with normal, reverse and thrust faults. From a hydrogeological point of view it is an aquifer that has limited apparent lateral connection towards the west, where it pinches out, and practically no connection with the sheets or units in the South (Capilla-Cuervo). In addition, this is the only unit in this sector that does not have a visible surface discharge (spring, hidden river input, etc.).

The line of the tunnel, which crosses the central part of the carbonate massif, would correspond approximately to the most likely zone of the groundwater watershed of the various aquifer units (Fig. 1), and it was considered as such in subsequent calculations. The lack of aquifer data for the central, elevated part of the Sierra means that this aspect cannot be precisely determined.

In terms of the geometry of the units cited above, little is known in general terms. Nonetheless, point data have been obtained from some boreholes whose stratigraphy has been logged. Thus, neither of the boreholes B and C (at 550 and 360 m depth, respectively) reach the impermeable substratum. In addition, two boreholes recently drilled at the eastern end of the Abdalajís unit reach 310 and 320 m depth in the aquifer matrix.

In general, the Jurassic carbonate units (the aquifers) throughout the whole Abdalajís mountain system can exceed 400 m in thickness (Cano 1991).

Climate and hydrology of the Sierras de Abdalajís

Analysis of the rainfall series was undertaken for the period 1984–2004. Mean annual precipitation in the region oscillates between 442 and 673 mm, and highlights the slight pluviometric contrast within the area. Mean precipitation over the whole system, obtained using data from 15 stations is 520 mm/year (Fig. 2). Rainfall in this area during the wettest year (1996) was 3.4 times than in the driest (1994). The wet year produced 195% of the mean value and the dry year 58%.

Statistical characterization of annual precipitation was achieved by fitting the mean annual values for the study area to a normal probability distribution function (Fig. 3). The characteristic years are the following:

- Driest year (1994): 303 mm
- Typical dry year (1999): 338 mm (<25% distribution curve)
- Typical average year (2001): 512 mm (=mean of the distribution)
- Typical wet year (2003): 685 mm (>75% distribution curve)
- Wettest year (1996): 1,013 mm

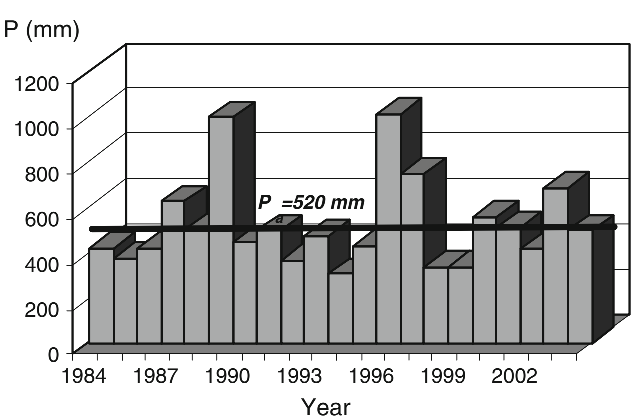

Fig. 2 Temporal distribution of precipitation in the study area

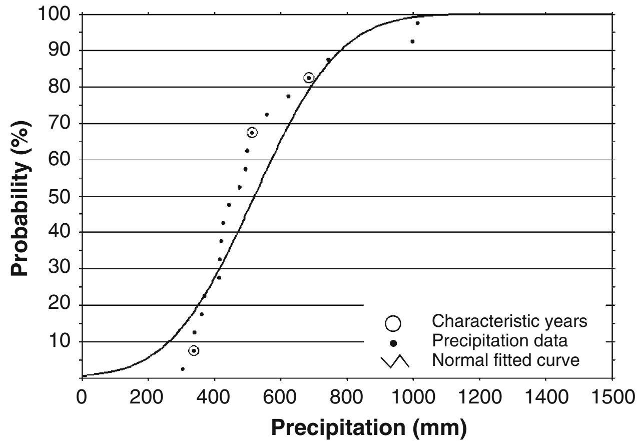

Fig. 3 Fit of annual precipitation to a normal probability distribution function; mean of all stations for the period 1984–2004

Figure 4 compares monthly precipitation in Antequera station (5 km east of Sierra de Abdalajís) with the discharge of the main springs in the area, and shows that, in general terms, monthly discharges respond to rainfall variations, but with a certain inertia or time lag due to the effect of the dewatering or depletion of the aquifer. Los Atanores and La Fresneda springs respond more rapidly to rainfall, while La Reina and Fuente Arriba springs seem to maintain a base flow. However, since March 2005, and coinciding with the drainage of the aquifers by the tunnel, the spring flows showed a downward trend, which was not reversed even after the autumn 2005 rains.

Analysis of discharge data and piezometric data

Table 1 shows the sampling points analyzed, with the indication of the draining aquifer. All these contribute to or depict discharge from the eastern part of the system (see Fig. 1). The western and north-eastern sectors will not be discussed from now on because they have a groundwater inflow towards to the river Guadalhorce, and any possible impact of the tunnel upon this does not cause water supply or pollution problems.

La Reina and Fuente Arriba springs are the lowest-lying discharge points in the system. They are situated in the La Capilla and Tajo del Cuervo Unit, respectively. The Atanores and La Fresneda are the other natural drainage points of the La Capilla and Tajo del Cuervo Unit, and these are found at slightly higher elevations.

Figure 5 shows the discharge of all the springs of the sector studied and the rainfall from March 2003 until 31 December 2005. In general, they all respond to precipitation, with more pronounced responses from Los Atanores and La Fresneda; on the other hand, these are also the springs that have a marked response to prolonged periods

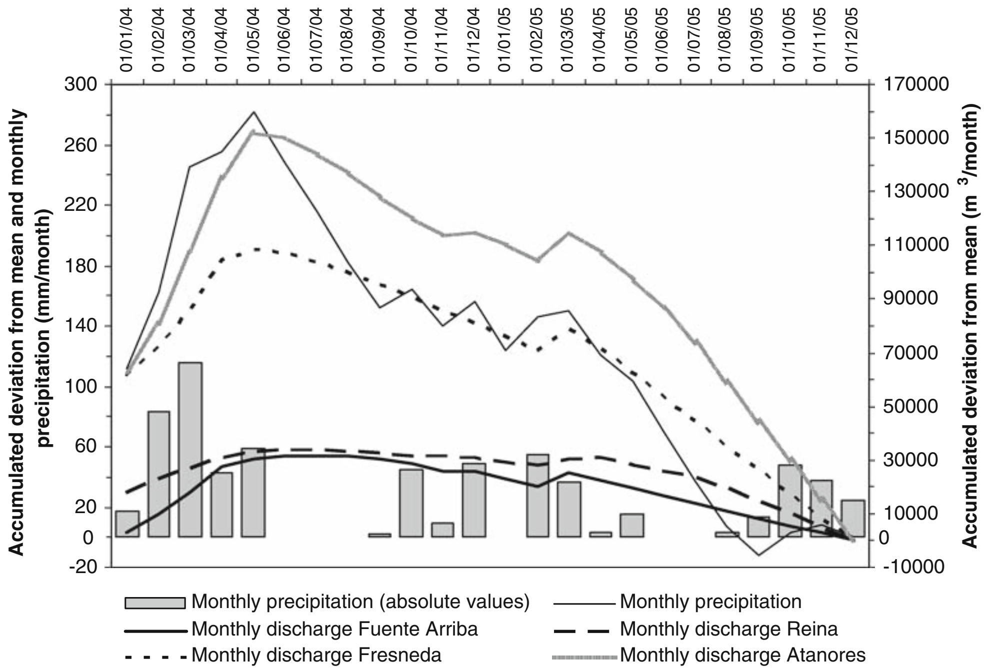

Fig. 4 Accumulated deviation from mean monthly precipitation in Antequera station (mm, left-hand *Y*-axis) and monthly flow figures (m^3/month, right-hand *Y*-axis) obtained at the main springs draining the system. Absolute monthly precipitation values are also shown (mm)

Table 1 Aquifer points analyzed in the study

Sampling point	Type	Aquifer unit	Elevation (m)/depth (m)
Los Atanores	Spring	La Capilla-Tajo del Cuervo	415
La Reina	Spring		390
La Fresneda	Spring		480
Fuente Arriba	Spring		325
Piezometer B	Piezometer		940–550
Piezometer C	Piezometer	Huma	808–360
Abdalajís	Piezometer	Abdalajís	445–200

of dry summer and/or external influence (end of 2005, as it will be discussed later), at least as far as the available logs show. La Reina and Fuente Arriba flowed throughout the period recorded; however, their flows are generally modest, even during rainy periods.

The discontinuous vertical line in the hydrographs in Fig. 5 indicates the moment from which a notable increase occurred in the flow draining the tunnels (24/03/2005). After this time, for all the springs the discharge rapidly dropped, an effect accentuated by the lack of rainfall during the spring, summer and early autumn (barely 25 mm from April to September). The springs situated at higher elevations (Los Atanores and La Fresneda) dried up over the summer months, whilst La Reina and Fuente Arriba maintained their base flow; although the flow fell as low as 1–2 L/s, it never disappeared completely at any time.

Figure 6 illustrates the evolution of the piezometers considered in the study (Table 1) from July 2003 until 31 December 2005. The only complete series comes from the Abdalajís piezometer; piezometers B and C include gaps in the records of 16 months. With regard to the quality of the data series, it needs to be noted that inspection of the logs indicates that some of the data are of doubtful validity; this is the case for the logs from piezometers B and C.

Piezometer C (over the Huma Unit) registered its highest levels in the autumn of 2003 and the beginning of 2004. During this period, there were coherent variations in water level and precipitation since the piezometer is located in a recharge zone. After a long gap in the data, the records began again in May 2005, with levels 150 m lower, and the absence of any appreciable variation suggests that the piezometer could have been dry.

Piezometer B (940 m a.s.l.), situated above the tunnel in the La Capilla Unit, maintained a constant level during 2003 and 2004, at a level of more than 600 m. After being repaired, it was reinstalled in August 2005, when a downward trend was recorded (20 m), some 200 m lower than when the bore was first installed.

The Abdalajís unit, located in the east, is the principal zone of discharge. The log of the piezometer in this unit is continuous and of good quality, and reflects the seasonal rising and falling responses to precipitation, as well as daily cycles resulting from pumping at nearby piezometers supplying water to the Valle de Abdalajís.

Correlation and spectral analysis can be considered as very suitable methods to describe and identify the structure and components of the aquifers, from which its hydrodynamic functioning is deduced, as well as to determine the lags between precipitation and different

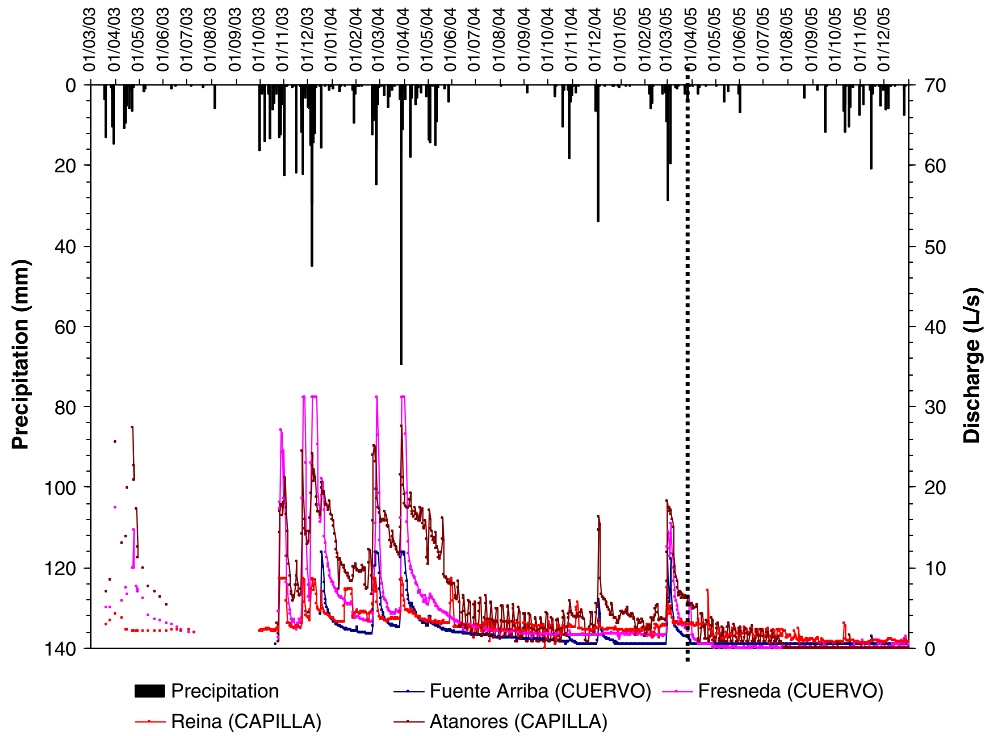

Fig. 5 Hydrographs of the principal springs in the study area. Precipitation measured at the Antequera station is shown as *bars*. The *dotted line* marks the onset of the main tunnel discharge

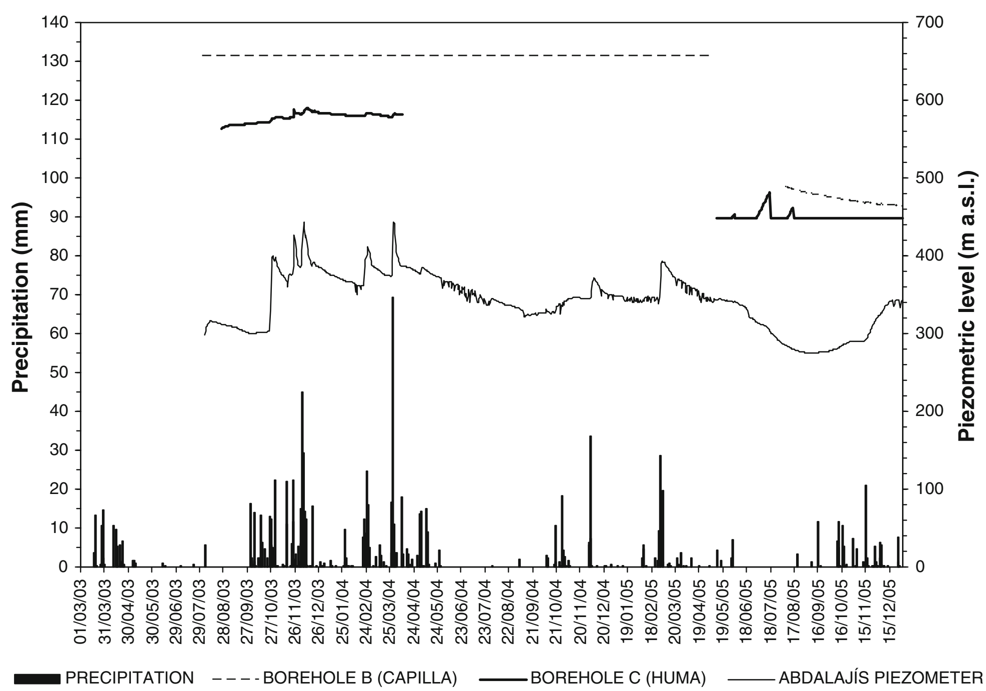

Fig. 6 Piezometric evolution of the main boreholes in the study area. Precipitation at the Antequera station is shown as a *bar chart*

hydrodynamic response of the aquifers (Rademacher et al. 2003). The main information that this analysis provides is the calculation of the effective memory, and the extent to which the input signal (precipitation) is modulated to produce a particular output signal (flow). The outflow is a characteristic of each system and gives an idea of the size of its reserves and the degree of regulation. Several authors have validated this method for characterizing karstic aquifers based on flow series of their main springs (Mangin 1984; Padilla and Pulido-Bosch 1995; Garay 2002; Jiménez et al. 2002).

Precipitation shows a typically random pattern, with a memory effect of 2–3 days (Fig. 7; Table 2), which confirms the temporal independence of rainfall in this sector, as well as a poor correlation (0.38) for a lag = 1 day and rapid fall in the correlogram.

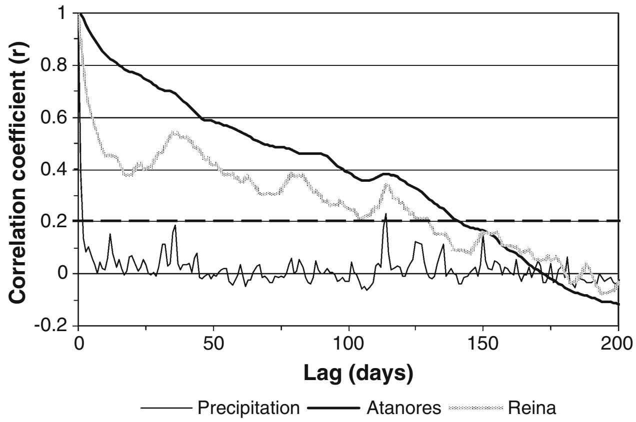

Fig. 7 Autocorrelograms of precipitation and discharge in Los Atanores spring (October 2003–December 2005)

The memory effect found in the flow record of the springs is represented in Table 2. In general, it shows a relative delay in the evacuation of flow from all the springs (from 57 days at La Fresneda to 141 days at Los Atanores; Fig. 7), and a variable moment as regards the time that the springs run dry (16 days in Fuente Arriba and 40 in La Fresneda). The memory of these systems is therefore medium-high, when compared 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 (72 days; Padilla and Pulido-Bosch 1995).

System behavior and hydraulic balance under natural conditions

Under normal conditions, the recharge area of the aquifer units is situated in the highest and most central part of the Sierra, approximately coinciding with the tunnel route (Fig. 1). This situation is also the most probable location of the hydrogeological subterranean watersheds of the aquifer units, although this would be subject to both seasonal (precipitation-rainfall), anthropogenic (pumping), and even year to year variation (wet and dry periods). The discharge areas would lie to the west (river Guadalhorce) and east (springs of Los Atanores, La Reina, La Fresneda and Fuente de Arriba) of the aquifer units, coinciding with the lower elevations. The Abdalajís unit does not have a visible surface discharge, though there probably is a hidden one at depth.

The hydraulic gradients are probably between 1.3 and 7%, depending on periods of dry weather or of recharge. Such high average values are indicative that the mean hydraulic conductivity is low or very low, due to the predominance of blocks of massive limestone in the storage areas, possibly with scarce karstic conduits.

At these latitudes, the system operation is determined by the quantity and seasonality of rainfall. Yearly, renewable resources come from precipitation during the wet season and are drained by the springs (along the eastern border) and by groundwater inflow towards the river Guadalhorce (along the western edge), though there are also point emergences here as well; some springs with an elevated flow are intercepted by the existing railway tunnel in this area. These natural overflows respond in this way to precipitation, though there is a certain delay which is quite small for these springs (1–2 days). Despite this delay, the regulation effect (hydrological reserve) of the aquifer units is moderate (16–40 days), with a certain persistence in flow over time that reflects inertia or generally moderate regulation periods (between 2 and 19 days, depending on the spring).

The analyses undertaken on the springs of the La Capilla-Tajo del Cuervo unit, as well as the estimated gradients, reflect the fact that in this aquifer there is a clear hierarchy between transmissive elements (with a rapid

Table 2 Summary of the main parameters from a simple time series analysis of precipitation, discharge and piezometric level analyzed in this study

Series	Maximum *r*	Memory effect (days)	Regulation time (days)	Peaks in spectral density (cycles in days/spectral variance)
Precipitation at Antequera	0.38	2–3	–	11/0.4
Discharge at Fuente Arriba	0.94	108–124 (16)	2	Secular
Discharge at La Fresneda	0.96	100–140 (40)	8	120/3.6 30/2.4
Discharge at La Reina	0.98	131–165 (34)	4	Secular
Discharge at Los Atanores	0.99	141–158 (17)	19	Secular 150/3.3
Piezometer level at Abdalajís	0.99	86–104 (18)	Very high	Secular, rapid fall 120/67.2 38/11.9 30/7.6

r Correlation coefficient

Table 3 Inflows into the aquifer for an average year, according to net rainfall and Kessler's method

P (mm)	PET (mm)	RET (mm)	Net rainfall (mm)	Infiltration (Kessler)	Inflow (hm^3)
512	946	348 (58%)	252	51% (307 mm)	2.1–2.6

P precipitation, *PET* potential evapotranspiration, *RET* effective evapotranspiration

reaction time) and other, capacitive ones (with a more prolonged reaction). The influence of these on the discharges is approximately the same.

To quantify the volume of water involved in the hydrological cycle a groundwater balance has been calculated. The principal input to the aquifer is infiltration from precipitation (Table 3), since hidden, lateral groundwater inflows are considered to be nil or insignificant. The main outflows from the aquifer comprise runoff from the springs as well as pumped abstractions (Table 4).

Balances have been calculated only for those units directly affected by the tunnel (8.5 km^2) and, at the same time, whose springs provide public water supply; i.e., the units of La Capilla-Tajo del Cuervo and Abdalajís. Mean values in the springs refer to the last 2 years, when a serious drought was registered.

Given that in any system in equilibrium the inputs must be similar to the outputs, one can say that the difference between these two parameters could probably correspond to unidentified emergences or pumped abstractions, as well as to hidden losses to adjacent systems that are difficult to quantify in this phase of the study, although this hypothesis is not supported by observations.

Table 4 Principal outflows per unit for an average year (hm^3). Mean value for the period 2003–2005 in parentheses

	Capilla-Cuervo	Abdalajís	Huma	Outflow (hm^3)
Springs	1–2 (0.4)	–	–	1–2
Pumpings	0.1 (0.07)	0.13	–	0.2
Total	1.1–2.1 (0.5)	0.13	–	1.2–2.2

Fig. 8 Southern tunnel entrances at Abdalajís

Impact of the tunnel on the hydraulic balance

Drilling of the double tunnel began on 15 November 2003 (Fig. 8). Given the drilling system of the tunnel-boring machine, the eastern tunnel was always drilled between 400 and 600 m ahead of the western one. Initially, since the rocks drilled did not possess a high aquifer potential, the water flux draining from the bores was foreseen at the outset (20–40 L/s); however, there was no infrastructure to measure it. From March 2005 (24 March for the eastern tunnel and 7 May for the western one), a large inrush of mud and water invaded the tunnels with an estimated instantaneous flow at times of more than 600 L/s, and this coincided with the penetration of the two tunnels into the carbonate rocks of the Sierras de Abdalajís.

It became necessary to measure the flow and its evolution through time, a question that was addressed at end of May 2005 initially by means of discontinuous measurements and later with continuous monitoring. The peaks of the most intense flow seen in the tunnel hydrographs occurred as the tunnelling machines (at different moments in the two tunnels) intersected geological milestones and hydrogeological units, such as those detailed in Fig. 9.

A detailed analysis of the geological profile of the tunnel was made and compared with the tunnel hydrographs and corresponding kilometer points that the drilling was to reach at each moment, i.e., as the cutting heads advanced.

The first event (not recorded in the flow data) coincided with penetration of the carbonate rocks of the Sierra de Huma. Specifically, the drilling cut into a fault zone within this unit, possibly one with large conduits, which suddenly dewatered producing a fall in the water table. Part of this episode was reflected in the hydrograph of the eastern tunnel (Fig. 9), in the initial part consisting of discrete data points. One can compare which aquifer and geological unit (color-coded) was being excavated with the variation in tunnel water discharge. The eastern tunnel had already crossed the Huma unit when the western one was still crossing Huma, and the next event was Event 2 (west).

Crossing the Triassic deposits (colored red in Fig. 9) of the Meleguetín Formation, hydrographs for both tunnels

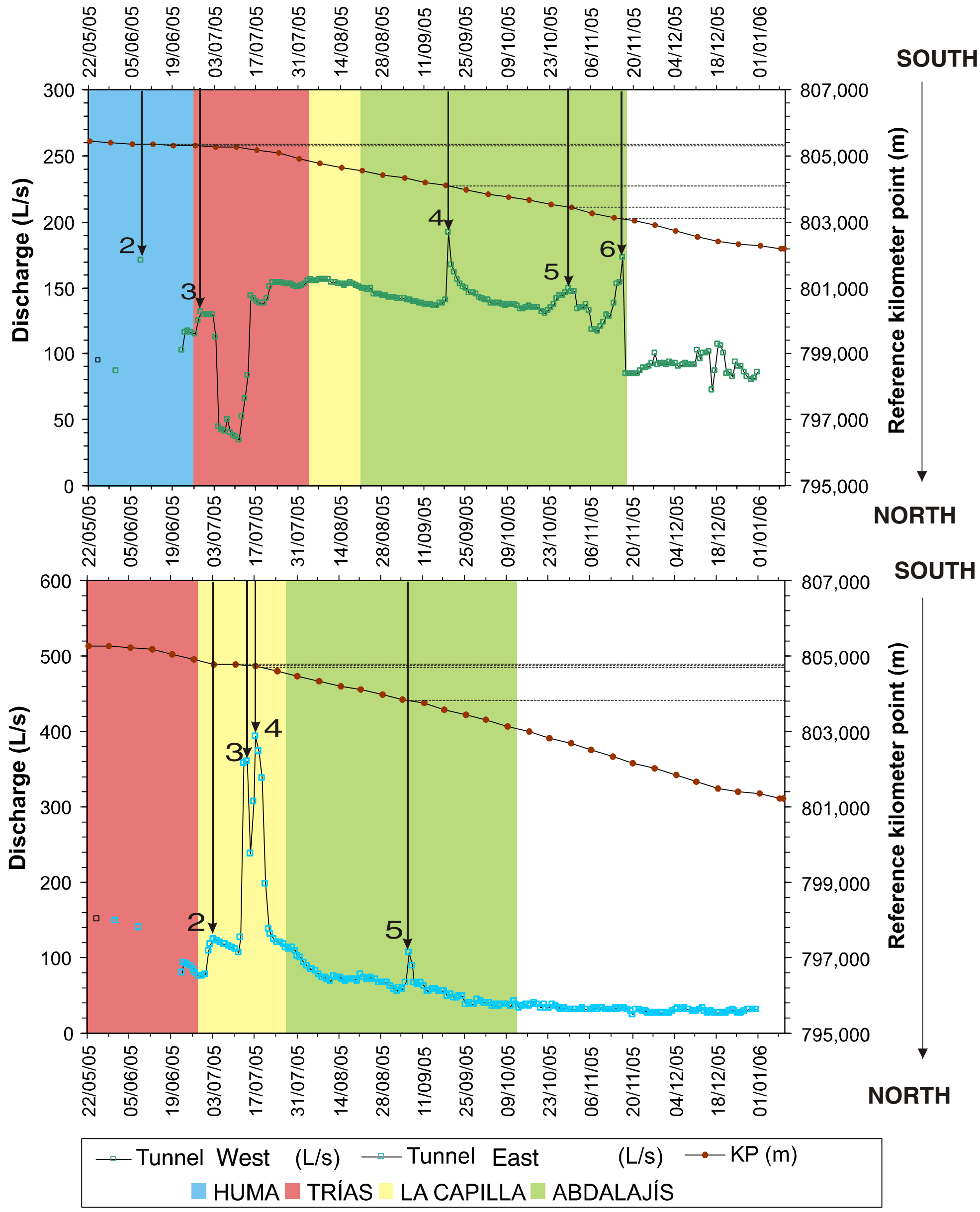

Fig. 9 Hydrographs of the tunnels front advance (kilometer point) with the notable flow events. *Different colors* indicate the units crossed

indicated a drop or stabilization of the flow drained, since these materials behave as a poor aquifers and, at the same time, have poor water quality. However, when the eastern tunnel crossed the La Capilla-Tajo del Cuervo unit (yellow in Fig. 9), the most pronounced peaks of flow were produced, because of the great dewatering occurred cutting the various geological–hydrogeological units. Subsequently, due to the recent dewatering of these units in this sector and lack of any precipitation for recharge, the western tunnel did not reveal any extraordinary flow event.

The draining effect of the tunnel in the aquifer can be described as a depression of the piezometric level along the route that is dependent on the hydraulic conductivity and storage coefficient of each stretch and, in particular, on the discontinuities. This drawdown could affect both the position of the hydrogeological watersheds as well as the gradients, giving rise to local inversions. A hydrogeological section has been drawn for the tunnel (Fig. 10), showing the most probable positions of the piezometric level under a natural regime (pseudo-natural) and under a regime influenced by the tunnel. It is possible that the most sudden inrush almost completely dewatered most of the aquifer in contact with the transmissive section being crossed. Sealing operations had the effects of reducing the outflow (now less because of the effect of the dewatering) and gradually increasing the hydraulic head leading to repercussions over the whole system.

The total volume of water drained from the tunnel during 2005 was at least 3.26 hm^3. Figure 11 shows the trend in monthly flows for each tunnel. The flow was

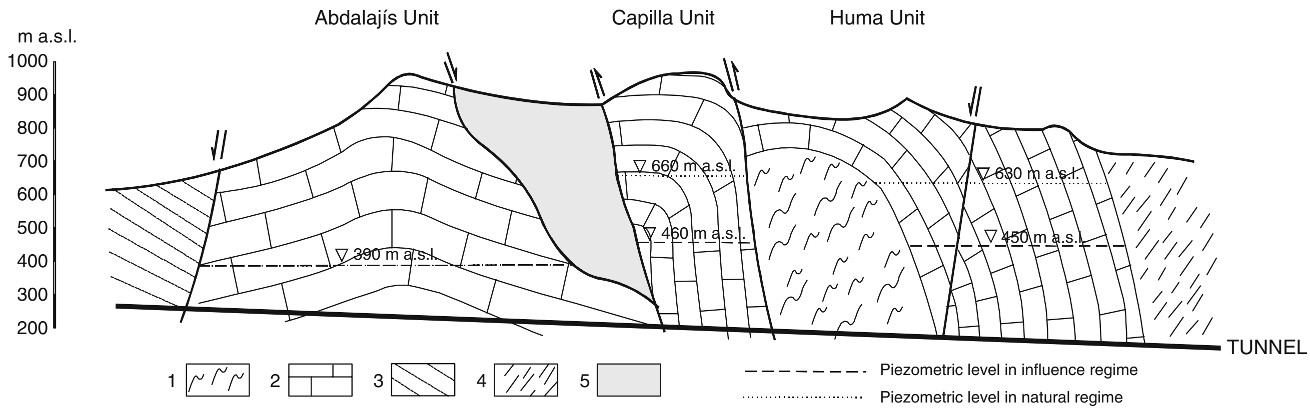

Fig. 10 Hydrogeological scheme of the tunnel route. *1* Triassic clays and gypsums (poor aquifer potential), *2* Jurassic limestones and dolomites (karstic aquifer units), *3* undifferentiated impermeable deposits, *4* Tertiary clays (aquiclude), *5* cretaceous marls and marly limestones (aquitard)

greater in the western tunnel, totalling 2.07 hm^3, as compared to 1.12 hm^3 in the eastern tunnel, despite the fact that the flow events in the eastern tunnel were more pronounced. It is logical to assume that this is due to the fact that the cutting of the eastern tunnel was in advance of the other, whilst the lesser volume drained could be due to more effective sealing of the tunnel lining.

The hydraulic balance calculated for the regime influenced by the tunnelling takes into account the volume drained by the tunnels, which act as a new outflow from the system. Logically, this balance can only be calculated for the year 2005 (Table 5). One must not forget that this year falls within a pronounced multi-year drought, with only 25 mm rainfall from April to September, and with annual precipitation (243 mm) lower than the driest in a 21-year time series. It must also be pointed out that the infiltration calculated for the year 2005 (by the Kessler method; Kessler 1965) is somewhat above average.

The results of the balance for 2005 (Table 5) show a marked impact of the drainage from the tunnel on the global volumes of water in the balance, leading to a deficit balance values of more than 2 hm^3. This deficit provoked the premature dewatering of the units and the loss of a great volume of water from March onwards, which is clear in the hydrographs for the resurgences from the eastern sector. High elevation springs (La Fresneda and Los Atanores) dried up first, leaving a limited base flow in the lower-lying springs (La Reina and Fuente Arriba), as the limited reserves that still persisted above their resurgence level became depleted. Nevertheless, the effect was accentuated by the virtually rainless spring and summer. The springs are partially connected to preferential and rapid flows, so that intense and/or prolonged rain will eventually recharge the system and allow them to appear again. This recharge is likely to occur during late autumn and winter, and has already been demonstrated by the rainfall of 27–30 January 2006 (not represented in Fig. 5) of more than 50 mm that converted the unit into a state of recharge and caused the springs to flow once again.

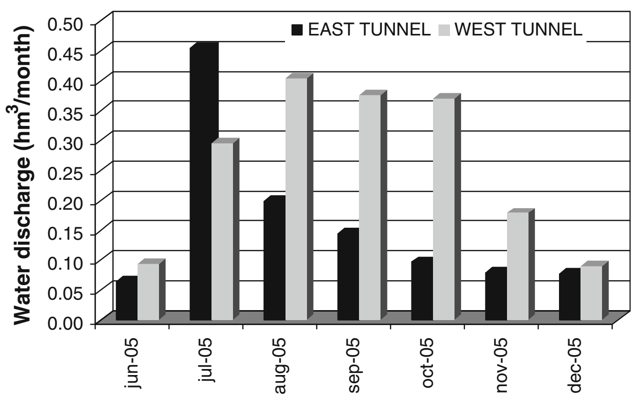

Fig. 11 Monthly evolution of the water discharge from the tunnels

Table 5 Summary of the water balance for the regime influenced by the tunnel

	Unit	Year 2005 P = 243 mm; I = 57%
Inputs (hm^3/year)	Capilla-Cuervo	0.5
	Huma	0.4
	Abdalajís	0.7
	Total	1.6
Outputs (hm^3/year)	Capilla-Cuervo	0.2
	Huma	–
	Abdalajís	0.12
	Tunnel	3.26
	Total	3.6
I–O Balance (hm^3/year)	Capilla-Cuervo	0.3
	Huma	0.4
	Abdalajís	0.5
	Total	−2

Similar behavior is seen in the record of water levels in Abdalajís, although here there was greater buffering and time lag.

It is possible to estimate the recovery time, which is the time needed to recharge the approximately 3 hm^3 of water into the aquifer units that originally drained to produce the drawdown of water levels. If infiltration is 50% of precipitation, it would be possible to achieve recovery, including storage, with approximately 530 mm precipitation; accordingly, at least 2 years average rainfall would be needed to re-establish the system.

Conclusions

This study allowed to analyze the hydrogeological features and functioning of the limestone aquifers of the Valle de Abdalajís for both the natural and tunnel-influenced regimes.

Under a natural regime, the complex system of carbonate aquifer has two drainage sectors. The more important of the two lies at the western end of the mountains line, and drains directly to the river Guadalhorce. The other lies at the eastern end and has numerous resurgence points, some of which can act as overflows and lie at elevations higher than the permanent springs. The considerable tectonic complexity of the area could also explain the complex hydrogeological setting.

Existing records for spring flow and changes in water level highlight that the response time between precipitation and infiltration is almost immediate. The memory is 17 days in Atanores, 34 days in La Reina, and 16 days for the Fuente de Arriba, all indicative of the existence of an elevated hydraulic diffusivity. Together with very rapid preferential flow paths, however, other slow flow paths have been identified that drain minor fractures, fissures and somewhat porous blocks. The former have a medium response time to precipitation events of 1–2 days, while the slower flows give a response in the system after 30 days, or even after 2 months in some cases. These base flows feed the springs with a perennial water supply during most years, on which the local populations depend.

The study highlights that the units dewatered as a result of the tunnel excavation will recover to their initial situation after no more than 2 years of *normal*, i.e., around average, precipitation. In fact, the rainfall at the end of January 2006 took a few days to reactivate the springs that had not flowed for months (such as Atanores and La Fresneda).

If the whole tunnel were sealed, as is the intention of ADIF, the company responsible for this stretch of tunnel, the hydraulic pressure on the tunnel would reach the pre-tunnel situation very quickly, and the recovery of the system, together with spring discharges and piezometric levels, would take place in 2 or 3 years with an average precipitation recharge to the aquifer.

Groundwater level logging instrument would be required above the top of the tunnel arch and in the boreholes along the tunnel route, furnished with alarm systems.

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