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MÁLAGA
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The European Conference on Karst Hydrogeology and Carbonate Reservoirs

Field trip guide: geomorphology and hydrogeology of carbonate and evaporitic karst massifs in the central sector of Malaga province

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EUROKARST 2022: Field trip across the central sector of Malaga province: geomorphology and hydrogeology of carbonate and evaporitic karst massifs

Key features

Departure: Saturday 25th May 8:00 am / Return: Saturday 25th May 7:00 pm approx.

Instructors and guide authors: José Manuel Gil, Matías Mudarra, and Juan Antonio Barberá

Center of Hydrogeology of the University of Málaga and Department of Geology. Faculty of Science. University of Málaga. E-29071. josemgil@uma.es; mmudarra@uma.es; jabarbera@uma.es

Location Map

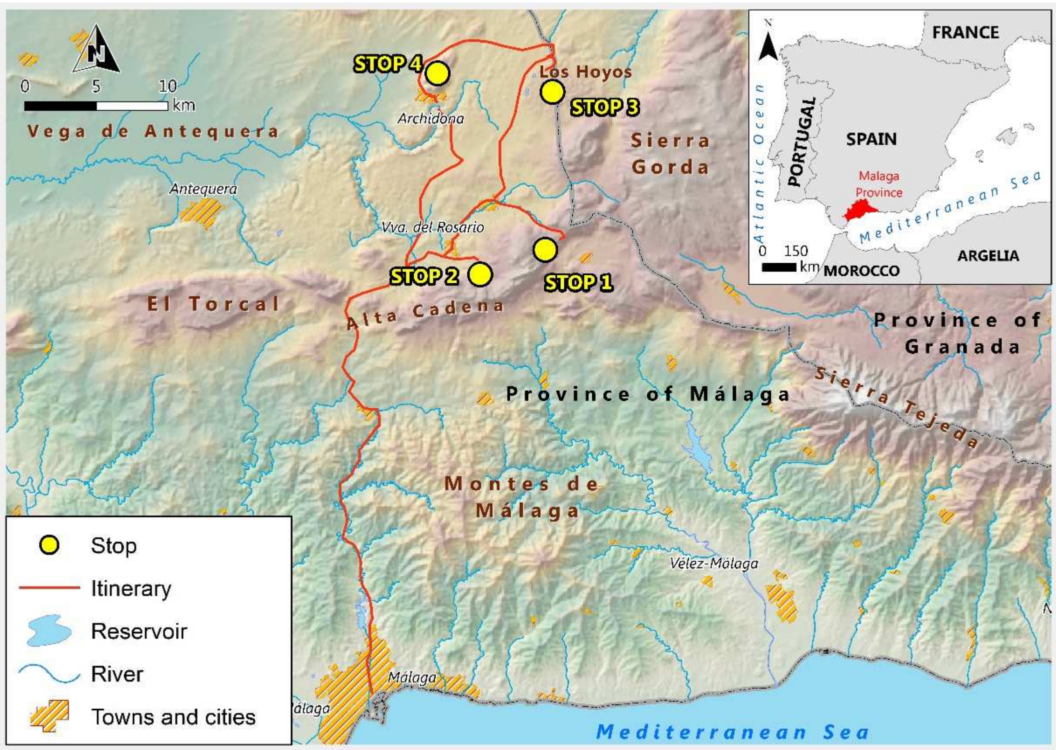

Figure 1. Itinerary and location of the stops during the field trip.

Introduction

This congress field trip takes place in the central-north part of province of Malaga, in southern Spain (Fig. 1). Guided by hydrogeologists from the Centre of Hydrogeology of the University of Malaga, participants will have the opportunity to visit some of the most exciting karst landscapes of Spain, developed on different lithologies:

- Sierra del Jobo (Alta Cadena Mountain Range)
- Los Hoyos area and Archidona wetlands
- Sierra de Archidona

Sierra del Jobo (Photo 1A) is composed of Jurassic carbonate rocks where the tectonic framework and the karstification phenomena have favored a noteworthy development of exo-karst landforms such as karrenfields, sinkholes, dolines, uvalas and springs (with different hydrogeological behavior). Experimental methods for improving the knowledge on karst recharge and evapotranspiration processes are been currently implemented in this area. On the other hand, Los Hoyos area (Photo 1B) is an evaporitic karst enclave of great geomorphological and environmental value, where hydrogeochemical processes explain the geodiversity and hydrodiversity that sustain biodiversity (for example in Archidona wetlands) and the cultural heritage (Gil-Márquez et al., 2022). Finally, Sierra de Archidona (Photo 1C) is a good example of recent research in a small carbonate aquifer in which novel management strategies are being explored to improve sustainable groundwater exploitation.

Photo 1. (upper –A-) Panoramic view of the Alta Cadena Mountain Range. (lower-left –B-) Grande lake, developed in evaporitic terrains of Los Hoyos area. (lower right –C-) Aerial view of Sierra de Archidona carbonate aquifer.

Stop 1: Sierra del Jobo (Alta Cadena). Monitoring recharge processes in karst aquifers

The Sierra del Jobo is included in the Alta Cadena (Photo 1A), a 25 km long and 4 km width carbonate mountain range located 30 km north of Malaga city (Fig. 1), with altitudes ranging from 600 to 1,640 m a.s.l. Climate conditions are typically Mediterranean, with rainfall mainly occurring from winter to spring time. The mean historic annual precipitation is below 600 mm in the lower altitudes, and more than 900 mm in the higher altitudes (Mudarra, 2012). The average annual air temperature varies between 11.2 ºC to 17.3 ºC. The vegetation is Mediterranean scrubland with Mediterranean forest patches and pines from reforestation.

Geologically, Sierra del Jobo and the surrounding areas are constituted of Jurassic carbonate rocks (Fig. 2), with a total thickness of 400-450 m (Peyre, 1974; Martín-Algarra, 1987). The carbonate rocks are mainly oolitic limestones, with a much lower representation of dolostones (which are stratigraphically below the limestones), being bounded at the base by Late Triassic clays and evaporite rocks, while at the top there are Cretaceous-Oligocene marly limestones and marls. Both Cretaceous and Triassic outcrops show a very limited extension in this area (Fig. 2). The geological structure is characterized by the existence of ENE-WSW lying folds, from which tectonic sheets, limited by overthrusts, have developed with vergence toward S-SE (Fig. 3). To the S and N, overthrusting carbonate rocks, outcrops of Flysch-type clays and sandstones exist. The set of geological units has been affected by more recent fractures, in a mainly NW-SE direction (Martín-Algarra, 1987).

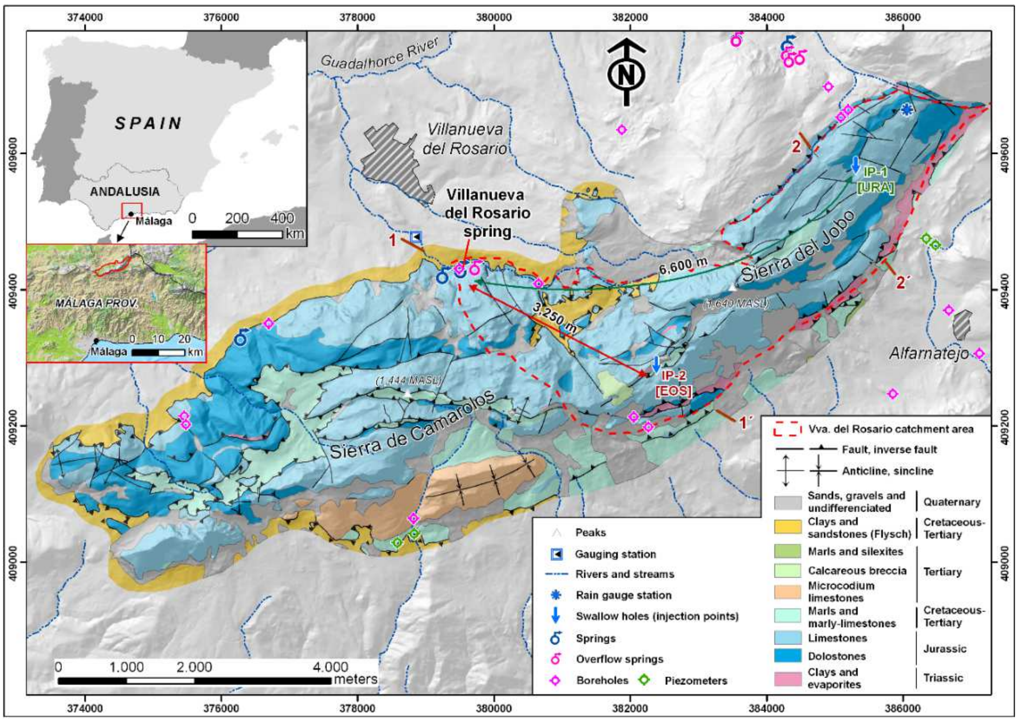

Figure 2. Hydrogeological map of the Alta Cadena. See location in Figure 1.

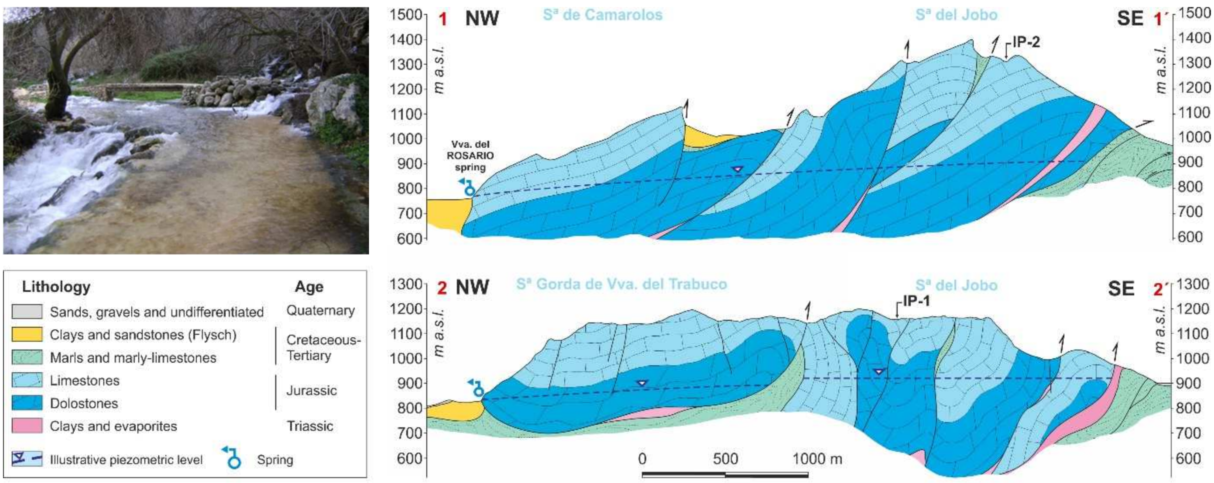

Figure 3. Cross section of Sierra del Jobo aquifer (Mudarra, 2012). See location in Figure 2.

In hydrogeological terms, the Sierra del Jobo aquifer is formed by fractured and karstified Jurassic carbonate rocks, with a surface area of 27 km^2. It is bounded at almost all its tectonic borders by Upper Triassic clays and evaporite rocks, Flysch clays and sandstones, and Cretaceous–Paleogene marls (Mudarra et al., 2014). Autogenic recharge takes place through direct infiltration of rainwater over the carbonate outcrops (exceptionally snow melt water). The groundwater drainage occurs mainly through two springs located at the northern edge of the aquifer (Fig. 2): Parroso and Villanueva del Rosario outlets; the last one will be visited during this trip. The mean water resources calculated for the historic period are 9.51 hm^3/year, equivalent to 49% of precipitation (Mudarra, 2012). Few sources of pollution exists on the recharge area of the aquifer, apart from some dispersed livestock farming.

The tectonic framework and the predominance of Jurassic oolitic limestone outcrops favor karstification phenomena and a noteworthy development of exo-karst landforms: karrenfields, dolines, sinkholes, shafts. Karst features are especially significant at higher altitudes, where there are also other exokarstic forms like small uvalas, developed following major fracture alignments. Some uvalas present karst swallow holes which become active during heavy rainfall. A patchy soil cover (up to 60 cm thick) can be found, especially where slope is low, i.e. in dolines-uvalas. The two main soil types are patchy leptosols that cover carbonate outcrops, with a thickness lower than 30 cm, and silty-clayey texture soil with a thickness of 10 to 70 cm that covers the Cretaceous–Paleogene marls (Marín et al., 2015).

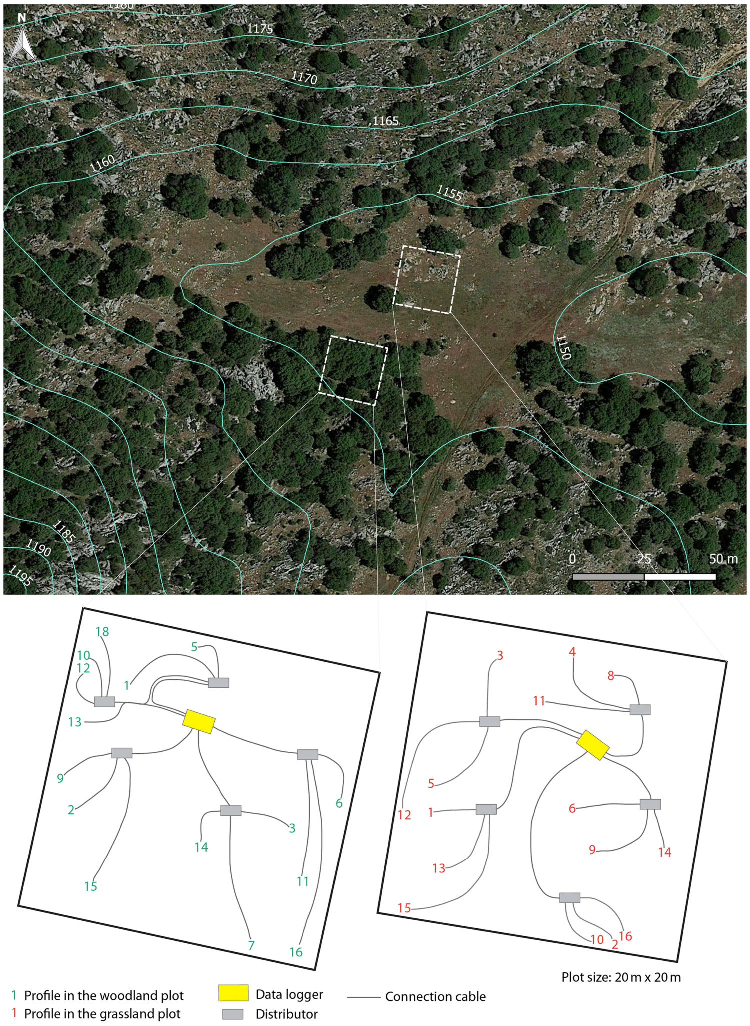

Figure 4. Plot locations, profile distributions, and cable connection maps at the Villanueva del Rosario experimental area (from Berthelin et al., 2020).

In the recharge area of Villanueva del Rosario Spring, two 20m x 20m plots with different land-use types (forest and grassland) were conditioned (Fig. 4) near a karst swallow hole in order to understand the partitioning of rainfall into infiltration, evapotranspiration, and groundwater recharge processes. Both plots are part of a world-wide monitoring network that will allow for the improvement of the understanding of soil and epikarst processes by including different karst systems with different land-cover types in different climate regions. With the title "Global Assessment of Water Stress in Karst Regions in a Changing World" the responsible of this project is Prof. Andreas Hartmann (University of Dresden, Germany). Each plot includes 15 soil moisture profiles randomly selected. Probes at different depths from the topsoil to the epikarst (in total over 45 soil moisture and temperature probes) were installed. Covering the spatio-temporal variability of flow processes through a large number of profiles, this experimental infrastructure will allow researchers to develop a new conceptual understanding of evapotranspiration and groundwater recharge processes in karst regions across different climate regions and land-use types, and this will provide the base for quantitative assessment with physically based modelling approaches in the future. First results have been published recently (Berthelin et al., 2020).

Stop 2: Villanueva del Rosario Spring

It is the main discharge point of the Sierra del Jobo aquifer, located at 770 m altitude (Figs. 3 and 5), in the tectonic contact between carbonate rocks and low permeability materials. The Villanueva del Rosario spring shows an annual mean discharge rate of 260 L/s and reacts rapidly to precipitation events, showing water flow variations from 15 to 2,500 L/s (Fig. 5). Mean response time lag among the rainfall (input signal) and the hydrodynamic response (output signal) is usually less than one day. This was confirmed after several tracer tests, whose results proved maximum flow velocity of 200 m/hour from the swallow holes (one of them sited near the experimental plots; see location in Figure 2) to the spring (Mudarra et al., 2014; Marin et al., 2015). The subsequent decreases in flow rate also occur quickly. During dry periods, the spring discharge is not enough for the water supply of 3400 inhabitants, so it is necessary to pump groundwater from two boreholes (one located in the spring and other one 1160 m eastward from the spring, Fig. 2), resulting the complete depletion of the spring. The depletion coefficient value, calculated in absence of pumping, is in the range of 1 - 3 x 10^{-2} (Jiménez et al., 2002; Mudarra and Andreo, 2011).

The typical karst functioning inferred from the hydrodynamic response is also evidenced by the quick variations in temperature, electrical conductivity (EC), and in the hydrochemical parameters analyzed in the water from Villanueva del Rosario spring (Fig. 5). Thus, during recharge events, spring water undergoes sharply decreases in temperature and EC, accompanied by falls in the values of almost all the chemical components. Even during low water conditions, short but significant dilutions may occur, in response to stormy rainfall events. In general, most of the components respond in a similar way to EC, except alkalinity and Ca^{2+} contents, which rise slightly rather than falling during some periods of flood. Contents of TOC and NO_3^- (natural tracer of recently infiltrated water) do not follow the general pattern of EC; on the contrary, they tend to be higher at the beginning of the hydrogeological year (in autumn), when the first recharge events occur, and decrease with falling water levels in the spring, until a fresh maximum is reached in the subsequent autumn flooding. Most of the discharge peaks in hydrograph coincide with slight increases in NO_3^- and TOC contents. This is due to the mixing of water from the saturated zone, which is drained by the spring before the recharge, with the recharge water, which circulates through the unsaturated zone and it has higher content of NO_3^- and TOC (Mudarra et al., 2014). The magnitudes of these dilutions are proportional to that of the recharge (Fig. 5). As the groundwater flow decreases, water mixing becomes more homogeneous, temperature rises and dissolution takes rise within the aquifer host rocks, mainly in the saturated zone; thus, there is a progressive increase in water mineralization, except for NO_3^- and TOC, which decrease as a result of the reduced contribution of recently infiltrated water from the soil and epikarst.

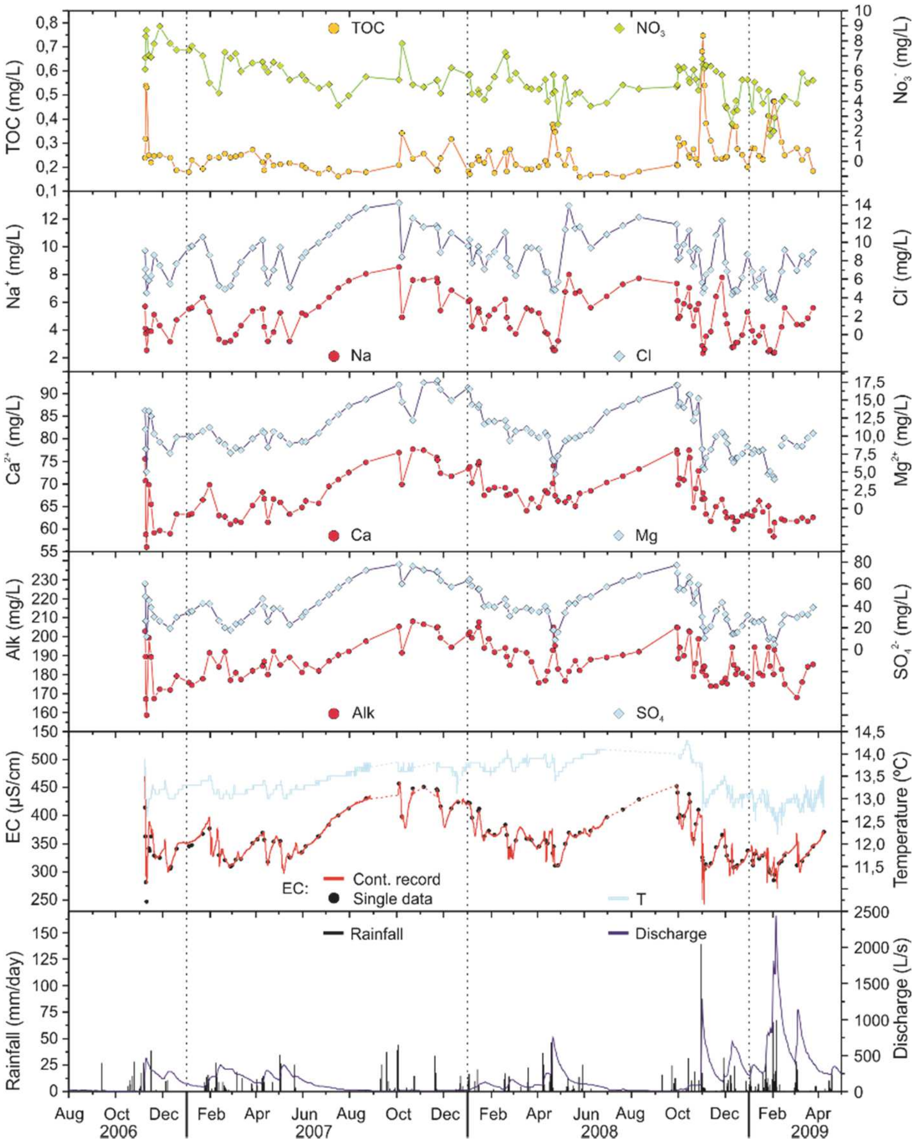

Figure 5. Temporal evolution of discharge and chemical composition of the water drained by Villanueva del Rosario Spring (Mudarra, 2012).

Hence, the sector of the aquifer drained by Villanueva del Rosario Spring shows a high degree of functional karstification, typical of conduit flow systems, with rapid drainage and a low capacity for natural regulation (Mudarra and Andreo, 2011). The karst drainage network is developed in both the unsaturated zone and the saturated one and both zones play similar roles in the functioning of the system, although it seems to be greater in the first of these. These characteristics mean that the volume of water resources stored is relatively small and that the karst system is highly vulnerable to contamination. This aspect should be considered for a better protection and management of water resources, since they have direct consequences on water supply and in the environmental preservation of groundwater-ecodependent systems (Marín et al., 2015).

Stop 3: Los Hoyos karst and Archidona wetlands

In northern Málaga Province, Triassic clays and evaporites greatly outcrop (Fig. 6). This materials belong to the so-called Chaotic Subbetic Complexes (CSC), an extensive megabreccia formed by multicolored marls and evaporite rocks of Upper Triassic (Keuper) age, as well as olistoliths (blocks) of diverse size, including limestone, dolostone, sandstone, and other Post-Triassic materials (Vera and Martín-Algarra, 2004). The inner structure of these rocks is disrupted and chaotic, as a consequence of the gravitational collapse and movement of the External Zone of the Betic Cordillera towards the Guadalquivir basin, during the Middle to Late-Miocene. Karstification processes over the evaporites give rise to surficial and underground karst forms. Thus, endorheic areas are abundant, many of which host wetlands at the bottom of their basins. Also, there are springs related to the CSC, many of which drain brine groundwater with high NaCl content (Carrasco, 1986). That is linked to the presence of halite at depth, although this mineral is absent at the surface as a consequence of its high solubility.

The hydrodiversity of the medium (hydrochemistry, water temperature, hydroperiod) is related with the existence of a hierarchized system of groundwater flows with different residence time within the rocks (Andreo et al., 2016). The position of wetlands regarding the groundwater table determines its typology (recharge, transitional, discharge). Furthermore, the degree of contribution of older groundwater flows increases towards spring and wetlands located at lower altitudes, which leads to higher mineralization of their waters (Gil-Márquez, 2018).

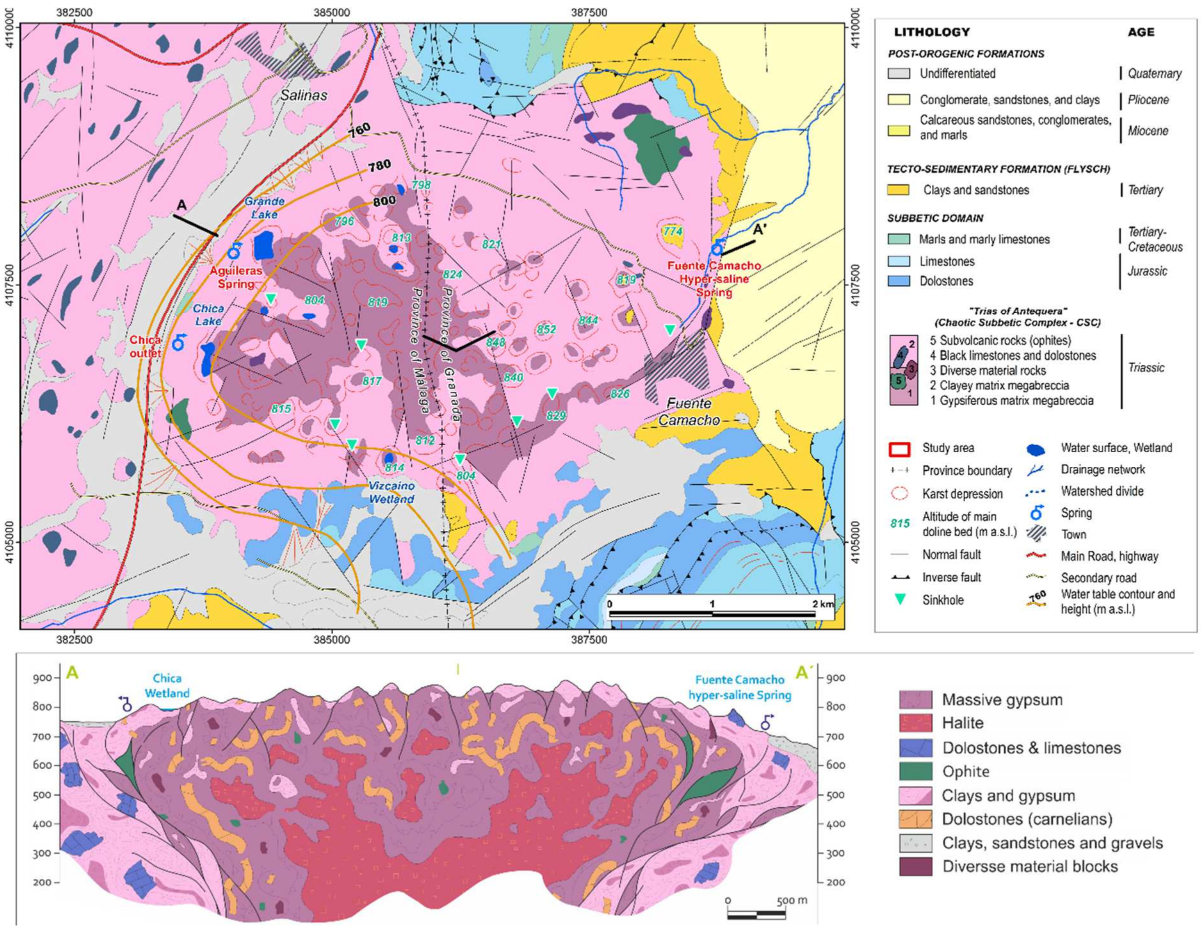

Figure 6. Geological-hydrogeological sketch and cross sections of Los Hoyos karst area. From Gil-Márquez et al. (2016). Location shown in figure 1.

Archidona wetlands (Grande and Chica) are located in the northeast of Malaga Province (Figs. 1 and 6). They are also protected by the Andalusian government as Nature Reserve and are included in the Ramsar List. Both wetlands are part of a larger geological, geomorphological and hydrological context, which includes the whole karst system of "Los Hoyos", a CSC outcrop of 20 km^2, whose origin may be linked to halokinetic processes (Calaforra and Pulido-Bosch, 1999).

Geologically, Triassic clays and sandstones are the main outcropping materials at "Los Hoyos" area. Among them, stratiform and irregular gypsum levels (salt rocks at depth), limestones, subvolcanic rocks (ophites), brecciated dolomites are included (Fig. 6). Though gypsum is typically massive it is sometimes found forming a polygenic breccia made out by gypsum pieces and clays, limestones and dolostones (Calaforra and Pulido-Bosch, 1999). The Triassic rocks are highly deformed, in a chaotic way, so it is hard to see the original stratigraphic relations between them. Furthermore, the diapiric processes related to the presence of evaporite rocks have caused a surface uplifting. As a result, Los Hoyos karst is elevated up to 50 m from the surrounding Quaternary materials (Fig. 6).

Over the diapiric structure, a singular karst landscape has developed, characterized by numerous dolines of different typology, collapses, sinkholes, swallow holes, uvalas, springs, etc. (Fig. 7). All together made Los Hoyos a place of particular interest from the geomorphological point of view. Most of the dolines and the small sinkholes are distributed in the central part of the diapiric structure due to the gypsiferous nature of its core. They present vertical borders and large detached blocks as they were generated by collapse processes, as a consequence of a more active terrain elevation that results in unstable changing landforms and even in the development of new collapses (Calaforra and Pulido-Bosch, 1999). Towards the edges, large dissolution dolines are developed, with flat bottoms that are commonly covered by clayey materials. Sometimes, the base of the dolines reaches the piezometric surface of the aquifer, resulting in the depression flooding, such as Grande and Chica wetlands. The main axes of these dolines are generally orientated along the direction of the diapire perimeter, proving a clear structural influence (Pezzi, 1977).

Figure 7. Aerial panoramic view of Los Hoyos area, Retrieved from www.archidonaturismo.es (upper left). Grande Lake from the southern edge (lower left). Chica Lake in dry period and wet periods (Upper right and lower right, respectively).

The presence of a diapiric structure, along with the high solubility of the evaporitic materials, has a remarkable influence on the hydrology and hydrogeology of "Los Hoyos" area (Linares, 2008). Furthermore, "Los Hoyos" karst constitute a small and interesting hydrogeological system, well delimited and defined by its borders. Recharge takes place by diffusive infiltration of rainwater on endorheic areas and permeable outcrops, but concentrated recharge is also produced via karst swallow holes (Fig. 6). Discharge occurs via springs or wetlands, located at the edges of the system or towards the surrounding quaternary deposits.

Aguileras spring is the main outlet of the system. It is placed at 787 m a.s.l. and has an estimated mean discharge of 15 L/s, and an average value of electrical conductivity close to 3 mS/cm (Gil-Márquez et al., 2016). Grande and Chica wetlands (Fig. 6) are karst depression whose beds (approximately 780 m a.s.l.) are below the phreatic level. They have a mean flooded surface of 7 ha. Grande lake is permanently flooded and its water column reaches a maximum height of 13 m. Chica lake is shallower (up to 8 m) and it can dry up during some droughts (Rodríguez-Rodríguez et al., 2007). It has a kidney-shaped form as its basin was formed by the coalescence of two nearby dolines. So, in low water conditions, Chica Lakes is split into two different water bodies (Fig. 6). Additionally, there are other dolines in the area that only remain flooded during a few months after exceptionally rainfall events. Under these meteorological conditions, a rise of the phreatic surface takes place, reaching the basement of the dolines and flooding them (Fig. 8). Finally, the dolines placed at higher altitude are only flooded for a short period after heavy rainfall.

The basins of Grande and Chica Lakes are relatively small (21 and 36 ha, respectively), so they do not receive significant runoff inputs. However, they have registered large wetland stage rises, up to 4 m in a single hydrogeological year. These rises present lag-times of several months from the main precipitation events, suggesting that the system delays the rainfall signal. Thus, such rises are caused by groundwater inputs, which are very important in the wetland water budget (Gil-Márquez, 2018). Water outputs take place via evaporation and infiltration. Normally, groundwater inputs are greater than the underground outputs although, in dry years, the hydraulic gradient upstream the lake decreases and the groundwater feeding to the wetland is more reduced than the respective groundwater outputs (Fig. 8).

Aguileras spring is about 300 m from Grande lakeshore, at a lower height than the usual range of the water surface in the wetland. The hydrodynamic response of the spring and the lake to the hydroclimatic conditions is quite similar. However, no direct connection exists from Grande Lake to Aguileras springs, as the isotopic signature of the water drained through the outlet does not show evidence of evaporation from free surface water (Rodríguez-Rodríguez et al. 2006; Gil-Márquez et al. 2016). Nonetheless, their hydrodynamic and hydrochemical similarities suggest that they both drain the same hydrogeological system.

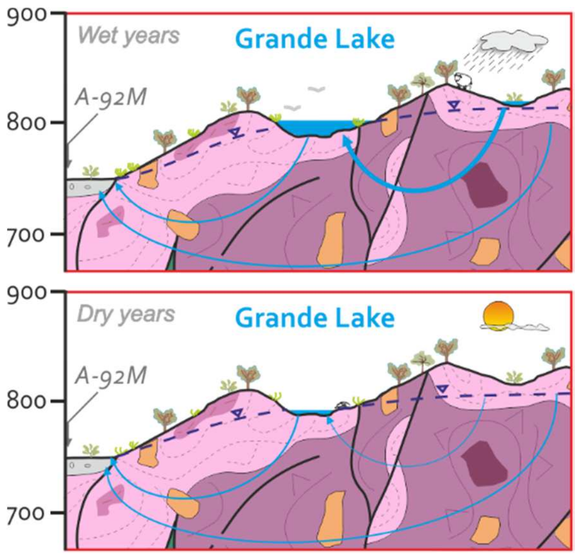

Figure 8. Hydrogeological conceptual sketch of Grande lake and surrounding areas.

Near Fuente Camacho village, at 720 m a.s.l., there is a discharge area (Fig. 6) draining sodium-chloride type water with high EC values (close to 200 mS/cm). Dissolved salt has been extracted from this water from the Paleolithic to the present day, and the antique infrastructures used by Romans are still preserved. The existence of brine springs is fairly common in the CSC outcrops. They are obviously related to the presence of halite at depth, but also to the contribution of groundwater of long residence time in the media (Andreo et al., 2016).

Stop 4: Sierra de Archidona: an impacted carbonate aquifer

Sierra de Archidona is located in the northern part of the Málaga province (Fig. 1). This relief has an elongated shape according to the NW-SE direction, with a 7 km length main axis, where maximum elevations may reach 1,000 m a.s.l. (Figs. 9 and 10). Dolostones and limestones of Lower Jurassic are mostly outcropping as part of a folded (overturned syncline) geological structure, in which clays with gypsum lithologies constitute the basement of the Mesozoic rock sequence (Linares, 2007).

Highly fractured and karstified carbonate Jurassic rocks (~ 6 km^2; DGOH, 1995) host a karst aquifer with limited extension and, therefore, groundwater resources. Recharge is produced by rainfall infiltration (average yearly rainfall of 600 mm) through carbonate exposures, while discharge was made through springs and artificial galleries towards the southern aquifer sector (at ~700 m a.s.l.) until 1980 (Linares, 2007). Today, discharge is induced artificially through pumping wells (Calderón, Moya and Conjuro; in Figure 10) for urban supply to Archidona town and some other associated little settlements (~9000 inhabitants).

Since 1980, the increasingly water demand motivated the intensive exploitation of the carbonate aquifer, so groundwater pumping surpasses the aquifer recharge, as it is evidenced by a sustained and general lowering of groundwater levels (Fig. 11). Thus, water resources account for 1.2 hm^3/year (Linares, 2007), of which mostly is intended to used for urban supply and agriculture (i.e. olive tree), in a lesser extent.

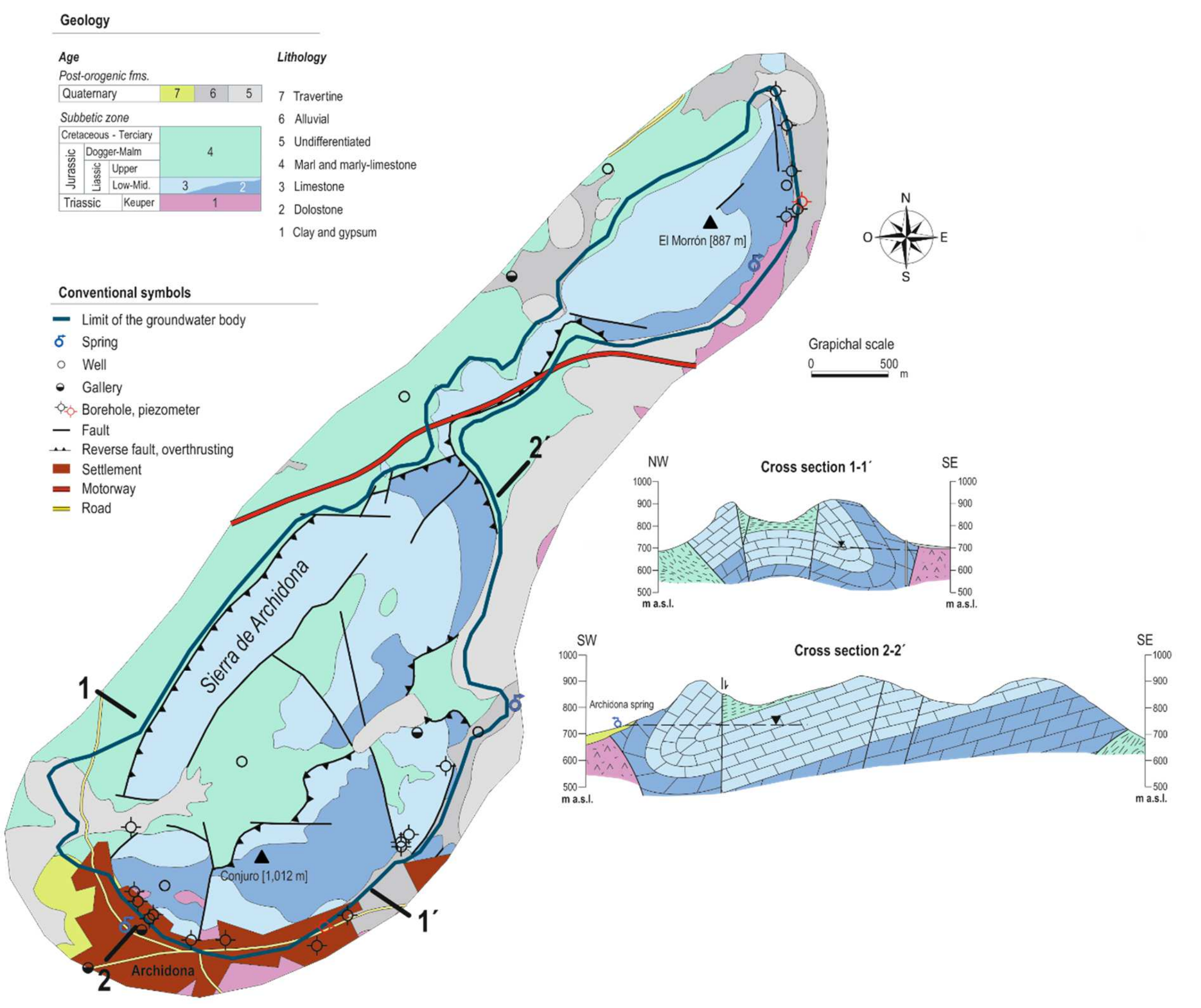

Figure 9. Hydrogeological map and selected cross-sections of the Sierra de Archidona carbonate karst aquifer (modified from Linares, 2007)

Figure 10. Aerial view of the main carbonate outcrops of Sierra de Archidona aquifer (left). El Conjuro pumping well (right), located in the SE border of the Archidona carbonate aquifer.

Groundwater flowing through Sierra de Archidona aquifer is generally of good quality for human consumption, with a low-intermediate degree of mineralisation (370-580 µS/cm) and a typical bicarbonate calcium hydrochemical facie. Among concentrated solutes, bicarbonate concentrations range between 170 and 280 mg/l, chloride between 10 and 20 mg/l and sulphates are detected in the range 30-40 mg/l (Linares, 2007). Although nitrates contents are on average low (20 mg/l), higher concentrations have been locally detected in pumped groundwater from agricultural practices, which pose the main threat for groundwater. This is the problematic why a protection perimeter (for the pumping well field of Archidona) of the aquifer was delineated as water for agriculture has becoming significant.

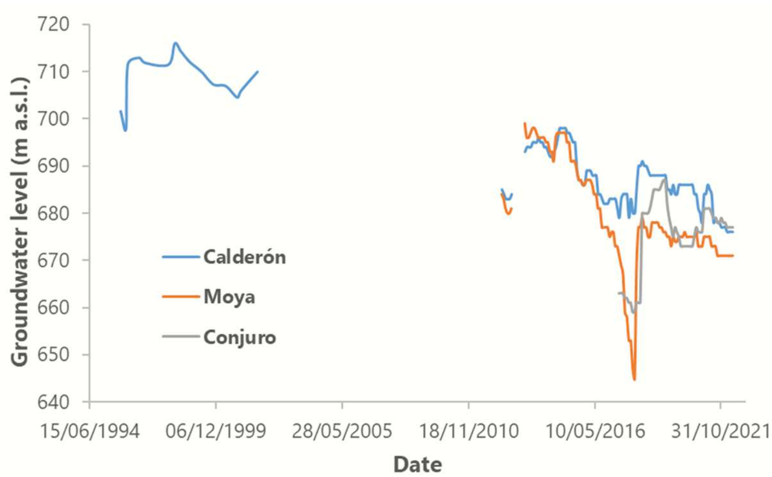

Figure 11. Groundwater lowering in the three exploitation wells of Sierra de Archidona for drinking water consumption. Groundwater depletion in the aquifer for drinking use is estimated in 2 m/year approximately.

The marked aquifer overexploitation (Fig. 11), a common issue in a good number of small carbonate aquifers in the area, is very often followed by groundwater quality impairment. During September 2012, the water supply of Archidona municipality suffered an episodic increase of turbidity and colouring, reason why health authorities obligated to the water company to stop pumps. The quality issue lasted two months and the population had to use water carried by tank trucks. Besides, this is not the only groundwater threat reported recently: two years before, an engineering project planned the construction of a tunnel for a high velocity train line (Bobadilla-Granada) crossing the Sierra de Archidona mountain (Sola y Bosch, 2014). Although a first draft projected the tunnel entrance below the regional groundwater level, efforts of local technicians in a coordinated action resulted in an artificial drainage gallery at an elevation of 688 m a.s.l. provoking minimum groundwater losses (ITGE-Junta de Andalucía, 1999).

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