Hypothesis on the hydrogeological context of wetland areas and springs related to evaporitic karst aquifers (Málaga, Córdoba and Jaén provinces, Southern Spain)

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Abstract

The northern sector of the External Zone of the Betic Cordillera (S Spain) is formed by an olistostrome unit known as the Chaotic Subbetic Complexes (CSC). This megabreccia is basically made of clays and evaporite rocks (gypsum and salt) of Upper Triassic (Keuper) age as well as other lithologies (dolostones, limestones, marls and calcareous sandstones) belonging to different ages (Jurassic, Cretaceous and Tertiary rocks). Despite of low permeability has been traditionally assumed for these materials, water flow and storage through them is possible due to the aquitard behavior of clays and sandstones and the presence of conduits generated by dissolution/karstification processes within the evaporite rocks. The lithological complexity of the CSC determines its hydrogeological heterogeneity, with groundwater flows of different length and various scales from recharge areas to discharge zones. Thus, wetlands and springs placed at lower altitudes are associated with large (regional) groundwater flows, of greater residence time within the aquifer, and they normally drain high salinity waters mostly connected with ascending flow. This work provides an overview of the main geological and hydrogeological aspects related to groundwater flow within the CSC on the basis of several case-studies. Conceptual models are proposed for these cases, since they are the base to carry out a genetic-functional classification of wetlands potentially useful for their management.

Key words: Evaporitic (karst) aquifer · Regional flow · Saline spring · Wetland · South Spain

1. Introduction

During the last decades, research on evaporitic karst areas has been mainly focused on aspects related to karstology and speleogenesis (Forti and Sauro 1996; Calaforra and Pulido Bosch 1999; Gutiérrez et al. 2004; Klimchouk and Aksem 2005), natural impacts (Galve et al. 2009; Gutiérrez et al., 2014) and human-induced geohazards (Johnson, 2008; Cooper and Gutiérrez, 2013). This is due to the fact that gypsum and halite are much more soluble than carbonate rocks. Consequently, karst in evaporitic rocks evolves at a much faster rate (even to a human time scale) and often causes severe problems, frequently fostered by anthropogenic factors. Furthermore, the high salinity of the groundwater stored in this type of medium has resulted in natural deterioration of water quality in many rivers and reservoirs (Sanz de Galdeano, 1983; Carrasco, 1986; Memon et al., 1999). Nevertheless, apart from some cases, such as the Palo Duro Basin in Texas, USA (Kreitler, 1989), or Ebro Valley in Spain (Acero et al., 2013), hydrogeological studies aimed on evaporitic materials have been scarce, since their water resources are normally low and of poor quality.

In Andalusia (southern Spain), in the southern border of Guadalquivir foreland basin (Fig. 1), a wide extension of terrain constituted fundamentally by Upper Triassic (Keuper) clays and evaporite rocks (gypsum and salt) exists, including other lithological blocks (olistolites) of Triassic to Miocene ages (Pérez-López and Sanz de Galdeano, 1994). All these materials appear as a chaotic mega-breccia highly deformed due to the gravitational collapse and movement of the External Zone (Subbetic) front towards the Guadalquivir basin, during Miocene (Rodríguez-Fernández et al., 2013). Outcrops of these rocks constitute a geological unit that has been termed by different authors as Guadalquivir Olistostromic Unit, Chaotic Subbetic Complexes –CSC- (Vera and Martín-Algarra 2004), or Subbetic Extensional Complex (Rodríguez-Fernández et al., 2013).

Traditionally, low permeability has been assumed for the CSC Unit due to the predominance of clays, marls and sandstones, although no specific data about permeability has been reported. In fact, it has been commonly considered in literature such as the impermeable base of the carbonate aquifers, formed by Jurassic dolostones and limestones, existing at the Subbetic Domain (Mudarra and Andreo, 2011; Barberá and Andreo, 2011; Martos-Rosillo et al., 2013). Nevertheless, the presence of evaporitic rocks (gypsum and salt), with high solubility increases the development of secondary porosity and permeability by dissolution/karstification processes. As a consequence, unstable karst conduits and cavities have been originated giving place to collapse and subsidence phenomena, sinkholes and surface depressions (Calaforra and Pulido-Bosch, 1999; Gutiérrez et al., 2008), which are typical features of karst aquifers. Similar processes and subsequent threats to the population has been described in other evaporitic karst areas of Europe (Parise et al., 2008; Ligouri et al., 2008), given the frequently outcropping of evaporitic rocks in surrounding areas of Mediterranean basin.

The high solubility of evaporitic materials plays a notable influence in the hydrology and hydrogeology of CSC outcrops. In general, most of the exokarst features are placed in smooth areas where a poorly defined drainage network exists, mainly in the hydrographic watershed of rivers. Consequently, surface depressions and wetland formation have taken place, which development has been accentuated by the recent elevation of the area, linked to diapiric or halokinetic processes (Pezzi, 1977; Linares, 2008). On the other hand, the lithological heterogeneity and the geological processes related to subsidence phenomena confers to the CSC materials a certain hydrogeological complexity, with groundwater flows of different length, to different scales, from recharge areas to discharge zones (Andreo et al., 2005). This approach to explain the hydrogeological behavior and groundwater flows through CSC material resembles to the Regional Gravity-Driven Groundwater Flow Model (GDRGF) proposed by Tóth (1963) and used by others authors in some karst basins (Memon et al., 1999; Goldscheider et al., 2010; Mádl-Szöny and Töth, 2015). Nevertheless, in detail, those models cannot be completely aplicable to understand the hydrogeological functioning of some specific evaporitic karst areas, considering their particularities in the geological and geomorphological framework (the medium is not strictly isotropic and homogeneous), as a consequence of karst processes. In fact, Calaforra (2004) proposed a preliminary hypothesis on this way for the evaporitic karst area of Antequera region.

Therefore, the aim of this work is to provide an overview of the main geological and hydrogeological aspects related to groundwater flows and karstification processes that take place within the CSC materials, on the basis of several case-studies wetlands and springs placed in three pilot areas (Antequera, Jarales and Brujuelo) from South Spain, (Fig. 1). With this end, information and observations compiled in these zones by several authors during the last years have made possible to improve the hydrogeological knowledge of CSC outcrops, as the basis to establish a hypothesis on the general hydrogeological functioning of these materials, which will be the starting point for more detailed researches. This will help for protection, management and if necessary, a hydrological restoration of some wetlands located in this context.

2. Geological and geomorphological settings

In general terms, the CSC are presented as a large olistostromic unit that covers the northern edge of the Subbetic Domain, from the province of Cádiz (SW) to Jaén (NE), in an elongated band of 300 km long and 60 km wide maximum (Fig. 1). This unit is formed by a Middle-Upper Miocene mega-breccia that is mainly made up of Upper Triassic rocks, although Jurassic (dolostones, limestones), Cretaceous (marly-limestones and marls) and Tertiary blocks (calcareous sandstones, marls) are also present in major or minor proportion. Upper Triassic (Keuper) age materials largely outcrop and confer the CSC an abundant presence of multi-coloured clay, sandstones, subvolcanic rocks (ophites) and evaporites (gypsum and salt). Small outcrops of limestones (Muschelkalk) and brecciated dolomites (Keuper) are often found over the above-mentioned materials. Gypsum is typically massive although it is sometimes found as a polygenic breccia made up by gypsum fragments and little parts of clays, limestones and dolostones (Calaforra and Pulido-Bosch, 1993). Despite halite is not present at the surface, due to its high solubility, its existence in depth is certain as can be inferred from groundwater hydrochemistry and boreholes drilled in evaporite outcrops (Carrasco, 1986; Calaforra, 1998).

The internal structure of the CSC is chaotic and disorganized, and the materials are presented with a significant degree of folding and brecciation as a result of having undergone a major deformation process during the Alpine orogeny. During the Lower and Middle Miocene, the olistolites that currently constituted the geological unit suffered gravitational transport processes and massive movements from the Subbetic Domain towards the Guadalquivir Basin (Vera and Martín-Algarra, 2004). In detail, the olistolites can be considered to different scales, ranging gradually from centimeters to hundreds of meters in size; from clayey masses containing little blocks, clearly encompassed and disorganized, until big masses of Subbetic units formed fundamentally by Jurassic and Cretaceous materials (Pérez-López and Sanz de Galdeano, 1994). Some of these Subbetic blocks have kilometers of continuity, constituting authentic tectonic elements with their internal structure well defined. In general, the smaller the size of the unit or the blocks that they include, the bigger disorganization degree of Triassic materials is. In some cases, the postorogenic sediments are included in the tectonic melange whereas in others they appear discordant on the CSC, showing varied dips.

Examples of karst morphologies developed on evaporitic materials are abundant in the CSC, both exo- and endokarst features: karrenfield, dolines, uvalas, and even poljes; sinkholes, potholes and caves. Cavities developed in gypsum are common such as Águila Cave and Agua Cave in Malaga province or Yeso Cave in Cordoba province. In some cases, the existence of diapiric phenomena, with large domes of subcircular morphology, can determine both the hydrology of the area and the distribution and typology of the largest karstic forms via its control over the hydrogeology (Calaforra and Pulido-Bosch, 1999). The diapiric structures emerge abruptly from the general relief pattern, separated from each other by deep canyons of fluvio-karstic origin. However, the most common landforms are karst depressions, originated from dissolution processes and affecting evaporitic rocks (Durán and Molina 1986; Calaforra 1998). The high solubility of gypsum, and especially halite, produces a rapid geomorphologic evolution, both in depth (endokarst) as in surface (exokarst). As a result, collapse and subsidence phenomena occur very often and formation of surface depressions (dolines, uvalas, poljes) take place (Benavente et al., 1992). Some of these endorreic areas present karst swallow holes which become active during stormy rainfall, keeping the areas without water or slightly flooded during short or very short periods of time. In contrast, where no sinkholes exist, dolines and karst depressions can remain flooded during variable periods of time after rainy episodes, or even in a permanent way, depending on their hydrological and hydrogeological regimes.

Therefore, many of the endorreic areas related to CSC materials constitutes wetlands and ephemeral lakes of variable size but of great environmental value (some of them are listed in the Ramsar Convention of Wetlands). Most of these wetlands appear grouped in complexes, located at different geomorphologic position: at watershed divides, near the river beds or at intermediate positions. Catchment areas normally have a relatively plain topography and runoff is diffuse due to the lack of a well-organized drainage network, with few minor stream channels that only are sporadically active during rainfall events. Nevertheless, in certain cases, streams may be more developed, and under exceptional stormy rainfall conditions, they acquire a torrential character that allows them to transport a substantial sediment load to the wetlands.

3. Hydrogeological context of pilot sites

3.1. Antequera area

In the northern part of Málaga province, in the upper part of Guadalhorce River Basin, there is an extensive and elongated outcrop of CSC materials with ENE-WSW direction, known as “Trias of Antequera” (Fig. 2). These materials are also placed under the Neogene-Quaternary deposits of Antequera depression. It is one of the more important karst areas developed on evaporitic rocks in Spain. Fuente de Piedra wetland is situated in this outcrop (Linares, 1990; ITGE, 1998), besides other wetland complexes such as Campillos, Antequera and Archidona-Los Hoyos (Almécija, 1997; Rodríguez-Rodríguez et al., 2006; Gutiérrez et al., 2008; Linares, 2008). Some of these wetlands are features that contribute to recharge subjacent aquifers, whereas others are related to transit groundwater flows towards saline springs located at discharge areas (base level): Guadalhorce River and its tributaries. The most remarkable discharge point is Meliones spring (Carrasco, 1986, Calaforra and Pulido-Bosch, 1999, Gutiérrez et al., 2008) placed at 345 m a.s.l. (Tab. 1), in a canyon equally named (Fig. 2). By means of discharge measurements and chemical analyses in different sections of the Guadalhorce River, in the surrounding areas of the spring, the existence of other saline springs was verified (discharge zone), with a total (mean) discharge rate between 20 and 45 l/s and with average electrical conductivity (EC) values between 90 and 200 mS/cm (Carrasco et al., 2007). Since 1976, the spring remains flooded due to the construction of a reservoir in the Guadalhorce River, and the spring is only exposed when the water level in the reservoir decreases (last time was 2005). This causes a severe degradation of the reservoir water used for water supply Málaga City. Moreover, there are other saline springs (Fig. 2), as Cañaveralejo (400 m a.s.l.) and Fuente Camacho (705 m a.s.l.), related to the wetland complexes of Campillos and Archidona-Los Hoyos, respectively. Finally, it is also possible to find springs located at higher altitude, as Cueva del Agua, La Peña, Montemayor, Las Pilillas, Rodahuevos, Saladilla, etc. (Fig. 2, Tab. 1), whose waters present lower mineralization.

The hydrogeological functioning of Trias of Antequera karst region is associated with absorption forms (dolines, sinkholes, collapses, caves, surface depressions) that exists in the area. The position and appearance frequency of these landforms are mainly determined by halokinetic phenomena (Calaforra and Pulido-Bosch described in 1999 until four large diapiric structures with subcircular morphology uplifted and inserted into the Triassic series). Once infiltrated, groundwater flows and, occasionally, is stored in conduits and in permeable zones that are expanded by dissolution/karstification processes, giving place to a system with superficial and deeper flows.

3.2. Jarales area

At the south of Córdoba province, between Genil (to the S) and Anzur (N) rivers (Fig. 3), there is a CSC plateau with high proportion of gypsum blocks and carbonate olistolites included within clays and marls. The outcrop is characterized by a smooth landscape, hills, no well-defined drainage network and the presence of numerous endorreic areas. Poljes and karst depression are well represented and some of them are often intersected by the water table, hence wetlands appear. The altitude of these karst features are comprised from 410-430 m a.s.l., at the center of the plateau, to 300 m a.s.l. towards the north, where several endorreic areas exist, aligned according to N-S direction (along 3 km). Drainage of these zones is produced through swallow holes, sometime obstructed, causing the temporary flooding of the depressions.

The most significant wetlands in the area are Taraje, Jarales, Amarga and Dulce (Moya, 1988; Andreo et al., 2005). All these conform, together with other ephemeral lakes, a complex of wetlands, most of them placed at the upper part of the outcrop (between 360-425 m a.s.l. Groundwater drainage occurs toward the north (where is located the Anzur River), and also toward the south (Genil River), via springs located beneath the riverbed or by a diffuse way (Fig. 3). The most important discharge points are named Lower Anzur (258 m a.s.l.) and Upper Anzur (306 m a.s.l.) springs.

3.3. Brujuelo area

The Brujuelo outcrop is located at the Guadalquivir River Basin, in the central-southern part of the province of Jaén (Fig. 4), in a relatively high plain area corresponding to the watershed between two tributaries of Guadalquivir River: Arroyo Salado (to the E) and Arroyo de la Cañada de las Charcas (to the W). Unlike other pilot sites, this area does not show abundant exokarst landforms; only some karst depressions partially flooded during rainy months and some surface collapses. The two most significant karst depressions are occupied by the ephemeral Brujuelo and Cirueña wetlands. The first one is placed to 458 m a.s.l., whereas the second one is to 464 m a.s.l.). No drainage network exists in the catchment area of wetlands. Nevertheless, both are connected by a drainage ditch starting from Cirueña wetland. At the same time, Brujuelo wetland is artificially drained by other trench, which begins in its center and continues towards the northwestern extreme, where a tunnel connects the wetland with a superficial stream.

The Arroyo Salado constitutes the hydrogeological base level of the system, where the main springs are situated (Fig. 4), and also where salt (halite) extraction is currently exploited due to the high salinity of the water. These springs appears from 440 m a.s.l. (Don Benito spring) to 375 m a.s.l. (San Carlos spring). Between both points a significant increase of stream outflow takes place as consequence of the groundwater contribution (Andreo et al., 2005). Other springs are the ancient salt exploitation of Brujuelo (425 m a.s.l.) and small discharge points at the proximities of the exit of the drainage tunnel of Brujuelo wetland, placed to 450 m a.s.l.

4. Results

4.1. Antequera area

Figure 2 and Table 1 shows and summarizes, respectively, the situation and the information of the main springs associated with the CSC materials belonging to the Trias of Antequera. Most of them are located in riverbeds of Guadalhorce River (Cueva del Agua, La Peña and Meliones springs), in stream over the CSC outcrops (Cañaveralejo, Montemayor, Las Pililllas, Rodahuevos), in the geological contact between these materials and Quaternary deposits of Antequera Basin (Saladilla, Borbollón, Gandigüela, Pinedilla) or related to wetlands (Molino de los Aguilera and Fuente Camacho in figure 2). Many of these springs are located in the surrounding of Gobantes area, at both banks of Guadalhorce River and with altitudes ranging between 345 and 500 m a.s.l (Tab. 1, Fig. 5). Nevertheless, in general, it is possible to observe an E-W decrease in the altitude values, from 795 m a.s.l. where Molino de los Aguileras spring is situated, to 345 m a.s.l. of Meliones spring (Fig. 2).

Other discharges from CSC materials occur by diffuse way towards the Guadalhorce River in those canyons where the main river and tributaries cross the CSC outcrops (Figs. 2 and 5). There is also discharge towards most of the wetlands established into the endorreic areas (Archidona and some from Campillos wetlands), and towards detritic permeable materials of Miocene and Quaternary age, principally to the Antequera Basin. Like springs, the altitude of the bottom of wetlands decreases from E to W, from about 795 m a.s.l of Archidona wetlands to 450 m a.s.l. of Campillos wetlands.

By sectors, the Archidona Wetland Complex (Calaforra, 1998; Linares, 2004) is formed by some ephemeral lakes placed to higher altitude and only flooded during short periods of time after rainfalls, and by other more permanent wetlands such as Grande and Chica (Fig. 2). These have been developed on a diapiric structure with sub-circular morphology (Calaforra and Pulido-Bosch, 1999; Fig. 2), in which a karst system has been formed, characterized by the presence of a high number of dolines and small-closed depressions. In the eastern border of the diapiric structure, the Fuente Camacho hypersaline spring (720 m a.s.l.) appears, draining water with mean values of EC and temperature of 190 mS/cm and 17.2 ºC, respectively (Tab. 1), and showing sodium-chloride type facies. Nevertheless, the main drainage point of the aquifer is Molino de los Aguileras spring, with an average outflow of 15 l/s and with lower mean values of salinity and water temperature (3 mS/cm and 16.9 ºC). The hydrochemical facies of the spring is calcium-sulphate type facies.

On the other hand, wetlands established on the plateau located at the south of Antequera (Caja, Viso and El Chaparral) are basically fed by superficial run-off and direct rainfall (Andreo et al., 2005). These are placed between 727 and 732 m a.s.l, at a significantly higher altitude than the regional piezometric surface defined by the diffuse discharge towards the Guadalhorce Canyon (Fig. 2), situated in the eastern part (approximately to 600 m a.s.l.). In fact, measured water table in nearby boreholes appears approximately 30 m down the bottom of wetlands (Andreo et al., 2005).

Regarding to Campillos Wetland Complex (Almécija 1997), location and altitude of most of the wetlands reveal a certain groundwater flowpath directed to Cañaveralejo spring (400 m a.s.l.). This is located approximately 3 km to the E of the wetland complex and constitutes a discharge point of the aquifer, whose waters present high salinity and temperature with mean values of 144 mS/cm and 19.5 ºC (Tab. 1), respectively, and showing sodium-chloride type facies.

In the Gobantes sector, Meliones springs drain 20-40 l/s (historic record) of hypersaline waters with EC until 200 mS/cm and sodium-chloride facies. Before the main spring was flooded by the reservoir water for the first time, Carrasco (1986) carried out *in situ* measurements of discharge, EC and water temperature, from August 1974 to December 1976, together with spring water sampling for posterior chemical determination of Alkalinity, SO_4^{2-}, Cl^-, Na^+, Ca^{2+} and Mg^{2+} in the laboratory. Figure 6 shows the temporal evolution of this dataset, jointly with the monthly precipitation recorded in this area during the same period. At the beginning of 1976, an increase in the discharge rate was clearly observed (maximum of 20 l/s) in response to several months of accumulated recharge. The increases in discharge rates produced a rise in EC values of more than 40 mS/cm, which later fell during periods of low flow conditions. These variations in EC were mainly caused by corresponding changes in Cl^- content, which increased progressively at the same time as the flow rate (Fig. 6).

Waters showing calcium-sulphate facies and EC values between 2 and 5 mS/cm are also found in other springs located in Gobantes sector but at higher altitude (Fig. 5, Tab. 1), such as Gandigüela (490 m a.s.l.), Pinedilla (505 m a.s.l.) and Borbollón (520 m a.s.l.). Besides, in this area there are springs such as Rodahuevos (420 m a.s.l.) and Pilillas (470 m a.s.l.) which drain water with an intermediate saline content (between 5 and 20 mS/cm) but also with sodium-chloride facies. In general, an exponentially inverse relationship exists between electrical conductivity of water and the altitude of springs located at this sector (Fig. 7), with a correlation coefficient (R^2) of 0.86. Therefore, the marked hydrochemical variations observed in this area suggest the existence of a clear hydrogeological heterogeneity, with groundwater flows of different length, scales and depths, from recharge areas to discharge zones.

Other significant springs that drain the CSC materials belonging to the Trias of Antequera (Fig. 2) are Cueva del Agua (630 m a.s.l.), La Peña (480 m a.s.l.) and Saladilla (470 m a.s.l.). The two first ones present calcium-sulphate hydrochemical facies, with mineralization values around 2.5 mS/cm (Cueva del Agua and La Peña), whereas Saladilla spring (17.7 mS/cm), located at the lowest altitude, drains waters with sodium-chloride type facies.

4.2. Jarales area

Figure 3 shows the geographical position and altitude of wetlands and ephemeral pond areas existing at Jarales region, as well as the main springs and wells. In the southern-central sector are located Taraje (420 m a.s.l.), Bacalaos (426 m), Molina de Ramírez (423), Canónigo (413 m) and Jarales (407 m) wetlands. To the northeastern border of Jarales wetland another appears (or an extension of this) at 410 m a.s.l. At the western part Dulce (370 m) and Amarga (360) wetlands are located, whereas old ponding zones that were dried up by ditches are found at the eastern side (at 374 m a.s.l.).

Altitude of these wetlands, together with the measurement of water table elevation at different points, permits to obtain an illustrative water table contour map of the region (Fig. 3). Thus, water table seems to be adjusted to the topographical surface. A hydrogeological dome is observed northward Genil River; from where groundwater flows in a radial way, preferentially northwards (to Anzur River). This interpretation of the groundwater flow paths is coherent with the position and altitude of the karst sinkholes responsible of the drainage of the endorheic areas placed at the northern end of the region (between 353 and 315 m a.s.l.). Therefore, provided information suggests that both superficial and groundwater flows occurs mainly towards Anzur River, where the most significant springs are located: Lower and Upper Anzur springs. First one has a mean EC and water temperature values of 150 mS/cm and 20.4 ºC, respectively, and a discharge rate between 1.5 and 100 l/s (Tab. 1). During rainfall events, significant increases in discharge rate, as well as rapid and sharp falls of up to 40 mS/cm, had been recorded (Gil et al, 2014). The second spring drains waters with average electric conductivity and temperature of 46.4 mS/cm and 20.7 ºC, respectively, whereas the mean flow rate is 2.3 l/s. In the Genil riverbed another spring (Salinillas, JS3 in Table 1) exists, placed approximately at 255 m a.s.l and 4 km to the SO of Jarales wetland (Fig. 3). Its waters present values of mineralization and temperature of 76.8 mS/cm and 21.4 ºC, respectively. The existence of this outflow confirms that discharge takes also place towards the southern edge of Jarales outcrop.

Piezometric sketch of figure 3 also indicates that groundwater flow and surface drainage network are in relative concordance. Taraje wetland and Canónigo and Bacalaos ponding areas, situated at higher altitudes (both topographically and piezometric), are just the first ones in drying off. On the contrary, Jarales and Amarga would be wetlands associated to the groundwater flow (transit) from recharge to discharge areas. In fact, the groundwater flow towards the last wetland can be appreciated in figure 3. Springs placed at Anzur and Genil River would be the final destination of regional flows.

4.3. Brujuelo area

There are no many water points at the Brujuelo study area, except few wells and several springs located in Arroyo Salado (Fig. 4). Most of the wells are placed near the wetlands, whereas the significant springs are located SE and N of wetlands. Northern springs are aligned according to SW-

NE direction. The water from the outflow area existing near the drainage tunnel end of Brujuelo wetland, at 450 m a.s.l., presents the lowest mean values of mineralization and temperature (12.5 mS/cm and 16.6 ºC, Tab. 1) of the area, although higher than the water from Brujuelo wetland (6.8 mS/cm and 16.2 ºC); both showing calcium-sulfate facies. About 1 km northwards, Brujuelo spring (425 m a.s.l.) has mean salinity and temperature values in its water of 119 mS/cm and 19.9ºC, respectively, and sodium-chloride facies. Finally, waters from San Carlos spring, situated at 375 m a.s.l. in the Arroyo Salado riverbed, presents the highest values of mineralization and temperature of the area (194 mS/cm and 20.1 ºC) and again sodium-chloride facies. At the SE, Don Benito spring drains hypersaline and relatively warm waters (170 mS/cm and 22.2 ºC) and a mean flow rate of 10 l/s, notably higher than the recorded in the previous springs (about 1-2 l/s). The physic-chemical characteristics of spring waters suggest the existence of a prominent hydrogeological heterogeneity in this area, with groundwater flows of different scale and depth.

From altitude of wetlands and springs and also water table measurements in wells from the surrounding area of Brujuelo and Cirueña wetlands, it is possible to estimate approximately the piezometric surface and the groundwater flow paths (Fig. 4). Both wetlands are placed in the transit of groundwater from the southern recharge areas, where there are some endorheic landforms which become flooded during rainy episodes, towards the northern discharge zone, where the main springs are located. The most local and shallow flows supply Brujuelo wetland (458 m a.s.l.), that is inundated when the piezometric level intersect the land surface.

5. Discussion

A large number of wetlands in southern Spain are originally and functionally related to CSC outcrops, which are vastly extended in Andalusia, especially on the left bank of Guadalquivir River (Fig. 1). On the whole, this unit shows a complex geological structure, due to the presence of numerous lithologies, among which are particularly important Triassic clays and gypsum. These formations are the substratum over the detrital materials from the Miocene and Quaternary age lay on. Triassic clayey and evaporitic rocks (halite and gypsum) determine the geomorphology of these areas. Karst subsidence phenomena that occur as a consequence of the dissolution of those evaporites lead to the formation of close depressions where wetlands, favored by endorheism, are settled down.

Clayey-evaporitic sediments are not impermeable, but rather they have a general aquitard or detrital aquifer behavior with some sectors of low permeability mainly where clayey enclaves are more abundant and developed. In fact, traditional pumping wells and new boreholes exist for irrigation in many areas (unique source for water resources at many cases), although unfortunately without permeability data from them. Results obtained at three different pilot sites prove that groundwater flow exists from the highest regions (recharge areas, fresh water wetlands, ephemeral and related to local flows) to the lowest regions (discharge wetlands and spring that drain high salinity water, eventually of higher temperature, and associated to regional ascending flows), passing through transit wetlands and springs among the two others (Fig. 8). This general flow model resembles to the proposed by Tóth (1963) for large sedimentary basins, although including some variations coming from the heterogeneity and the singularity of the karst media, and from the particularities observed in each sector. Hence, the three pilot areas selected in this work constitute examples of the hydrodiversity of wetlands placed in the CSC materials, which are represented in the general hydrogeological conceptual model shown in Figure 8.

The hydrochemical variability observed in the groundwater within the Trias of Antequera region reflects the hydrogeological complexity existing in these CSC outcrops. Calaforra and Pulido-Bosch (1999) relate this variability to the halokinetic movements in the Triassic belt of Antequera, which had a decisive influence on the hydrogeological evolution of the area, with consequent outcrops compartmentalization in several systems that are more or less independents from each other. Thus, springs placed at higher altitude and with calcium-sulphate facies would be linked to the karst in gypsum whereas saline and hipersaline springs had to do with deeper groundwater that flow through the salt core of the diapire. However, the presence of a base level corresponding to Meliones springs suggests that the different outcrops of the Trias of Antequera behave, on the whole, as a regional aquifer with groundwater flows that drain through the point of lowest altitude (Fig. 9). This is consistent with the discharge rates (between 20 and 40 l/s, as seen in section 4.1) and physic-chemical characteristics of Meliones spring waters (Fig. 6), with the highest values of mineralization and temperature of the region (between 80 and 200 mS/cm and 19.6 ºC). Carrasco (1986), from the analysis of stable isotopes of water, noticed the possibility that recharge area of Meliones spring was in a range between 400 and 800 m a.s.l., which is the same range of the Trias of Antequera outcrops. This author also denoted that the water from the springs with sodium-chloride facies had tritium concentrations lower than the rainfall occurring after 1957, although all of them presented tritium with a thermonuclear origin, leading to the conclusion that those waters may had been the result of a mixture of different kind of waters, previous and subsequent to this year.

All this information, jointly with the field observations carried out in the framework of this research, is coherent with the conceptual cross section for the hydrogeological functioning of the Trias of Antequera outcrops (Fig. 9). This sketch, that integrate the different groundwater flows taking place within these materials, at various scales and depth, shows the location of wetlands in the hydrogeological context of this sector of the CSC. Thus, local groundwater flow paths occur relatively close to the surface, from recharge areas (diffuse and concentrated) to directly adjacent discharge zones such as wetlands (mainly transit type) or springs. The water residence time of these flows within the CSC should be commonly short or very short. This, coupled to the aforementioned, results on those waters generally presenting the lowest EC and water temperature values and calcium-sulphate facies. In this context, wetlands such as Caja and Viso and some others placed at Campillos and Los Hoyos wetland complexes (Fig. 2) would be located above the water table (as has been observed in adjacent wells), defining recharge features for the aquifer. They only would receive water inputs from rainfall and runoff of the nearby areas and uniquely during rainy periods.

On the opposite end of the sketch proposed in figure 9, regional groundwater flows would appear with longer periods of residence within the terrain, which reach a greater depth and cover a greater distance, even from central sector of Trias de Antequera outcrops. Along its way, those depth flows would be gradually acquiring higher mineralization and slightly high temperature until they converge in the Gobantes area, from where they are drained through Meliones spring and some other with similar physic-chemical characteristics. Therefore, Meliones spring is the discharge point of saline regional groundwater flows. Among these two extremes, an intermediate type of groundwater flow exists, ranging from a large spectrum of lengths, depths and residence time within the aquifer. As a result, spring and wetland waters mainly related to these intermediate flows would show diverse physic-chemical characteristics and hydrochemical facies, ranging from calcium-sulphate to sodium-chloride type facies, depending on the lithology of materials where water has flowed and on its residence time. Example of intermediated flows could be the flow trough the karst conduit between Sima del Águila area and Guadalhorce river (Fig. 10). Besides, wetlands sited in this context, such as Campillos Wetland Complex or Chica wetland in Archidona-Los Hoyos Complex (Almécija, 1997; Linares, 2008), present a marked influence of groundwater flows in their functioning, especially when it comes from variations in the piezometric level, so that these wetlands are flooded in high water conditions whenever the water table reaches their bottom. On the contrary, during dry periods, water table decreases under the altitude of the bottom of wetlands, resulting on them being dried up (Andreo et al., 2005).

The presence of areas with a higher development of karstification in the Trias of Antequera, linked to the outcropping gypsiferous rocks at the center of domes, changes locally the general conceptual model. This is particularly clear in Gobantes area (Figs. 5 and 10), where the abundance of preferential infiltration features leads in each recharge event the mixing of “young water” with the water of the regional flow paths described above. This observations was already pointed out by Carrasco (1986) and Calaforra and Pulido Bosch (1999) as well as several technical reports carried out in the area with the purpose of managing the saline discharge from Meliones springs to the Guadalhorce reservoir. As it has been shown in Figure 6, they also noted the existence of obvious increments of flow, salinity and temperature of the water during rain episodes, with their later decreasing after precipitations. In other words, every rainfall event provokes the participation of the whole aquifer, both the shallow unsaturated zone and the deeper saturate zone. Consequently, a piston effect is produced and it moves towards the spring the water previously stored in the saturated zone, with a longer residence time within the system, higher EC and water temperature (Fig. 6).

The hydrogeological heterogeneity presents in the Trias of Antequera (province of Malaga) is partially comparable to other CSC outcrops such as the existing in Jarales and Amarga surrounding areas (province of Cordoba). In this case, it is possible to recognize again the presence of groundwater flows with diverse scales and depths, convergent towards wetlands, streams and springs; placed in the Anzur and Genil riverbeds, which define the base level of the system (Fig. 11). Nevertheless, this area also shows several particularities that distinguish it from other CSC outcrops: occurrence of a high number of humid zones and ponding areas; groundwater drainage towards the N and S, by means of three springs (Springs JS1 and JS3 placed to the same altitude, Tab. 1); existence of a SW-NE outcrop where it is possible to observe a significant development of karst landforms. The fact that most of wetlands are situated at similar altitude range, in the central part of the plateau, provokes that the bottom of these remains above or nearby the water table. In this context, piezometric variations, though of slight magnitude, could suppose a significant alteration in the water regime of wetlands, changing from clear features for aquifer recharge during most of the time to being integrated into groundwater flows (transit wetlands) and fed by these waters with short residence time in the system. That is the functioning of Jarales wetland, whereas the groundwater component is determinant in the hydrological regime of Amarga wetland, situated at lower altitude (Andreo et al., 2005; Moral et al. 2008; 2013). In fact, Amarga is permanently flooded whereas Jarales remains dry 60% of the time, with alternating multiannual periods of inundation and drought (Moral et al. 2013).

In addition to diffuse flow component, the existence of several endorheic areas with functional karst sinkholes in the northern sector of Jarales area indicates that a portion of groundwater flows rapidly through a karst drainage network (Fig. 11). This has been preferentially developed following an approximate N-S direction, coinciding with a higher presence of evaporitic rocks in this sector. To the south of the network, Taraje wetland appears, whereas in the northern end the main discharge of the system is produced trough Lower Anzur spring. The rapid responses of this spring to precipitation events, with sharp, significant increases in discharge rates and with decreased in water mineralization are typical of conduit flow systems, with rapid drainage and a low capacity for natural regulation (Gil et al., 2014). However, physic-chemical variations and hydrodynamic response of Upper Anzur spring are indicative of diffuse flow aquifers. Therefore, in the whole, the hydrogeological functioning of Jarales study area is defined by deep diffuse and ascending groundwater flows, with long residence time within the system, high salinity and relatively high temperature, together with an additional flow component (colder and lower mineralized) that occur rapidly into the karst network during rainfall events (Gil et al., 2014, Fig. 11).

Finally, Brujuelo outcrop shows a hydrogeological behavior marked by a clear hierarchization of groundwater flows, from short and shallow paths (with low mineralization and residence time within the system), until the deepest and longer paths (with high salinity and water temperature). The first ones are responsible of feeding to Cirueña and, especially, Brujuelo wetlands during rainfall periods, so that the accumulated water in them may be again infiltrated into the subsoil. The ditch and the drainage tunnel existing in the NW end of Brujuelo wetland contributes significantly to this purpose. Once infiltrated, water joins to groundwater flows that are drained by the outflow area located northward the end of the drainage tunnel. These are the second type of flow path (deeper and with greater permanency into the system) in the conceptual sketch of Figure 12. The third type of flow path (deeper enough and coming from longer distant recharges areas located at the south) would be represented by waters drained by Brujuelo spring (clearly with higher salinity and water temperature). San Carlos spring (with the highest average values of salinity and water temperature among all the springs in the area) would represent the base level of the system and, consequently, the convergence point of ascending regional groundwater flows.

Unlike Trías of Antequera or Jarales outcrops, no significant development of exo and endokarst landforms have been identified in Brujuelo area that could contribute to increase the hydrogeological heterogeneity. However, Don Benito spring, with higher mean discharge rate than Brujuelo and San Carlos springs, as well as also high salinity and water temperature (Tab. 1), could constitute another discharge point of regional groundwater flows coming from the south; from an area where numerous carbonate olistolites have been identified, and even a sinkhole (placed to 3.3 km at the south of the wetlands, Fig. 4). Hence, Brujuelo outcrop and, especially, Arroyo Salado define a preferential zone for groundwater discharge that take place in this part of the CSC Unit. The hydrological relationships between wetlands and the different types of flows, as well as the degree of hydrogeological complexity of this zone (and the rest), has not been completely specified and it is the aim of current researches.

6. Conclusions

In spite of being traditionally considered as impervious rocks, the CSC materials show a certain hydrogeological behavior. The presence of wetlands, dolines and sinkholes at highland and spring near rivers are evidence of the hydrogeological functioning of this system. However, the lithological complexity of the CSC as well as the karst development due to dissolution of evaporites confer to those materials a considerable hydrogeological heterogeneity. Besides, the lack of hydrological information related to groundwater within the CSC makes even more complicate to reach a good understanding of the hydrological functioning.

Thus, wetlands and springs placed at lower altitudes normally drain high salinity and temperature waters, and they are associated with large (regional) and ascending groundwater flows, of relatively greater residence time within the aquifer. Wetlands located in these contexts turn into discharge places of groundwater (discharge wetlands), where the period of seasonal flood is generally prolonged or even permanent. On the contrary, if phreatic groundwater level remains below the bottom of wetlands, these constitute a recharge component in the water balance of the aquifer system (recharge wetlands); they are generally ephemeral and with low salinity water. Finally, wetland areas located in an intermediate position between recharge and discharge zones (transit wetlands) do not constitute the last destination of groundwater flows, but rather they go towards other wetlands and springs situated at lower altitudes.

The previous approach to explain the hydrogeological relationship between evaporitic karst wetlands and related aquifers, inspired by Tóth, is appropriate to describe the hydrodiversity and the general hydrogeological context of wetlands placed in the CSC as a whole. Nevertheless, in detail, this model cannot be completely valid to understand the hydrogeological functioning of some evaporitic karst areas, taking into account several particularities in the geological and geomorphological framework.

Therefore, further studies are necessary in order to quantified and characterize the direction and length of groundwater flows, to identify regional discharge point and to establish the age of their waters using dating techniques, to determine the relationship between wetlands and springs and where appropriate, to define the limit of aquifers. For instance, Tritium and He isotopes data are in progress at the Helium Isotopes Laboratory at the University of Bremen. The obtained results will be useful for the development of a genetic-functional classification of wetlands with an evaporite-karst origin, allowing their appropriate management, protection and restoration. One of the goals to achieve are the right delimitation of protection zoning, identification of anthropogenic impacts and pressures and the proposal of corrective and remediation measures against deterioration of wetlands.

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Figure and table captions

Figure 1: Geological sketch of the main units of the Betic Cordillera located at the south of Andalucia, showing the spatial distribution of CSC outcrops and the three pilot areas selected in this work.

Figure 2: Geological-hydrogeological map of Antequera study area and surrounding areas, displaying the geographical position and altitude of the main springs and wetland complexes.

Table 1: List of studied wetlands and springs sorted by study areas, indicating altitude, and EC and water temperature values from previous works as well as new measurements (2013 - 2015).

Figure 3: Geological-hydrogeological map of Jarales study area and surrounding areas, showing the geographical position and altitude of wetlands and ephemeral pond areas and springs. Figure also includes a piezometric sketch and deduced groundwater flow paths.

Figure 4: Geological-hydrogeological map of Brujuelo study area and adjacent areas, displaying the geographical position and altitude of Brujuelo and Cirueña wetlands and the main springs. Figure also includes a piezometric sketch for this area.

Figure 5: Detailed geological-hydrogeological map of Gobantes area with the geographical position and altitude of the main springs. Situation corresponds to the green box in Figure 2.

Figure 6: Temporal evolution of discharge rates, electrical conductivity, temperature and the principal chemical components, measured in the water drained by Meliones spring, respect to accumulated monthly precipitation.

Figure 7: Relationship between electrical conductivity and altitude of springs located at Gobantes sector.

Figure 8: General hydrogeological conceptual model of CSC materials and related wetlands and springs.

Figure 9: Conceptual sketch of the general hydrogeological functioning of Trias de Antequera study area.

Figure 10: Conceptual sketch of the hydrogeological functioning of Trias de Antequera outcrops in Gobantes area. See location in Figure 5.

Figure 11: Conceptual sketch of the hydrogeological functioning of Jarales study area. See location in Figure 3.

Figure 12: Conceptual sketch of the hydrogeological functioning of Brujuelo study area. See location in Figure 4.