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Hydrochemical and isotopes studies in a hypersaline wetland to define the hydrogeological conceptual model: Fuente de Piedra Lake (Malaga, Spain)

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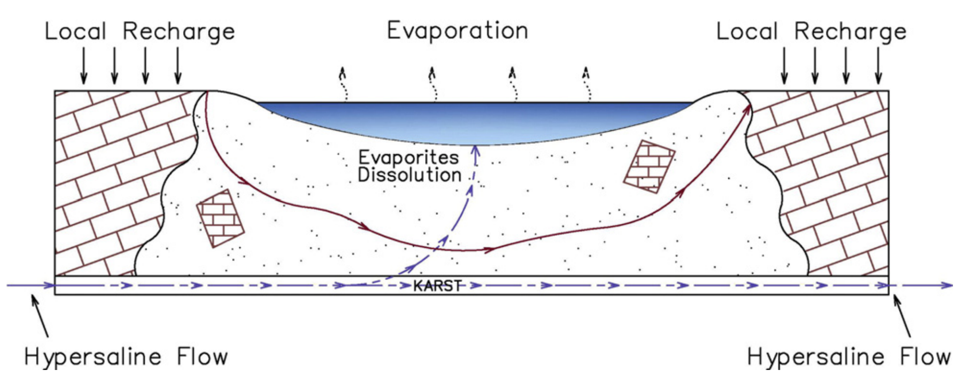
HIGHLIGHTS

- The existence a deep brine related with the karstic system of Chaotic Subbetic Complex (CSC), is proposed.
- The deep brine of karstic system of CSC is due to dissolution of halite.
- The recharge system would mainly in carbonate blocks.

GRAPHICAL ABSTRACT



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ABSTRACT

The Fuente de Piedra lake is a hypersaline wetland of great extension (13.5 km^2) and rich in aquatic birds and other species. It became therefore the third Spanish wetland to be included in the Ramsar convention and has been a "nature reserve" since 1984. The lake has an endorheic basin (150 km^2) with variable-density flows dominated by complex hydrogeological conditions. The traditional conceptualization of endorheic basins in semiarid climates considered that the brine in this hydric system was exclusively of evaporative origin and was placed only in the lake and its surrounding discharge area in the basin. Previous geophysical and hydrochemical studies identified different types of waters and brines. In this work, natural tracers (Cl^-, Br^-, Na^+, Mg^{2+}) and environmental isotopes (^{18}O, ^{2}H, ^{14}C, ^{13}C and ^{3}H) were employed to a) discriminate different types of brines according to their degree of evaporation and genesis, and b) to estimate residence times of brine waters and identify recharge areas of the different flow subsystems. A conceptual model of the hydrogeological system of the lake basin and its links to a regional karst system is proposed.

1. Introduction

The Fuente de Piedra lake (Malaga, Spain) saline wetland was one of the first three Spanish wetlands included in the Ramsar Convention. The lake was declared to a Special Protection Area for Birds in 1987 and to a

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Nature Reserve in 1984. The lake has an area of 13.5 km^2 and an endorheic basin of 150 km^2. It is located in the south of Spain. Between 1995 and 2008 the average annual values of precipitation, potential evapotranspiration and average annual evaporation were 467 mm, 830 mm and 1467 mm, respectively (IGME, 2009). The basin boundaries are defined by the Mollina and Humilladero mountain ranges (Fig. 1). This region contains numerous endorheic basins associated to small lakes, whose origin is considered to be similar to the Fuente de Piedra Lake system - progressive sinking by dissolution and collapse of evaporitic deposits (Durán et al., 2002).

The hydrogeological system of the Fuente de Piedra lake is complex, in particular due to the geology of the area and various types of waters - shallow freshwater, brackish water and brine (shallow and deep) (Heredia et al., 2009).

The hydrogeological system of the Fuente de Piedra lake has been studied since 1975. In the first decades of research, the brine was considered of evaporative origin and it was placed in the lake discharge zone (Linares, 1990; IGME, 1984; ITGE, 1998), which is the usual conceptual model of playa lakes in arid or semiarid environments (Rodriguez et al., 2005; Rodriguez et al., 2015). Benavente et al. (2003) pointed out unknown features of the system and considered alternative conceptual models. They suggest that: 1) lake sediments could lay on low permeability deposits or, to the contrary, on karstified evaporites; 2) a discharge from karstified levels towards the lake could exist; 3) the origin of the brines is mainly, but not exclusively, due to evaporation processes. Heredia et al. (2004) identified hydrochemically evolved brines that discharge into the lake through upwards flows. Rodriguez et al. (2005) found dissolved evaporites in the brines and modelled upwards deep flows below the lake. Kohfahl et al. (2008) found evidence of Triassic evaporates dissolution using hydrochemical modelling. These works studied the brines around the lake from shallow boreholes (depth < 35 m), identifying a discharge into the lake by deep regional flows. Calaforra et al. (2002) suggested a geological model that postulates that the dissolution process of the gypsum at deep levels is supported by regional upward hypersaline flows. They would cause an underlying gypsum hyperkarstication, which, in turn, would have caused the subsidence-endorheism of the lake.

Ruiz et al. (2007), Ibarra et al. (2008) and Heredia et al. (2009) have applied geophysical techniques and detected several brine enclaves in the mid and upper basin, close to the northern and western watershed divide. They are located between 50 m and 100 m of depth and have heterogeneous dimension, shape and continuity. Subsequent mechanical drillings confirmed this geophysical interpretation and found brine enclaves and karst levels in the upper and middle basin, and a karst level in a depth of about 65 m around the lake (see Supplementary data: Fig. 1).

The deep brine was identified and sampled in deep boreholes (depth > 100 m), located in the upper and median watershed of the lake (IGME, 2009; Heredia et al., 2009). This allowed to establish the hypothesis that deep flows discharge into the lake, as proposed in the previous conceptual models (Benavente et al., 2003; Heredia et al., 2004; Rodriguez et al., 2005; Kohfahl et al., 2008), correspond to the hypersaline flows of regional character (Calaforra et al., 2002).

Based on hydrochemical characterization, Heredia et al. (2009) and Montalván et al. (2012) indentified different types of groundwaters and brines (Fig. 2):

- Carbonatic blocks are of bicarbonate calcium type with TDS values below 650 mg/l.
- Miocene aquifer is of chloride-sulphate calcium-magnesium type and its TDS values vary from 1 to 5 g/l.
- Brackish water in CSC marly-gypsum matrix is of sulphates-chlorides magnesium-sodium type and its TDS varies from 12 to 47 g/l.
- Surface waters in the basin is of chloride sodium-magnesium type and its TDS varies from 12 to 148 g/l (Fuente de Piedra lake: 62 g/l–69.6 g/l).
- Brine enclaves in upper and mid lake basin (such as the hypersaline brine springs in the Guadalhorce basin) show only the chloride sodium facie. This suggests that both brines originate from dissolution of halite, with TDS values from 250 g/l to 332 g/l.

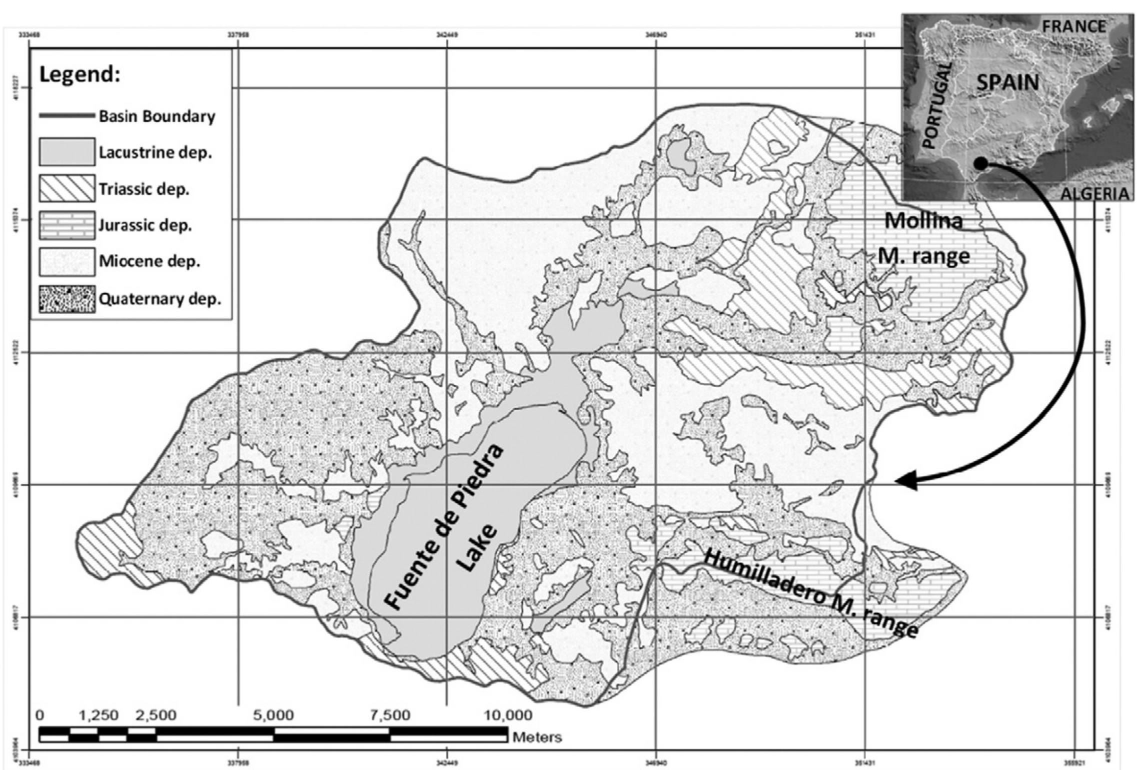

Fig. 1. Geological map of the studied area between the Guadalquivir and the Guadalhorce river basins. The watershed boundaries are defined by the Mollina mountain range in the Guadalquivir basin, and the Humilladero mountain range in the Guadalhorce basin.