USE OF ENVIRONMENTAL TRACERS TO CHARACTERIZE A COMPLEX HYDROGEOLOGICAL SYSTEM UNDER VARIABLE DENSITY CONDITIONS: CASE OF THE SUBSURFACE BRINE OF FUENTE DE PIEDRA (SW SPAIN)

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Abstract

The Fuente de Piedra lake hydrological system (Málaga, Spain) is characterized by a great complexity from the geological and hydrogeological point of view. Groundwater circulation is characterized by the existence of several layered flow systems, as a result of marked density contrasts between fresh groundwater, brackish waters and a dense subsurface brine. These underground flow systems discharge into the lake, generating, together with surface water, an endorheic basin. The brine found below and around the lake floor presents a large variation in salinity, reaching a TDS value about five times that of seawater. The Fuente de Piedra lake has been declared Natural Reserve and is one of the first Spanish wetlands incorporated into the Ramsar Convention, since it is, after the Camargue wetland (France), the most important place of flamingo nesting in the Western Mediterranean. Water management is a key issue in the strategy for conservation of the Reserve. The main objectives of the research conducted in the basin by the Geological Survey of Spain are the adequate hydrogeological characterization of the system, the development of a consistent conceptual model of groundwater flow and the evaluation of the relationship between groundwaters and surface waters. It is expected that this information will help to improve fresh water management in the basin. In this paper, some of the preliminary results achieved by using hydrogeochemical and isotope techniques are presented, as well as a new hypothesis of the origin and evolution of the Fuente de Piedra brine.

Keywords: variable-density; groundwater flow; Fuente de Piedra lake (Spain); hydrochemical techniques; environmental isotope techniques, wetlands.

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Introduction

In many regional flow systems developed in sedimentary basins, not only topography and the geological structure constitute the most relevant factors in defining groundwater flow patterns. In many instances, the time and spatial variability of fluid density (generally fresh groundwaters and brines) controls, to a large extent, the flow patterns of groundwater circulation. This parameter often is the key factor for defining a consistent conceptual model of groundwater flow patterns involving several groundwater bodies. In these cases, the fact of disregarding density contrasts leads to an improper definition of groundwater flow paths, to underestimate the magnitude of underground flow, the discharge and recharge rates, as well as the residence time of groundwater. The groundwater system of Fuente de Piedra lake (FPL), SW Spain, Malaga province, is one of the cases where disregarding density effects leads to the incorrect definition of a conceptual model coherent with all hydrogeological and hydrochemical observations.

The Fuente Piedra lake collects surface waters from an area of limited extension (~150 km^2), about 10 times the area of the average flooded area of the lake, 13.5 km^2 (Figure 1). The catchment area is located in the north of the Málaga province, in a water divide zone between the basin of the Guadalquivir river, discharging into the Atlantic Ocean, and the Guadalhorce river basin, flowing towards the Mediterranean Sea. In this region there are numerous endorheic basins associated to small lakes, whose origin is supposed to be similar to that of the FPL system: progressive sinking by dissolution and collapse of evaporite deposits, in accordance with the geological-genetic classification of wetlands in Southern Spain (Durán *et al.*, in press).

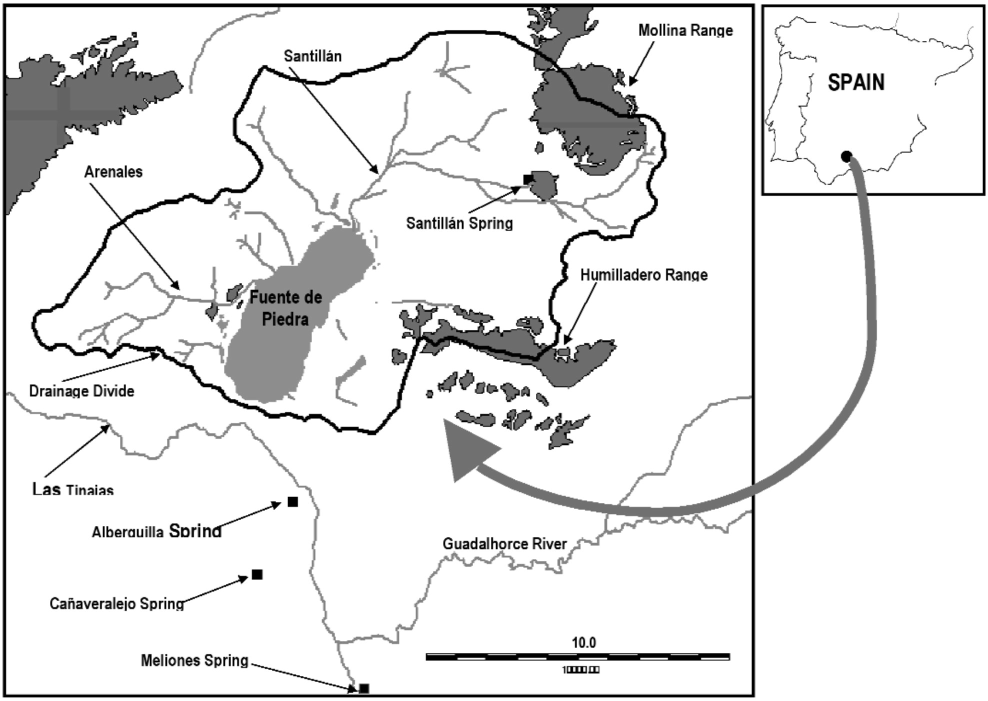

Figure 1. Location and geographic features of the Fuente de Piedra lake basin.

Mean annual precipitation and mean potential evapotranspiration (EVT) in the FPL basin have been estimated to amount 460 $mm \cdot yr^{-1}$ and 830 $mm \cdot yr^{-1}$, respectively (ITGE, 1998). The interannual distribution of the amount of precipitation presents large variability (from ca. 300 to 1000 $mm \cdot yr^{-1}$), while the seasonal distribution shows a maximum between November and February. Due to the large surface of the lake and the high EVT rate, the FPL, except for the period 1962 to 1971, becomes dry during summer. The available water resources of the Fuente de Piedra basin have been estimated to amount 20 to $23.6 \cdot 10^6$ $m^3 \cdot yr^{-1}$; of which $6 \cdot 10^6$ $m^3 \cdot yr^{-1}$ correspond to direct precipitation over the lake, 5.6 to $7 \cdot 10^6$ $m^3 \cdot yr^{-1}$ to runoff and 8.6 to $10.8 \cdot 10^6$ $m^3 \cdot yr^{-1}$ to groundwater inflow (Linares, 1990; ITGE, 1998), although these estimates present large uncertainty. Several small and mid-sized towns located in the basin mainly use groundwater for water supply, amounting $0.6 \cdot 10^6$ $m^3 \cdot yr^{-1}$. The main economic activity in the area is agriculture, and this is why the uncertainty of the consumption associated to this activity is large.

Due to the presence of a rich bird population, the FPL was declared in 1982 Natural Reserve. This system was one of the first Spanish wetlands incorporated into the Ramsar Convention. Wetlands are complex ecosystems, and at the same time, fragile. Water management is critical in defining a sustainable conservation strategy. Multiple interests and water demands are present: water supply to the population, conservation of the Natural Reserve, agriculture and food transformation industry. Although water demands are considered from the administrative point of view -Spanish Water Law and the Hydrological Plan of the hydrological basins in South Spain-, the sustainable management of water resources in the basin is still limited by the absence of a consistent conceptual model of the groundwater system and a proper water balance.

The main objective of the present study is to obtain a better hydrological characterization of the whole system, and the definition of a consistent conceptual model, taking into account all observations made during the last decades. This conceptual model should provide the basis for the development of a numerical model that will take into account the density-dependence of the several groundwater flow systems. At the same time, the model will provide a tool for the management of the water resources of the whole basin, attending the needs of the local population and those of the natural Reserve of Fuente de Piedra. Besides the conventional hydrological tools, hydrochemical and isotope techniques have been used in this stage of the study.

Main hydrogeological features

As mentioned above, the relationship between the surface and underground components of the hydrological system of the FPL are rather complex, due to the existence of several flow systems. Both surface and ground waters discharges into the lake are controlled by density differences.

The Triassic sediments, resedimented during the Neogene, previously considered as materials of very low permeability, crop out in several sectors of the Fuente de Piedra basin and in the Guadalhorce river basin. Traditionally, it has been assumed by many authors that these materials constitute the impermeable limit of productive aquifers (mainly Miocene sediments and Jurassic limestones, see Figure 2). However, nowadays there is a clear evidence that the materials of Triassic origin present permeable units and, locally, deposits of gypsum and other evaporitic minerals that easily became karstified. There are evidences, in other areas outside the FPL basin, of rapid and important flows in sectors with abundant karstified, massive gypsum deposits. Additionally, slow flows in detritic materials have been identified in many Triassic aquifer units. Dissolution of salts and other water-rock processes, enhanced by long residence times of groundwater in the aquifer systems, are in principle, the main mechanisms responsible of the marked salinization found in most of the deeper flow paths.

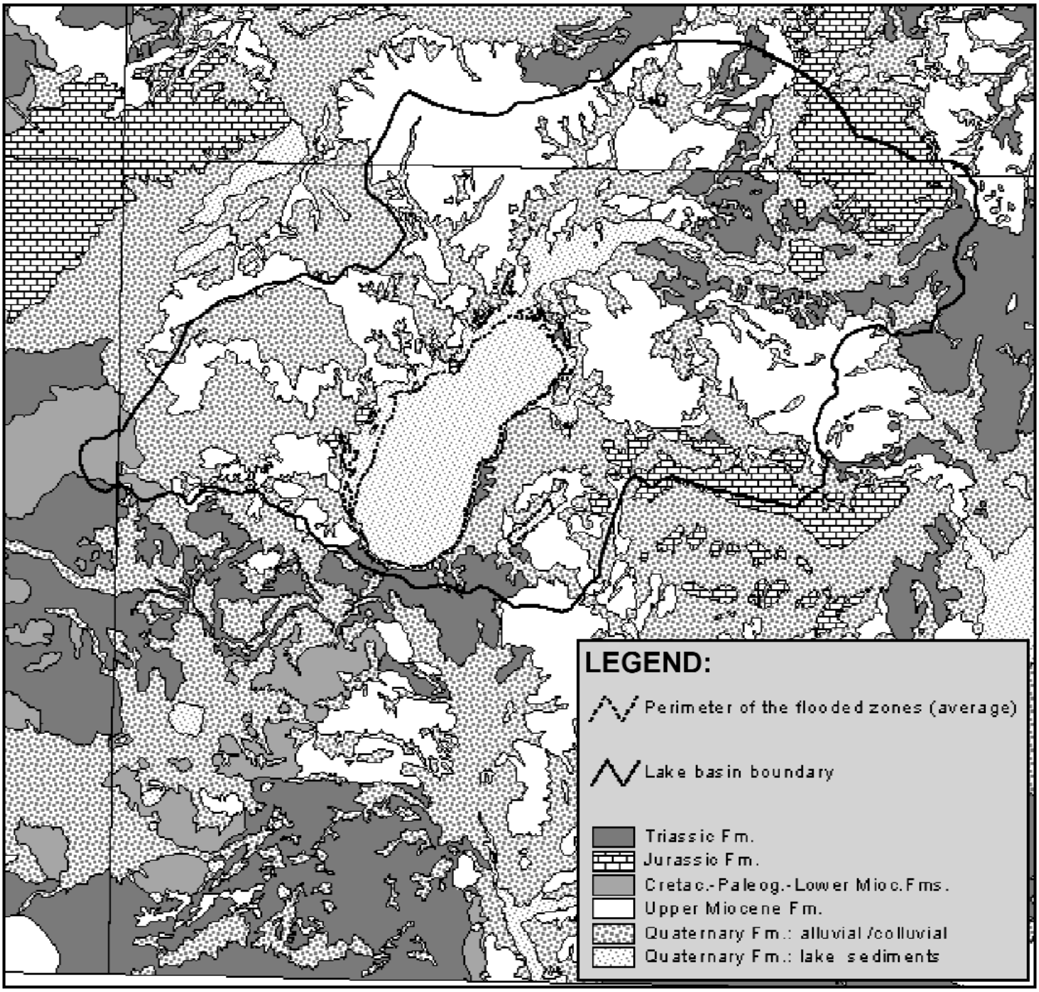

Figure 2. Regional geological map of the studied area.

Evaporation on the lake surface constitutes the main water output of the FPL system, until reaching halite saturation and forming salt deposits on the lake floor that have been historically exploited. To explain the large amount of salt exploited in the FPL, a large influx of saline groundwater to the lake has been invoked. The subsurface brine under the lake floor reaches a salt content above five times that of seawater, and different roles for deep groundwater flows and evaporation have been postulated to explain its origin and recent evolution. Despite the intensive pumping in the area close to the brine (more than 50 active pumping wells near to the freshwater/saltwater mixing zone), the stability in time and space of the intrusion wedge has been confirmed by numerous field measurements during the last decade (Benavente *et al*., 2003).

Due to the geological structure of the area and to some water balances calculated in the past, it has been postulated that part of the deeper flow paths under the lake may join regional fluxes developed in Triassic materials, resedimented during the Neogene. It has also been suggested that these deep flows may discharge outside the FPL basin, through saline springs located in the Guadalhorce river basin. The present study has also addressed the aspects related to the dynamics of deep groundwater flows.

Three main hydrogeological units have been defined according to the geological structure of the FPL basin, the hydraulic properties of the aquifer levels and the chemical and isotope characteristics of groundwater. The aquifers described in the following paragraphs are (figures 1 and 2):

a) Jurassic carbonates forming small ranges on the N and E borders of the FPL basin
b) Miocene and Quaternary detritic sediments in the central part of the basin
c) The brine below and around the lake floor, mainly hosted by Quaternary and Miocene sediments.

Additionally, some groundwater samples collected in the Guadalhorce river basin have been included in the discussion regarding the origin and dynamics of the brine.

Hydrochemical and isotope characterization

The following tasks have been conducted during the last months to investigate the relevant aspects on the origin of the brine and groundwater flow patterns:

- Evaluation of the spatial distribution of salinity in groundwater, through the systematic measurement of electrical conductivity and temperature profiles in wells and piezometers.
- Flow-tests based on the single-well dilution technique using NaCl and ^{131}I as tracers. These tests were used to identify the existence, type and magnitude of water flows inside of wells and piezometers. The tests were performed on different hydrogeological environments; fresh and brackish groundwater (Jurassic and Miocene aquifers), and in the brine under the Fuente de Piedra lake. The analysis of the temporal changes in the concentration of tracers provided important information on the fluxes inside the boreholes and wells.
- Sampling for chemical (major ions and trace elements) and isotope analysis (oxygen, hydrogen, carbon) and related field work. After the identification of different types of groundwater in selected boreholes and wells, through temperature and conductivity profiles, samples from different depths were collected for hydrochemical and isotope measurements.
- Chemical and isotope analysis were carried out in selected samples. For dating purposes, tritium and carbon-14 were measured in a few samples. ^{18}O and D contents were analysed in all sampled points. Chemical and isotope analyses have been conducted at the Isotope Hydrology Laboratory of CEDEX (Centro de Estudios y Experimentación, Madrid), using the standard analytical protocols. The ionic concentrations are expressed in $mg \cdot L^{-1}$, tritium contents in tritium units (T.U.), ^{14}C activities as percent Modern Carbon (pMC), and the stable isotope contents as deviations in ‰ (δ), with respect

to the respective international standards, V-SMOW for $\delta^{18}O$ and δD, and V-PDB for $\delta^{13}C$. Typical uncertainties are ± 0.4 T.U. for tritium, ± 1.0 pMC for ^{14}C, ± 0.1 ‰ for $\delta^{18}O$, ± 1.0 ‰ for δD and ± 0.3 ‰ for $\delta^{13}C$.

- Well-logging (natural gamma, point resistivity and spontaneous potential) was conducted on selected boreholes.

Main groundwater bodies in the Fuente de Piedra basin

Based on the hydrogeological framework of the FPL basin and in the chemical and isotope contents of groundwaters, three main water groups have been identified. The results of chemical and isotope analysis of representative samples of the hydrogeological domains cited above are presented in Table 1. The main hydrological and hydrochemical features of the groundwater types are described in the following paragraphs:

Table 1. Concentration of major ions and isotope contents for representative samples of the different water types identified in the Fuente de Piedra basin, (2003-2004).

SAMPLE	Elev. (m)	TDS (mg L^{-1})	Na^+ (mg L^{-1})	Ca^{++} (mg L^{-1})	mg^{++} (mg L^{-1})	Cl^- (mg L^{-1})	NO_3^- (mg L^{-1})	$SO_4^=$ (mg L^{-1})	HCO_3^- (mg L-1)	$\delta^{18}O$ (‰)	δD (‰)	Tritium (T.U.)	$\delta^{13}C$ (‰)	^{14}C (pMC)
Jurassic aquifers														
IGME-3 Mollina Santillán	459	498	21.7	69.0	29.6	36.5	27.3	50.0	262.3	-5.94	-38.2	---	---	---
Mollina NW-1	489	549	18.4	92.8	31.6	38.8	19.3	52.7	292.8	-6.15	-38.2	1.30±0.3	---	---
Humilladero, Water supply	477	511	23.9	95.8	20.7	48.9	30.9	31.1	257.4	-6.04	-45.1	2.40±0.4	-10.4	49.1±0.9
Fuente Piedra, Water supply	480	567	29.5	101.7	22.6	56.4	31.4	51.8	272.1	-5.73	-41.7	2.45±0.4	-9.6	68.6±0.9
Humilladero- Ferradores	522	860	132.3	105.9	27.7	229.3	13.9	40.6	301.3	-5.73	-40.6	1.42±0.3	---	---
Miocene and Quaternary aquifers														
Food processing factory	449	925	100.6	154.7	18.2	202.9	71.5	95.6	274.5	-5.61	-36.5	3.43±0.4	-10.8	75.2±1.0
SGOP-2 (74)	454	858	125.0	107.2	29.7	251.1	16.6	65.3	223.3	-5.38	-33.9	---	---	---
Villaromero (La Herradura)	449	1082	93.0	187.8	19.1	217.4	183.5	143.3	234.2	-5.09	-37.3	---	---	---
Fermontas	450	1251	140.8	217.7	25.5	354.4	115.7	159.0	234.2	-5.27	-41.6	---	---	---
IGME-2 La Coneja	447	1318	132.9	260.7	21.0	282.2	29.5	258.6	162.3	-4.87	-36.6	---	---	---
Llano Málaga	421	1528	140.7	244.7	44.0	246.9	108.0	413.9	325.7	-5.26	-36.9	---	-10.6	81.0±1.0
IGME - 4 La Albina	414	4044	416.8	594.4	321.1	1747.2	55.9	532.1	356.2	-5.22	-37.9	3.89±0.5	---	---
Brine below and around the lake floor														
UGr-Las Latas Southern zone	410	23290	5277.2	1470.8	1078.0	10068.5	0.0	4850.8	490.4	-4.96	-39.8	1.30±0.3	-10.4	74.2±0.7
SGOP-3 La Herriza	442	93080	28226.0	3430.0	3589.0	54783.0	0.0	2886.0	3.7	-2.08	-23.5	0.43±0.3	-9.6	5.2±0.7
UGr-La Vicaria	416	138100	38536.0	5634.0	3888.0	86252.0	0.0	3528.0	262.3	-1.36	-22.0	0.00±0.2	---	---
UGr-1 North zone	412	148312	43760.0	3726.0	5856.0	89500.0	0.0	4883.0	281.8	-2.39	-22.4	0.77±0.2	-14.6	71.9±1.0
UGr-2 North zone	410	193408	58779.0	2953.0	7640.0	116984.0	0.0	6216.0	225.7	1.03	0.70	---	-15.0	2.3±0.8
UGr-3 Laguna Norte	410	171156	50811.0	2793.0	7333.0	104106.0	0.0	5511.0	219.6	-1.19	-15.7	0.30±0.2	-16.0	52.9±1.0
UGr-El Ancón	409	126882	38742.0	2436.0	5558.0	73667.0	0.0	5879.0	212.3	-2.01	-20.6	1.00±0.2	-13.6	62.2±0.9
UGr-El Charcón	410	162138	46561.0	3054.0	8055.0	96314.0	0.0	7483.0	275.7	0.22	-7.70	0.30±0.2	-14.6	32.3±0.8
Noria El Ancón	410	175003	52764.0	2082.5	8020.0	102024.0	0.0	9297.0	246.4	5.70	5.8	3.64±0.3	---	---
Guadalhorce basin														
Alberquilla	416	644	79.2	92.6	12.4	135.9	41.2	37.8	240.3	-5.45	-40.3	2.24±0.3	---	---
Alberquilla campo	434	1813	362.0	145.5	34.7	637.1	54.2	117.5	431.9	-5.91	-33.4	4.08±0.4	---	---
La Saladilla	460	15918	4100.4	1065.2	202.8	7749.2	32.4	2490.0	278.2	-6.28	-40.7	3.49±0.4	---	---
Cañaveralejo (spring)	400	73314	25488.0	1392.0	399.0	42118.0	0.0	3652.0	264.7	-5.59	-41.3	4.90±0.5	---	---
Cañaveralejo (well)	399	114529	42113.0	1092.0	111.0	66386.0	88.0	4521.0	218.4	-5.96	-38.4	2.71±0.4	---	---
Cañaveralejo (spring, high temp)	404	118691	43385.0	1612.0	292.0	67616.0	65.0	5449.0	272.1	-5.67	-37.1	4.07±0.5	-5.7	38.4±0.9
Meliones (left bank, well)	369	92520	33526.0	182.0	747.0	53486.0	51.0	4282.0	246.4	-6.50	-47.5	6.16±0.6	---	---
Meliones (summer 2003)	369	164224	58362.0	2210.0	1506.0	96354.0	150.0	5400.0	241.6	-5.66	-44.5	8.14±0.7	---	---

Groundwater in the Jurassic carbonate deposits

These materials crop out in the NE of the basin and constitute the highest elevations around the FPL area –Humilladero and Mollina ranges– (see figures 1 and 2). From the hydrochemical point of view, groundwater samples collected in these aquifer units (see Figure 3) present the typical calcium-magnesium bicarbonate facies (Figure 4), showing the lower TDS values of all analysed samples, generally below 1 mS·cm^{-1} (~ 0,7 g·L^{-1}). Due to the good quality of the groundwater extracted, supply wells for several small towns were drilled in these materials, generally with a maximum depth around 120-160 m.

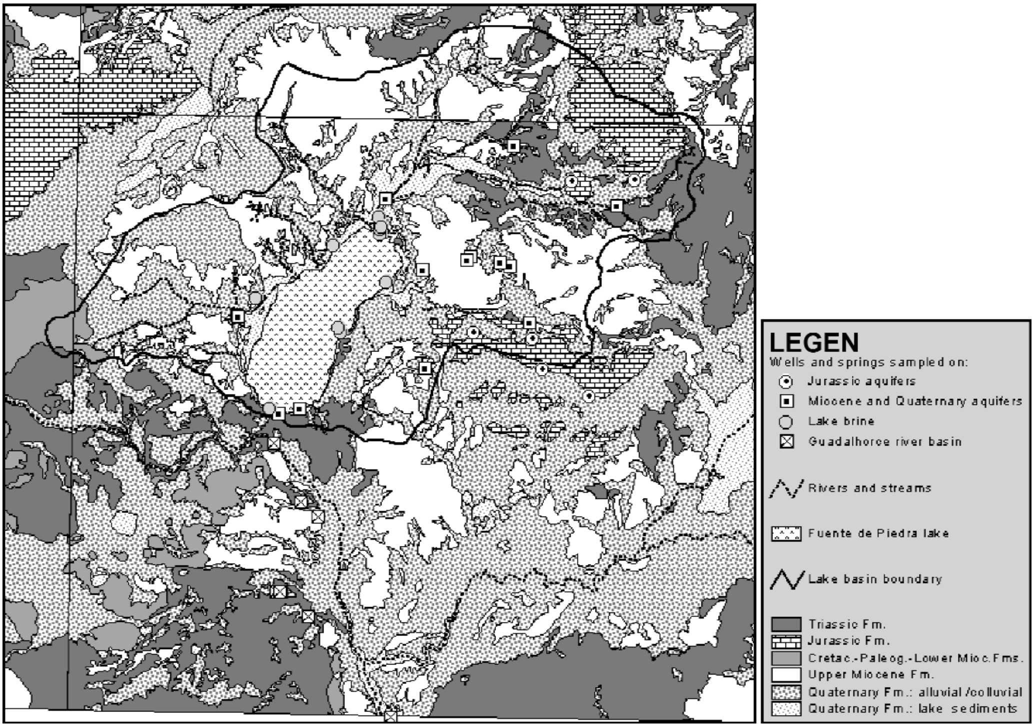

Figure 3. Sampling points of groundwater in the Fuente de Piedra lake basin.

The tritium contents found in these waters samples (Table 1) are lower than present values in precipitation (3-5 T.U.). These low tritium values and the pronounced lowering of the piezometric levels indicate that the intensive exploitation of these units has lead to the extraction of groundwater from deeper horizons, characterized by longer residence time in the aquifer. Contrary to the initial guesses, radiocarbon values measured in these samples are also systematically lower than those found in groundwater from the Miocene aquifers (Table 1), supporting the previous statement.

Additionally, nitrate concentrations in these groundwaters are relatively high (10 - 30 mg·L^{-1}). No clear source for the ion exists in the carbonate ranges. It is assumed that the low tritium contents and the presence of nitrates is fact is the result of the intense exploitation of these good-quality waters, leading to the mining of deep waters of large turnover time, and the inflow of recent, shallow groundwater from the adjacent Miocene aquifers located at the foothills of the Jurassic ranges. The intense agricultural activity in the area and the use of fertilizers resulted in the increase of exploitation of these good-quality waters and the inversion of the natural groundwater flow from the Miocene units. The intense exploitation of the Jurassic aquifers has lead to the inversion of the natural flow, allowing the mixing of relatively older groundwater from the Jurassic aquifer and recent groundwater from the Miocene aquifers (see below).

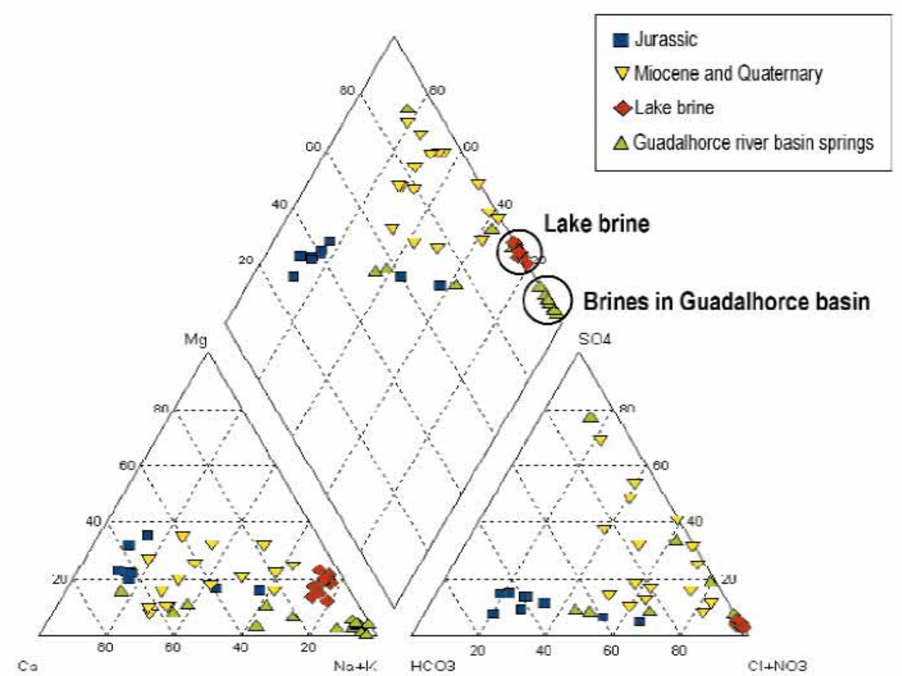

Figure 4. - Piper diagram showing the main hydrochemical features of the different types of groundwater sampled in the Fuente de Piedra lake basin.

Groundwater in the Miocene and Quaternary aquifers

The detritic and calcareous deposits of Miocene age extensively crop out in the area located between the FPL and the ranges formed by Jurassic carbonates. The area occupied by these sediments is relatively flat, with gentle slopes. The greatest thickness of Upper Miocene deposits is located to the North-East of the FPL, where the deepest well reaches more than 100 m (Figure 2). Most wells in this area provide sufficient water for agriculture and the food processing industry. The hydraulic properties of the aquifer are remarkable, constituting an excellent aquifer of high yield. The most productive wells of the basin are located oin the Miocene aquifer and are intensively used for irrigation. Its shallow character, the intensive use of fertilizers and the existence of return irrigation flows have resulted in the high nitrate contents observed in most wells sampled in these units.

In the lower stretch section of the Santillán stream (Figure 1), Darcy velocities of groundwater in the order of 3 $m \cdot d^{-1}$ were measured by the single-well dilution technique in summer time, probably affected by nearby pumping, despite the relatively elevated salinity of groundwater. Lower flow velocities were measured in the same well in winter time (about 1 $m \cdot d^{-1}$), when pumping was absent in the area.

Due to the presence of evaporite salts trapped in the sediments, groundwater in the Miocene and Quaternary aquifers presents high salinity values and is geochemically more evolved, showing a transition from calcium-bicarbonate waters to the chemical facies found in the brines sampled on the lake shore (Figure 4). In some cases, calcium-sulphate waters were sampled, probably being the result of the dissolution of gypsum crystals, derived from sediments of Triassic origin, reworked during the Miocene. Electrical conductivity (EC) ranges from 1.2 to 7 $mS \cdot cm^{-1}$ (1 to 5 $g \cdot L^{-1}$ TDS). Besides the dissolution of gypsum and of carbonate calcretes in soils, irrigation return flows also play an important role to explain the high salinity found in several areas covered by Miocene sediments. Tritium contents and nitrate are similar to the values found in present-day precipitation (Table 1), supporting the observations indicating the good hydraulic properties of these aquifers.

The brine below and around the Fuente de Piedra Lake

The lake waters shows a marked seasonality in TDS during the year, reaching halite saturation during the summer period, and forming salt deposits that are dissolved during the first rains in October-November. The subsurface brine sampled in several piezometers located in the vicinity of the FPL presents constant TDS values below a depth of 6-10 m. However, this Na-Cl brine presents a wide spatial variability around the FPL, from 20 to 200 $g \cdot L^{-1}$, as shown in Figure 5. The temperature and EC profiles measured in these piezometers located in the shoreline of the FPL from 1992 to 1998 (Benavente *et al.*, 2003) showed the great temporal stability of these profiles and of the interface position between the brine and fresh groundwaters. The stability of the interface position was observed for different water levels in the lake, seasons and climatic series. The analysis of the salinity profiles in the piezometers drilled around the lake shows a regular pattern, with higher salinity levels measured in the NE section of the FPL and lower values in the SW (Figure 5).

From the geochemical point of view, the FPL brine presents the features of a highly evolved geochemical system. While most of the brines draining Triassic sediments in the Guadalhorce river basin (Meliones and Cañaveralejo springs) are almost exclusively formed by sodium and chloride as major ions, the FPL brine presents a higher proportion of Ca^{++} and Mg^{++} ions (see Figure 4). Such composition is most likely the result of an intense water-rock interaction with the rock matrix and a long residence time of the brine under the lake floor. The low ^{14}C activity (about 2 pMC) found in the most saline sample (UGr-2, in Table 1) indicates the long residence time of the subsurface brine in the system. Besides the leaching of salts present in the Triassic sediments by deep groundwater flows towards the FPL, another possible origin of the FPL brine is the existence of trapped connate seawater. The mixing between the surface waters of the lake and the brine produced the relative "recent" tritium and ^{14}C values found in other brine samples.

The shallow character of the brine, its geochemical features and the lack of spatial homogeneity in the TDS contents suggest that a "source" of the brine is required in the northern edge of the FPL to explain the observed spatial distribution. In this case, the intermediate salinity values would be the result of dilution of the concentrated brine by underground fluxes directed towards the FPL floor, in the centre of the basin. The presence of a salt diapir(s) in the zone has been previously suggested to explain the presence of saline lakes and the brine in the area.

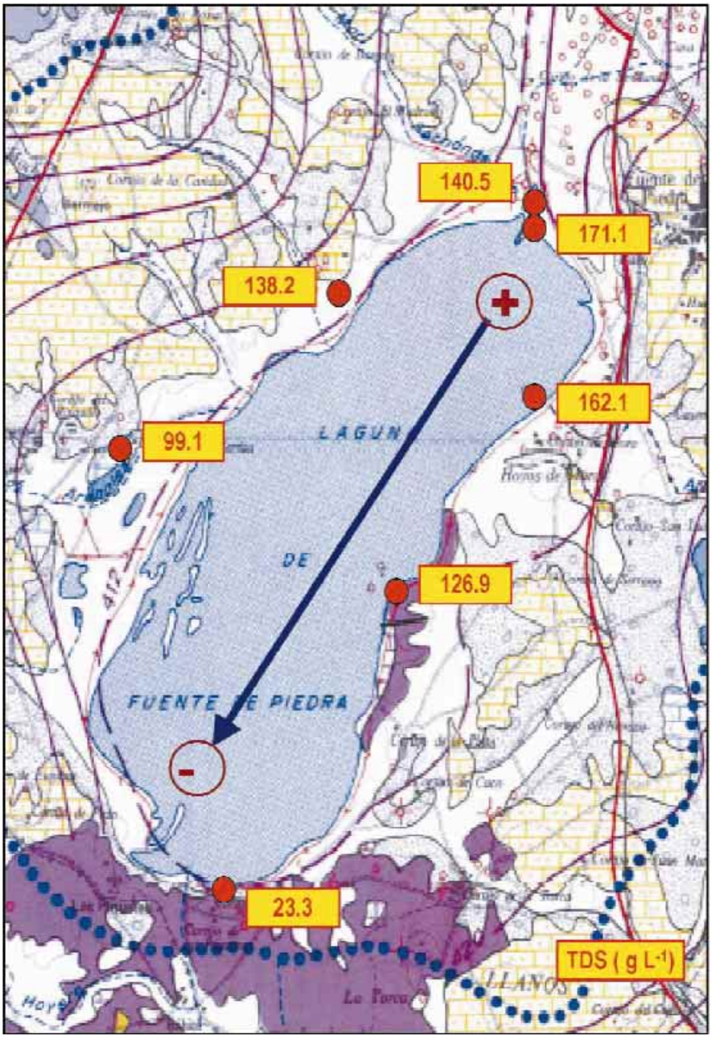

Figure 5. Computed total dissolved solid (TDS in g L^{-1}) of the Fuente de Piedra brine measured at a depth of about 10 m in selected boreholes around the lake. A clear trend in salinity is observed, with values ~ 170 g·L^{-1} in the NE to less thean 25 g·L^{-1} in the SW.

A flow-test with ^{131}I as tracer in La Herriza borehole (see location in Figure 1) showed the existence of a vertical upward flow between 140 y 120 m depth (Figure 6). The flow velocity was about 0.5 m h^{-1}, which corresponds to Q = 0.2 a 0.4 L h^{-1}. The existence of a thin confining layer at a depth of 120 m, responsible of the observed flow, was shown by the gamma ray profile (Figure 6). A small horizontal flow was identified at a depth range between 50 and 90 m (Figure 6). The low tritium contents found in these samples (Table 1) indicate the slow dynamics of the brine, although it appears very close to the surface.

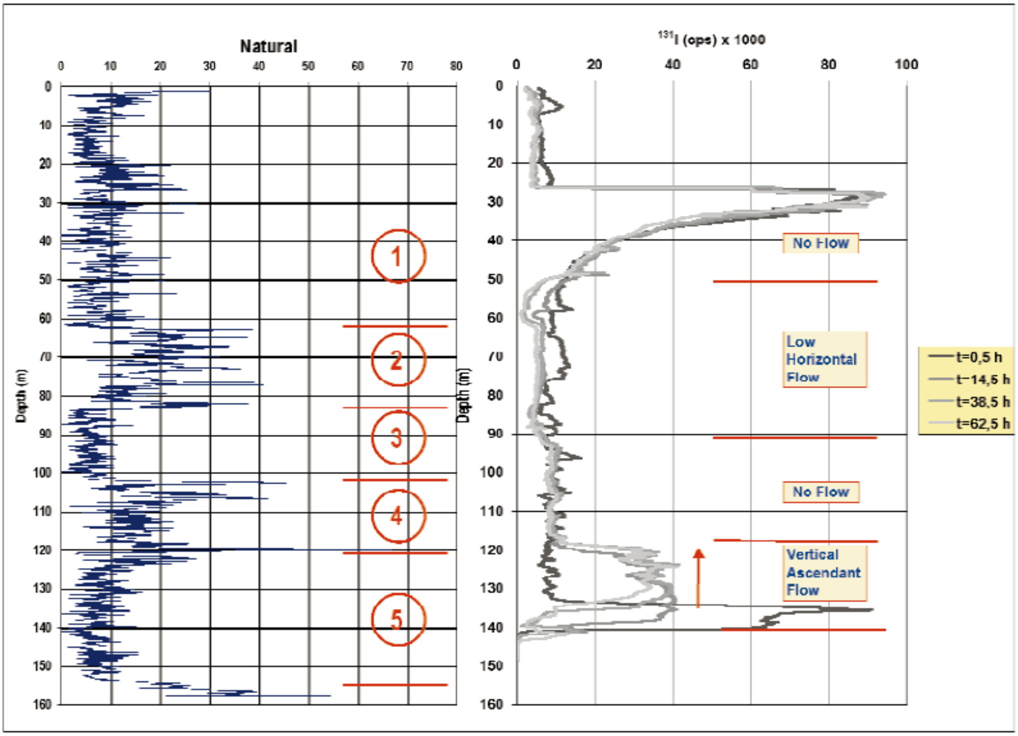

Figure 6. - Natural gamma log and results of a flow-test with ^{131}I (single-well technique) conducted in La Herriza borehole.

Springs in the Guadalhorce river basin

During the first stages of the study, the investigation of the existence of deep groundwater flows mixing with regional fluxes lead to consider areas outside the FPL basin as discharge points. Several springs (e.g.Meliones and Cañaveralejo), located in the Guadalhorce river basin (see figures 1 y 2) and oin sediments of Triassic origin, were sampled for chemical and isotope analyses. Although the salinity contents were similar to those found in the brine of the FPL basin, a marked contrast in ionic ratios and isotope contents was found (figures 4 and 7). The chemical composition of these samples showed the particular and differential chemical character of the FPL brine.

Contrary to the Fuente de Piedra brine, these springs show high tritium and nitrate contents (Table 1), indicating a relative rapid circulation of groundwater in these sediments of Triassic origin. Also from the chemical point of view, there is a marked contrast between the two brines, indicating, as previously mentioned, a different origin and dynamics of the two systems. As previously shown, the chemical composition of these springs is mainly of the NaCl facies, reflecting a rapid transit time and the limited magnitude of the geochemical changes affecting these waters, since only dissolution of halite is required to explain its origin. As shown below, a marked contrast in the stable isotope content was also found.

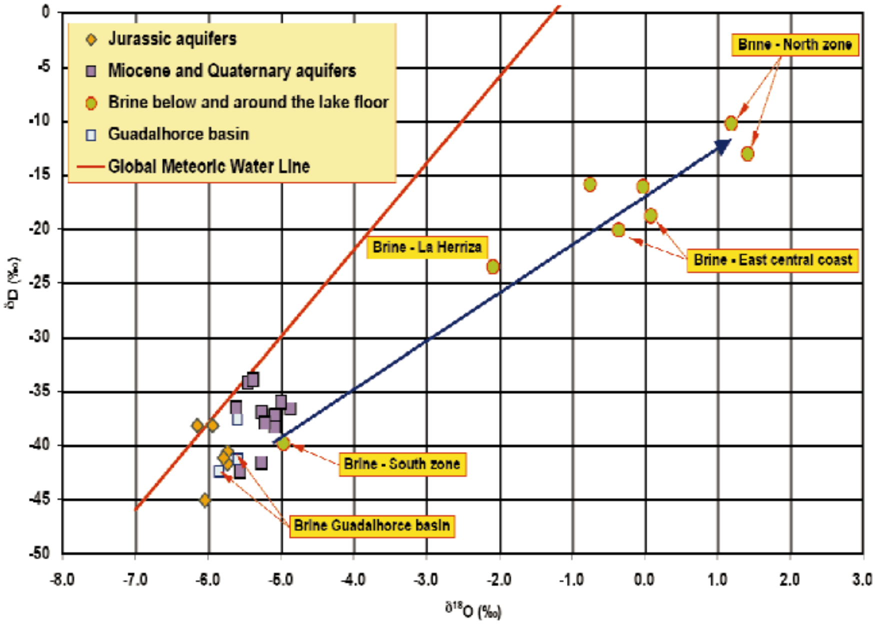

Figure 7. $\delta^{18}O$-δD relationship of fresh waters and brines sampled in 2003 in the Fuente de Piedra basin.

Stable isotope contents

The stable isotope contents ($\delta^{18}O$ and δD) have been measured in a number of samples representing the main types of groundwaters described in previous paragraphs. The $\delta^{18}O/\delta D$ relationship for the four water types is shown in Figure 7. The most negative isotope values (about –6‰ for $\delta^{18}O$) have been found in fresh low-salinity groundwater samples collected oin wells tapping the Jurassic aquifers, which corresponds to areas of higher altitude (about 700 m, vs 410 m.a.s.l. of the lake floor). These samples are situated close to the Global Meteoric Water Line (GMWL).

The $\delta^{18}O$ values of samples collected oin the Miocene and Quaternary aquifers are generally more enriched than the values found in the Jurassic limestones, but still they appear close to the GMWL in the $\delta^{18}O/\delta D$ diagram (Figure 7). This observation is coherent with the lower elevation of the Miocene materials. However, the fact that all groundwater points are clearly located below the GMWL indicates the importance of partial evaporation of rainwater before or during infiltration. Due to the importance of agriculture in the area, this enrichment is most probably locally enhanced by irrigation return flows. The high nitrate contents found in numerous wells and boreholes indicate the fast transfer of fertilizers and pollutants to groundwater, which means a rapid infiltration through the soil and the aquifer itself.

The isotope composition of the FPL brine shows a large spread of $\delta^{18}O$ and δD values, as it was found for the salinity values (Table 1 and Figure 8). As expected, the most enriched sample (+1.0 ‰ in $\delta^{18}O$) corresponds to the more saline sample (171 g L^{-1}), which was sampled on the northern edge of the lake. This value is typical of geochemically evolved connate waters, probably a relict of trapped seawater. The stable isotope content of the FPL brine supports this hypothesis. The rest of the brine samples of lower salinity appear in a theoretical mixing line between the typical values of fresh waters and the FPL brine (Figure 8). As suggested by the chemical composition, the heavily enriched $\delta^{18}O$ value of the FPL brine reflects a different origin of this brine with respect to other brines sampled in the Guadalhorce basin.

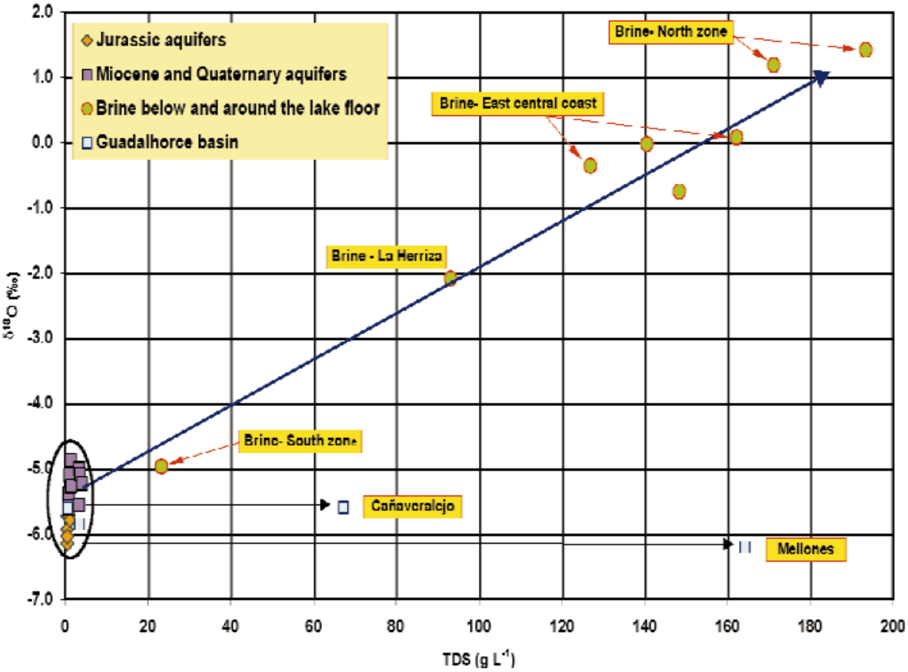

Figure 8. $\delta^{18}O$-TDS relationship of fresh waters and brines sampled in 2003 in the Fuente de Piedra basin.

Conclusions

The preliminary hydrochemical data obtained in this study allowed deriving the following statements on the groundwater flow patterns in the basin:

- Both the development of the conceptual model of the system and the numerical modelling cannot be properly represented unless a careful consideration of the density variations of the involved flow systems.
- Freshwater flow in the basin is linked to the Jurassic and Miocene aquifers, defining flow lines towards the FPL. The Jurassic aquifer is subjected to intensive exploitation and probably a reverse of

the original groundwater flow is affecting the quality of this resource. The Miocene aquifer presents good hydraulic properties, as confirmed by the hydrochemical study and the tracer tests conducted. Most probably, the recharge rate over these sediments is larger than anticipated.

- Despite the intense pumping in areas located near to the brine-fresh groundwater interface, the piezometric observations and the salinity profiles indicate a marked stability of the position of the interface for, at least, several years. The brine salinity below and around the lake, at a depth below about 10 m, shows minor changes with depth. However, there is a marked spatial variability, with values ranging from 170 $g \cdot L^{-1}$ in the NE area (Santillán), 100 $g \cdot L^{-1}$ in the central part, and about 25 $g \cdot L^{-1}$ in the SW.
- Both chemically and isotopically, the FPL brine shows a marked geochemical evolution, contrary to other brines sampled in the Guadalhorce basin, indicating that most probably it represents connate waters. The long residence time of the FPL brine is confirmed by the absence of tritium, even in shallower samples collected at a depth of a few meters and 14Cc values close to the detection limit. The chemical and isotope results obtained in this study provide additional constrains to the proposed hypothesis on the origin and temporal evolution of the FPL brine.
- The sharp density contrast between the Fuente de Piedra brine and the shallow groundwaters in the Miocene aquifers suggests the existence of independent and stratified flow systems.
- The marked hydrochemical and isotope differences between the Fuente de Piedra brine and other saline discharges outside the basin strongly suggests the absence of a deep groundwater flow fed by saline waters recharged in the FPL basin.

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