Physicochemical characteristics of playa-lake sediments located in the western External Betics

Características físicoquímicas de sedimentos de lagunas situadas en las Zonas Externas de las Béticas Occidentales

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ABSTRACT

In the western External Betics several temporal saline water bodies (playa-lakes) constitute singular environments that are protected due to their ecological and hydrological values. Changes in their hydrological status due to both natural and human-induced changes alter the characteristics of their sediments. A detailed determination of the pH and electrical conductivity in the sediments of six playa-lakes within a range of degradation statuses was made in this study. The detailed examination of such geochemical variables has allowed us to establish three categories of degradation in the studied systems. Our results highlight the extreme vulnerability of this playa-lakes caused mainly by human activities, particularly those related to land-use change for agriculture, as well as the necessity of its protection based on scientific criteria.

Key-words: *physicochemical parameters, saline lake, endorheic basin, geochemistry, environment.*

RESUMEN

En las Zonas Externas de las Béticas occidentales varias masas de agua salinas temporales (lagunas tipo playa) constituyen ambientes singulares que se encuentran protegidos por sus valores ecológicos e hidrológicos. Las variaciones en su estado hidrológico debido a cambios naturales o inducidos por el hombre alteran las características de sus sedimentos. En este estudio se realizó una determinación detallada del pH y la conductividad eléctrica en los sedimentos de seis lagunas que presentan un rango variable de estados de degradación. El examen de tales variables geoquímicas nos ha permitido establecer tres categorías de degradación en los sistemas estudiados. Nuestros resultados destacan la extrema vulnerabilidad de estas playas causada principalmente por actividades humanas, particularmente aquellas relacionadas con el cambio de uso de suelo para la agricultura, así como la necesidad de su protección con base en criterios científicos.

Palabras clave: *parámetros fisicoquímicos, laguna salina, cuenca endorreica, geoquímica, medio ambiente.*

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Introduction

Saline playa-lakes are conspicuous hydrological systems scattered throughout the External Betics (southern Spain). These playa-lakes are usually small (from a few to several hundreds of hm^2) and shallow (normally not exceeding 1 m deep), with a flat surface when they dried up in summer. They are susceptible to variations in the quantity and quality of water supply, due to their intrinsic isolation from open water bodies. Also, they are vulnerable to both natural and anthropic modifications of their closed watersheds. In the second half of the 20th century, agriculture management (direct drainage or groundwater withdrawal) and infrastructure activities within the watershed (e.g., construction of linear infrastructures such as roads or irrigation channels) have led to playa-lake damage and degradation. Proper management and restoration of saline playa-lakes must consider such alterations. The importance of shielding playa-lakes (Höbig et al., 2016) against morphological changes produced by ditching, draining, removal of land or high sediment accumulation rates is evident.

A detailed analysis of the main physicochemical characteristics (i.e., electrical conductivity - EC, pH_{KCl}, pH_{H2O}) of the sediment profiles of saline lakes are key factors to detect changes in their hydrological status. Soil pH is an important property because it affects the chemical, biological, and physical soil processes (Stefanovics et al., 1999). Thus, pH is often considered the "master variable" of soil. In turn, EC as a proxy of the soil salinity is also crucial for the understanding of the hydrological functioning of playa-lakes.

In this work, we have determined these physicochemical characteristics of surficial (up to 1 m deep) sediments from six playa lakes in the study zone.

The objective of such study is to categorize these playa-lakes to help us interpreting future geochemical, hydrological and geological data, as well as to determine the recent tectonic movements and the consequent changes in the distinct playa-lakes.

Geological setting and sampling sites

The study area is located in the western External Betics, near the city of Antequera (Fig 1). The climate of the area is classified as Csa according to Köppen and Geiger (Beck et al., 2018). It presents a humid winter, with maximum rainfall values normally attained in November and December, and a dry summer, with minimum rainfall values in July. The average annual rainfall is 546 mm, and the average annual temperature is 15.3 °C according to climate data collected between 1999 and 2019 (es.climate-data.org).

The Betic chain is the northern branch of the Gibraltar Arc, which was built up by the Neogene continental collision of the Alboran microplate with the South Iberian Paleomargin to the North and the Maghrebian paleomargin to the South. The External Betics are composed of paleomargin-derived sedimentary formations and Flysch trough units. Both were deformed and detached from their respective basement (e.g., Balanyá et al., 2012 and references therein). The study area is located in the outer western External Betics. The stratigraphic sequence includes Triassic gypsum-rich marls and clays with scarce dolostone bodies, as well as Jurassic to Cretaceous carbonatic rocks of the internal and middle Subbetic units. Miocene marine calcarenites and marls unconformably overlie the Mesozoic units (Fig. 1).

From a morphostructural point of view, the study area defines the water divide between the Atlantic (to the North) and Mediterranean (to the South) basins in this segment of the Betics. It is bounded by two NE to ENE striking dextral transpressional zones, the Algodonales-Badolatosa shear zone (ABSZ, Jiménez-Bonilla et al., 2015; García et al., 2016) to the North and the Torcal shear zone (TSZ, Díaz-Azpiroz et al., 2014) to the South (Fig. 1). The area between both shear zones is topographically depressed and presents a low-lying relief. These features, together with the widespread presence of Triassic impermeable materials, favor the development of several endorheic basins (Fig. 1). These endorheic zones typically present a central playa-lake with main incomes from direct precipitation and surface runoff, and main outcomes from evapotranspiration and, occasionally also anthropic uses (Rodríguez-Rodríguez et al., 2012). The studied playa lakes are Ratosa Playa-lake (RaL) and Dulce Playa-lake (DL) in Málaga, Gosque Playa-lake (GL) in Seville, and other three study areas in different degradation stages as playa-lakes from less degraded to extinct playa-lakes: Herriza de los Ladrones (HL) Playa-lake, Nava (NL) Playa-lake, and the so-called Roman Playa-lake (RL) (Fig. 1). Faults affecting Mesozoic and upper Miocene rocks appear spatially related to some of these endorheic basins.

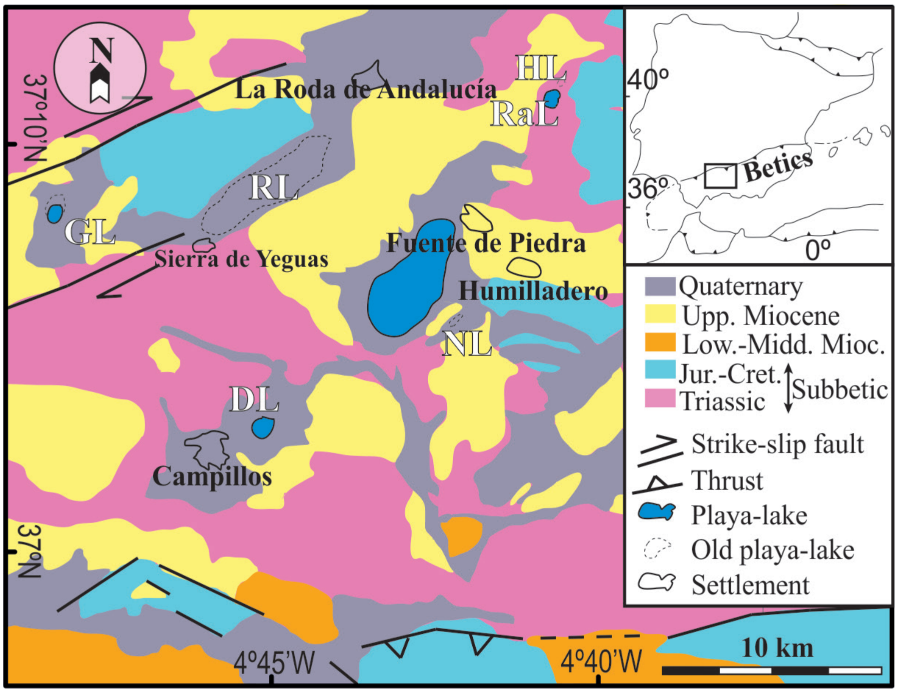

Fig. 1.- Study area showing the geological setting and the playa-lakes location under study. See figure in colour on the web.

Fig.1.- Área de estudio mostrando el contexto geológico regional y la ubicación de las lagunas en estudio. Ver figura en color en la web.

Methods

Sampling was carried out on 10 representative locations according to the research objectives with an extendable hand auger (Fig. 2).

Drill cores were extracted every 20 cm down to a maximum depth level of 1 m. These samples were then described and subjected to a pretreatment according to the ISO 11464:2006.

There are two methods for determining the pH of sediments. Active acidity reflects the pH that prevails under the current circumstances, but the data obtained by measuring reserve acidity can be reproduced more accurately later, because it represents the maximum possible acidity of the soil. Active acidities were measured from a 1:5 suspension (sediment - distilled water with pH 7). The measurement of reserve acidity was also carried out in a suspension of 1:5 (soil - 1M KCl solution). Both measurements were carried out in accordance with the current international standard (ISO 10390:2005). HACH HQ 11d device combined with IntelliCAL PHC101 glass electrode was used for pH measurements. In each case, two parallel measurements were made, resulting in a total of 112 pH measurements.

The determination of electrical conductivity (EC) was also carried out from a 1:5 suspension (sediment - distilled water with pH 7) according to the international standard (ISO 11265:1994). In this case, a WTW Cond 3110 instrument was used. A WTW TetraCon 325 electrode was connected to the device. The electrical conductivity of the sediment was measured from duplicated subsamples of 3 distinct levels in most cases, resulting in 56 measurements. According to the protocol, two parallel measurements were carried out in each sample to assure the representativeness of the data.

Results and discussion

Based on the detailed description of the extracted drill-cores, a short summary of the lacustrine sediments is made in order to give an insight of the most significant sedimentological characteristics of these playa-lakes.

There are two sampling points at the Ratosa Playa-lake with the sampling depth of 1 m (Fig. 2). The extracted silty-clay sediments from the two distinct sampling points show slight differences. The most notable ones are the change in colors and the presence of concretions in the sediment columns. RaL-1 is greyish in the upper 0.80 m whereas the same applies only to the upper 0.40 m of RaL-2, although both samples contain Fe-Mn concretions at about 0.80 m. The observed variability likely represents alterations in the redox conditions. The lake was completely dry on the day of sampling (03/05/2021) and the groundwater table was 0.40 m deep at sampling point RaL-1, the deepest part of the lakebed, and at 0.60 m at sampling point RaL-2, at the shoreline.

Two 1 m-long sediment columns were extracted from the Dulce Playa-lake sampled on 01/10/2021 (Fig. 2). These columns share the same sediment structure. The brownish coloured sediments of the Dulce Playa-lake are silty-sand in the upper 0.40 m and silty-clay from 0.40 m downwards. The DL-1 sediment column contains remains of mollusks in the upper 0.20 m and from 0.40 m changes its brownish colour to blackish accompanied by the appearance of 500 µm long gypsum crystals. The depth range between 0.40-0.80 m contains fine and rounded quartz gravel. From 0.80 m the ocher-coloured clayey sediment contains lime. The DL-2 sampling point has the same sedimentology,

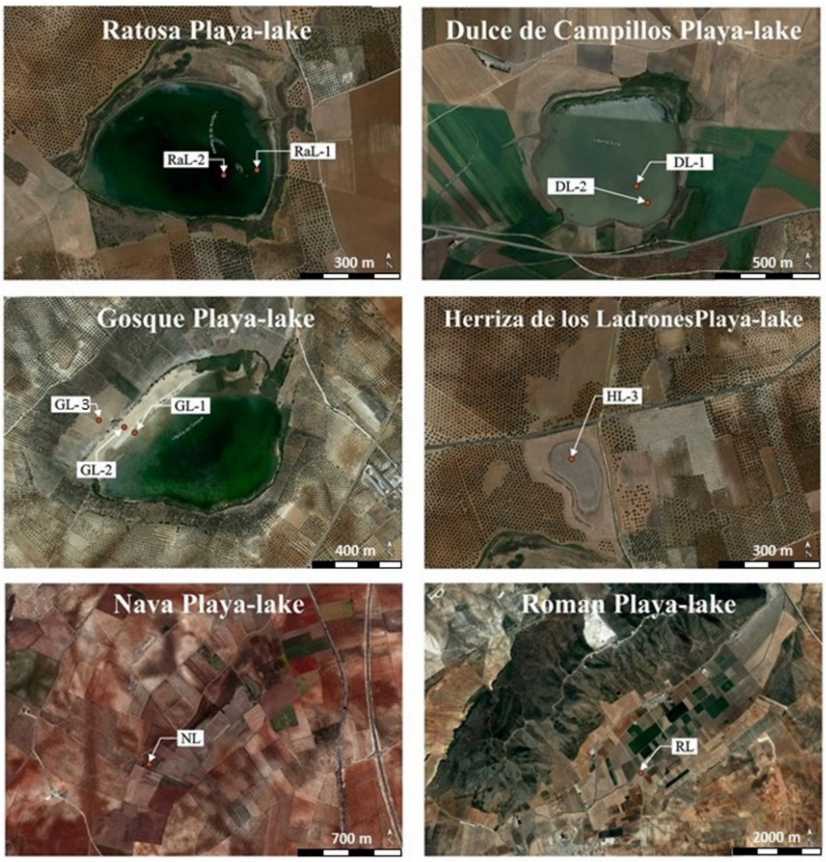

Fig. 2.- Sampling points in the study areas (Satellite image source: Google Earth). See figure in colour on the web.

Fig. 2.- Puntos de muestreo en las áreas de estudio (Fuentes de imágenes de satélite: Google Earth). Ver figura en color en la web.

however it has a second horizon of smaller gypsum crystals at 0.80 m.

Three hand probes were carried out at the Gosque Playa-lake sampled on 12/03/2021 (Fig. 2). It is noteworthy that this was the only playa-lake with water coverage at the time of sampling. The extracted 1.15 m long sediment columns share the same structural characteristics: in general, grayish clayey silt. The GL-1 sample has dark grey colour from the surface down to 0.55 m. The sample was taken from a zone with relatively permanent water coverage. From 0.55 to 1.15 m the sediment turns yellowish and more compact. This depth range contains lime concretions. The GL-2 column has grey colour and does not present the yellowish layer, however the compactness and the lime concretions are present at the same depth range. The GL-2 sampling point is located at the lake shore, where intense water level changes occur. The GL-3 sampling point is further out of the lakebed. Sediments of the GL-3 column have the same sedimentological characteristics as those from GL-2.

The Herriza de los Ladrones Playa-lake was sampled on 03/05/2021 (Fig. 2). The manual probe reached 1.10 m, extracting very loose, low humid sediment, which did not present the typical identification marks of lacustrine sediments, but was rather an inceptisol with well-developed horizons. It has a humic horizon A in the upper 0.40 m. Under this horizon there is a layer of yellowish coloured silty clay with granular structure. There is a gradual transition to a more clayey and lighter shaded yellowish sediment towards the end of the drill-core.

The hand probe reached 0.60 m at the Nava Playa-lake on 01/10/2021 (Fig. 2), obtaining a highly resistant layer, which suggests that the clayey sediment is at the beginning of the lithification process. The cut surface was very firm and shiny. There was a second hand auger probe carried out at 0.50 m where a caliche layer was present. The extracted loose sediments consist of silty sand with an intense brownish colour without any change in the structure down to 0.60 m.

The extinct Roman Playa-lake was sampled on 12/03/2021 (Fig. 2). The hand probe reached 0.90 m. The sediment column does not present horizons, it has the same brownish clayey-silt sediment with fine sand and mollusks remains through the whole sediment column.

The geological structure, climatic and hydrographic properties determine the soils formed in the study area. Although the investigated sites are located relatively close to each other, in an area of 18 hm^2, the developed sediment profiles present significant differences, mainly according to the current degradation stages of the playa-lakes. The obtained results of pH and EC from 10 distinct drill cores from 6 playa-lakes are presented in Table I, and mean values are summarized in Figure 3. The potential acidity values of the playa-lake sediments are quite balanced around pH=8. There are differences among the active and potential acidity means, detecting the largest deviations between the two values in the sediments of the Gosque Playa-lake.

The active acidity of the examined sediments varies between 7.93 (DL-1, 0-10 cm) and 10.00 (GL-1, 80-90 cm). Based on mean pH values, the largest difference is between the Dulce and Gosque playa-lakes data, that is, these are the end members of the examined playa-lakes according to the active acidity of their sediments.

Salty waters and sediments have a very strong alkalinity of 9-11 pH due to the presence of alkaline salts. The cause of salinization in soils and sediments is the accumulation of mobile alkaline and alkaline earth metal salts in the fluctuation zone of the groundwater table, and even in the root zone (Bohn et al., 2001).

Significant differences in EC values reflect distinct hydrological functioning of the playa-lakes. The highest values were obtained from the surface sediment of the Ratosa Playa-lake. There is a noticeable decreasing trend in EC values from the deeper zones of the lakebed towards the shoreline of the Ratosa and Dulce playa-lakes. However, this trend is reversed in the Gosque Playa-lake and this is partially due to the geological and geomorphological setting of its lakebed. The Gosque Playa-lake has an antique lakebed separated from the current one with a slope. This ancient lakebed has a much darker and less clayey sediment, compared to the other two sediment columns from the site. However, the main reason for the reversed trend is the water coverage of the present lakebed. The water homogenizes the salt content of the sediments; thus, these salts cannot accumulate on the surface.

The EC values show significant differences between the two sediment columns RaL-1 and RaL-2 from the Ratosa Playa-lake (Table I). The reason is the position of the sampling points. The highest values are expected in the central and deeper part of lakebed, as confirmed by the recorded data. The importance of topography and micromorphology is supported by the theoretical model of groundwater flow in small drainage basins (Tóth, 1963) and the model of gravity driven flow system for shallow depths (Erdélyi, 1976). The lowest values were measured in the Gosque Playa-lake, and in the three degraded lakes (Herriza de los Ladrones, Nava, and Roman). The latter have broken hydrological cycles, in contrast to the Gosque. Although the sediments of the Gosque playa-lake have the lowest electrical conductivity values, they are also the most alkaline ones among the studied areas. This might be due to the geological and geochemical setting of the lake, which favor the formation and accumulation of highly alkaline salts.

Conclusions

Based on the main physicochemical characteristics of the investigated playa-lake sediments and the current condition of the playa-lakes, we made three categories, according to the classification of saline and alkali soils of the US Salinity Laboratory USSL-USDA (Richard, 1954).

The first category includes only the Gosque Playa-lake. The sediments of its lakebed are characterized by high average alkalinity (around pH_{KCl} = 8) and low average electric conductivity (EC = 0.32 dS/m). These sediments are considered non-saline alkali sediments. The reason for this phenomenon might be the accumulation of highly alkaline salts, which significantly increases the pH.

The Ratosa and Dulce playa-lakes are characterized by pH values around pH_{KCl} = 8 and quite variable but rather high electric conductivity values. In this case, there are great amounts of dissolved salts in the sediment, but the proportion of the alkaline salts is lower than in the case of the Gosque Playa-lake according to the measured pH and EC values. The sediments of this group are considered saline-alkali sediments.

The third group is that of the degraded playa-lakes, Herriza de los Ladrones, Nava and Roman playa-lakes. The lacustrine sediments from these sites preserve relatively high pH values; in fact, generally higher than sediments in the second category. However, leaching of their surface sediments is advanced due to drainage (e.g, Roman playa-lake) and/or direct cultivation of the basin (e.g, Herriza de los Ladrones playa-lake). This situation remarks the extreme vulnerability of these ecosystems. These sediments are non-saline-alkali sediments, but we consider these lakes form a distinct group because of their altered hydrological behavior.

The presented work forms part of a greater geochemical study of playa-lakes. The correct interpretation of the geochemistry of lacustrine sediments is, in fact, indispensable for the development of the hypothesis of the hydrological functioning of playa-lakes in the context of recent tectonics.

Author contributions

L.H. and M.D.A. conceived the presented idea. L.H. developed the theory and performed the computations. J.D.R. and M.R.R. verified the analytical methods. A.J.B., J.D.R., M.D.A. and M.R.R. encouraged L.H. to investigate the geochemical aspect and supervised the findings of this work. All authors discussed the results and contributed to the final manuscript.

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Sample depth (cm)	pH_{KCl}	pH_{H2O}	EC (dS/m)
Ratosa Playa-lake			
RaL-1 sample	**8.13**	**8.39**	**13.14**
0-10	8.00	8.21	15.09
40-50	8.05	8.45	11.72
90-100	8.36	8.5	12.61
RaL-2 sample	**8.2**	**8.46**	**9.86**
0-10	7.98	8.21	12.83
40-50	8.31	8.62	7.82
90-100	8.30	8.54	8.93
Dulce Playa-lake			
DL-1 sample	**7.61**	**8.21**	**6.07**
0-10	7.48	7.93	5.40
40-50	7.43	8.14	7.65
90-100	7.94	8.57	5.17
DL-2 sample	**7.72**	**8.11**	**3.7**
0-10	7.73	8.08	3.12
40-50	7.65	8.06	4.07
70-80	7.78	8.21	3.91
Gosque Playa-lake			
GL-1 sample	**7.92**	**9.49**	**0.32**
10-20	7.78	8.92	0.20
40-55	7.85	9.56	0.36
80-90	8.13	10.00	0.42
GL-2 sample	**8.14**	**9.9**	**0.91**
10-20	8.05	9.81	0.65
30-40	8.22	9.99	1.17
GL-3 sample	**8.17**	**9.5**	**2.28**
10-20	8.16	9.62	1.85
40-55	8.18	9.39	2.72
Herriza de Los Ladrones Playa-lake			
HL	**7.78**	**8.61**	**1.5**
0-10	7.56	8.96	0.29
60-70	7.82	8.48	1.93
90-100	7.98	8.40	2.29
Nava Playa-lake			
NL	**7.45**	**8.58**	**0.25**
0-10	7.44	8.61	0.28
20-30	7.48	8.49	0.25
40-50	7.44	8.63	0.24
Roman Playa-lake			
RL	**7.9**	**8.98**	**0.23**
10-20	7.72	8.71	0.18
55-65	7.99	9.05	0.24
70-80	7.99	9.17	0.28

Table I.- Measurement results of pH and electrical conductivity (EC). In bold are presented the mean values of parameters for each sample.

Tabla I.- resultado de las mediciones de pH y conductividad eléctrica (EC). En negrita se representan los valores medios para cada muestra.

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