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ORIGINAL ARTICLE

Hydro-morphological characteristics and hydrogeological functioning of a wetland system: a case study in southern Spain

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Abstract The analysis and interpretation of physical and limnological parameters combined with hydrochemical (major ions and stable isotopes) analyses enabled us to evaluate the hydrogeological functioning and the hydrogeochemical evolution of groundwater in two adjacent lakes related to a karstic aquifer (Archidona, southern Spain). Lake water, groundwater and the outflow from a spring, were monitored periodically from 1998 to 1999 and sporadically from 2000 to 2006. The evolution of groundwater chemistry from recharge (dolines) to discharge areas (spring) showed an increment of 20% in magnesium and 15% in sulphate, and such higher increments were recorded for the water from the lakes, suggesting the existence of different hydrogeological paths. A simple water budget model, together with morphological interpretation, suggests that groundwater discharge into the lakes is of relative importance to the input into these systems. Finally, we believe that the development of a new typology for hydro-morphological elements, by means of several hydrological factors and the assessment of pressures and impacts will be useful for the correct management of these lakes and other semi-arid aquatic ecosystems.

Keywords Aqueous geochemistry · Environmental isotopes · Karst · Lake typology · Southern Spain

Introduction

The wetlands of Andalusia have a long history of degradation, and there is evidence of a continuing decline over the twentieth century. Some authors claim that more than half of the flooded surface of Andalusian wetlands is actually drained out (Montes et al. 2004). Rapidly growing populations and technological capabilities have resulted in widespread drainage of land for habitation and agriculture. A significant number of laws exist for the protection and wise use of Andalusian wetlands. There are many advantages to the development of a single consistent definition and classification scheme, acceptable to all organizations with an interest in wetlands. In that sense, the application of the recent European Water Framework Directive (WFD) also justifies the study of these water bodies, and of every lake, river and aquifer. All these elements must be managed within the frame of a basin-wide perspective. In order to improve the management of such ecosystems using scientific rather than political criteria, more investigation is needed. The WFD suggests a hierarchical approach to the identification of wetlands (WFD-CIS No. 12 2003). Therefore, it is important for researchers and technical specialists in water management throughout Europe, to have a clear understanding of the relationships among surface and ground water bodies and wetlands, in order to understand how these systems might be encompassed within the cycle of river basin planning. In this sense, to assess the identification of small elements of surface water

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and their potential designation as significant and discrete water bodies, a prudent, step-by-step approach is suggested. The issue of ''size limits'' is discussed in the WFD, and the following systems A and B are proposed for defining surface water typology (WFD-CIS No. 2 2002). According to the WFD, a surface water typology can be either:

- System A: A simple typology specified by watershed area, geology and distance from source (in the case of a river), or
- System B: A more flexible approach constituted of both obligatory and optional environmental variables.

If the system B approach to typology is adopted, it must achieve at least the same degree of differentiation as would be achieved using system A (Dodkins et al. 2005). Additionally, the environmental variables making up the typology are, ideally, not subject to impacts; otherwise, an impact would result in a monitoring site being allocated to the incorrect wetland type (WFD-CIS No. 3 2002). Henceforth, hydrology managers may be able to identify surface water bodies, such as wetlands, using additional criteria designated to take account of local circumstances and therefore assist in the River Basin District management planning process.

In Andalusia, work has been undertaken since 1997 in developing a methodology for wetland monitoring, classification and protection. The mission statement of the Andalusian Wetland Plan (Montes et al. 2004) is to preserve the ecological integrity of Andalusian wetlands, promoting their wise use and to preserve their ecological, socio-economic and historical-cultural functions. It also establishes the instruments for inter-administrative coordination, to allow the integration of other policies, such as the WFD. This paper presents a new approach based on hydrogeological and limnological data to implement the new methodologies addressed by the WFD; inspired by the Archidona Lakes Natural Reserve, a wetland located in the centre of Andalusia and which is a protected area. This study is intended to constitute a basis for comparison and assistance to other researchers and specialists in water management throughout Europe and elsewhere.

The information published to date on the Archidona Lakes is scarce and, from a limnological point of view, is limited to a report on the phytoplankton (Rosa 1992), in which a dominance of cianophytes in Lake Chica and diatoms in Lake Grande has been found on an annual base. Indicators of faecal contamination (Gomez 1994) suggest there is significant contamination in Lake Chica (100% of the analysed faecal coliforms were *Escherichia coli*) and slight contamination in Lake Grande (only 20% of the faecal coliforms analysed corresponded to *E. coli*). A recent publication by the author studied the hydrological regime of ten playa-lakes in southern Spain, based on water budgets over a 5-year period (1997–2001), including the lakes of Archidona (Rodríguez-Rodríguez et al. 2006).

The main objectives of this study are: (a) to analyse and interpret the physical and hydrogeological parameters in two surface water bodies (lakes) from a basin-range perspective; (b) to examine the hydrological factors responsible for the differences found between the two lakes; (c) to develop a new typology for hydro-morphological elements and hydrochemistry, adaptable to the semi-arid conditions of the wetlands of southern Spain.

Methodological approach

Study site

The lakes are located in the south of Spain, in the region of Antequera (see Fig. 1a), at an altitude of 790 m ASL and in the municipality of Archidona. From a geological point of view, the area is located over the Sub-Betic Units of the Betic Cordillera (Vera 2004), defined in this sector as *Triassic Gypsum of Antequera* (TGA) unit (Calaforra and Pulido-Bosch 1999; Cruz-Sanjulián 1974). The TGA unit is characterized by the dominance of clayey marls and evaporitic materials. The evaporites are constituted of

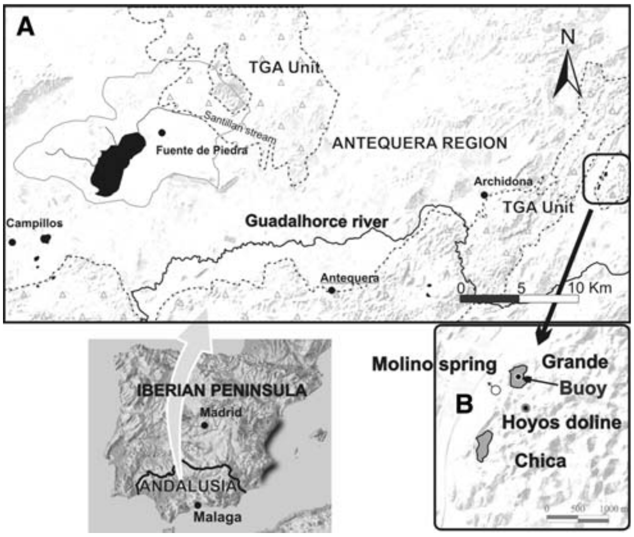


Fig. 1 **a** General setting and location of the TGA unit materials. **b** Study site. Lake Grande and Lake Chica, Hoyos doline and Molino spring gypsum and halite, the former outcropping at the centre of diapiric structures and the latter deposited as sub-surface layers. This is proven by the existence of numerous sodium–chloride springs and cores (Carrasco 1986).

The occurrence of diapiric processes in other locations of the Triassic belt of the Betic Cordillera has been reported and their relation with the formation of saline and hypersaline lakes and springs is well-known (Rodríguez-Estrella 1983). The Grande and Chica lakes are located in the outer part of a diapiric structure that constitutes a Triassic karstic aquifer, the "Lagunas-Los Hoyos" aquifer at 800 m ASL (Carrasco et al. 2004), to the north of the Sierra Gibalto, which rises to 1,024 m ASL (Fig. 2). Its origin as a diapiric dome of approximately 12 km^2 and resultant karstic morphology within the Lagunas-Los Hoyos aquifer is conspicuous, as can be seen in a slope map of the region (Fig. 2) derived from a Digital Terrain Model (AME 2005). Their similar origins result in the lakes presenting a similar type of morphometry, although significant differences exist between the hydrologic regimes and the chemical composition of their waters. The main springs draining this karstic aquifer are also represented in Fig. 2: the Molino spring is located at the western edge of the aquifer and presents a SO_4–Ca water-type (E.C. 3.5 mS/cm). This spring discharges a steady flow of approximately 15 l/s. The Fuente-Camacho spring is located at the eastern edge of the aquifer and presents a lower flow (1 l/s) of high salinity and Cl–Na water-type. This spring was formerly exploited as a *salina* (salt-mine).

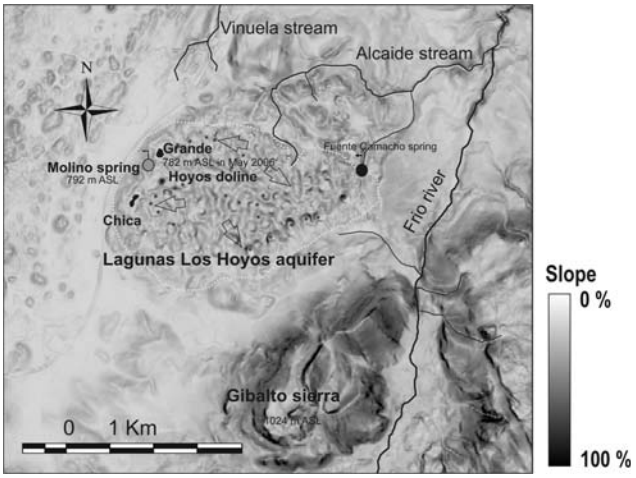


Fig. 2 Slope map of the Lagunas-Los Hoyos aquifer. *Arrows* indicate main groundwater flow directions. Slope (0% = flat, 100% = 1:1)

Data acquisition

Sampling surveys from 1997 to 1999, which was an exceptionally humid period, were undertaken every 3 months and sporadically until May 2006. Subsequent morphological surveys were made occasionally from 2000 to 2006. Littoral water samples were taken at a distance of 4 m from the shore. Pelagic water samples were taken at the centre of both lakes, where a fixed buoy was installed (Fig. 1b). A 15-thermistor chain was attached to the buoy, in order to obtain bihourly temperature data from the water column from July 1998 to January 1999. Depth profilings of lake chemistry were undertaken in August 1998 and March 1999. The bathymetry of the lakes was elaborated using a depth probe. Groundwater samples were collected from the Molino spring and the Hoyos doline (Fig. 1b).

Major ions, nitrates, total ammonia, total nitrogen, total phosphorus and orthophosphate were measured using ion chromatography and spectrophotometry techniques, at the Water Research Institute (University of Granada). Stable isotopes of oxygen and hydrogen (i.e. ^{18}O and D) were measured at the Lake Grande and Molino spring. Analysis was made using the CO_2 equilibration technique (Epstein and Mayeda 1953) in the Zaidin Stable Isotope Laboratory (CSIC). Hydrogen was prepared from 1 to 5 µl samples by reduction over Zn at 550°C (Tanweer et al. 1988). Analytical uncertainties were 0.2‰ for δ^{18}O and 1‰ for δ^{2}H.

GIS was employed to determine flooded surface and watershed characteristics; several hydro-morphological surveys were undertaken to check the results obtained. The Archidona weather station (see Table 1 for details) was selected to obtain monthly averages of precipitation (mm), air temperature (°C) and potential evapotranspiration (mm). These data are public and accessible through a link from the Spanish Ministry of Agriculture Fisheries and Food web-page (www.mapa.es). Daily evaporation was obtained from a "Class A" evaporation tank located at Fuente de Piedra weather station.

Data analysis

Analyses of the data acquired were carried out in order to establish the typology of the lakes studied, in accordance with the recommendations of both the Andalusian Ministry of Environment and of WFD guidelines. Three main tools were employed in developing the typologies:

Table 1 Morphometric characteristics of the lakes and climatic conditions in the study area

Lake	MFS (km^2)	AFS (km^2)	Watershed (km^2)	W/AFS	Max. length (m)	Max. depth (m)	Max. volume ($m^3 \times 10^5$)	W/M. vol. (m^{-1})	Average slope w/shed (%)
Grande	0.09	0.06	0.14	2.33	455	13.20	5.68	0.90	17.39
Chica	0.10	0.07	0.31	4.43	525	8.30	2.29	1.56	16.01

Name	Province	Altitude (m ASL)	Years rainf.	Initial year	End year	Years temp.	Initial year	End year
Archidona	Málaga	700	36	1961	1996	23	1974	1996

Archidona	O	N	D	J	F	M	A	M	J	J	A	S	Total
Precipitation (mm)	60	91	90	79	81	61	58	35	21	5	5	28	614
Temperature (°C)	15.6	11.8	8.7	7.4	8.9	11.4	13.0	17.0	22.1	26.2	25.7	22.1	15.9
PET (mm)	60.1	29.6	17.6	13.9	18.4	34.2	44.8	77.9	120.8	163.3	149.3	102.9	832.8
Evaporation (mm)	90.8	58.6	38.1	40.5	54.9	83.6	89.9	115.4	178.4	218.6	201.6	151.1	1321.5
Water holding capacity (mm)	0	61.4	100	100	100	100	100	57.1	0	0	0	0	
AET (mm)	60	29.6	17.6	13.9	18.4	34.2	44.8	77.9	78.1	5	5	28	412.5
Surplus (mm)	0	0	33.8	65.1	62.6	26.8	13.2	0	0	0	0	0	201.5

PET potential evapotranspiration, *AET* actual evapotranspiration

- basin-scale morphometric analysis;
- a simple water budget model within the lakes;
- hydrogeological interpretation of hydrochemical and isotopic data.

Bathymetric data were processed in Surfer© and several morphometric elements were obtained, namely maximum water flooded surface (MFS), average flooded surface (AFS), maximum length, mean width, maximum width, mean depth, maximum depth, shoreline length, shoreline development and volume (Table 1). Morphometric analysis of the watershed was carried out using a Digital Terrain Model developed by the Andalusian Ministry of the Environment (AME 2005).

As commented above, a lake water budget model was developed for this study. In any water body (reservoir, lake or aquifer) the equation of the water budget is expressed as:

$$\Delta V = P - E + S_i - S_o + G_i - G_o \qquad (1)$$

In the present case, certain clarifications should be noted: $\Delta V(L/T)$ is the change in lake storage (i.e. water level). For average conditions, this component may not change on an annual scale, but significant variations may be expected on a monthly scale. In this study, ΔV is the result we obtained from the water budget model. Thus, validation of the model can be accomplished by comparing the model's results with the time series of the water level of the lakes. The components of Eq. 1 are expressed in L^3 and the result is then transformed into L to obtain a value for the evolution of the water level. P (direct precipitation) is estimated by multiplying $P(L)$ by the averaged flooded area at each time interval to obtain $P(L^3)$. E (evaporation from the flooded surface) is estimated from evaporation data (L), corrected and multiplied by the averaged flooded surface to obtain $E(L^3)$. To estimate S_i (surface water inflow or surface run-off) and G_i (sub-surface water inflow or groundwater input), a soil-water budget in the watershed was made (Jensen et al. 1990), assuming 100 mm water holding capacity (Table 1). The soil-water budget is a simple accounting scheme used to predict soil-water storage, evapotranspiration and water surplus. Surplus is the fraction of precipitation that exceeds potential evapotranspiration, calculated by the Thornthwaite method (Thornthwaite and Mather 1955), and is not stored in the soil. The simple model used here does not distinguish between surface and sub-surface run-off, so surplus includes both. For this study, the main purpose of calculating the soil-water budget was to estimate surplus, which serves as input to sub-surface run-off and surface water inflow to the lakes. As the lakes are terminal, S_o is zero. G_o is groundwater output (recharge) from the lakes to the Lagunas-Los Hoyos aquifer. This term is not computed in the equation because it is assumed that negligible groundwater recharge from the lakes will occur in this kind of dryland wetlands. Likewise, no regional groundwater discharge from the aquifer to the lakes is expected to occur a priori. This assumption has major hydrogeologic and management implications. Low hydraulic conductivity of the materials in the study area and the lack of hydrogeologic devices such as piezometers, or open wells make it difficult to measure such components.

If the evolution of the water level in the lake is similar to that observed in the field, then it is assumed that the water budget is correct. In that situation, the only water inputs to the lake are P and $S_{\mathrm{i}} + G_{\mathrm{i}}$. If regional groundwater discharge or hydrological alterations of the watershed such as drainages take place, then the result would not fit the average evolution of the water level observed in the lake. This methodology is validated by successful previous applications of the water budget model in other Andalusian wetlands which have been undertaken recently (Benavente et al. 2006a, b).

Hydrochemical characterization of surface and groundwater in the study area (see Fig. 1b) was assessed. Additionally, isotopic analyses in Lake Grande and the Molino spring were undertaken. The origin and evaporative processes of natural waters can be determined by the study of the relations of stable isotopes of oxygen and hydrogen (Zimmermann 1979). These isotopes, usually employed as tracers in hydrogeology, are expressed as ratios from the heavier to the lighter one relative to the Standard Mean Ocean Water (R_{SMOW}) and reported in the δ notation in ‰.

Establishing typologies

After analysis, the hydrological interpretation of the acquired data was applied in order to establish a typology of the studied systems. The high structural and functional heterogeneity of the Andalusian wetlands justifies the establishment of a classification system that uses various geomorphologic and hydrological indicators (Montes et al. 2004). Moreover, in the case of wetlands, the justification for using various optional factors is greater, since the obligatory factors in the WFD (latitude, longitude, distance from source and surface area) were developed for a fluvial-type water body classification typology. The correct management of a wetland cannot take place without a precise knowledge of the hydro-morphological elements that determine its hydrological functioning.

Choosing hydro-morphological factors to establish a lake typology does not mean that biological indicators are ignored. In fact, the typology proposed in this study provides enough information to explain the existence and abundance of many biological taxocenoses. Selecting a hydrological system of classification is useful as it properly synthesizes the characteristics of the water body. This system considers a basin-range perspective, as recommended in the WFD (WFD-CIS No. 2 2002).

The climatic regime, as well as the lithology and topography of the watershed, determines the typology of any given water body. At the same time, it determines the distribution of surface and groundwater and the type of soils and vegetation.

The hydrological components of the typology have been grouped into five factors: the water input route, the drainage (water output) route, length of the wet period, renewal rate and hydrochemistry. Table 2 sets out the hydrologic factors that were established.

Results and discussion

The morphological components of the lakes studied are shown in Table 1. Note that the lake area is expressed as the AFS, in km^2, since the flooded area shrinks in summer due to high evaporation rates, leading to the desiccation of the lake. This is not the case of Lake Grande, a permanent water body, but in the case of Lake Chica, total desiccation could occur

Table 2 Hydrological factors and typology of the Andalusian wetlands (after Montes et al. 2004)

Classification level	Level 1	Level 2
Water input route	Epigenic domination of surface water inputs from the watershed	Meteoric waterSurface run-offSub-surface water
	Hypogenic domination of groundwater flows	Unconfined aquiferConfined aquiferLocal or regional size
	Mixed	Both routes of water input
Drainage route	Open drainage	Surface run-offInfiltration
	Closed drainage	Evapotranspiration
Length of wet period	Permanent no fluctuating	Anthropogenic (in semi-arid climates)
	Permanent fluctuating	Normally mixed
	Seasonal	Indicate periodicity
	Intermittent	
Renewable rate	High	Indicate water volume implicated in the balance
	Medium	
	Low	
Hydrochemistry	Salinity	Hydrochemical facies

during exceptionally long periods of drought. Lakes and playa-lakes in drylands are normally small (Williams 1999); in the Antequera region, average AFS for wetlands is 1.08 km^2 (Rodríguez-Rodríguez 2002). The areas of Lake Grande and Lake Chica are 0.059 and 0.068 km^2, respectively, hence they can be considered small even for a dryland with a semi-arid climate such as southern Spain. The lakes are situated at a similar altitude (Lake Grande, 789 m ASL; Lake Chica, 787 m ASL) their watersheds being relatively small (Lake Grande: 0.14 km^2; Lake Chica: 0.31 km^2). The average slopes of the watershed are 17.4 and 16.0%, respectively. These values contrast with those measured in other playa-lakes in the Antequera region, which range from 4 to 8%. For example, Fuente de Piedra playa-lake, an extensive salt-lake located to the west of the systems studied (see Fig. 1a) has an average slope of 5.4%. Maximum length, perimeter and other morphological components are similar in both lakes, with differences of less than 15% (Table 1). A morphological index that has been found useful in the determination of a lake typology is the relation *W*/AFS (see Table 1). In a similar way, Schindler's ratio (*W*/*V*) has proved useful for typology purposes in other European lakes (Kolada et al. 2005). In a terminal lake environment under the same average climatic conditions *W*/AFS varies slightly, since (assuming negligible groundwater discharge) the evaporation from the AFS must equal water inputs (surplus) from the watershed (*W*). In the case being studied, the surplus from the soil-water budget amounts to 201 mm/year and the annual evaporation (*E*) is 1,321 mm/year (Table 4). A simple *E*/Surplus operation gives a result of 6.57, which is considerably higher than the AFS/*W* values for the lakes studied, as shown in Table 1.

Maximum depths, measured after a 3-year wet period that concluded in 1997, were 13.2 m for Lake Grande and 8.3 m for Lake Chica, this being one of the deepest natural lake systems in southern Spain (Montes et al. 2004). In order to illustrate the morphology of the lake's basins, bathymetric maps and 3D views of the lakes are shown in Fig. 3. Examination of such maps and the geomorphology of the area suggest that the origin of Lake Chica corresponds to the coalescence of two dolines of different sizes (uvala). Figure 4a shows topographic profiles in the study area. Both lakes are located near a contact between karst evaporites and Triassic marls that constitute the impermeable sealing of the aquifer. This contact is situated at an altitude of approximately 800 m ASL. During recent field surveys (May 2006), it was observed that the position of the Molino spring (792 m ASL) is several metres above the altitude of the water surface in Lake Grande (782 m ASL, May 2006). This hydrogeological setting implies that the lakes could be confining the aquifer in that sector, since the Triassic marls are fairly impervious (see Fig. 4b). In that situation, one might expect some groundwater discharge through the semi-permeable lake bottom sediments. Water salinities in the Molino spring (3.05 mS/cm) and in Lake Grande (4.93 mS/cm) are similar, and so evaporative concentration in the lake may have been produced from a mixture of run-off water (low salinity) and groundwater.

The relative abundances of the different classes and functional groups of zooplankton in the lakes are similar. The dominant sub-class of crustaceans in both lakes is copepoda, most of them in the adult stage. The sub-class ostracoda is more abundant in Lake Grande and the number of cladocerans is similar in the two lakes.

The population dynamics of the different taxonomic groups show an inverse relation between sub-class cladocera and rotifers in Lake Grande. In Lake Chica, *Diaphanosoma* appears in summer; all the groups have similar population dynamics to those observed in Lake Grande.

Differences in the thermal structure and the vertical distribution of the salinity within the lakes are notable. Lake Grande can be classified as a monomictic lake, with a mixing period lasting from September to February. In the summer, a thermocline was found to develop at a depth of 6 m. The stability of the water column reached values of 2.5×10^{-6} kg m^3. Electrical conductivity in the water column of Lake Grande remained constant throughout the year.

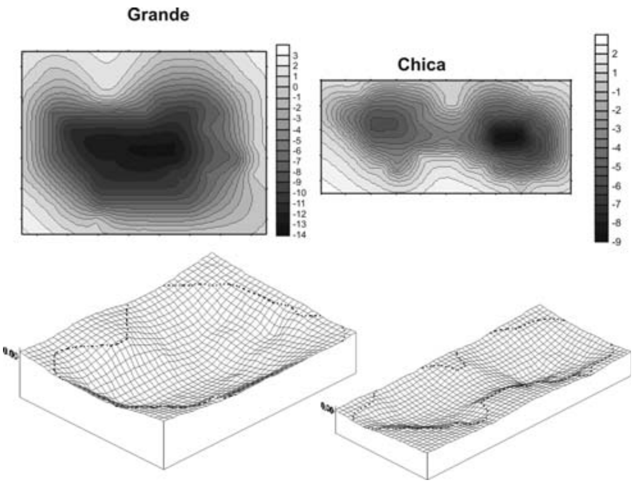


Fig. 3 Bathymetry and 3D diagrams of Lake Grande and Lake Chica

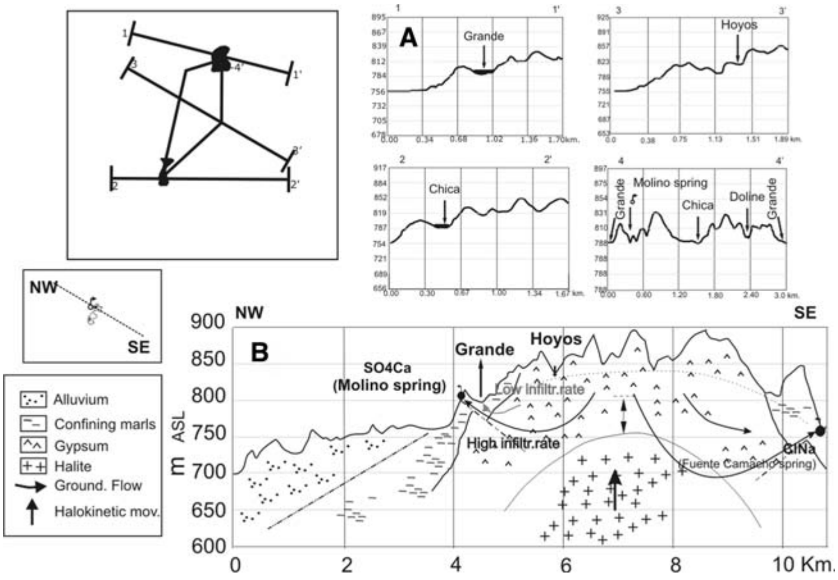


Fig. 4 **a** Topographic profiles in the study area. **b** Hydrogeological scheme of Lake Grande and Lake Chica (real NW–SE cross-section)

In Lake Chica, the electrical conductivity of the water column increased at a depth of 6 m, such that two density layers could be distinguished. This situation remained unchanged throughout the year in the central part of the lake. Hence, the lake can be classified as meromictic (i.e. it is a lake whose waters are permanently stratified and do not circulate completely), due to the existence of a deep dense strata of saline water and a shallow brackish-water layer separated by a chemocline. The increase in temperature that is detected in the monimolimnion must be due to physical and biological processes such as solar radiation absorption and the anaerobic decay of organic matter, respectively.

The cations calcium and potassium have similar concentrations in both water bodies, the only exception being the monimolimnion of Lake Chica, see Table 3.

Sodium and chloride concentrations are significantly higher in the mixolimnion of Lake Chica than in the epilimnion of Lake Grande, whereas magnesium concentration is similar. In the monimolimnion, the concentration of ammonium is high, confirming the prevalence of reduction processes. In addition, the presence of nitrates is scarce. Previous studies in meromictic lakes have shown that the differences between the chemistry of mixolimnion and monimolimnion exhibit similar patterns to that observed in Lake Chica (Cloern et al. 1983).

Results from the water budget model, expressed in dam^3 (i.e. m^3 × 10^3), can be observed in Table 4. The evolution of the theoretical water level (WL) obtained presents a reasonable fit to that observed in the field on a monthly scale. However, an annual diminution of the WL of 41.7 and 1.1 cm for average conditions is forecasted for Lake Grande and Lake Chica, respectively (Fig. 5). Water deficits of 25×10^3 and 8.2×10^3 m^3 were obtained for the two lakes. These results indicate that regional groundwater discharge could be expected in these systems; otherwise, results from the water budget imbalance would be negligible on an annual

Table 3 Physical and chemical characteristics in Lake Grande and Lake Chica (August 1998)

Chica	Mixolimnion	Monimolimnion	Grande	Epilimnion	Hypolimnion
pH	7.9	7.7	pH	8.3	7.7
E.C. (μS/cm)	4,140	7,830	E.C. (μS/cm)	3,200	3,280
Na^+	340	644	Na^+	116	124
K^+	2.9	180.0	K^+	8.9	10.3
Mg^{2+}	116	373	Mg^{2+}	112	114
Ca^{2+}	463	383	Ca^{2+}	458	511
Cl^-	466	919	Cl^-	183	195
SO_4^{2-}	1,475	2,036	SO_4^{2-}	1,550	1,586
HCO_3^-	96	445	HCO_3^-	67	192
NH_4^+	0.01	3.60	NH_4^+	0.02	1.47
NO_3^-	3.30	1.80	NO_3^-	2.28	2.13
Salinity	2,958	4,981	Salinity	2,494	2,730

Data in ppm, unless otherwise specified

Table 4 Results from the water budget model

	P (dam^3)	$S_i + G_i$ (dam^3)	E (dam^3)	SH (dam^3)	ΔV (mm)	WL (m ASL)
Grande						
O	3.6	0.0	5.4	6.0	–30.8	788.969
N	5.5	0.0	3.5	6.0	32.4	789.002
D	5.4	2.9	2.3	6.0	100.7	789.102
J	4.7	5.6	2.4	6.0	132.6	789.235
F	4.9	5.4	3.3	6.0	116.6	789.351
M	3.7	2.3	5.0	6.0	16.1	789.368
A	3.5	1.1	5.4	6.0	–12.8	789.355
M	2.1	0.0	6.9	6.0	–80.4	789.274
J	1.3	0.0	10.7	6.0	–157.4	789.117
J	0.3	0.0	13.1	6.0	–213.6	788.903
A	0.3	0.0	12.1	6.0	–196.6	788.707
S	1.7	0.0	9.1	6.0	–123.1	788.584
Total	36.8	17.5	79.3			
Chica						
O	4.7	0.0	7.1	7.8	–3.1	787.997
N	7.1	0.0	4.6	7.8	3.2	788.003
D	7.0	7.9	3.0	7.8	15.3	788.015
J	6.2	15.2	3.2	7.8	23.3	788.023
F	6.3	14.6	4.3	7.8	21.3	788.021
M	4.8	6.2	6.5	7.8	5.7	788.006
A	4.5	3.1	7.0	7.8	0.8	788.001
M	2.7	0.0	9.0	7.8	–8.0	787.992
J	1.6	0.0	13.9	7.8	–15.7	787.984
J	0.4	0.0	17.1	7.8	–21.4	787.979
A	0.4	0.0	15.7	7.8	–19.7	787.980
S	2.2	0.0	11.8	7.8	–12.3	787.988
Total	47.9	46.9	103.1			

P direct precipitation, $S_i + G_i$ surface and sub-surface run-off, *E* Evaporation, *SH* soil humidity, ΔV volume increment, *WL* water level, *dam*^{3} m^3 × 10^3

scale. *W*/AFS computations (2.33 and 4.43) from Table 1 are in accordance with these results. If *P* and run-off ($S_i + G_i$) were the only water inputs into the lakes, the *W*/AFS index would be nearer to 6.57 (*E*/Surplus), as remarked above.

In Fig. 6, values of δ^{18}O and δD (‰) measured in the Molino spring and Lake Grande were plotted, together with other isotopic data taken from other playa-lakes in the Antequera region (Rodríguez-Rodríguez et al. 2006). The global meteoric water line, GMWL (Craig and Gordon 1965) and the local meteoric water line, LMWL (Almécija 1997) are also shown. Stable isotopes of oxygen and hydrogen are shown as ratios from the heavier to the lighter one, relative to the Standard Mean Ocean Water (R_{SMOW}). In meteoric water analyses measured worldwide, R_{SMOW} fits a straight line on a δ^{18}O–δD plot. This line is called the GMWL and its equation is $\delta D = 8\delta^{18}\mathrm{O} + 10‰$. During evaporative enrichment of water, water vapour has a reciprocal depletion in both isotopes and plots on the same evaporative line, but on the left side of the GMWL. Thus there could exist a LMWL in different regions. If sequential samples were taken from different water reservoirs, namely water from wells, springs or lakes, different evaporative lines could be determined. Back extrapolation along these lines to the origin on the LMWL would show the initial isotopic composition. Additionally, isotopic enrichment values would give an idea of the rate of evaporation from any given water body and of surface–groundwater relations. Isotope analyses from water samples in other playa-lakes and groundwaters from piezometers in the Antequera region show, with some dispersement, a uniform alignment. The deviation in the slope with respect to the LMWL in these temporary playa-lakes is caused by the process of isotopic fractioning by evaporation of the surface water, since the lakes are flooded, in October–November, until their drying at the end of the summer. The water input takes place mainly by surface or subsurface run-off. The isotopic division is subsequent to the recharge of the playa-lakes: they are therefore epigenetic lakes according to the hydrological regime.

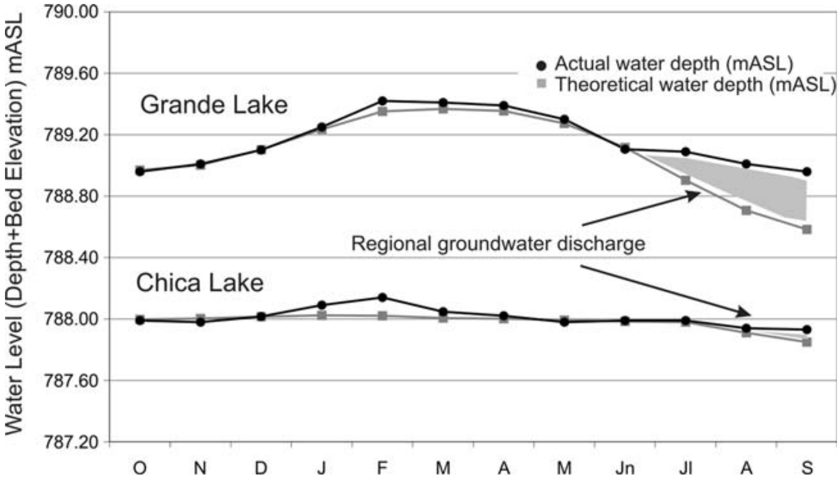


Fig. 5 Evolution of the theoretical and actual water level (mm) in the lakes studied at a monthly scale

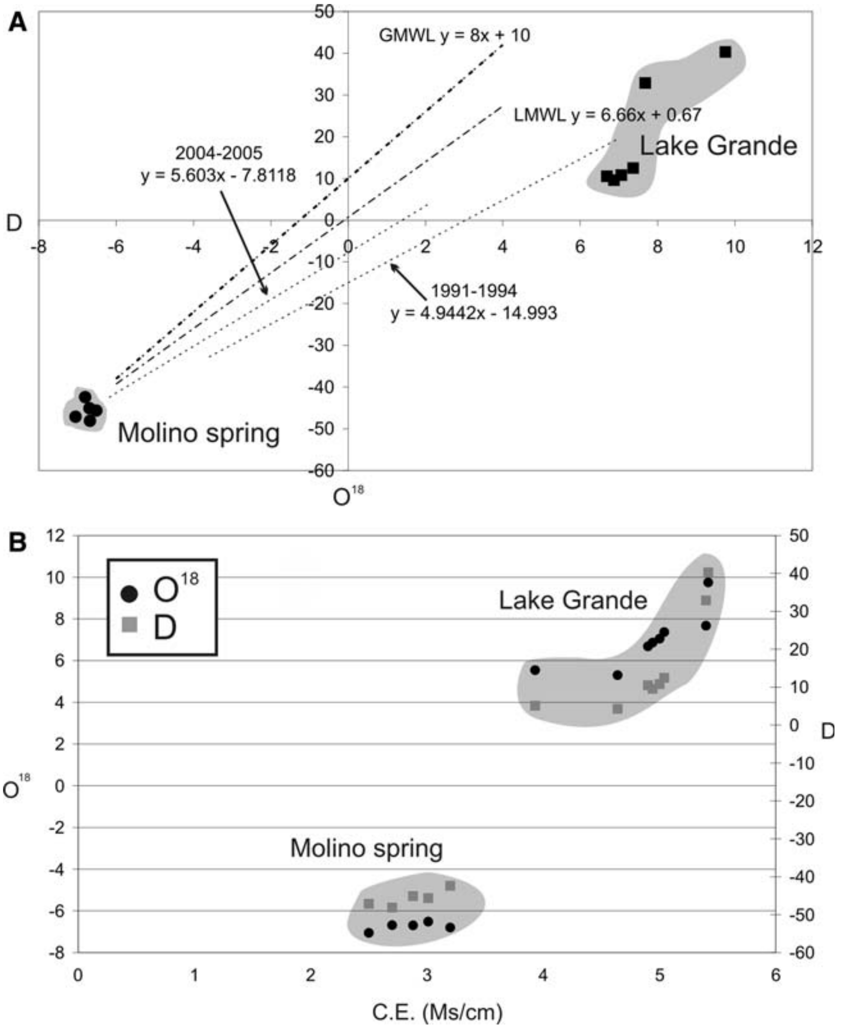
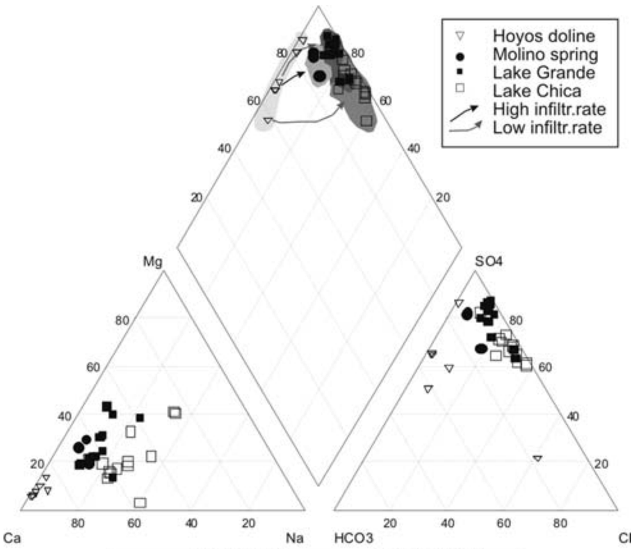


Fig. 6 **a** Isotopic results on a ^{18}O–D plot of Molino spring and Lake Grande, together with other ephemeral playa-lakes in the Antequera region (modified from Rodríguez-Rodríguez et al. 2006). **b** E.C.-^{18}O and D plot in Lake Grande and Molino spring

Results from the Molino spring provide a reasonable fit to the layout of the meteoric lines (GMWL and LMWL). Greater isotopic concentrations have been measured in the water of Lake Grande, with a maximum in September 1994 (δ^{18}O = 9.75 and δD = 40.3‰). The data are grouped at the upper end of the LMWL. The water in this lake must have undergone more intense isotopic division. This implies a longer average residence time of the water in the lake. Results derived from the analysis of the isotopic data at the study site suggest a hydrological functioning in which Lake Grande receives groundwater discharge from the karstic aquifer, which implies that the Molino spring must partially drain such an aquifer, as is shown by its isotopic content, which is similar to that of meteoric water. These aquifers may have a relatively high infiltration rate due to the existence of numerous dolines and, consequently, the water does not undergo any significant evaporation processes.

Figure 7 includes a Piper diagram showing hydrochemical data and a summary of some statistics in the system studied. The probable hydrochemical path proposed is as follows: rainwater percolating through the dolines rapidly dissolves gypsum even in the unsaturated zone. High infiltration rates and preferential flow paths through fractures and faults change the water chemistry slightly on their way to the main discharge areas (Molino spring, see Fig. 4). Low infiltration rates into the lakes through confining marls and clays, and subsequent evaporative enrichment, change the hydrochemical composition of the water in both Lake Grande and Lake Chica.

Additionally, karstic aquifers are fairly compartmentalized, and so the Molino spring and Lake Grande may be hydrogeologically disconnected. Isotopic marking and hydrogeochemistry partly validate this hypothesis, although this assumption remains to be confirmed in subsequent investigations.



	HOYOS DOLINE				MOLINO SPRING			
	Min	Max	Average	St. Dev.	Min	Max	Average	St. Dev.
Na	4.0	11.1	**6.2**	2.6	70.0	152.5	**110.8**	47.0
Ca	159.0	598.0	**321.5**	176.0	502.0	646.0	**597.2**	65.0
Mg	8.9	22.0	**16.5**	5.6	114.4	147.0	**130.6**	17.8
Cl	7.0	550.0	**111.8**	215.9	77.0	196.7	**134.0**	66.0
SO4	182.1	1356.0	**530.0**	424.6	973.6	1603.0	**1287.5**	343.0
TDS	608.2	2210.3	**1240.3**	609.1	2361.9	2795.9	**2509.7**	199.5

	LAKE GRANDE				LAKE CHICA			
	Min	Max	Average	St. Dev.	Min	Max	Average	St. Dev.
Na	89.0	284.0	**151.1**	58.4	127.0	1145.1	**399.9**	316.7
Ca	210.0	903.9	**576.3**	173.8	375.0	788.5	**566.1**	107.6
Mg	78.0	396.0	**167.5**	106.1	20.0	766.5	**197.9**	230.6
Cl	144.0	840.0	**270.0**	208.2	220.0	1941.6	**625.6**	511.9
SO4	936.0	2979.0	**1880.0**	618.6	1013.0	4386.3	**1967.5**	956.1
TDS	1722.0	4299.0	**2780.5**	725.9	2248.0	4061.0	**3109.9**	517.9

Fig. 7 Piper diagram and summary of the basic statistics in the system studied. The number of Piper samples represented is in agreement with the statistics results shown below (data acquired from 1997 to 2006)

Classification of the investigated lakes

The interpretation of the results obtained enables us to classify the lakes according to the typologies established by the Andalusian Ministry of Environment (Montes et al. 2004) and suggested in the WFD (WFD-CIS No. 12 2003) and also to determine pressures and impacts affecting these ecosystems (Table 5). Water budget results show that the water input takes place mainly by surface and sub-surface run-off and also by groundwater discharge from the Lagunas-Los Hoyos aquifer. Therefore, according to the water input route, both Lake Grande and Lake Chica could be classified as mixed. Drainage takes place by evapotranspiration, this assumption being confirmed by isotope analysis. The length of the wet period ranges from 6 to 8 months for the majority of the playa-lakes in Andalusia (Benavente et al. 2006a, b; Carrasco et al. 2004; Montes et al. 2004), due to the semi-arid climatological conditions. In the case under study, Lake Grande is a permanent fluctuating water body and Lake Chica is semi-permanent, displaying a low renewable rate. This peculiarity could be explained by the water input route and the morphology of the basin. The slopes of the watersheds and the lake basins are considerably higher than in other Andalusian playa-lakes, as commented before. Water samples from the lakes and groundwater reveal a mixture of cations and sulphate types, due to the aridity of the climate and the lithology of the watersheds. Hydro-morphological surveys have proved useful in establishing water body pressures and impacts. The principal pressures affecting Lake Grande and Lake Chica are derived from agricultural management and the addition of fertilizers and pesticides. Water pumping from the Lagunas-Los Hoyos aquifer must be controlled in order to reduce the risk of shortening the wet period and AFS. Furthermore, the scarcity of permanent water bodies in Andalusia means there is a need for long-term monitoring of hydrogeological indicators (water level, hydrochemistry, etc.) both in the aquifer and in the lakes.

Concluding remarks

Several authors have pointed out the interconnected nature of the hydrological and hydrochemical processes occurring in wetlands and the significance of morphological analyses of their watersheds (Cech 2003; Cruz-Sanjulián and Benavente 1996; Kolada et al. 2005; Maltby 1986; Mitsh and Gosselink 1993; Vincent et al. 2002; Wetzel and Likens 1991; WFD-CIS No. 12 2003; Williams 1999). The conflicts and constraints arising in the management of wetlands require

Table 5 Typology, physico-chemical conditions and pressure/impact assessment in Lake Grande and Lake Chica

	Classification					Pressure/impact assessment				
	Input route	Drainage	Length wet period	Renewal rate	Hydrochemistry	Nutrients	Ground. abs.	Drainage	Global pressure	Impact assessment
Grande	Mixed	Closed	Permanent fluct.	Low	SO_4–Ca	M	W	W	Low	Not apparent
Chica	Mixed	Closed	Semi-permanent	Medium	SO_4–Ca	M	W	W	Low	Not apparent

M moderate, *W* without; *fluct.* fluctuating us to have an accurate understanding of their hydrological functioning; the use of limnological and hydrogeological tools could contribute to such an understanding (Cruz-Sanjulián and Benavente 1996). By the end of 2015, all water bodies, including wetlands, must achieve good ecological status, this year marking the deadline established by the WFD for environmental objectives to be met (WFD, Art. 4). If this objective is to be achieved, there must be systematic hydrological studies in such water bodies and typologies must be developed.

In the present contribution, well-known hydrological and hydro-morphological tools, together with a new methodological approach on water budget methodologies, were applied to classify two small water bodies in southern Spain. It is hoped that this study might serve as a case study for Basin District Managers over a wider area. Furthermore, this general approach can complement the methods used in integrated catchment management processes. In the future, it will be necessary to verify and complete this methodology using biological elements in the framework of the European Water Directive.

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