LIMNOLOGICAL CHARACTERIZATION OF AN EVAPORITE KARSTIC LAKE IN SPAIN (LAKE ARREO)

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RESUMEN

El lago de Arreo es el cuerpo de agua más profundo sobre sustrato evaporitico de la Peninsula Ibérica. En este estudio se presentan los aspectos básicos de la morfometria y las caracteristicas físicas y quimicas del ciclo anual 1993-94. La morfometria indica una forma del lago, según la terminologia de Håkanson (1981), de tipo Vcx-Cmi, dominando las zonas poco profundas. Un subsistema palustre se extiende sobre 2/3 de la superficie del lago. Desde el punto de vista quimico el lago *es* subsalino y de composición Ca-(Mg)-(Na)-SO_4-HCO_3-(Cl). Las aguas subterráneas ejercen una gran influencia. Los dos periodos de estratificación estudiados muestran, entre sí, claras diferencias de conductividad, nutrientes y concentraciones iónicas en los diferentes compartimentos del lago. El lago present6 holomixis en el periodo de estudio, pero con una mezcla invernal muy breve, indicando una tendencia hacia la meromixis.

Palabras clave: lago de Arreo, lago subsalino, lago karstico evaporitico.

ABSTRACT

Lake Arreo is the deepest water body on evaporite rocks in the Iberian Peninsula. Morphometry and a physical and chemical cycle were studied in 1993-94. Morphometry corresponds to a Vcx-Cmi lake form (after symbols of Håkanson (1981)), dominated by shallow regions. A palustrine subsystem extends over 2/3 of lake surface. Chemically, the lake is subsaline Ca-(Mg)-(Na)-SO_4-HCO_3-(Cl). Subterranean waters have a strong influence on the lake. The two periods of stratification studied revealed clear differences in conductivity, nutrients and ionic concentration in the different compartments of the lake. The lake was holomictic in the period studied, but with a very brief complete mixis in winter; indicating a tendency towards meromixis.

Key words: lake Arreo, subsaline lake, evaporite karstic lake.

INTRODUCTION

Spain has a rich and varied assortment of lakes that are currently the object of scientific attention (Montes & Duarte, 1992). Nevertheless, our knowledge of Spanish water bodies that originate on evaporite rocks is scant, perhaps due to their rarity and small size.

On the other hand, the scarcity of these aquatic systems gives them great environmental value due to their genetic singularity. This study provides basic data on the main Iberian aquatic system of this type.

STUDY AREA AND METHODS

Lake Arreo is situated in the Basque Country (North of Spain), co-ordinates UTM 30TWN0036, in the basin of the Ebro river, at an altitude of 655 m.a.s.l. It is bordered by cultivated land and mediterranean forest.

Climate is transitional between oceanic and mediterranean. January is the coldest month, with an average temperature of 4.7 °C, and July the warmest, with an average temperature of 19.8 °C. Annual average precipitation is approximately 670 mm. November is the wettest month, with an average precipitation of 82.45 mm.

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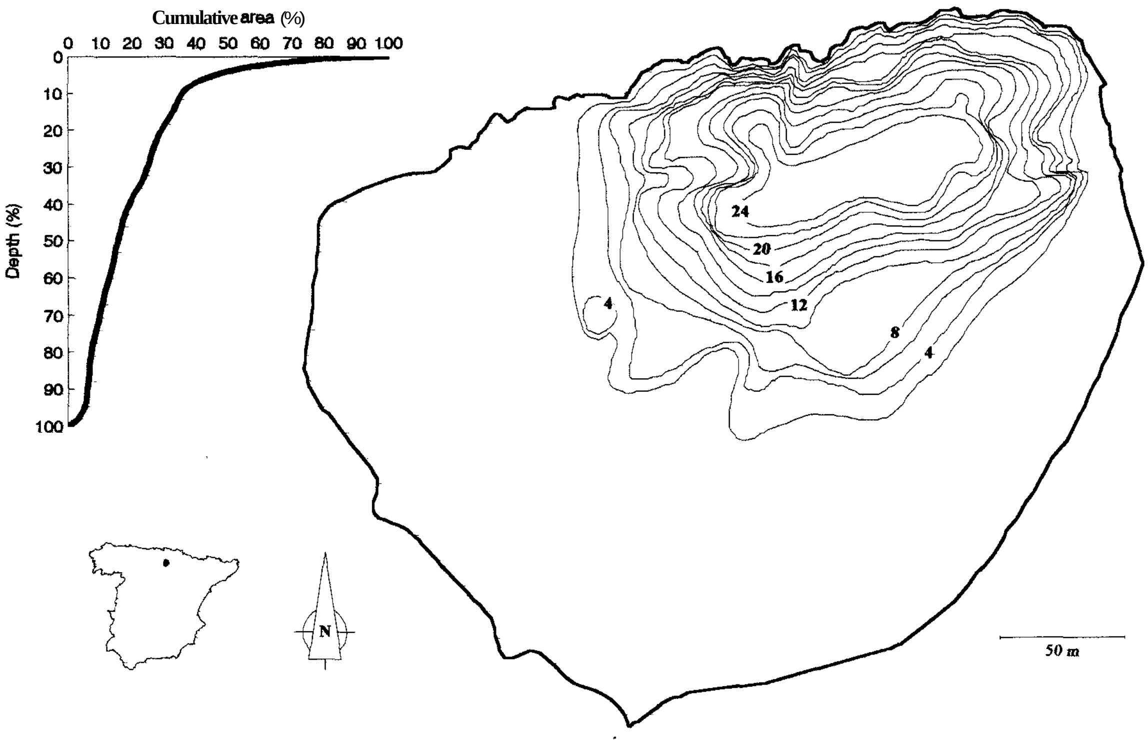

Figure 1. Bathymetric map and relative hypsographic curve of lake Arreo. *Mapa batimétrico y curva hipsográfica relativa del lago de Arreo (S: punto de muestreo).*

A small stream, the Arroyo del Lago, flows into the lake from the East and outflows to the West, where it meets the Ebro river.

Lake Arreo is the deepest water body on evaporite rocks in the Iberian Peninsula. Its basin was formed by dissolved evaporites of the diapir of Salinas de Añana, the salted chimney that outcrops in higher formations by gravitational tectonics in North Spain (Ríos, 1963).

Monthly sampling was carried out from 9 September 1993 to 25 August 1994. Samples were taken at the point of maximum depth, in the inflowing and outflowing streams, and in a subterranean spring situated 50 m from the lake.

Temperature, conductivity (at 25 °C) and oxygen concentration were measured at 1 m intervals with WTW instruments. Water samples were collected in Kemmeler type bottles. Hydrochemistry was measured according to **APHA** (1986) (titration for alkalinity, hardness and calcium; argentometric method for chloride; ultraviolet spectrophotometric screening for nitrate; colorirnetric method for nitrite; ascorbic acid method for soluble reactive phosphorus; molybdosilicate method for total reactive silica). **A** colorimetric method was used following Golterman & De Graff Bierbrauwer-Wiirtz (1992) to measure sulfate. An Orion EA940 expandable ion analyzer with a selective electrode was used to measure potassium (Orion 93-19 electrode), sodium (Orion 97-11 electrode) and ammonium (Orion 95-12 electrode).

Bathymetry was performed using a Furuno FE-4300 echo-sounder. Fourteen transects and numerous separate measures were made. The outline of the lake, in which we have reconstructed the echo-sounding profiles, was obtained from a 1:2000 scale aerial photograph. The morphometrical study follows Håkanson (1981).

RESULTS

Morphometry

The bathymetric map of lake Arreo, and the main morphometrical parameters are shown in figure 1 and Table 1, respectively. The lake has a single basin associated with the northeast zone. Depths greater than 24 m were found, although the lake has a preponderance of shallower zones. The greatest depths occur over a very small area of the lake. Steepest slopes are situated in the north and related to a fault. The lake is very convex in the upper part and concave in the bottom (Vcx-Cmi, using symbols of Håkanson, 1981). A more extensive morphometrical study has been reported by Rico *et al.* (1995).

Physicochemical characteristics of water

Physicochemical characteristics of lake Arreo are shown in figure 2 and Tables 2 and 3.

Temperature
The thermal stratification is highly stable. Thermocline only disappeared completely from the end of December to the beginning of March; a complete mix was only obtained during January and February. The minimum temperature registered was 4.6 "C in February, and the maximum was of 27.4 "C in August. The vertical temperature range was 22.1 "C between surface and bottom in the period of stratification. Maximum temperature gradient detected was 6.1 °C/m between 4 and 5 m depth in September.

Dissolved oxygen
Oxygen ranged from 5.8 mg/l to 12.4 mg/l at the surface, and from 0 mg/l to 3.7 mg/l at the bottom. The highest values, in August 1994, were 24.4 mg/l at -5 m. Anoxic conditions prevailed for much of the year in the deepest areas. Oxygen at the bottom was only detected for a short period of time.

pH
pH fluctuated around 8.0. Maximum and minimum were 8.20 and 7.57. The system was well buffered.

Conductivity
Conductivity ranged from 1307 µS/cm to 1608 µS/cm. Vertical variability showed clear differences over time. Average conductivity in the hypolimnion increased by 11.5% with respect to the epilimnion in the first period of stratification. A clear chemocline was found between -12 and -16 m, which moved to -20 m during the overturn period in January, and finally disappeared in February. This situation did not occur again in the second period of stratification, when the chemocline did not appear and average conductivity in the hypolimnion only increased by 3.2% with respect to the epilimnion.

Ionic concentrations
The ionic distribution in the lake was Ca^{2+}(63%)>Mg^{2+}(21.3%)>Na^{+}(15.3%)>K^{+}(0.4%) for cations, and SO_4^{2-}(50.9%)>HCO_3^{-}(30.4%)>Cl^{-}(18.7%) for anions. Carbonate was not found.

Ions accumulated in the hypolimnion during the first period of stratification. Calcium had an average value of 10.19 mEq/l. The greatest increases

Table 1. Morphometncal parameter values of lake Arreo (symbols **according** to Håkanson, 1981). *Valores de los parámetros morfométricos del lago de Arreo (simbología según Håkanson, 1981).*

Area	a	6.57 Ha
Shoreline length	l_o	1025 m
Shore development	F	1.13
Maximum length	L_{max}	338 m
Maximum width	$\underline{B}_{max}$	246 m
Mean width	B	194 m
Maximum depth	D_{max}	24.8 m
Mean depth	D	5.3 m
1st quartile depth	D_{25}	7.4 m
Median depth	D_{50}	1 m
3rd quartile depth	D_{75}	0.2 m
Relative depth	$\underline{D}_r$	8.57 %
Mean slope	α	19.21 %
Volume	V_p	0.35 hm3
Volume development	V_d	0.64
Direction of major axis		ENE-WSW
Lake form		VCx-Cmi

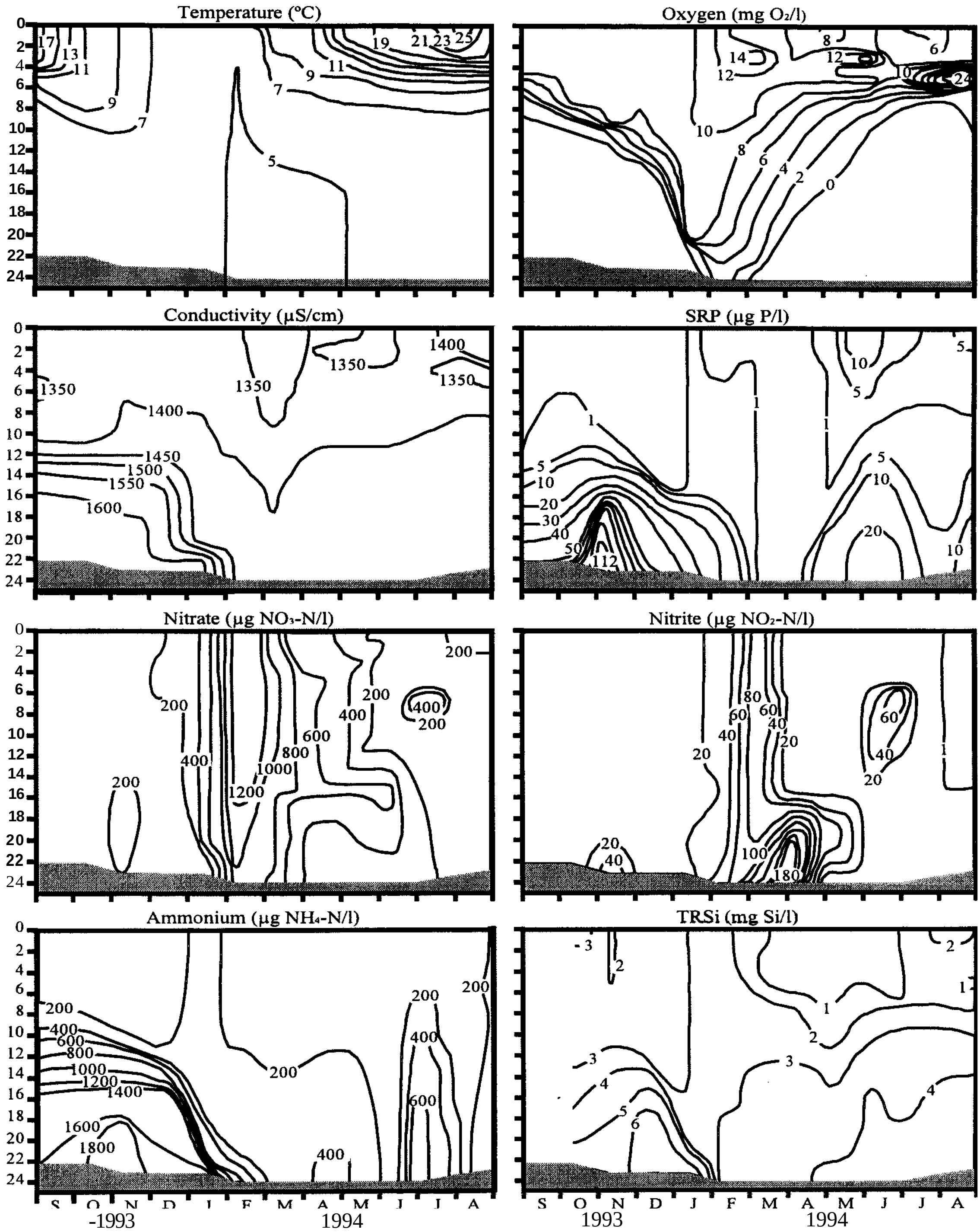

Figure 2. Depth-time distribution of physicochemical variables in **lake** Arreo during annual cycle 1993-94. *Distribución* ***projundidad-tiempo de las variables fisicoquímicas en el lago de Arreo durunte el ciclo anual 1993-94.***

Table 2. Mean values and standard deviations (given in parenthesis) of conductivity and major ionic concentrations of lake Arreo, associated stream, and spring. ***Valores medios y desviaciones estandar (entre paréntesis) de la conductividad y las concentraciones de iones mayoritarios del lago de Arreo, del arroyo asociado y del manantial.***

	Cond. (µS/cm)	Na^+ (mEq/l)	K^+ (mEq/l)	Ca^{2+} (mEq/l)	Mg^{2+} (mEq/l)	HCO_3^- (mEq/l)	SO_4^{2-} (mEq/l)	Cl^- (mEq/l)
LAKE								
First stratified period								
Epilimnion	1397	2.18	0.04	9.42	2.97	4.70	7.49	2.73
	(4)	(0.22)	(0.01)	(0.86)	(0.55)	(0.21)	(1.58)	(0.10)
Metalimnion	1386	2.25	0.05	9.55	3.27	4.86	6.55	2.72
	(43)	(0.18)	(0.01)	(1.03)	(0.38)	(0.22)	(0.92)	(0.18)
Hypolimnion	1558	2.65	0.05	10.19	3.85	5.02	7.18	3.16
	(74)	(0.32)	(0.01)	(0.90)	(0.68)	(0.19)	(1.16)	(0.35)
Second stratified period								
Epilimnion	1371	2.41	0.07	9.41	3.30	4.42	7.21	2.78
	(44)	(0.43)	(0.007)	(1.00)	(0.32)	(0.44)	(0.79)	(0.27)
Metalimnion	1370	2.38	0.06	9.43	3.22	4.13	7.21	2.70
	(27)	(0.30)	(0.007)	(0.26)	(0.42)	(0.38)	(1.40)	(0.14)
Hypolimnion	1415	2.31	0.06	9.60	3.20	4.47	7.46	2.75
	(28)	(0.28)	(0.007)	(0.32)	(0.41)	(0.39)	(0.78)	(0.22)
Both stratified periods								
Epilimnion	1387	2.27	0.05	9.42	3.10	4.59	7.37	2.75
	(30)	(0.33)	(0.01)	(0.84)	(0.49)	(0.34)	(1.28)	(0.18)
Metalimnion	1373	2.33	0.06	9.48	3.24	4.42	6.95	2.71
	(32)	(0.26)	(0.01)	(0.67)	(0.39)	(0.48)	(1.24)	(0.15)
Hypolimnion	1459	2.42	0.06	9.80	3.41	4.65	7.38	2.89
	(81)	(0.33)	(0.01)	(0.63)	(0.55)	(0.43)	(0.89)	(0.33)
Mixed period								
	1408	2.25	0.06	9.94	3.16	4.66	9.24	2.82
	(45)	(0.17)	(0.004)	(0.26)	(0.21)	(0.20)	(1.29)	(0.18)
STREAM								
Inflow	1240	0.71	0.05	9.81	3.31	5.19	7.08	0.90
	(85)	(0.09)	(0.01)	(1.09)	(0.69)	(0.75)	(0.96)	(0.12)
outflow	1344	1.87	0.06	9.10	3.31	4.53	7.73	2.34
	(20)	(0.30)	(0.01)	(0.79)	(0.75)	(0.61)	(1.03)	(0.35)
SPRING								
	8265	62.36	0.33	13.88	3.90	5.61	18.57	63.89
	(2112)	(18.62)	(0.05)	(4.45)	(1.50)	(0.63)	(9.81)	(19.96)

with respect to the epilimnion were in magnesium (29.6%), sodium (21.6%) and chloride (15.7%). Average values found in the hypolimnion were 3.85 mEq/l, 2.65 mEq/l, and 3.16 mEq/l, respectively. Such accumulation was not repeated in the second period of stratification. Sulfate concentration varied with anoxia conditions and the formation of sulfide; maximum values were found in the mixed period, when sulfide is not present, with an average value of 9.24 mEq/l.

The inflowing stream showed the same ionic distribution as the lake, but the proportions **of** chloride and sodium were lower (6.8% and 5.1%, respectively). These ions were dominant in the spring water (72.5% and 77.5%, respectively).

Sulfide

This element was not measured consistently over the whole year, but values higher than 250 µM were found.

Nutrients

The dynamics of soluble reactive phosphorus **(SRP)** is related to mixing and stratification **in** the

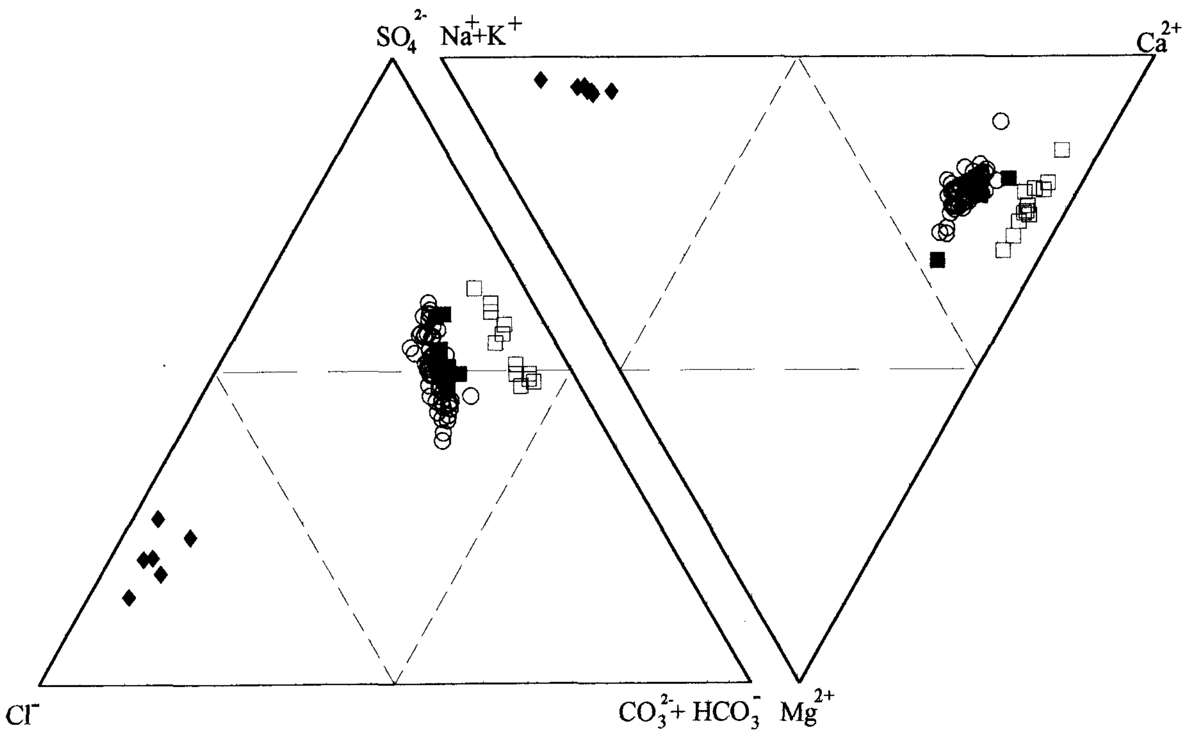

Figure 3. Relative anionic and cationic composition of samples in lake Arreo (circles), associated stream (inflow: open squares, outflow: full squares), and spring (diamonds). *Composicidn relativa de aniones y cationes de las muestras del lago de Arreo (círculos), del arroyo asociado (ajluente: cuadrados vacíos, ejluente: cuadrados rellenos) y del manantial (diamantes).*

lake, and the photosynthetic activity of primary producers. SRP was present at low concentrations in the epilimnion (SRP < 5µg P/l), and, analysing the inorganic nitrogen values (see below), it can be considered limiting for planktonic productivity. A small increase in SRP concentration was detected at the surface in the spring of 1994, which influenced on primary productivity (see dissolved oxygen figure). Moderately high values of SRP were found in the hypolimnion, with an average concentration of 14 µg P/l; maximum values were found in the first period of stratification at the bottom (112 µg P/l).

The dynamics of inorganic nitrogen are also related to the circulatory processes in the lake. NO_x concentrations were very low during the first period of stratification in the epilimnion, with average values of 113 µg NO_3-N and 4 µg NO_2-N. Nitrogen mainly occured in the form of ammonium in this period, when it was concentrated in the hypolimnion with an average value of 1.41 mg NH_4-N. Nitrification occured with mixing and oxygenation of the water column, and nitrate and nitrite showed maximum values (1.40 mg NO_3-N/l in February, and 183 µg NO_2-N/l in April). The initial distribution of the nitrogen forms was restored during the second period of stratification, but there were differences in concentration between the two.

Total reactive silica (TRSi) showed the same tendency, with a depletion in the epilimnion and an accumulation in the hypolimnion. Redistribution of this nutrient took place during the mixing period. Maximum values of TRSi were found at the bottom (6.54 mg Si/l) during the first period of stratification.

Transparency

Transparency, measured as Secchi depth, ranged from 4.54 m to 1.37 m, with an average value of 3.39 m. Minimum value was registered in June, which when the wind was strong. The maximum value was recorded in December. Secondary maximum and minimum were achieved in August (4.35 m) and February (2.80 m), respectively.

DISCUSSION

According to Hammer (1986) lake Arreo is subsaline. Its hydrochemical composition is unusual. Sulfate, bicarbonate, calcium and magnesium are the main ions, although there are significant amounts of sodium chloride of subterranean origin. The composition of the subterranean water could be inferred from spring samples, taken close to the lake (Table 2). The ionic composition of samples from the lake and the outflowing stream are intermediate between the inflowing stream and the spring (Fig. 3). Therefore, their composition does not merely reflect the influence of the surface waters. For this reason, lake Arreo is not a typical water system formed by the dissolution of impermeable evaporite rocks, whose waters have the same ionic composition as the surface waters.

Lake Arreo was holomictic during our study. However, the lake tends towards meromixis. Complete winter mixis was very short. Moreover, the different behaviour of the conductivity, nutrients and ionic concentration in the hy-

Table 3. Mean values and standard deviations (given in parenthesis) of nutrient concentrations of lake Arreo. *Valores medios y desviaciones estándar (entre paréntesis) de las concentruciones de nutrientes del lago de Arreo.*

	SRP (µgP/l)	NH_4^+ (µgN/l)	NO_2^- (µgN/l)	NO_3^- (µgN/l)	TRSi (mgSi/l)
LAKE					
First stratified period					
Epilimnion	<5	74	4	113	2.50
	(1)	(69)	(2)	(69)	(0.38)
Metalimnion	<5	342	5	63	2.74
	(0)	(337)	(4)	(52)	(1.01)
Hypolimnion	34	1406	8	130	4.90
	(38)	(484)	(18)	(116)	(1.45)
Second stratified period					
Epilimnion	5	37	14	386	0.85
	(4)	(75)	(38)	(404)	(0.84)
Metalimnion	<5	111	15	348	1.27
	(4)	(105)	(25)	(277)	(0.90)
Hypolimnion	7	291	37	491	3.37
	(7)	(172)	(58)	(376)	(0.82)
Both stratified periods					
Epilimnion	<5	64	7	201	1.99
	(3)	(74)	(26)	(300)	(0.90)
Metalimnion	<5	168	14	305	1.49
	(3)	(218)	(22)	(241)	(1.29)
Hypolimnion	14	604	31	419	3.68
	(27)	(584)	(53)	(365)	(1.15)
Mixed period					
	9	419	19	624	2.97
	(2)	(415)	(7)	(480)	(1.10)

polimnion with respect to the epilimnion, during both periods of stratification, suggests that this study probably began after a meromictic period.

The tendency towards the meromixis can be explained by the morphometry of the lake, with its deep basin associated with a great escarpment that partially protects **it** from the dominant winds. The stability of stratification in lake Arreo is also indicated by morphometrical parameters such as the relative depth (Håkanson, 1981), a significant factor in the development of metalimnetic oxygen maxima (Eberly, 1964). The relative depth of lake Arreo may explain the maximum oxygen value detected in the second period of stratification, and repeated in another period of the study not considered here (unpublished data), the latter indicating oversaturation of nearly 200%.

Physical, chemical and morphometrical characteristics show that lake Arreo is an aquatic system formed by palustrine and lacustrine subsystems. The palustrine subsystem, with a permanent mixed period, is not a reduced littoral zone of the type commonly seen in normal lakes. Thermal stratification reveals that the palustrine subsystem extends over 2/3 of lake surface, and it is characterized by gentle slopes and a great abundance of aquatic macrophytes. The lacustrine subsystem is confined to a small area of the lake, and its waters might not mix totally in some year. Anoxic conditions and the presence of sulfide near the surface may indicate bacterioplanktonic primary production.

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