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Recent evolution of Lake Arreo, northern Spain: influences of land use change and climate

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Abstract We present a high-resolution, multiproxy reconstruction of the depositional history of Lake Arreo, northern Spain, for the last 60 years. We conducted sedimentological, geochemical and diatom analyses in short cores and made a detailed comparison with regional instrumental climate data (1952–2007), limnological monitoring of the lake (1992–2008) and recent land use changes that affect the lake catchment. Chronology is based on "floating" discontinuous varve counts and ^{137}Cs and ^{14}C dates. Four periods were identified in the Lake Arreo recent history: (1) prior to 1963, varved facies intercalated with fine turbidite deposits, and diatom assemblages dominated by *Cyclotella taxa* indicate predominantly meromictic conditions, (2) from 1964 to 1978, permanent anoxia persisted in bottom waters, as shown by similar facies and diatom assemblages as before, though detrital layers were coarser, (3) from 1979 to 1994, sediment delivery to the lake increased and laminated, clastic facies were deposited, and (4) from 1995 to 2008, dominance of massive facies and an increase in *Fragilaria tenera* and *Achnanthes minutissima* reflect relatively lower lake levels, less frequent bottom anoxia with more frequent water column mixing, similar to modern conditions. The period 1952–1979 was a time of meromixis and varved facies deposition, and was characterized by higher rainfall and less intense agricultural pressure in the watershed. There were two short humid periods (1992–1993 and 1996–1998) when monitoring data show more anoxic weeks per year and relatively higher lake levels. Increased cultivation of small landholdings in 1963, and particularly after 1979, caused a large increase in sediment delivery to the lake. The inferred lake evolution is in agreement with monitoring data that suggest a transition from dominantly meromictic conditions prior to 1993–1994 to a predominantly monomictic pattern of circulation since then, particularly after 2000. The synergistic effects of intensive water extraction for irrigation and lower rainfall since 1979, and particularly since 1994, brought the long period of meromictic conditions in Lake Arreo to an end. Water balance and sediment delivery to the lake are dominant factors that control the limnological and mixing conditions in Lake Arreo and they must be considered in management and restoration plans.

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Introduction

Relatively small, deep lakes frequently experience annual periods of anoxic bottom conditions, but development of permanent water-column stratification (meromixis) is less common and is controlled by several factors including basin morphology, changes in water inflows, lake level and wind stress (Hakala 2004). Although they are prone to water column stratification, the small and relatively deep karstic lakes on the Iberian Peninsula are generally not meromictic (Miracle et al. 1992). Protracted stratification has been documented only in Lakes Montcortés (Camps et al. 1976), La Cruz (Rodrigo et al. 2001) and Banyoles (Miracle and Alfonso 1993). Limnological surveys have been carried out in Lakes La Cruz (Rodrigo et al. 2001; Romero-Viana et al. 2008), Montcortés (Camps et al. 1976; Modamio et al. 1988), and Arreo (Chicote 2004; González-Mozo et al. 2000) in an effort to understand their water circulation dynamics.

Lake Arreo is one of the few relatively deep (z_{max} = 24 m) karstic lakes in Spain and developed in gypsum formations. The 15-year-long record of monitoring data from Lake Arreo (Chicote 2004; González-Mozo et al. 2000) constitutes an exceptional limnological record from the Iberian Peninsula. These monthly surveys document a decrease in the number of weeks of anoxia per year since 1994 and large water level fluctuations during the last 15 years. Changes in water-column mixing and oxygen content at the lake bottom depend upon several limnological and hydrological factors that are, in turn, controlled mostly by climate (temperature, precipitation, wind, among others) and human impacts (water consumption and land uses in the watershed). Although the instrumental record shows drought periods during the last few decades and written records document changes in farming intensity in the Lake Arreo watershed, no comprehensive study has assessed how both climate and anthropic factors have affected recent lake dynamics. Plans to manage and restore the lake require a better understanding of recent changes and paleolimnological data can provide information to formulate conservation policies.

We present a high-resolution record of the recent history of Lake Arreo using sedimentological, geochemical, mineralogical and diatom data from sediment cores. The data were collected to evaluate the climatic and human factors that controlled the evolution of Lake Arreo during the last few decades. Chronological control for cores was based on varve counting, complemented by radiometric techniques (^{14}C, ^{137}Cs). Comparison of paleolimnological results with local climate datasets and relatively long limnological monitoring records, which are scarce in Spain, as well as documented human activities, provides insights into the complex interactions between lake sediments, climate change and human activities.

Study site

Lake Arreo (42°46′ N, 2°59′ W; 655 m a.s.l.), also named Lake Caicedo de Yuso, is located on the southwestern edge of the Salinas de Añana diapir, an ellipsoidal, halokinetic structure developed in Upper Triassic evaporite formations in the NW Ebro River Basin, northern Spain (Garrote Ruíz and Muñoz Jiménez 2001) (Fig. 1). The lake watershed (287 ha) is composed of Triassic clay and gypsum-rich Keuper facies with some volcanic rocks (ophytes) (Fig. 1c). The dissolution and collapse of evaporites was the main mechanism for basin formation, and Lake Arreo is the best example in Spain of a karstic lake formed in evaporites. The northern margin of the lake is bounded by an ENE-WSW fault (Martín-Rubio et al. 2005). Recent alluvial and palustrine sediments surround the lake.

The regional climate is of transitional Atlantic-Mediterranean type. Mean annual precipitation is 670 mm. November is the wettest month, with a mean precipitation of 82.5 mm. Monthly average temperature fluctuates between 19.8°C in July and 4.7°C in January (González-Mozo et al. 2000).

Vegetation of the area corresponds to a transition between Eurosiberian and Mediterranean bioclimatic regimes (Peinado Lorca and Rivas-Martínez 1987). Apart from cultivated areas, most of the lake catchment is forested with *Quercus faginea* on the north-facing slopes, and *Q. rotundifolia*, *Q. pyrenaica* and *Pinus sylvestris* on drier soils and the south-facing slopes. *Fraxinus angustifolia* and *Ulmus minor* are also present in the area. More degraded areas are

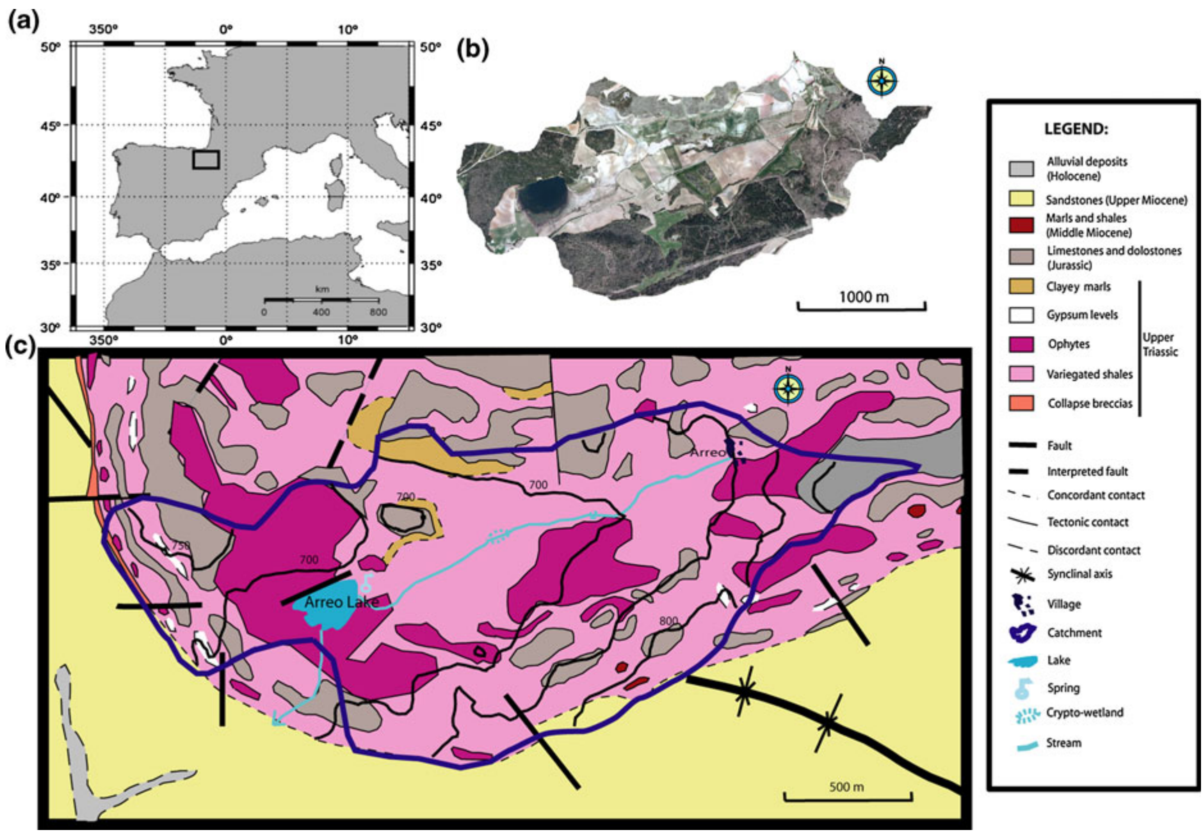

Fig. 1 Location map of Lake Arreo: **a** Location of the study area within the Iberian Peninsula **b** 2009 aerial photograph of the Lake Arreo drainage basin; cultivated areas are more abundant in the central-northern part, while forested areas and shrubland occupies the southern areas. **c** Geologic map of the area around Lake Arreo

covered by Mediterranean shrubs such as *Juniperus communis*, *Aphyllantes monspeliensis*, *Lavandula latifolia* and *Thymus vulgaris*. Cultivated areas and grazing pastures occupy the lower-altitude areas of the watershed (38% of the total area), forest represents 42% and shrubland covers 15% (Fig. 1). The lake shoreline is colonized by hygrophytic vegetation, mainly *Cladium mariscus* and *Phragmites australis*.

Lake Arreo is one of the deepest karstic lakes on the Iberian Peninsula ($z_{max} = 24.8$ m). The lake (6.57 ha) has a shallow platform that occupies 2/3 of its total surface area. It also possesses a deep funnel-shaped basin (Rico et al. 1995) (Fig. 2b). The lake is hydrologically open, with a small stream that enters the lake from the east and a small ephemeral outlet, a tributary of the Ebro River, which flows westward (Figs. 1c, 2b). There are also several saline springs in the watershed. Chemically, the lake is subsaline, with an electrical conductivity of 703–1,727 µS/cm from 1993 to 2009. It has a Ca–(Mg)–(Na)–SO_4–HCO_3–(Cl) ionic composition (González-Mozo et al. 2000).

The lake has two different depositional and ecological subsystems defined by the bathymetry: (1) the shallow platform in the SW (2/3 of the lake area), where waters mix throughout the year and sediment is characterized by palustrine deposition and vegetation, and (2) the deep basin of the north with seasonal water stratification. Diatoms in surface waters are mainly *Cyclotella distinguenda* var. *unipunctata*, *Fragilaria capucina* var. *gracilis*, and occasionally *Fragilaria ulna* and *F. tenera*.

Materials and methods

Four data sets were used in this study: (1) sediment cores, (2) regional climate data, (3) limnological monitoring data and (4) documentary data on land use changes. Two long sediment cores (ARR04-1A-1K

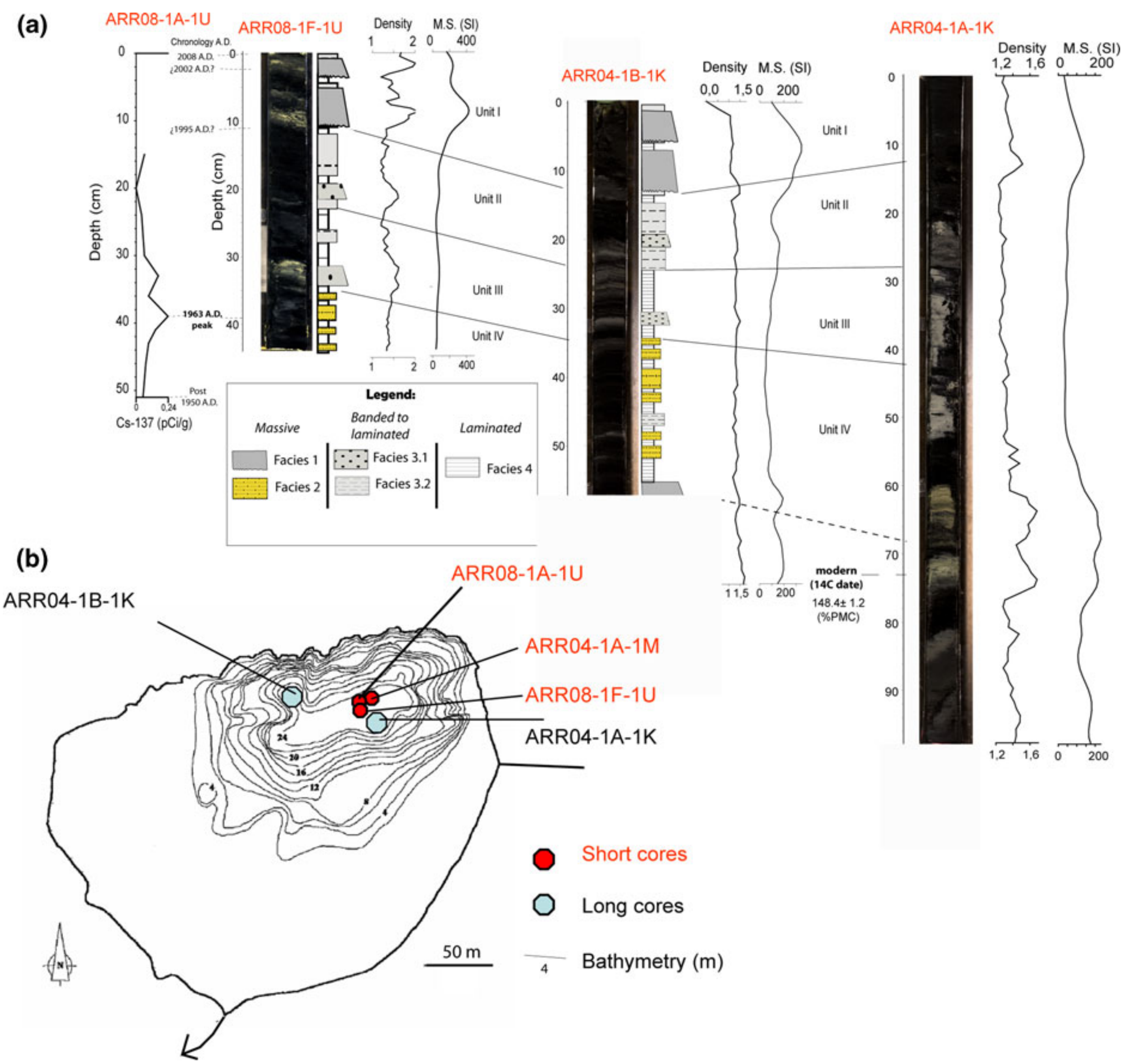

Fig. 2 **a** Lithostratigraphic correlation of cores ARR04-1A-1K, ARR04-1B-1K and ARR08-1F-IU. Each core image is accompanied by its sedimentological profile and magnetic susceptibility and density core logs. For the ARR08-1A-1U core, the ^{137}Cs activity profile is also shown. The position of the AMS ^{14}C date in the ARR04-1A-1K core is indicated **b** Bathymetric map of Lake Arreo, modified from Rico et al. (1995), and location of the cores

and ARR04-1B-1K) and one short core (ARR04-1A-1M) were retrieved in May 2004 from the deepest area of the lake (Fig. 2) using a modified Kullenberg piston corer and a platform from the Limnological Research Center (LRC), University of Minnesota (USA). In 2008, two short cores (ARR08-1F-1U and ARR08-1A-1U) were obtained using a UWITEC gravity coring system. Physical properties were measured at 1-cm resolution with a Geotek multi-sensor core logger (MSCL) at the LRC. Subsequently, cores were split in half lengthwise and imaged with a DMT core scanner. ARR08-1A-1U and ARR04-1A-1M were sampled for biological remains and dating analysis and inter-core correlations were achieved by extrapolating sedimentation rates from parallel cores.

ARR08-1F-1U was sampled every 2 cm for total carbon (TC), total inorganic carbon (TIC), total organic carbon (TOC) and total nitrogen (TN).

TC and TIC contents were determined by a UIC model 5011 CO_2 Coulometer, with TOC content calculated by subtracting TIC from TC. TN values were obtained with a VARIO MAX CN elemental analyser. Mineralogical analyses were carried out on selected samples from ARR04-1A-1K using an automatic X-ray diffractometer, Cu–Kα, 40 kV, 30 mA and graphite monochromator. Relative mineral abundance was determined using peak intensity following the procedures of Chung (1974a, b).

The uppermost 52 cm from the ARR04-1B-1K core were sampled for large thin sections (100 × 15 × 35 mm). They were prepared using the freeze-dry technique (liquid nitrogen) and subsequent impregnation with epoxy resin (araldite) under vacuum (Brauer and Casanova 2001). An Axioplan 2 imaging optical microscope with 50 × magnification was used for microfacies studies and varve counting in selected intervals (Brauer and Casanova 2001). Chronology of the short cores was established by varve counting in core ARR04-1B-1K, and ^{137}Cs dating in core ARR08-1A-1U, the latter carried out by gamma ray spectrometry at the St. Croix Watershed Research Station, MN (USA). A single AMS radiocarbon date from the ARR04-1A-1K core was generated at the Spanish National Accelerator Centre.

Sedimentary facies were defined following the method of Schnurrenberger et al. (2003), which includes compositional and mineralogical analyses, visual description and microscopic smear slide observation. Cores were correlated using physical properties, sediment composition and sedimentary facies. Elemental geochemical composition in core ARR08-1F-1U was obtained by X-Ray Fluorescence (XRF) using the ITRAX XRF core scanner from the Large Lakes Observatory, Duluth, MN (USA) with 20 mA current, 30 s count time and 30 kV voltage at 1-mm resolution. Results for each element are expressed as intensities in counts per second (cps).

Samples from ARR04-1A-1M were cleaned with hydrogen peroxide and dilute (10%) HCl for diatom analysis. Specimens were mounted in Naphrax and analyzed using an inverted microscope. At least 400 diatom frustules were counted per sample. Taxonomic identification and assignment of habitat preferences were made using specialized literature (Krammer and Lange-Bertalot 1986, 1988, 1991a, b; Lange-Bertalot 2001; Krammer 2002). Relative abundances of planktonic and benthic taxa were used to obtain the P/B index.

The monthly average of daily maximum and minimum temperatures and monthly amount of daily precipitation for the period 1950–2007 were obtained from 18 (precipitation) and 12 (temperature) AEMET (Spanish Meteorological Service) meteorological stations. Data were subjected to Quality Control (QC) tests (Aguilar et al. 2003) to identify errant values and ensure internal consistency and temporal and spatial coherence of the data. A relative homogeneity reassessment of monthly averaged data, based on the Standard Normal Homogeneity Test (SNHT) developed by Alexanderson and Moberg (1997) was then applied to the monthly precipitation and temperature series, following the SNHT procedure described by Brunet et al. (2006).

Regional time series of maximum and minimum temperatures, as well as precipitation for the period 1950–2007 were constructed by averaging daily anomalies and then adding back the base-period mean (1961–1990), according to the method of Jones and Hulme (1996) for separating temperature into its two components, the climatology and the anomaly. To adjust the variance bias present in regional time series associated with varying sample size, we applied the approach developed by Osborn et al. (1997).

Limnological monitoring was carried out monthly to quarterly since 1993 (González-Mozo 2000; Chicote 2004). Temperature and oxygen measurements and water sampling were carried out at 1-m depth intervals over the deepest site in the lake using WTW instruments. Lake water level was measured using land references and echo-sounding until November 2001 when an automatic stage gauge was installed.

Aerial photographs from the middle and late twentieth century (1956, 1978, 1991, 2009) were used to map the relative abundance of forested versus cultivated areas and to reconstruct major changes in land use over the last 60 years. Local archives were investigated and Arreo inhabitants were interviewed about recent uses of the lake.

Results

Sedimentary facies

Four sedimentary facies were identified in the cores (Figs. 2a, 3a): massive (facies 1 and 2), banded to

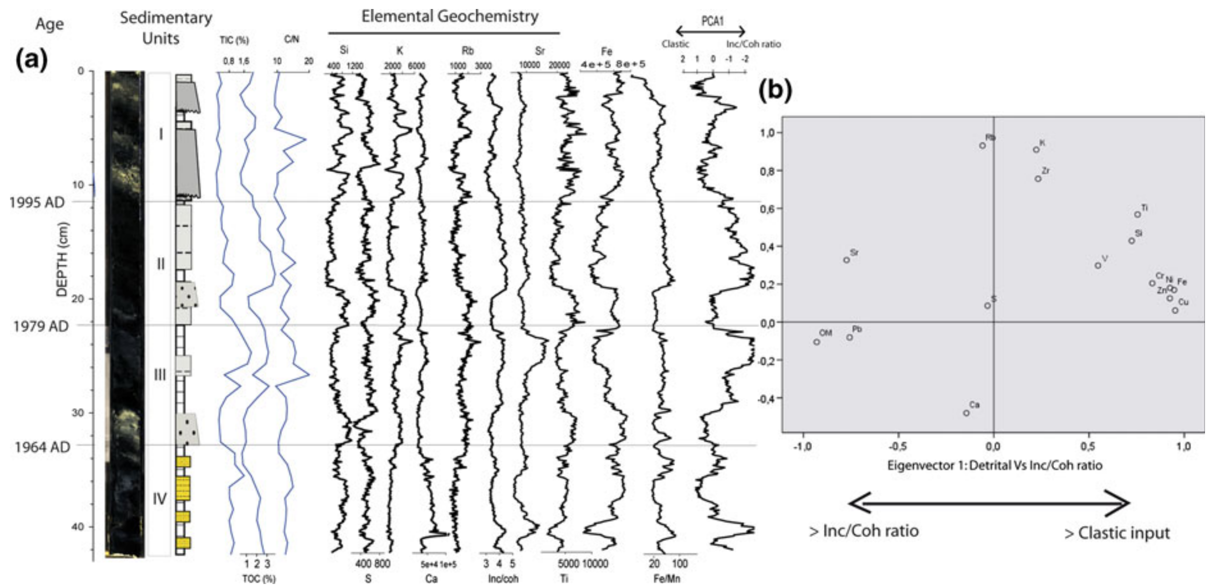

Fig. 3 **a** Sedimentological and geochemical (TIC, TOC, C/N and XRF) profiles from the different lithostratigraphic units defined in the ARR08-1F-IU core. Facies legend is shown in Fig. 2; **b** Principal Component Analysis carried out with the geochemical (XRF) data from the Lake Arreo sequence

finely laminated (facies 3) and varved facies (facies 4). The two massive facies have low carbonate (TIC values 0.2–0.3%) and organic matter content (TOC generally $< 1\%$), but differ with respect to grain size, texture and sedimentary structures. The grayish, massive facies 1 occurs in cm-thick, non-graded silty sand layers, with erosive basal surfaces and high magnetic susceptibility (MS) and density values. The coarse grain size suggests a high-energy depositional environment, absence of grading, and short transport, with limited current or wave action. This facies has the highest plagioclase content (up to 35%) and a high content of mafic minerals (pyroxene crystals). These characteristics point to mass wasting processes at the steep ophyte scarp on the north shore of the lake, documented in 1995 and 2002, as the origin of this facies.

Massive facies 2 is characterized by mm- to cm-thick, fine-grained layers, composed mainly of clay minerals (>80%). The fine texture indicates rapid deposition in distal areas of the lake of suspended clay-rich materials that were transported by creeks that drain the catchment during flooding episodes. This process has been observed in other Iberian lakes, e.g. Lakes Montcortés (Corella et al. 2010), Estanya (Morellón et al. 2009), and Taravilla (Moreno et al. 2008), as well as elsewhere, for example Lake Brienz (Sturm and Matter 1978).

Banded to finely laminated facies 3 occur as 1–5 mm-thick layers of clayey, quartz and carbonate-rich silt, with more abundant organic matter (TOC up to 2.3%) and diatoms. These facies show a fining-upward grain size distribution, and relatively high MS and density values. There are two types of detrital layers within facies 3, those with (banded subfacies 3.1) and without (laminated subfacies 3.2) a coarse basal layer with an erosive base and abundant plant remains. Occurrence of an erosive base may reflect underflow processes in which the inflowing water had density greater than lake water at any level (Sturm and Matter 1978). Subfacies 3.1 also displays higher MS values and greater layer thickness. Gypsum crystals with clear evidence of reworking (eroded, rounded and corroded surfaces) appear in some levels. The coarser and graded texture of these layers suggests deposition by strong turbidity-type currents, involving reworking of littoral areas. Such a process is likely related to stormy periods, similar to those described by Noren et al. (2002) and Moreno et al. (2008) in other lacustrine settings.

Varved facies 4 have the highest TIC and calcite content (up to 20%) and TOC up to 3%, and the lowest clay mineral content (<50%). They correspond to biogenic varves and are composed of three laminae; (1) a white layer with sharp boundaries, mainly composed of rhombohedric, endogenic calcite crystals, (2) a brownish organic matter-rich layer composed of diatoms (sometimes monospecific blooms of *Cyclotella distinguenda* var. *unipunctata*), amorphous aquatic organic matter, detrital calcite, quartz, clay minerals and pyrite; and (3) a greyish fine silt to clayey mud layer with a fining upwards texture composed of irregular, rice-shaped detrital calcite, irregular quartz grains, terrestrial plant remains at the base, and clay minerals. Varves in lake deposits reflect sedimentation with limited bottom bioturbation due to anoxic conditions (O'Sullivan 1983; Brauer 2004; Zolitschka 2007). In small, relatively deep karstic lakes such as Arreo, deposition and preservation of laminated, varved facies 4 occurred when bottom anoxia prevailed during most of the year, a condition that usually corresponds to relatively higher lake levels and reduced wind stress (Brauer 2004; Martín-Puertas et al. 2008).

Using TOC values, facies can be assigned to two categories (Fig. 3a): (1) varved facies 4, characterized by high TOC, up to 3.1%, and (2) clastic facies 1, 2 and 3, characterized by low TOC values, 0–2.3% on average. Occasional, relatively high TOC values within these clastic facies are due to large fragments of terrestrial and littoral plant remains, usually at the base of detrital layers. Higher C/N ratios, up to 20 (Fig. 3a), occur in facies 1 and 3, indicating the predominance of terrestrial over aquatic plants as the main source of organic matter in these detrital facies (Meyers and Lallier-Vergès 1999; Meyers 2003).

Core correlation and stratigraphy

Stratigraphic correlation between cores ARR08-1F-1U and ARR04-1B-1K was achieved using sedimentary facies, magnetic susceptibility, density and XRF profiles (Fig. 2a). The sedimentary sequence of Lake Arreo is described by a composite column that uses the upper part of ARR08-1F-1U, with the sediment–water interface preserved, and the lower part of ARR04-1B-1K.

The Lake Arreo sedimentary sequence was divided into 4 main lithostratigraphic units (Units IV, III, II and I). Unit IV (43–30 cm) is composed of varved facies 4 with intercalated fine massive facies 2. Unit III (30–24 cm) is composed of varved facies 4 with intercalated facies 3.1 and displays high organic matter and carbonate content. Unit II (24–12 cm) is composed of laminated facies 3.2 with intercalated facies 3.1 and varved facies 4. Unit I (12–0 cm) is coarser and composed of massive facies 1 with thinner intercalations of laminated facies 3 and some varved facies 4.

Facies, TOC/TIC values and mineralogy clearly distinguish the lower and middle part of the sequence (units IV and III), with a predominance of varved facies 4 characterized by finer sediments, higher endogenic calcite precipitation and higher organic matter accumulation. The top of the sequence (units II and I) is dominated by coarser and more detrital, laminated to massive sediments (Fig. 3a).

Elemental geochemistry

The high-resolution XRF geochemical record obtained from core ARR08-1F-1U shows a clear correspondence with sedimentary facies distribution (Fig. 3). Three main groups of elements, each of which is related to a sedimentary facies, can be observed: (1) Si, K, Ti, Fe, Mn, V, Cr, Ni, Zn, and Cu, with variable, but predominantly higher values in massive and banded facies; (2) Rb, also related to the clastic facies, but more abundant in finer facies 3; and (3) Sr, with maximum values in varved facies 4. Sulfur and calcium show complex patterns because they are associated with clastic, endogenic and diagenetic minerals. Sulfur is related to both detrital gypsum from massive facies and diagenetic iron sulfides in laminated, organic matter-rich facies. Calcium has two main sources, detrital calcite and gypsum in the massive facies and endogenic calcite in the laminated facies. Si-related elements show fluctuating, but high values in unit I, and relatively lower values in units II, III and IV. Sulfur shows an inverse relation with Si-related elements in the coarser layers from the uppermost part of the sequence (unit I) and at the base of unit II, while it is directly correlated with Si-related elements throughout the lower part (units II, III and IV). The coarser layers have higher amounts of silicates and lower contents of gypsum and/or pyrite. Finer detrital layers seem to include higher amounts of detrital gypsum, from Triassic Keuper facies. We compared the incoherent and the coherent scattered radiation (inc/coh ratio) in the spectrum obtained by

XRF to TOC and found a strong relation (Fig. 3a), similar to what has been seen in other lakes, e.g. Lake Raraku (Sáez et al. 2009). This suggests the inc/coh ratio can provide a high-resolution record of organic matter content in the sediments.

No geochemical variable can be interpreted as a definitive indicator of anoxic conditions at the lake bottom. The down-core profile of Fe/Mn shows a correlation with facies distribution, but does not closely follow the Ti or Fe curve, suggesting a relationship with bottom-water redox conditions, as relatively less Mn is released from the sediments to the water under more oxic conditions (Schaller and Wehrli 1996). Thus, the Fe/Mn ratio displays fluctuating, but generally lower values, indicative of more oxic conditions in upper unit I and the lower portion of unit II, while units IV, III and the upper part of unit II show higher values (Fig. 3).

The Principal Component Analysis (PCA) carried out using the XRF elemental dataset (16 variables and 426 cases) confirms an inverse relation between elements associated with detrital minerals (silicates, gypsum) and those associated with organic matter and endogenic mineral phases (e.g. calcite) (Fig. 3b). The first eigenvector represents 53.1% of the total variance, and is controlled mainly by V, Si, Ti, Cr, Zn, Ni, Fe and Cu at the positive end and Sr, Pb, and inc/coh at the negative end (Table 1). Lead is preferably adsorbed to organic matter during periods of anoxia (Martín-Puertas et al. 2009), whereas Sr is included in calcite crystals that precipitate in saline waters. Positive eigenvector 1 scores represent higher clastic input and characterize intervals in the sequence dominated by increased sediment delivery to the lake (Fig. 3a, b). On the other hand, negative eigenvector 1 scores indicate higher organic matter content and characterize the middle and lower part of the sequence (unit II, III and IV), with more abundant laminated organic matter-rich facies (Fig. 3a, b). Interpretation of eigenvector 2 (16.9% of the variance), controlled by Rb, K, and Zr at the positive end, and clastic input and Ca at the negative end (Table 1), is more complex because Ca reflects both endogenic calcite from facies 4, as well as detrital gypsum (Fig. 3b).

Diatoms

Diatom assemblages are composed of 63 taxa distributed among 22 genera (Fig. 4). *Navicula*, *Fragilaria* and *Gomphonema* are the genera with more species (8, 7 and 6, respectively). Only 6% of the taxa have a relative abundance of ≥5% in at least one sample, while 22% of taxa have abundances of 1–5%, and the rest had <1%.

Most of the taxa (61 spp.) are typical of benthic habitats *sensu lato* (i.e. epipelion, periphyton, epiphyton) or are tychoplanktonic species. The only strictly planktonic taxa are two species of the genus *Cyclotella* (*C. distinguenda* var. *unipunctata* and *C. pseudostelligera*). The four sedimentary units defined previously show similar composition and relative abundance of diatoms. The most abundant species in the whole sequence are *Cyclotella*

Table 1 Principal component analyses (PCA)

	Axis 1	Axis 2
A		
Eigenvalues	8.49	2.70
Percentage (%)	53.06	16.86
Cum. Percentage	53.06	69.93

	Cu	Fe	OM	Ni	Zn	Cr	Sr	Pb	Ti	Si	V	Rb	K	Zr	S	Ca
B																
Eigenvector 1	0.95	0.95	−0.93	0.93	0.92	0.83	−0.77	−0.76	0.76	0.72	0.55	−0.06	0.22	0.23	−0.03	−0.14
Eigenvector 2	0.06	0.17	−0.11	0.18	0.13	0.20	0.33	−0.08	0.57	0.43	0.30	0.93	0.91	0.76	0.09	−0.48

A The eigenvalues for the two main axes are shown. Percent of the variance explained by each axis is also indicated. *B* Factor loadings for every variable in the two main axes

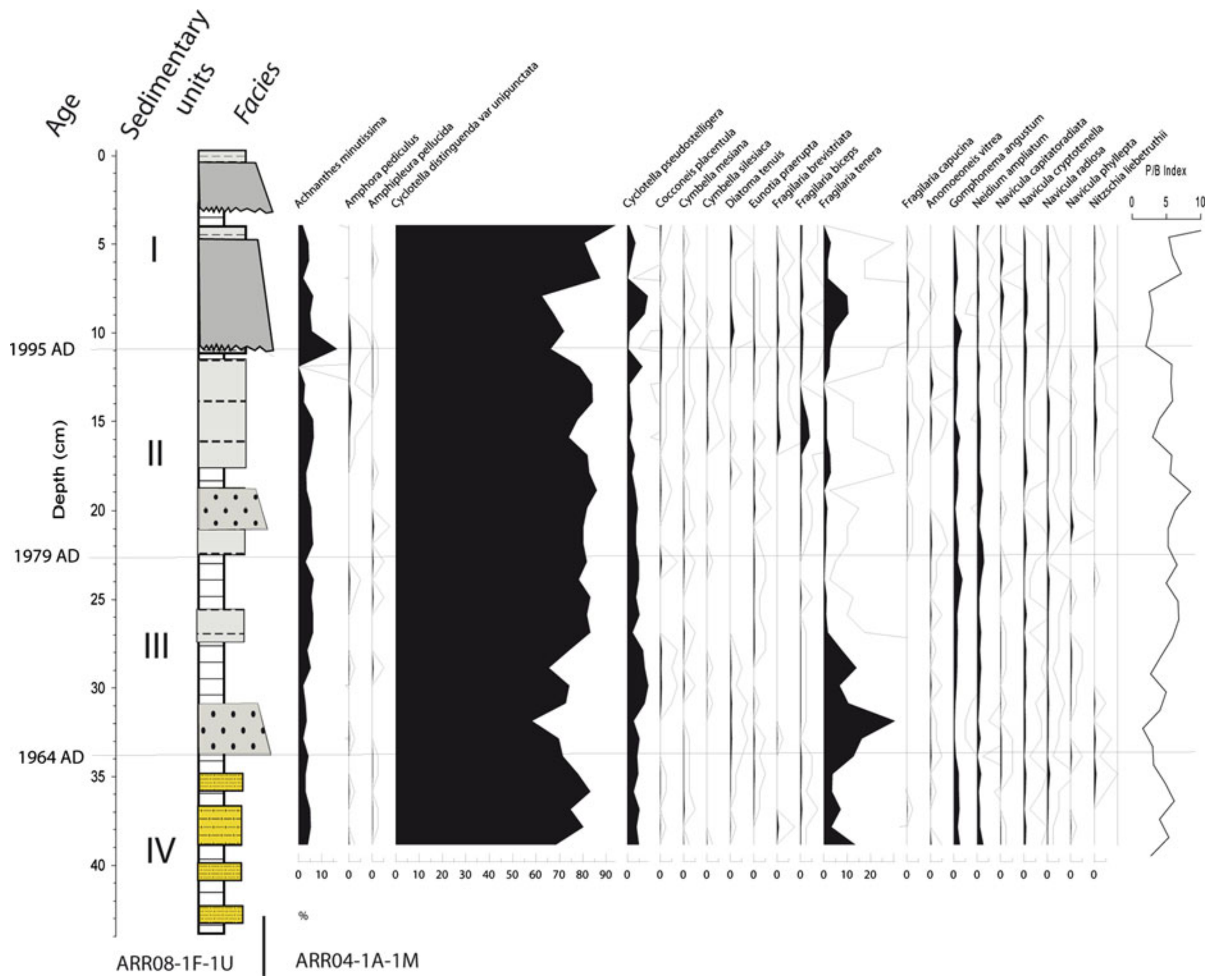

Fig. 4 Diatom stratigraphy and planktonic vs. benthic (P/B) ratio for the ARR04-1A-1M core. Sedimentary units, core image and the sedimentological profile from core ARR08-1F-1U are also indicated. Facies legend is shown in Fig. 2

distinguenda var. *unipunctata*, *C. pseudostelligera*, *Achnanthes minutissima* and *Fragilaria tenera*. The planktonic species *C. distinguenda* var. *unipunctata* is dominant in all the sedimentary units, with a relative abundance between 58 and 94%. Tychoplanktonic *F. tenera* has higher percentages in two intervals, between 8 and 10 cm (base of unit I), with values up to 11%, and between 29 and 34 cm (base of unit III), with a maximum abundance of 31%. Periphytic *A. minutissima* has similar percentages in the four sedimentary units, with a maximum of 17% at 11 cm (unit I) (Fig. 4). The P/B index displays lower values at the base of units III and I as a consequence of reduced abundance of *Cyclotella distinguenda* var. *unipunctata*, the most common diatom in the sequence.

Age model

The chronology of the Lake Arreo sequence is based on varve counting in core ARR04-1B-1K, ^{137}Cs dating of core ARR08-1A-1M, and an AMS ^{14}C date from core ARR04-1A-1K (Figs. 2, 5). A reliable ^{210}Pb chronology could not be obtained due to the low and variable ^{210}Pb activity (0.2–0.4 pCi/g) throughout the core. The low ^{210}Pb activities suggest that high sediment accumulation rate diluted atmospheric input of unsupported ^{210}Pb. Although ^{137}Cs values are generally low (0.05–0.09 pCi/g), there is a peak (0.23 pCi/g) at 39–40 cm. There is ^{137}Cs activity to 52 cm depth. Assuming no downward migration of ^{137}Cs, this suggests this depth postdates AD 1950 (Fig. 2a). The radiocarbon date on the

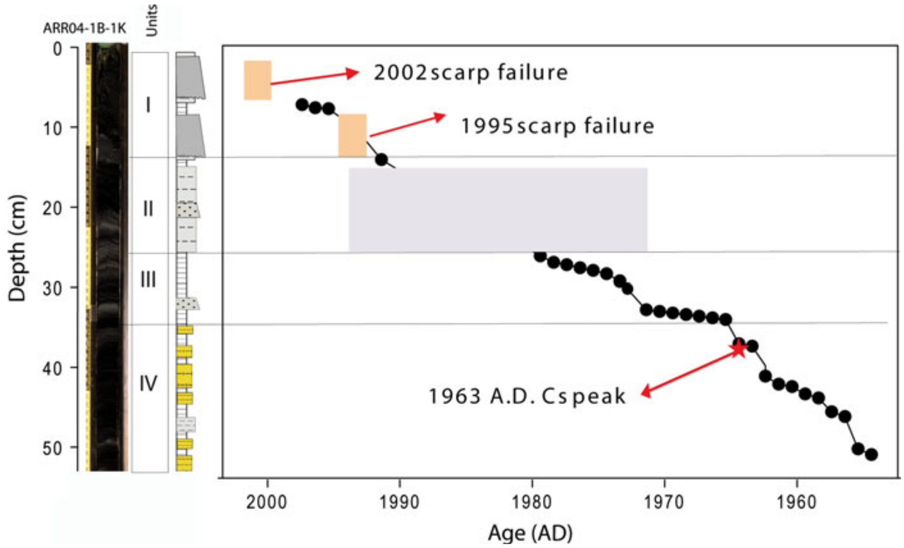

Fig. 5 Age model from the Lake Arreo core based on varve counting and ^{137}Cs dating. Horizontal grey-shaded bar represent periods without varve preservation. Facies legend is shown in Fig. 2

terrestrial macrorest sample at 75 cm (base of Unit IV) in core ARR04-1A-1K (Fig. 2b) yielded a modern age (148.4 to ±1.2% modern), coherent with the ^{137}Cs peak and the high sedimentation rate suggested by low ^{210}Pb activities.

Thirty varves were counted in the top 52 cm of core ARR04-1B-1K, which spans from AD 1952 to 1998. The "floating" varve chronology is anchored by the AD 1963 ^{137}Cs peak (ARR08-1A-1M). Two additional chronological tie points are provided by the mass wasting deposits in the northern margin of the basin associated with documented scarp failures in 1995 and 2002 (facies 1). We assumed a constant sedimentation rate in the intervals where varves were absent and applied linear interpolation. The sedimentation rate is high ($\sim$ 10 mm/yr) and similar for the four defined units: IV (1952–1963), III (1964–1978), II (1979–1994) and I (1995–2007).

Climate data

Trends for regional time series of maximum and minimum temperature were calculated on an annual basis using slope estimation methodologies (Sen 1968). For the period 1952–2007, the maximum and minimum temperatures show significant ($p < 0.01$) increases, more so for maximum temperature (0.16°C/decade) than for minimum temperature (0.14°C/decade). We compared the climate data that prevailed during the deposition of each sedimentological unit to the sediment characteristics to investigate the influence of climate on sedimentation dynamics. Temperature averages for 1952–1963 (unit IV), 1964–1978 (unit III) and 1979–1994 (unit II) (Table 2) display similar averages, while the 1995–2007 period (unit I)

Table 2 Precipitation, maximum and minimum temperature data from the regional series obtained from 18 (precipitation) and 12 (temperature) meteorological stations in surrounding areas

Time interval (AD)	Annual	Winter	Spring	Summer	Autumn
Precipitation (mm)					
1952–1963	1043.8	345.0	245.5	155.8	304.7
1964–1978	1039.9	304.5	299.7	162.7	272.6
1979–1994	991.9	284.5	290.9	153.7	262
1995–2007	959.7	304.8	251.5	140.8	274.3
Minimum temperature (°C)					
1952–1963	7.46	2.55	6.09	12.81	8.65
1964–1978	7.15	2.62	5.52	12.4	8.04
1979–1994	7.55	2.62	5.88	12.93	8.83
1995–2007	8.03	3.31	6.49	13.76	9.05
Maximum temperature (°C)					
1952–1963	16.79	9.46	16.18	23.87	17.73
1964–1978	16.55	9.47	15.03	23.89	17.58
1979–1994	17.03	9.85	15.52	24.46	18.22
1995–2007	17.50	10.20	16.75	25.11	18.19

shows an increase of 0.7°C for average maximum temperature and 0.6°C for average minimum temperature, with large increases in both during spring and summer. Changes in precipitation during the last 50 years are also noticeable, with a significant decrease (−21 mm/decade, $p < 0.05$) for the period 1952–2007. The 1952–1978 period was somewhat wetter (mean annual precipitation of 1044 mm until 1964 and 1040 mm until 1978) than the last three decades (Table 2). Relatively drier years occurred in 1957, 1963, 1968, 1970, 1973, 1976, 1980–1984, 1985–1987, 1989–1990, 1994–1995, 1998–2003, and 2005–2006. More humid years occurred in 1952–1956, 1958–1962, 1964–1967, 1969, 1971–1972, 1974–1975, 1977–1979, 1984, 1988, 1991–1993, 1996–1997, 2004 and 2007.

Land use changes

Farming and forest management have been the main economic activities in the Lake Arreo catchment. Wheat, oats, barley and legumes were the dominant crops in the ninetieth century, while potatoes, sugar beet and colza oil were introduced afterwards (Chicote 2004). We identified four main periods of land use in the catchment using analysis of aerial photographs and historical documents (Fig. 6; Table 3):

1. Prior to 1963—forest dominated the watershed (158 ha) and cultivated areas represented about 34% (98 ha), while shrubland covered only 15 ha. Flooded areas and wetlands also accounted for about 15 ha. The process of concentrating regional smallholdings started in 1963 (BOE no. 216; 9/9/1963) and affected some areas of the Caicedo de Yuso municipality.
2. 1963–1979—changes in agricultural crops and the structure of farm fields were noticeable after the concentration of regional smallholdings. Another local smallholding concentration (BOE no. 130, 31/05/1975) ended in 1979. This altered the catchment, as larger crop fields replaced small, traditional farm lots. Some forested areas were cleared and cultivated areas (105 ha) and

Table 3 Land use areas in the Lake Arreo catchment

Land use	Area (ha)			
	1956	1978	1991	2009
Urban area	1	0.51	0.77	0.92
Forest	158	98.19	122.06	120.13
Shrubland	15	68.94	22.66	43.71
Wetland	15	13.66	14.15	13.48
Cultivated area	98	105.93	127.60	108.99

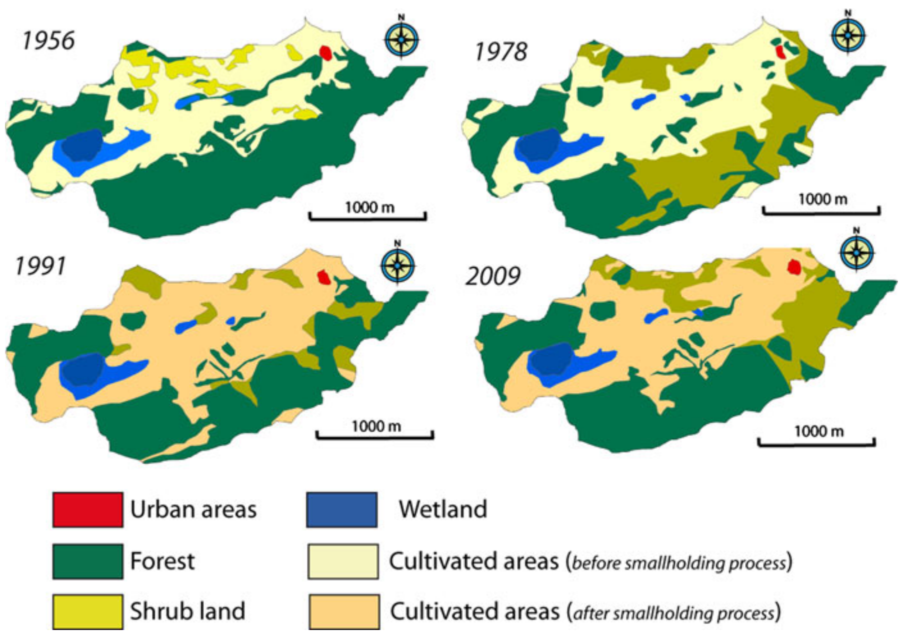

Fig. 6 Land use changes in the Lake Arreo catchment during the last 50 years based on aerial photographs

shrublands increased (Fig. 6; Table 3). Furthermore, there was a reduction in wetland surface area (13.6 ha).

3. 1979–1992—there was a decrease in shrubland area from 68 ha in 1979 to 22 ha in 1991 and cultivated areas reached their maximum extent by 1991 (127 ha, 44.4%).
4. 1992–2009—wetlands decreased to a minimum (13.5 ha), while shrubland increased to 43 ha in 2009, an expansion linked to a large decrease in the cultivated area (109 ha in 2009).

Limnological monitoring

Monthly water column data demonstrate that Lake Arreo has been warm monomictic (holomictic) during the last 15 years (Fig. 7). The stratification-mixing cycle has varied and included an anoxic period of 19–46 weeks/year, with a mean of 28 weeks. Measurements of conductivity, nutrients and ion concentrations in the 1993–1994 cycle showed two periods of water stratification. In particular, there was an increase in salinity in the hypolimnion during the first stratification period in summer 1993 that has not been recorded since. It is suspected that the lake may have been meromictic at earlier times in its history (González-Mozo et al. 2000).

During the monitoring period, maximum water extraction was carried out by late summer. Average lake level in September dropped over the years from 1993 to 2000, and in 2002, due to increased water extraction for irrigation (Fig. 7). During the maximum decline recorded in 2002 (4.7 m), the south and west littoral platform areas emerged and the palustrine depositional environment disappeared.

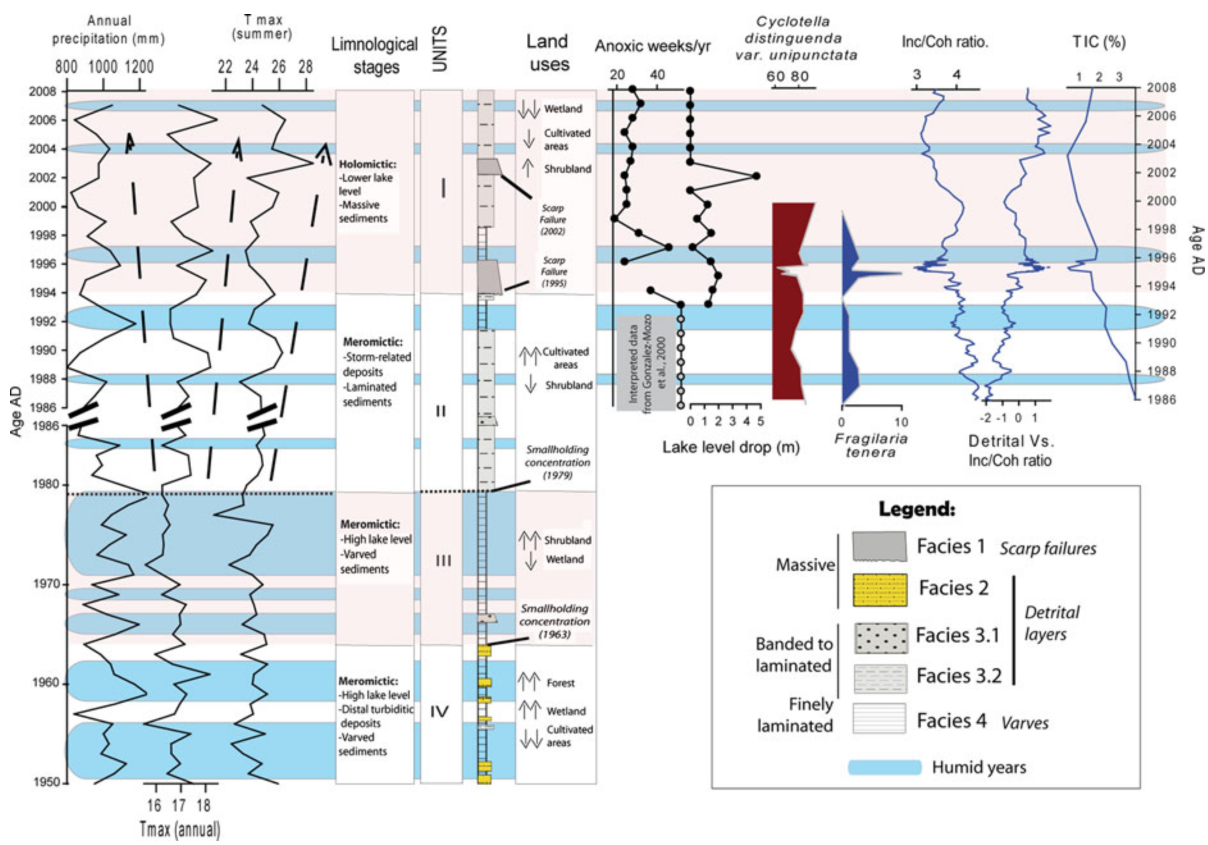

Fig. 7 Evolution of Lake Arreo during the last six decades. Comparison of the meteorological data (from *left* to *right*, annual total precipitation, annual maximum temperature, summer maximum temperature), and summary of the four limnological stages in Lake Arreo since 1952 with the stratigraphic column and limnological monitoring, biological and geochemical data collected since 1986

Discussion

Bathymetric (Rico et al. 1995) and thermal features (González-Mozo et al. 2000) of Lake Arreo are conducive to development of a permanently stratified water column, similar to what has been seen in other Iberian karstic lakes. Furthermore, the 1993–1994 survey by González-Mozo et al. (2000) suggested meromixis in previous years. Lake monitoring data, however, demonstrate complete mixing once a year (warm monomixis) in Lake Arreo during the last 15 years. The holomictic conditions contrast with studies from other lakes in which anthropogenic influences triggered meromixis due to increases in trophic state, e.g. Brownie Lake, USA (Swain 1984), and Barldeggersee, Switzerland (Lotter et al. 1997). Shifts toward holomixis have also been documented, whether due to anthropogenic activities such as construction (Tyler and Bowling 1990), or to a combination of climatic and anthropogenic factors (Holzner et al. 2009).

Our multiproxy analysis of sediment cores from Lake Arreo was designed to infer changes in limnological and mixing conditions during the last 60 years and test the hypothesis that holomictic conditions in the lake developed recently. We compared reconstructed depositional environments in the deepest part of the basin with limnological data, climate records and land use changes, which allowed us to evaluate the main factors that controlled lake evolution, and particularly, the water column mixing pattern in the lake.

Changes in diatom assemblages and deposition of varved/laminated versus massive facies allow insights into predominance of mixing versus stratification in the lake and past lake level fluctuations (Tracey et al. 1996; Schmidt et al. 1998). Dominance of planktonic *Cyclotella* species, mainly *C. distinguenda var. unipunctata*, throughout all the sedimentary units reflects dominance of open-water environments during the last 50 years. This diatom species is favored under stratified water column conditions because its small size reduces the sinking rate and enables it to remain in the water column. Moreover, species of *Cyclotella* require more light and less nutrients than other taxa and consequently often dominate stratified water columns (Carney 1987; Reynolds 1997; Interlandi and Kilham 2001).

The modern water column circulation pattern in Lake Arreo evolved from (1) a period characterized by predominantly meromictic conditions prior to 1979 during which biogenic varves were deposited, (2) a transitional phase of persisting meromictic conditions, but higher clastic input related to increased smallholding farming activities after 1979, and (3) a stage of predominantly holomictic (warm monomictic) conditions in the mid 1990s. Analysis of sedimentology and biological remains identified four main periods in the recent lake history.

1952–1963—a predominantly meromictic lake with frequent, fine turbidite events

Deposition and preservation of annually laminated facies 4 during the period 1952–1963 (unit IV) indicates anoxic bottom conditions in the deep areas of the lake throughout the year, i.e. meromictic conditions. This period is characterized by: (1) relatively high organic matter concentrations (TOC values up to 3.2%), (2) preservation of endogenic calcite laminae, indicating carbonate production in the epilimnion and anoxic conditions at the bottom of the lake, and (3) relatively low C/N ratio, indicating a relatively high contribution of organic matter from aquatic sources (Fig. 3).

Sedimentation of turbidite deposits (finer facies 2) during the 1952–1963 period (unit III), intercalated within the varved facies 4, suggests deep-water conditions, coherent with the period of highest precipitation (Table 2) and maximum wetland expansion (Table 3). During these periods when the lake overflowed the outlet, littoral areas would have been completely inundated, and the large belt of littoral vegetation (Table 3; Fig. 6) would have acted as a barrier for coarse sediments, favouring sedimentation in the distal areas of fine-grained material enriched in clay minerals.

1964–1978—a predominantly meromictic lake with less frequent and coarser turbidite events

Onset of more abundant, coarser detrital deposits (facies 3) in unit III (1964–1978) coincides with the beginning of land use changes in the watershed. In 1963, smallholding concentration started in the municipality, and as a result, cultivated areas and mechanization of agriculture in the watershed increased (Table 3; Fig. 6). Reduction of the vegetation belt around the lake (Table 3) favored the input of coarser clastic material into the lake, and consequently, better development of facies 3 and the absence of fine turbidite deposits (facies 2). Deposition of varved facies 4 during this period suggests stable and relatively high lake levels, coherent with relatively high precipitation and lower temperatures (Table 2; Fig. 7).

The tychoplanktonic species *Fragilaria tenera* has maximum abundances at the base of unit III during intervals with massive, detrital facies. Speed of diatom sedimentation increases with cell size (Diehl et al. 2002; Reynolds 2006) and larger species such as *Fragilaria tenera* float poorly and need turbulent conditions to remain in the water column (Reynolds 1984). *Fragilaria tenera* peaks may reflect periods with longer mixing conditions in the lake. However, their association with coarser facies may also indicate reworking from littoral areas where they could be more abundant. Peaks could reflect a taphonomic effect, with more tychoplanktonic diatom frustules transported from the littoral environments to the deepest areas of the lake during periods of increased sediment delivery. Thus, the *Fragilaria tenera* peak at the base of unit III could coincide with higher water turbidity related to the sharp increase in sediment delivery into the lake after agricultural activities increased in the watershed.

1979–1994, a predominantly meromictic lake with high sediment delivery

Sedimentation of laminated facies 3 characterizes unit II and marks a major change in the depositional system. Although varved facies 4 occurred only during a short interval that coincides with a humid year (1992–1993), preservation of fine laminations in facies 3 suggests predominantly anoxic conditions at the lake bottom. Compositional and geochemical indicators also indicate a trend toward increased clastic input in unit II. Increased sediment delivery to the lake would have been caused by the second concentration of smallholdings in 1979 that increased the cultivated area in the lake′s watershed (Table 3). Relatively drier conditions during the 1979–1990 period (Table 2; Fig. 7) could also have contributed to a decrease in lake level and favored transport of littoral sediments to the distal areas of the lake.

1995–2008—a predominantly holomictic lake with high sediment delivery

A significant change in depositional conditions in the lake occurred in 1995 when clastic, coarse massive facies 1 was deposited. Scarp-failure deposits in the northern littoral areas of the lake were described by Martínez-Torres et al. (1992). Two documented catastrophic failures of the northern scarp, in 1995 and 2002, provided abundant clastic material to the lake and might be responsible for deposition of the two distinctive sandy layers at 10–8 cm and 3–2 cm depth. The scarp failure in 1995 occurred during a period of a 2-m lake level drop, which entailed a 39% reduction in lake surface area. The 2002 event occurred during a 4.7-m lake level drop. Both lake level declines were caused by illegal water extraction for farms during droughts (1994–1995 and 2001–2002). Low lake levels could have triggered scarp instability as they induce higher than normal shear stresses on the slope, and subsequent failure. The peak in *Fragilaria tenera* and the slight increase of periphytic species *Achnanthes minutissima* at the base of unit I could be related to reworked material from littoral areas during a period of relatively lower lake level when palustrine environments were closer to the deepest, central part of the lake, enabling the transport of coarser material along with littoral diatoms to the deepest environments.

Monitoring and instrumental data illustrate the relationship between varved facies and limnological variables. Varved facies 4 was deposited during the 1996–1998 period of relatively higher rainfall, greater number of anoxic weeks per year and higher lake levels (Fig. 7). During these three years, although the lake was holomictic, the mixing period occurred during a short period of time, in particular the 1996–1997 hydrological year. Furthermore, there was reduced water extraction during that year (Fig. 7), allowing preservation of varved facies 4. Thus, reduced summer water extraction and higher precipitation are key factors controlling mixing in Lake Arreo. The good correlations between number of anoxic weeks per year, increased precipitation, and some sedimentological variables related to laminated deposits (increased organic matter and endogenic calcite content), support the hypothesis of increased meromictic behaviour of the lake during periods of laminated facies deposition prior to 1995 (Fig. 7).

Dominance of coarser facies after 1995, and particularly after 2000, is interpreted to have been a consequence of increased farming activities and decreased lake level caused by high water extraction for irrigation and several droughts. Traditional crops in the area were winter cereals until the 1980s when sugar beet cultivation expanded and water extraction for irrigation purposes increased in spring and summer. The lake level decrease would have triggered longer holomictic periods during deposition of banded and massive detrital facies. The increase in sediment delivery to the lake may also be linked to the increase in agricultural fields and shrubland area in the upper part of the watershed and the reduced palustrine environment (Table 3; Fig. 6). Human activities in the Lake Arreo catchment were the factor that triggered a change in the lake's circulation pattern towards holomixis since 1995. Although water extraction stopped shortly after 2002, the system has not yet recovered its previous limnological dynamics, particularly its mixing pattern. In order to define and successfully implement management policies to restore Lake Arreo, anthropogenic pressure must be reduced to previous levels.

Conclusions

The multiproxy study of short cores from Lake Arreo provides an opportunity to investigate the links among recent sedimentation processes in the karstic lake, anthropic use of its catchment and recent climate fluctuations. The interplay between land use changes and climate fluctuations has controlled the sediment deposition and water column mixing dynamics of Lake Arreo during the last few decades. Our multiproxy study found a clear correlation between an increase in precipitation, the number of weeks per year of deepwater anoxia and formation of laminated/varved facies. The dominance of planktonic species of the genus *Cyclotella* reflects the dominance of long periods of stable stratification during the last 50 years. On the contrary, peaks in *Fragilaria tenera* and *Achnanthe*s *minutissima* reflect periods with increased mixing, lower lake levels and greater turbidity.

Four main stages have been inferred for the lake since the 1950s. During the period 1952–1963, a time of low agricultural pressure and higher rainfall, lake level was high and stable, maintained at the lake outlet, and anoxic conditions prevailed. After a concentration of smallholdings in 1963, farming activities increased, but lake level remained high. Only after the second smallholding concentration in 1979 did sediment delivery to the lake increase and formation of varved facies cease. The greatest limnological change occurred during the last two decades (1995–2008) and was characterized by decreasing lake levels caused by lake water extraction for irrigation, decreased precipitation and increased clastic delivery from scarp failures (facies 1). As a consequence, the lake became holomictic.

Although holomixis has prevailed in recent years, implementation of more stringent lake water management policies may restore the deep basin of the lake to its meromictic condition. Understanding the recent dynamics of water column mixing in Lake Arreo and its relationship with changes in climate and human activities would increase the accuracy of long-term reconstructions of past global changes and help define target limnological conditions for management agencies.

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