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Human impact since medieval times and recent ecological restoration in a Mediterranean lake: the Laguna Zoñar, southern Spain

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Abstract

The multidisciplinary study of sediment cores from Laguna Zoñar (37°29′00″ N, 4°41′22″ W, 300 m a.s.l., Andalucía, Spain) provides a detailed record of environmental, climatic and anthropogenic changes in a Mediterranean watershed since Medieval times, and an opportunity to evaluate the lake restoration policies during the last decades. The paleohydrological reconstructions show fluctuating lake levels since the end of the Medieval Warm Period (ca. AD 1300) till the late 19th century and a more acute dry period during the late 19th century – early 20th century, after the end of the Little Ice Age. Human activities have played a significant role in Laguna Zoñar hydrological changes since the late 19th century, when the outlet was drained, and particularly in the mid-20th century (till 1982) when the spring waters feeding the lake were diverted for human use. Two main periods of increased human activities in the watershed are recorded in the sediments. The first started with the Christian conquest and colonization of the Guadalquivir River Valley (13th century) particularly after the fall of the Granada Kingdom (15th century). The second one corresponds to the late 19th century when more land was dedicated to olive cultivation. Intensification of soil erosion occurred in the mid-20th century, after the introduction of farm machinery. The lake was declared a protected area in the early 1980s, when some agricultural practices were restricted, and conservation measures implemented. As a consequence, the lake level increased, and some littoral zones were submerged. Pollen indicators reflect this limnological change during the last few decades. Geochemical indicators show a relative decrease in soil erosion, but not changes in the amount of chemical fertilizers reaching the lake. This study provides an opportunity to evaluate the relative significance of human vs. climatic factors in lake hydrology and watershed changes during historical times. Paleolimnological reconstructions should be taken into account by natural resources agencies to better define lake management policies, and to assess the results of restoration policies.

Introduction

Lakes in the inland areas of Spain have been part of the cultural landscape for several millennia. Human activities around the lakes included not only the use of water, but also other associated resources as salt minerals, fishing and hunting, and farming. Some archaeological sites suggest a significant use of the lake resources and the watersheds since the Neolithic, with an increase during Roman times, and particularly in the last few centuries (Ebro Basin, Davis 1994; Salines Lake, Giralt et al. 1999; Estaña Lake; Riera et al. 2004). In Mediterranean areas, where water resources are scarce, historical human activities have been a decisive factor in the lake hydrology and, particularly, agricultural practices a main forcing in the depositional dynamics of the lake systems (e.g., Salada de Chiprana, Ebro Basin; Valero-Garcés et al. 2000a). On the other hand, most paleorecords indicate that vegetational and hydrological changes in the Mediterranean regions of Spain during the last glacial cycle were responses to effective moisture crises rather than to temperature fluctuations (Pons and Reille 1988; Davis 1994; Peñalba et al. 1997; Giralt et al. 1999; Valero-Garcés et al. 1998, 2000b, 2004; Carrión 2002; Carrión et al. 2003; González-Sampériz 2004). Paleohydrological tools applied to lake records may provide the needed rainfall and effective moisture reconstructions to better understand climate fluctuations in Mediterranean Spain, and also contribute to unravel the relationship between the different cultures with the environment in the past. During the last 20 years, government agencies have tried to implement plans for lake and watershed management in many of the Spanish wetlands. In most cases, little was known of the lake dynamics and the previous history of the system, and consequently neither the "pristine" stage to be preserved nor the results of the conservation efforts could be evaluated. In these cases, the study of the sedimentary record bring the only consistent way to establish targets to be achieved in any management plan to restore those natural conditions (Hutchinson 2005; Cohen et al. 2005).

Climate and human impact are main factors controlling lake dynamics, but they have played a variable role through times, particularly in historical periods, and it is usually difficult ascribing specific limnological changes to specific human activities (Valero-Garcés et al. 2000a; Bradbury et al. 2004; Kienel et al. 2005). Paleolimnological studies have shown the effects of intensified erosion caused by land clearance in small (Hutchinson 2005) and large (Cohen et al. 2005) lakes, the development of hypereutrophic conditions (Bradbury et al. 2004) and the effects of tourism development and industrialization (Tylmann 2005). Reconstruction of environmental, anthropogenic and climatic forcings during historical times is also problematic because of the difficulties of obtaining an accurate chronology.

Here, we present results of paleolimnological investigations at Laguna Zoñar, the deepest (up to 15 m) lake in the lowlands of Andalucía (Spain). The lake is spring-fed and has no surface outlet, making it a good candidate for paleohydrological reconstructions. The lake is located in the Campiña Cordobesa, a region south of Córdoba with a long history of agricultural practices and currently dedicated almost exclusively to the cultivation of olive trees. Archaeological and historical records suggest that the lake and its watershed have been affected by human activities since Roman times and particularly in the late 19th and 20th centuries (Montilla Archaeological Museum Archives). In the 1960s, the waters from the springs were diverted for human use, lake level lowered, and the outlet creek became non-functional. Since the area was declared Natural Park in the early 1984, some conservation measurements have been implemented, lake level has recovered, and some vegetated littoral areas have been submerged. The rapid response of the lake system during the last decades to hydrological fluctuations and to human impact in the watershed provides an opportunity to assess how decadal to centennial hydrological and environmental changes are archived in lake sediments. Paleolimnological studies in Laguna Zoñar allow an assessment of the interaction between humans and the environment against a background of climate variability, and help to define conservation policies in Mediterranean wetlands and lakes.

Study site

Physical setting

The Laguna Zoñar is located in the southern margin of the Guadalquivir River Basin, close to the Sub-Betic tectonic domain of the Betic Range (IGME 1988) (Figure 1). Marine formations (yellowish sandstones, siltstones, marls and calcarenites) were deposited over the allochthonous sub-betic formations during the Upper Miocene. Triassic rocks composed of carbonates, claystones, evaporites and igneous rocks (ophiolites) outcrop along the faults. Karstic processes affecting the limestone and evaporite formations resulted in large and shallow depressions filled with fine clastic materials and reddish soils. Permanent and ephemeral lakes are located in larger depressions, likely related to faults. Laguna Zoñar, Rincón and Amarga are permanent brackish and saline lakes; Laguna Salobral, Tiscar and Jarales are ephemeral saline lakes.

The southern area of the Cordoba province has a semi-humid Mediterranean climate with about 538 mm of annual rainfall (range 1100–300 mm) (Figure 1a) and an average temperature of 16.1 °C. Over 70% of the precipitation occurs in late fall and early winter (November–December). Evapo-transpiration is estimated between 1500 and 1750 mm yr^{-1} (Enadimsa 1989).

Laguna Zoñar (37°29′00″ N, 4°41′22″ W, 300 m a.s.l.) is the deepest (up to 15.4 m) and largest (37 ha, surface area) of the 10 lakes that belong to the Natural Park of the Southern Córdoba (Figure 1). Its origin has been related to tectonic, karstic and diapiric activity (Moya 1984; Sánchez et al. 1992). The elongated lake shape, following the dominant regional tectonic direction (N 45°–50° E), indicates a clear tectonic control. On the other hand, the location close to Triassic outcrops stresses the importance of diapirism in the genesis of these structures. Finally, an open doline has

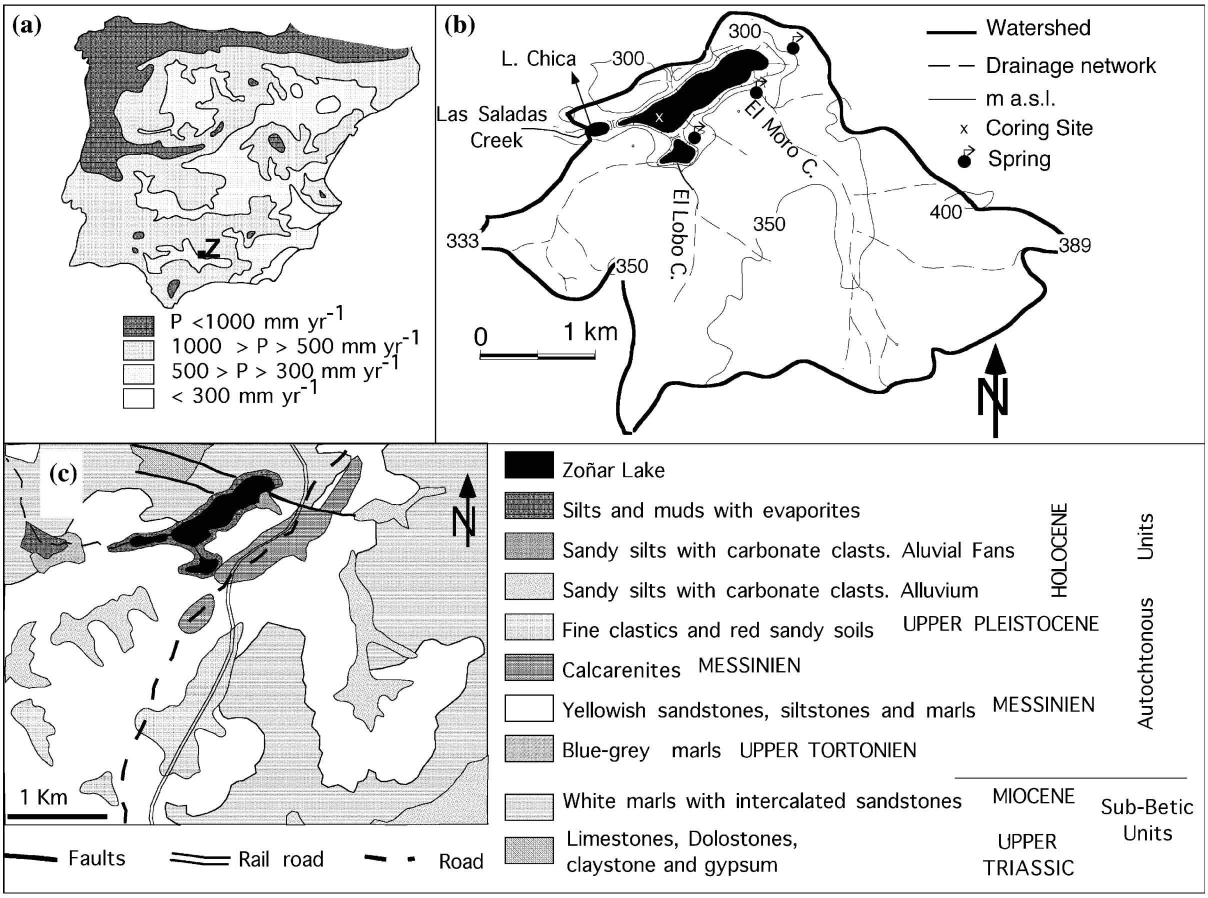

Figure 1. Geographic and Geological setting of Laguna Zoñar. (a) Annual Rainfall distribution in Spain (Capel Molina 1981) and location of the Laguna Zoñar (Z). (b) The Laguna Zoñar watershed. The main three spring are from SW to NE: Eucaliptus, Zoñar and Escobar. (c) Geological map of the Zoñar Lake (IGME 1988).

been mapped between the mouths of the Lobo and Moro creeks to the south and east of the lake (IGME 1988), raising the possibility of a karstic origin at least for some areas of the Zoñar Basin.

The lakes and wetlands comprise unique environments where some endangered species as the White-headed Duck (*Oxyura leucocephala)* live. Aquatic submerged vegetation is dominated by *Naja marina* and *Zannichellia pallustris*. A wide (5–15 m) area with littoral emergent vegetation (*Phragmites australis*, *Typha domingensis*) surrounded the lake before the early 1980s. The southeastern depression close to the mouth of the Lobo Creek is totally occupied by littoral vegetation.

Limnology and hydrology

The estimated lake water volume ranged between 2.8×10^6 m^3 during the 1980s (maximum water depth was 15.7 m) to 1.9×10^6 m^3 in the early 1990s (maximum water depth was 12.3 m) (detailed references in Enadimsa 1989 and Valero-Garcés et al. 2003). Waters are saline (2.4 g l^{-1}), alkaline (alkalinity values in surface waters between 3–5 mg l^{-1}; pH between 7.1 and 8.4) and dominated by (Cl^-) – (SO_4^{2-}) and Na^+ (Table 1). The lake is monomictic with a water temperature range between 9 and 27 °C and an average Secci Disc depth of 3 m. It shows a thermocline and oxycline at about 4 m depth between May and September (anoxic below 6 m), and it is mixed in winter (November–February).

Several ephemeral creeks enter the lake, but the main water input are the Zoñar, Escobar and Eucaliptus springs located in the southern margin of the lake. (Figure 1b). The Zoñar and Escobar springs are the most important (average flows, 3.5 l s^{-1} and 1 l s^{-1}, respectively). Springs waters are (HCO_3^-) – (Ca^{2+}), while lake waters are (Cl^-) – (Na^+). Currently, Laguna Zoñar does not have a surface outlet, although historically the Arroyo de las Salinas in the northwestern corner of the lake was functional and evacuated the water to the Cabra River and into the Genil River watershed. This outlet connected with a smaller, shallower lake (Laguna Chica) and some saline wetlands that occupied the valley.

The input to the lake during an average year (Enadimsa 1989) is as follows: rainfall, 0.177 Hm^3; runoff, 0.168 Hm^3; groundwater, 0.4 Hm^3; springs, 0.073 Hm^3. The only output is through evaporation, estimated as 0.8 Hm^3 per year. The surface area of the Lobo and Moro creeks watersheds are about 9.64 km^2 (Enadimsa 1989). Several small watersheds (8.23 km^2) are located over aquifer formations draining into the lake, and they are also part of the hydro-geological watershed of the lake. The main aquifers are the Miocene calcarenites and the Quaternary alluvial deposits, and the Laguna Zoñar is the discharge area for both aquifers. A hydrological survey during the year 1984–1985 (Moya 1986) and the data collected by the regional government since 1982 show that both lake level and spring flows quickly respond to rainfall during the hydrological year and also at a decadal time scale. During the prolonged dry period of 1992–1995, lake level dropped to a minimum of 11 m (Figure 2), but quickly recovered after the humid 1996–1997 years. The isotopic composition of the lakewaters plots to the right of δD- δ^{18}O meteoric water line (Valero-Garcés et al. 2003), suggesting that evaporative processes play a significant role in the lake hydrology.

Table 1. Main limnological parameters of Zoñar Lake.

Lake Surface	37 ha
Watershed surface area	876,78 ha
Max. depth	15.4
Salinity	1–2.4 g l^{-1}
E.C.	2.5–3 mS cm^{-1}
Water type	Cl–(HCO_3)–(SO_4)//Na–(Mg)–(Ca)
Alkalinity	3–5 mg l^{-1} (surface)
pH	8–9 (surface), 7.4–7.8 (bottom)
Chemocline	May–September (3–6 m water depth)
Oxygen	Anoxic bottom from May to September

Methods

The Laguna Zoñar watershed was identified and mapped using topographic and geological maps. Water chemical composition, lake level fluctuations and changes in land uses monitored since 1982 by Andalucian Government Environmental Agencies were compiled. A seismic survey was conducted with a 3.5 Khz seismic profiler in June 2002. Unfortunately, sediment penetration was extremely poor and only bathymetry and bottom basin morphology could be reconstructed (Valero-

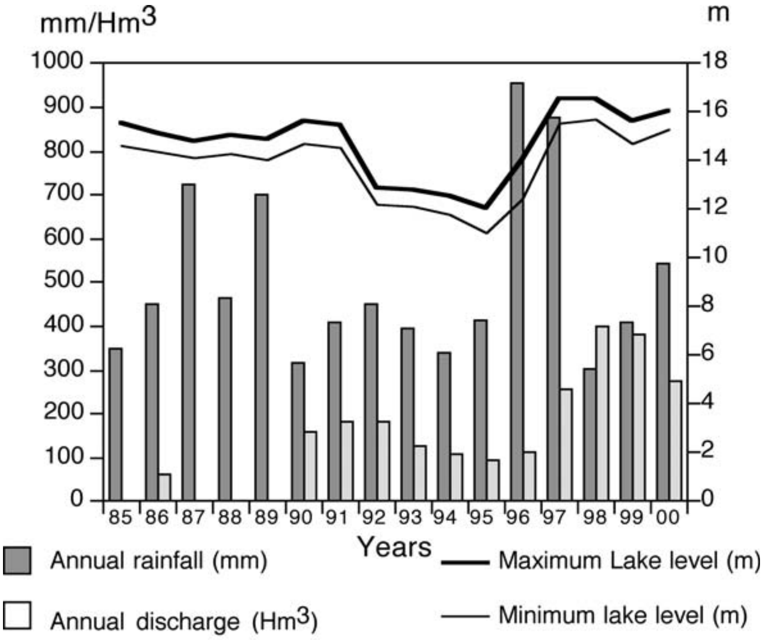

Figure 2. Relationship between annual water input (rainfall and spring flow) and lake level (maximum and minimum) during the period 1985–2000 (Data from the Environmental Agency of the Andalucian Government).

Garcés et al. 2003). Low seismic penetration is commonly caused by the presence of gas, and in Zoñar Lake it could result from decomposition of the abundant organic matter, both transported from the watershed and originated in the lake. Two sediment cores (ZON-01-1A: 1.72 m long, and ZON-01-1B, 1.17 m long) were retrieved in the deepest area of Laguna Zoñar (14.5 m water depth). The 1.17 m long core was sub-sampled in the field at 0.5 and 1 cm intervals for ^{210}Pb and ^{137}Cs dating. Magnetic susceptibility was measured with a Bartington magnetic susceptibility bridge every 2 cm only in core ZON-01-1A. The ZON-01-1A core was split in two halves and sedimentary facies were defined by macroscopic visual description including color, grain-size, sedimentary structures, fossil content, and by microscopic smear slide observations (Schnurrenberger et al. 2003). The core was sub-sampled for organic matter, carbonate, grain size, mineralogy, trace element geochemistry, pollen, diatoms, and ostracodes. Organic matter content was determined by loss-on-ignition analyses at 450 °C (Heiri et al. 2001) and carbonate content with a Barahona calcimeter (CSIC 1976). Although LOI is not an accurate stand-alone technique for the estimation of the carbon content (Boyle 2004; Santisteban et al. 2004) it provides a useful characterization of the sediment composition and the sedimentary facies. Whole sediment mineralogy was characterized by X-ray diffraction, and relatively mineral abundance was determined using peak intensity. Grain size was determined using a Coulter particle size analyzer (Buurman et al. 1997). Samples were treated with 10% hydrogen peroxide in a water-bath at 80 °C to eliminate the organic matter, a dispersant agent was added and ultrasound treatment was used prior to measurement.

Bulk sediment samples (0.5 g) were digested with HF (48%) in microwave (Milestone 1200 mls). Analyses for main elements composition were performed by atomic emission spectrometry using an inductively coupled plasma ICP-OES with solid state detector (Perkin Elmer Optima 3200 DV).

Pollen grains and spores were sampled every 10 cm and extracted in the laboratory by the classic chemical method (Moore et al. 1991) using Thoulet dense liquid (2.0) for palynomorph concentration) and *Lycopodium clavatum* spore tablets to calculate pollen concentration. Pollen diagrams were constructed using Tilia, TiliaGraph and Corel Draw software. Ostracode valves were separated from 2-cm-thick slices taken every 20 cm, following the procedure described by Forester (1988). Samples for diatom analysis were taken every 10 cm and prepared following standard procedures (Renberg 1990). At least 400 valves were counted per sample at 1000× using a Nikon Eclipse 600 microscope with Nomarski differential interference contrast optics. Raw diatom counts were converted to percent abundances.

The chronology is constrained by two AMS ^{14}C dates from the longer core ZON-01-1A (593 ± 38^{14}C yr BP at 124–126 cm depth, and 1771 ± 38^{14}C yr BP at 166–167, Table 2) analyzed at the Arizona Dating Facility and by ^{210}Pb and ^{137}Cs dating in the parallel shorter core (ZON-01-1B) performed at the St. Croix River Station (University of Minnesota). Both cores were correlated using sedimentary facies, grain size, and organic matter profiles (Figure 3).

Results

Chronology

The ^{210}Pb activities in the measured samples range between 0.384 and 1.658 pCi g^{-1} and fluctuate irregularly throughout the core (Figure 4). There is no discernable down-core trend and dates cannot be reliably modeled from the Zoñar ^{210}Pb data. The low ^{210}Pb activities values are somehow unexpected in a semi-humid region (average annual precipitation more than 500 mm) and it could be related to dilution of the atmospheric ^{210}Pb by high amounts of eroded soil. There is measurable radio-caesium to a depth of 75 cm in core ZON-01-1B with a clear peak at 70–71 cm. Although given the high variability in sedimentation rates it is not possible to exclude ^{137}Cs percolation, we feel confident that the peak represents the 1963 horizon. The cumulative mass of sediment overlying this 1963 peak indicates a very high rate of burial, which accounts for the low and irregular ^{210}Pb activities due to dilution of the atmospherically-derived ^{210}Pb by eroded soil material. The sharp drop-off in ^{137}Cs below 70–71 cm in Zoñar is also due to the lowest concentration of ^{137}Cs below the 1963 peak, according to the global pattern of the radioisotope fallout during the early period of atmospheric nuclear testing. Another factor in addition to the lower ^{137}Cs inputs was dilution from high erosion during this period in which soils had not yet become enriched in ^{137}Cs. A likely date of 1963 at 70–71 cm in core ZON-01-1B represents a mean sedimentation rate of 1.5 cm/yr^{-1} or 1.0 g cm^{-2} yr^{-1} during the last half century.

The ^{14}C AMS dates (593 ± 38^{14}C yr BP from aquatic macrophyte remains at the 124–126 cm depth, and 1771 ± 38^{14}C yr BP from pollen concentrate at 166–167 cm interval) indicate that the Zoñar core ZON-01-1A covers almost the last 2000 yrs and suggest the presence of a hiatus between the dated intervals (Figure 5). Sedimentological data support the presence of a hiatus at 140 cm depth where an erosive surface is evident. Based on the age of the upper sample (about AD 1350), and the 1963 horizon correlated between both cores, the average sedimentation rate for that interval (Sedimentary Units 3 and 2, see below) is about 1.6 mm yr^{-1}. The ^{210}Pb and ^{137}Cs analyses in the parallel core ZON-01-1B indicate a much higher sedimentation rate for the upper Unit 1 (between 0.7 and 1.8 cm yr^{-1}). This fits with the assessment of large fluvial input from the Lobo and Moro Creek during the last decades. The different thickness of the upper Unit 1 in core ZON-01-1A (25 cm) and core ZON-01-1B (70 cm) (Figures 3, 4 and 5) suggests an uneven sedimentation rate over the basin, characteristic of limnic systems dominated by fluvial processes. Sedimentation rates for laminated facies (Unit 2)

Table 2. AMS results for core ZON-01-1A.

Sample	Material	Lab number	δ^{13}C	^{14}C fraction Modern	Fm error	^{14}C yr BP	^{14}C yr Error	Calibrated year BP(2σ)
124—126 cm	Aquatic macrophytes	AA47855	−28.0	0.9288	0.0044	593	38	537–651
166–167 cm	Pollen concentrate	AA60921	−27.1	0.8021	0.0038	1771	38	1591–1817

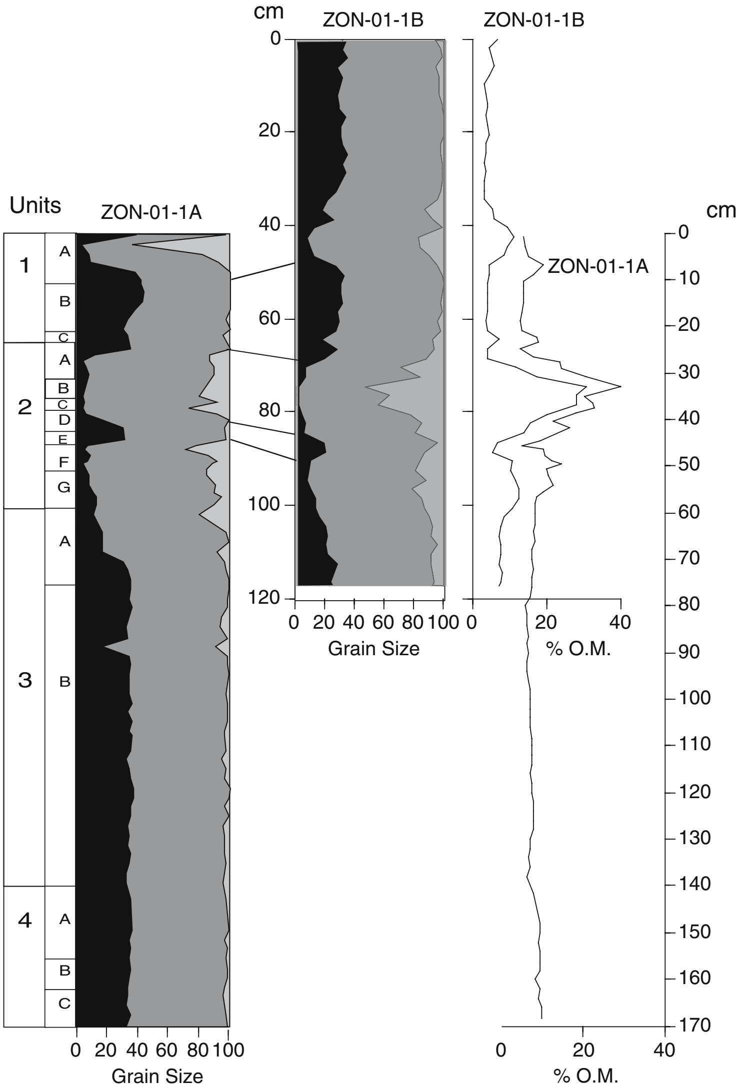

Figure 3. Correlation between the two cores ZON-01-1B and ZON-01-1A using sedimentary facies, grain size, and organic matter profiles.

are likely to be smaller than for massive facies of Unit 1 where clastic input is higher.

The age model including the ^{137}Cs-derived chronology for the upper Unit 1 and the ^{14}C AMS dates is coherent with the pollen data. The sharp increase in *Olea* pollen percentages between 30 and 40 cm in core ZON-01-1A (Figure 6) and between 75 and 100 cm in core ZON-01-1B (Figure 4) marks the *Olea* rise horizon due to the increase in olive tree cultivation in the region during the late 19th century.

Sedimentology

The 170 cm long core (ZON-01-1A) is composed of decimeter-bedded, massive, brownish and gray sediments with an intercalated (24–59 cm depth) interval composed of finely laminated, variegated sediments (Figure 5). Sediments are mostly composed of silicate (quartz and clays) and carbonate (calcite) grains, lacustrine and terrestrial organic matter and biogenic particles (diatoms, ostracodes). Eight sedimentary facies have been

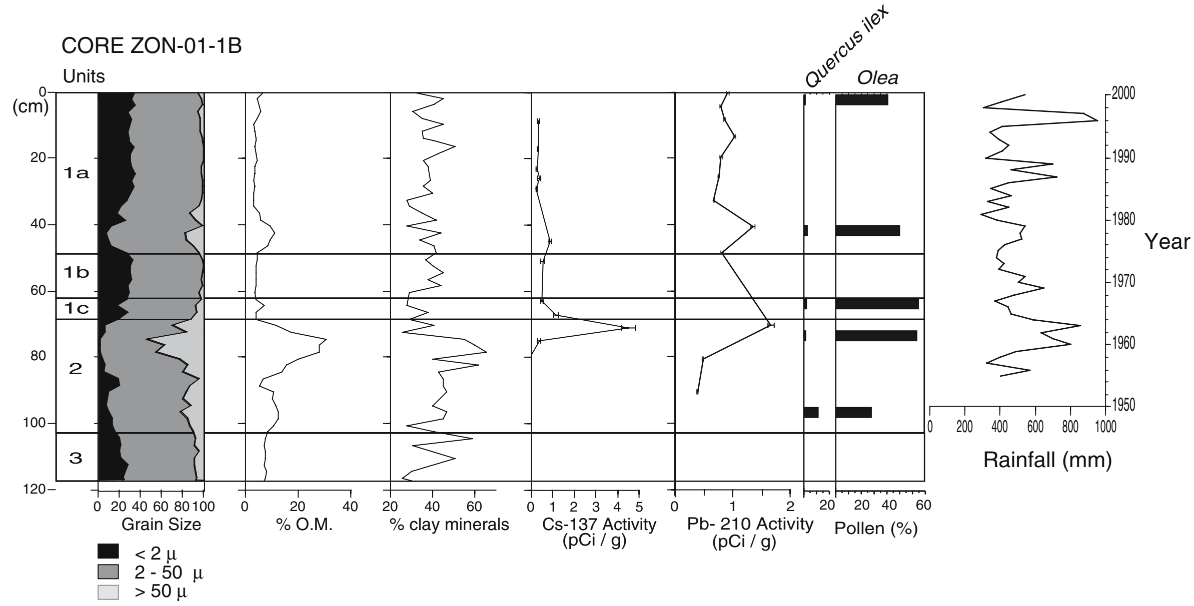

Figure 4. Sedimentary Units, sediment composition indicators (grain size distribution, organic matter and clay mineral content), selected pollen taxa, and profiles of ^{210}Pb and ^{137}Cs age from core ZON-01-1B. Sedimentary Units are correlated with those described in core ZON-01-1A. The inset shows the annual rainfall in the nearby Aguilar Meteorological Station since 1950s.

identified after integration of visual description, microscopic observation, grain size, and sediment composition analyses (LOI and XRD) (Table 3). Facies 1–5 are massive to faintly laminated carbonate mud with variable composition and bedding. Facies 6–8 are organic-rich, finely laminated facies. Facies are described in detail in Table 3 and in Valero-Garcés et al. (2003).

The eight facies in the Zoñar core group in two Facies Associations. Facies Association I integrates cm- to dm- bedded, massive to slightly laminated calcite muds (F 1, 2, 3 and 4). Facies Association II integrates finely laminated (F 7 and 8), organic-rich (F 6) and cm-thick, massive, calcite mud (F 5) facies. Facies Association I represents deposition in Laguna Zoñar during periods of variable, but significant clastic input. The absence of lamination in the sediments indicates intense bioturbation activity, and likely frequent oxic conditions in the water column. Although salinity and lake level during deposition of these calcite mud could vary, the lacustrine system remained a freshwater lake. The higher siliciclastic content, the presence of macrophyte rests and intraclasts, and the erosive nature of the lower contacts in some layers indicate depositional conditions for Facies 4 characterized by higher energy and higher fluvial input. These conditions would occur in the littoral environments of Laguna Zoñar and also during flooding episodes that could reach the deepest areas of the lake. Gray facies represent mixed lacustrine and alluvial deposition in the central areas of the lake during flooding episodes. Brown layers, with higher carbonate and diatom content and presence of ostracodes, would point to more littoral conditions, and, consequently, to lower lake levels. Lake level fluctuated during deposition of facies association I at relatively higher stand, close to today's levels.

Facies Association II represents deposition in Laguna Zoñar during a period of lower clastic input, and chemical and limnological conditions more conducive to development of benthic bacterial–algal communities. Preservation of fine laminations indicates absence of bioturbation, most likely provoked by reduced oxygen in the bottom waters. The irregular nature of the lamination suggests laminae are not varves. Variegated, organic-rich laminated facies occur in many brackish-saline lakes where conditions are more suitable for algal–bacterial communities than for other lacustrine biota and where anoxia

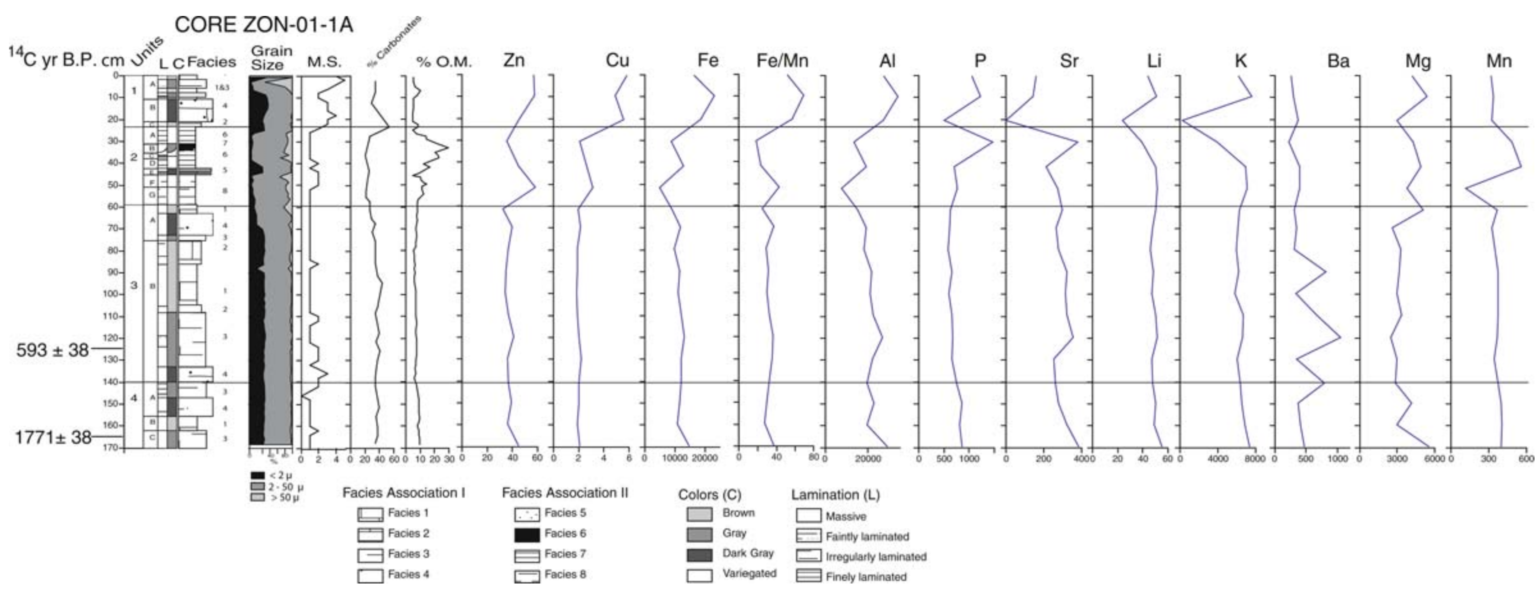

Figure 5. Sedimentary facies and Units, magnetic susceptibility, sediment composition indicators (grain size distribution, organic matter and carbonate content), selected geochemical profiles (values in ppm) and ^{14}C AMS dates from core ZON-01-1A.

Table 3. Sedimentary facies in Zoñar cores.

Facies	Description
Calcitic facies	
Facies 1. cm-bedded, massive to faintly laminated, brownish calcite mud.	These are cm-thick (Units 1 and 4) and dm-thick (Unit 3) layers with gradational boundaries. O.M. <10%, Quartz <10%. Presence of relatively large (40 × 10 microns) charcoal particles, and oxidized organic matter particles (soil-origin). Depositional subenvironment: sublittoral to distal lacustrine.
Facies 2. Laminated (1–5 mm), dark and light brownish calcite mud.	Layers are less than 5 cm thick, with sharp, planar contacts. Microfacies similar to Facies 1. Fine-grained (<10 microns) calcite is commonly dominant. Quartz and sulfide contents are lower than in Facies 1. Depositional subenvironment: distal lacustrine.
Facies 3. Massive to faintly laminated gray calcite silty mud.	These are cm- to dm-thick layers. Grain size coarser than Facies 1 and 2. Quartz grains may be larger than 100 microns. Depositional subenvironment: sublittoral lacustrine with alluvial influence.
Facies 4. cm-to dm-bedded, faintly laminated to massive, dark gray silty calcite mud with organic matter.	Dark gray layers are between 5 and 10 cm thick and they commonly show sharp boundaries with the underlying beds and more gradational with the overlying beds. Both calcite grains populations are present, although the coarser grains commonly dominate. Relatively high quartz content (up to 15%). Both carbonate and quartz grains are coarser than in other facies. Sulfide content is the highest of the massive facies (1–4). Organic matter remains showing cell-structures are common and also opaque, oxidized, organic matter fragments. Depositional subenvironment: distal to sublittoral with alluvial influence.
Facies 5. cm-thick, massive gray calcite silty mud.	Massive, cm-thick layers (1–2 cm thick) with sharp upper and lower boundaries. They are composed of homogeneous dark gray silty calcite mud. Quartz content is relatively higher than in previous facies, although never more than 10%. Sulfide content is high (up to 15%). Depositional subenvironment: flood deposit in distal areas.
Organic facies	
Facies 6. cm-thick, massive, dark brown organic ooze.	These are cm-thick layers with irregular, erosive lower boundaries and sharp, planar upper boundaries. Homogeneous, greenish–brownish, amorphous remains of aquatic origin (algal). Diatom content is also high, up to 15–20%. Calcite content is relatively low (about 30%) and mostly composed of rice-shaped, euhedral, about 10 microns long crystals. Depositional subenvironment: benthic algal mat in distal areas.
Facies 7. Finely laminated (about 1 mm thick), variegated (gray, brown, white, green) organic ooze and calcite mud.	Four different types of laminae: gray, brown, green and white. Organic matter content is high (20–30%), and quartz is low (<10%), although always present. Sulfide content is variable (5–15%), higher in the darker gray laminae. Small (<10 microns), rice-shaped crystals dominate the calcite components. Green laminae are mostly composed of diatoms and the sediment type ranges from diatom ooze to carbonate diatomaceous mud. Brown laminae show large composition variability from organic (algal and diatomaceous) ooze to organic, diatomaceous calcite mud. Whitish to light gray laminae are fine calcite mud (euhedral crystals between 5–10 μ long). Gray laminae are calcite mud with higher content of coarser calcite grains, and lower diatom and organic matter content. Clay minerals dominate over quartz grains. Depositional environment: brackish to saline lake with benthic algal mat.
Facies 8. Irregularly laminated (>2 mm thick) variegated (gray, brown, green) organic ooze and calcite mud.	Similar to facies 7, but laminae are thicker and more irregular in thickness and the nature of contacts varies from sharp to diffuse, and sometimes crenulated. Gray and brown laminae dominate. Depositional subenvironment: brackish to saline lake with benthic algal mat.

is facilitated by chemical water stratification: Lake Bogoria, Africa (Renaut and Tiercelin 1994), Mono Lake, USA (Newton 1994), Lake Hayward, Australia (Coshell and Rosen 1994), Salada Chiprana, Spain (Valero-Garcés et al. 2000a) are some examples. Water depth for this laminated facies ranges from playa-lake settings to relatively deep meromictic lakes. In Zoñar sediment core, diatom blooms and 'carbonate whitings' events are registered as thin green and white laminae, respectively. Coarser grain size in the laminated intervals from Unit 2 is caused by the abundance of diatoms (Figure 5). Rare flooding episodes would deposit thin clay-rich gray laminae (Facies 5). Clay mineral content is higher in these laminated, organic-rich facies than in the massive calcite mud (Figure 4) suggesting lower energy and deposition out of suspension. Relatively higher salinities and lower lake levels could be expected in Laguna Zoñar during deposition of this facies association.

Four main units have been identified in core ZON-01-1A (Figure 5): Unit 1 (0–24 cm) composed of cm-bedded brown and gray sediments; Unit 2 (24–59 cm) composed of laminated sediments; Unit 3 (59–140 cm) composed of decimeter-bedded gray and brown sediments, and Unit 4 (140–170 cm) composed of cm-bedded gray and brown sediments. The boundaries between the upper three units are defined by the occurrence of fine (<1 mm) lamination in Unit 2; the limit between Units 3 and 4 is marked by the occurrence of an irregular, erosive surface. A number of subunits have been defined according to the facies (Figure 5 and see also Valero-Garcés et al. 2003 for a detailed stratigraphy). The upper three units have been correlated between both cores using sedimentary facies, and sediment composition (organic matter contents and grain size). Facies association II only occurs in Unit 2 and facies association I in Units 1, 3 and 4.

Geochemistry

The chemical composition profiles (Figure 5) show more constant values in the lower Units 4 and 3 and higher variability in the upper Units 2 and 1. Aluminum and iron contents are relatively constant in Units 3 and 4 (Fe: 1–1.2%; Al: 1.5–2.5%), slightly decrease at the base of Unit 2 (Fe: 0.5%; Al:0.7%) and start an increasing trend at 50 cm (base of subunit 2 F) till almost the top of Unit 1 (Fe: 1.8%; Al: 2.7%). The top sample shows a slight decrease in both, aluminum and iron. Aluminum reflects the Al-silicates content of the sediments, so it can be considered as a proxy for alluvial input. Iron is also an indicative of soil erosion in the watershed, but it also may be adsorbed on clays, or precipitated as colloids and oxides. Both profiles are coherent with increasing erosion in the Zoñar watershed during deposition of Unit 2 and 1, and a small decrease in the last years. Peaks in Fe concentration coincided with peaks in the Fe/Mn ratio, which has been interpreted in other lakes as an evidence of changes in supply from the catchment more than changes in the redox conditions in the lake (Boyle 2001). Potassium and lithium show constant compositions through the sequence except in the organic, laminated facies of Unit 2. Metals such as zinc and copper used in fertilizers also show constant values in Units 4 and 3 and increasing values in Units 2 and particularly 1 (almost double for Zn and threefold for Cu). No signs of lowering content of those elements in the sediments occur at the top sample. Manganese values peak at the laminated, algal mat intervals and coincide with lower values of the Fe/Mn ratio. Higher Mn concentrations in the sediments seem related to strong redox gradients at the sediment/water interface, as those expected during deposition of the laminated mats. Phosphorous concentrations are higher in the laminated facies of Unit 2 and Unit 1, and their peaks correlate with intervals of higher organic matter content. Lower values of Sr in the upper Unit 1 could be explained by dilution due to increased input of low Sr marine sediments (Miocene calcarenites).

Ostracods

The ostracode assemblage from Zoñar (ZON-01-1A) is characterized by individuals of *Ilyocypris* sp., a few *Candona* sp. and *Potamocypris* sp. This assemblage suggests an environment with shallow and flowing water likely affected by stream input. The number of ostracode valves in the sediment samples is very low, and some samples lacked any ostracods. The sample from the top sediments (Unit 1: 2–4 cm) contains only *Ilyocypris* sp., suggesting significant stream input into the lake. Samples from Unit 2 (22–24, 42–44 cm intervals), the top of Unit 3 (62–64 cm interval) and another sample from a faintly laminated interval in Unit 3 (122–124 cm) are devoid of ostracodes. The presence of authigenic calcite in these intervals suggests that the absence of ostracodes is not due to carbonate dissolution processes. Most likely, restricted water circulation and low oxygen contents in the deep areas of the lake as indicated by laminated sediments impeded survival of benthic ostracodes. Most individuals in the remaining samples from Units 3 and 4 are *Ilyocypris* sp.

(102–104, 142–144 cm), indicating oxic bottom conditions and significant stream input into the lake prior to deposition of Unit 2. *Candona* sp. is only present at 82–84 cm, which could indicate relatively deeper waters with more restricted circulation. Finally, the sample from Unit 4 (162–164 cm) is dominated by *Potamocypris* sp. individuals, a nektic ostracode that is typical of littoral environments.

Pollen

Pollen assemblages in samples from both cores are typical of Mediterranean landscapes dominated by *Olea europaea*, evergreen*Quercus* and Cupressaceae. *Olea* percentages are the highest in the top samples (up to 80%) reflecting the large increase in olive tree cultivation since the late 19th century. The relative abundances of pollen taxa in core ZON-01-1A are shown in Figure 6. A few samples were analyzed in core ZON-01-1B (Figure 4) to correlate both cores. Three pollen zones have been identified based on the pollen assemblages.

Pollen Zone ZO-III (160–140 cm). This zone corresponds to sedimentary Unit 4. Terrestrial plants are dominated by Mediterranean trees and shrubs (50–60%): evergreen *Quercus*, *Pistacia*, *Rhamnus*, *Thymelaea*, *Lycium*, *Cistus*, Ericaceae, *Ephedra*, Fabaceae (Genisteae), Lamiaceae, *Hedera helix*, etc. *Olea* is also present, but in lower percentages than in the upper zones. The submerged *Myriophyllum spicatum* reaches the maximum abundances in this zone, suggesting higher lake levels and fresh waters. The abundance of *Botryococcus* and the occurrence of colonies of *Pediastrum* also points to relatively high lake levels. Algal spores and spiny acritarch show the highest percentages and fungal remains the lowest in the whole sequence. The presence of Zignemataceae zigospores, *Gloeotrichia* sheats, *Rivularia* heterocyst, the fungal spore types *Pluricellaesporites* and *Dyadosporites* (Carrión et al. 2001), and the microfossils 179 and 989 (Carrión and van Geel 1999) indicate a mesoeutrophic aquatic environment.

Pollen Zone ZO-II (140–35 cm) includes sedimentary Units 3 and the lower part of Unit 2. The AP/NAP ratio slightly increases. The low *Pinus* percentages suggest long distance input. Terrestrial vegetation is similar than the previous zone, although a growing trend in *Olea* suggests increasing cultivation at a regional scale or just around the lake. *Myriophyllum* percentages remain low and *Tamarix* disappears in the lower part of this unit. Hygrophytes abundance and variety increase (Cyperaceae, *Juncus*, *Typha*, *Sparganium)*. In the upper part of pollen zone II, corresponding to sedimentary Unit 2, *Myriophyllum* decreases until disappearing at the top of the unit, and *Sparganium* increases suggesting expanding littoral areas. Algal spores are still well represented, although in lower percentages than in zone III. This unit is characterized by the highest percentages of fungal spores and other palynomorphs: *Palaeomycites*, *Monoporisporites*, *Chaetomium*, *Diporisporites*, *Dyadosporites*, *Pluricellaesporites*, *Didimoporisporonites*, *Dicellaesporites* (Carrión et al. 2001). These assemblages represent increasing littoral areas colonized by plants and also an increase in trophic conditions in the lake, likely with an increase in particulate organic matter in the water.

Pollen Zone ZO-I (35–0 cm) corresponds to the upper sedimentary Unit 2 and Unit 1. *Olea* is the dominant taxa, which reflects the large increase in olive tree cultivation since the late 19th century (Ortega Alba 1975) The typical Mediterranean component (Cupressaceae, evergreen *Quercus*, *Lycium*, *Cistus*, *Ephedra*, *Genista-Adenocarpus*, etc.) is well represented. Aquatic macrophytes taxa decrease and eventually *Myriophyllum* and *Potamogeton* disappear. However, *Potamogeton* and *Tamarix* appear again at the top of the sequence, suggesting a relative fresher waters and an increase in lake level during modern times.

In pollen zones III and II, indicators of human activity are common: *Rumex*, *Plantago*, *Vitis*, Cichorioideae, Chenopodiaceae, *Artemisia*, *Centaurea*, Urticaceae, and also *Cerealia* type. In pollen zone I, most of these taxa disappear. Algal spores are also greatly reduced. Fungal spores and Ascomycete sporocarps are abundant, which suggests that eutrophic conditions are similar to those of the previous pollen zone II. However, eutrophic conditions were not extremely high, because the fungal spores percentages are relatively small compared to other sites (Carrión and Navarro 2002). The presence of *Pseudoschizaea* cysts has been interpreted as an indicator of seasonal subaerial exposure in the lake margins (Carrión 2002), although the paleocology of this organism remains unclear (Scott 1992).

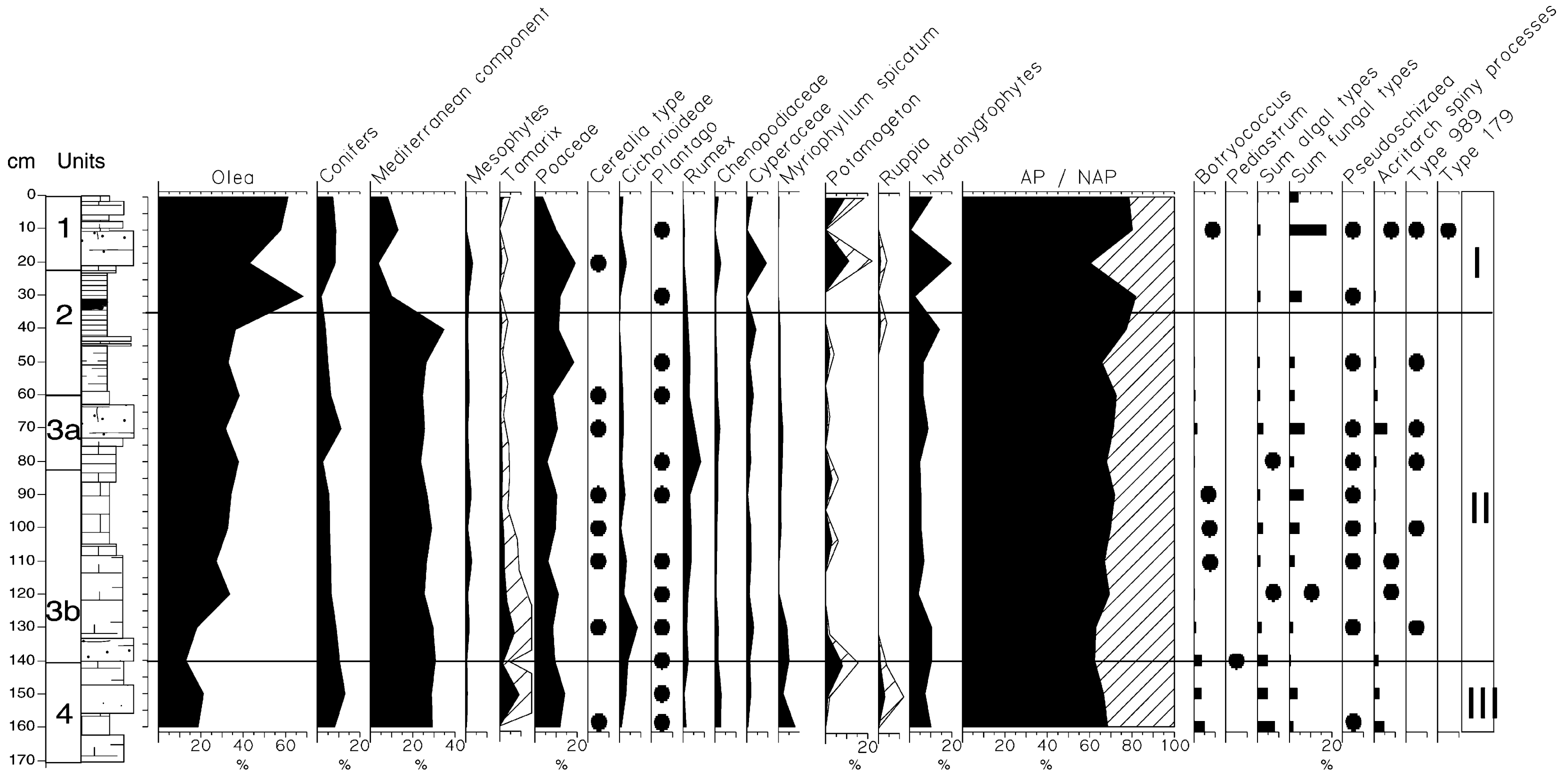

Figure 6. Pollen diagram with main taxa for core ZON-01-1A. (hatched pattern 5× exaggeration). Sedimentary facies associations are also shown. Dots indicate 'presence' with percentages minor than 2%.

Only five samples were analyzed in core ZON-01-1B to characterize the pollen assemblages of the main units defined (Figure 4). The location of the *Olive* rise (between 75 and 100 cm) provides a time horizon to correlate both cores.

Pollen assemblages from aquatic and littoral plants serve as paleohydrological indicators. Pollen samples from Zone III contain the highest percentages of *Myriophyllum spicatum* and relatively high of *Potamogeton* and *Ruppia*. Although *Ruppia* is an indicator of moderate saline waters, the pollen association suggest lake waters were fresher than today, likely due to a higher fluvial input. In zone II, taxonomic diversity is the highest, and pollen percentages of plants from vegetated lake margins (*Tamarix*, *Sparganium*) increase. Freshwater aquatic plants progressively decrease and hygrophytes plants typical of littoral vegetation reach the highest percentages at the top of this zone. At this time, littoral vegetated areas surrounding the lake would have reached the largest size and lake waters would be chemically more concentrated. In zone I, the decrease in hygrophyte pollen content and the increase in *Potamogeton* and *Myriophyllum* is interpreted as a reflection of the decreasing surface area occupied by the vegetated littoral zone when lake levels were relatively higher.

Diatoms

Diatom assemblages in core ZON-01-1A are dominated by the tychoplanktonic *Fragilaria brevistriata*, and the periphytic *Cocconeis neothumensis* throughout most of the core (Figure 7). Some levels have also large numbers of the planktonic *Cyclotella meneghiniana* and the periphytic *Amphora pediculus* among others. Reworked marine diatom taxa include *Chaetoceros* resting spores, *Actinoptychus senarius*, *Thalassionema nitzschioides*, *Asteromphalus* sp. and *Neodenticula* sp. Their presence indicates periods of increased sediment input to the lake from the Miocene marine calcarenites, the dominant lithology in the watershed. Five diatom assemblage zones (DAZs) have been defined (Figure 7).

DAZ ZON-V (161–141 cm)

This zone is dominated by the salinity – indifferent (Tapia et al. 2003) euplanktonic *Cyclotella meneghiniana* and, towards the top of the zone, by the freshwater tychoplanktonic *Fragilaria brevistriata*. These taxa suggest an environment characterized by open water conditions and moderate depth at the coring site.

DAZ ZON-IV (141–111 cm)

Fragilaria brevistriata and the freshwater benthic *Amphora pediculus* are the main taxa in this zone. The co-dominance of the latter in the assemblage points to a lowering of the lake level compared to the previous DAZ.

DAZ ZON-III (111–71 cm)

Fragilaria brevistriata is still a co-dominating taxa in this zone, but the oligosaline benthic *Cocconeis neothumensis* becomes the predominant species, which suggests, as in the previous zone, lower lake levels, but of more saline conditions.

DAZ ZON-II (71–51 cm)

Both *Fragilaria brevistriata* and *Cocconeis neothumensis* show a decrease in this zone which is dominated by the planktonic *Cyclotella meneghiniana*, suggesting a new increase in water levels.

DAZ ZON-I (51–30 cm)

This zone represents a substantial change in diatom assemblages, which are now dominated by benthic forms of both freshwater (mainly *Cymbella microcephala* and *Fragilaria capucina* var. *gracilis*) and saline (mainly *Cymbella affinis*, *Cocconeis placentula* and *Nitzschia elegantula*) preferences. This zone also shows an important increase in the allochthonous marine taxa such as *Chaetoceros* spp. and *Thalassionema nitzschioides*. The dominance of benthic taxa suggest lower lake levels, but the mixture of freshwater and saline forms also points to rapid changes in the contribution of freshwaters. Flooding episodes could explain not only those changes, but the increase in the percentages of marine reworked taxa as well.

The upper 30 cm of the core is considered a non-countable interval. Some levels show no diatom preservation, and the levels where diatoms were preserved are almost 100% composed of non-countable *Thalassionema* spp. small fragments. This zone denotes an increase in the erosion activity of the basin responsible for the input of allochthonous diatoms to the lake from the Miocene marine rocks.

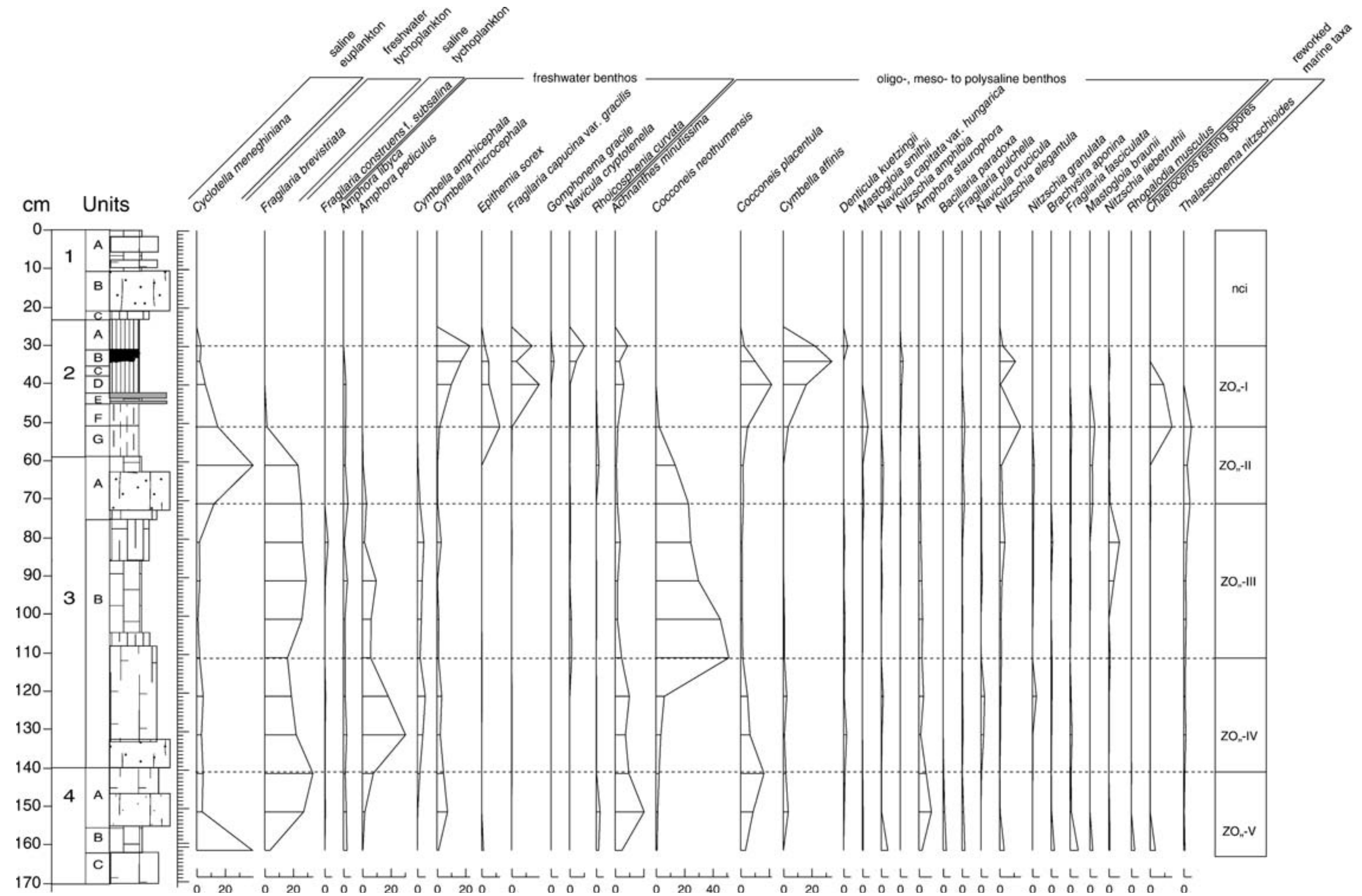

Figure 7. Diatom percent abundance diagram of ZON-01-1A for taxa ≥2% (nci = non countable interval). Sedimentary facies associations are also shown.

Discussion

Results from the two studied cores provide a record of past climate, environmental and human-induced changes in the Laguna Zoñar watershed since early Medieval times, and also an opportunity to test the impact of the restoration measurements applied by the regional government during the last 20 years. In Figure 8, we summarize the proxy-records and compare them with the main historical events and the available climate reconstructions. We distinguish six main periods of human and climatic interactions in the watershed:

Period 6: prior to mid-13th century

This period is represented by sedimentary Unit 4, composed of facies arranged in cm-thick sequences that suggests relatively rapid changes in depositional environments in a lake highly influenced by fluvial input, and with prevalent oxic conditions at the bottom of the lake. The boundaries between the three subunits could correspond to depositional hiati, however the only sedimentological evidence for an unconformity occurs at the top of the unit, where an erosive surface marks the base of the next sequence. Chronological control for this unit is provided by the basal AMS date (165 cm, 1771 ± 38^{14}C yr BP, ca. AD 300) and the estimate age of the erosive surface at the top (around 1250 AD). Most likely, the unit represents deposition during the post-Roman and early Visigoth Age; the sediments corresponding to the Muslim Period have been eroded.

A strong fluvial influence in this sediment interval is marked by coarser, more clastic facies arranged in fining upward sequence, and the presence of *Potamocypris* sp., a nektic ostracode typical of littoral environments. The dominance of planktonic diatoms and aquatic plants such as *Myriophyllum* points to relatively higher lake levels than today and probably fresh waters with low chemical concentrations. The Arroyo de las Salinas outlet was likely functional and lake level was at the highest. The large flooding episode at the base of Unit 3 (140 cm, facies 4, magnetic susceptibility peak) was more related to climatic factors (increase in precipitation) than to increased disturbance of the watershed. Enhanced fluvial activity has been documented in several Iberian river basins during the cooler Holocene climate events such as the Early Medieval Ice Advance (6–10th century) and the Little Ice Age (15–19th century), and less significant fluvial dynamics occurred during the Medieval Climate Optimum (Peña-Monné et al. 1998; Benito et al. 2003). The 10–11th century is generally characterized in Europe as one of the warmest historic periods (the so-called Medieval Warm Period). In northern and central Europe severe winters were somewhat less frequent and less extreme during the MWP, AD 900–1300, than in the ninth century and from 1300 to 1900 (Pfister et al. 1998). In Spain, high flood frequencies were registered in most of the Atlantic watersheds during the late MWP (AD 1160–1210) (Benito et al. 2003).

Probably, the regional vegetation during this period comprised sclerophyllous formations of evergreen *Quercus*, *Olea europaea sylvestris*, *Ceratonia siliqua*, *Pinus*, *Juniperus* and Mediterranean shrubs; mesohygrophytic vegetation with deciduous trees in protected areas as humid gorges, rivers (*Alnus*, *Fraxinus*, *Populus*, *Ulmus*) and some herbaceous extensions. The high percentages of *Olea* in the Zoñar record since the base indicate that olive trees were a significant element of the Mediterranean landscape. In diverse paleopalynological studies from the Mediterranean area of Iberia, a notable presence of *Olea* has been detected since the last glaciation (Carrión 1992; Burjachs and Julià 1994; Pérez-Obiol and Julià 1994; Carrión and van Geel 1999; Carrión 2002; Pantaleón-Cano et al. 2003). As far as more recent times are concerned, the presence of *Olea* is also detected in northern regions of Iberia from the Early Holocene (Davis 1994; Riera and Esteban 1994), and the mid-Holocene in the Balearic islands (Yll et al. 1996, 1997).

Nevertheless, the expansion of *Olea* in historical times is due to human intervention. The cultivated olive was introduced in Spain by the Phoenicians and Greeks, although wild olive was probably used by the indigenous people. An increase in pollen percentages around 5–10% appears in several sites in Portugal (Van den Brink and Janssen 1985) and northeastern Spain (Saladas de Alcañiz: Davis 1994; Estaña lake: Riera et al. 2004) coinciding with the Roman Period. Various tree and shrub taxa (*Olea*, *Castanea*, *Juglans*, *Vitis*, *Fraxinus*, *Platanus*, etc.) are clearly cultivated from

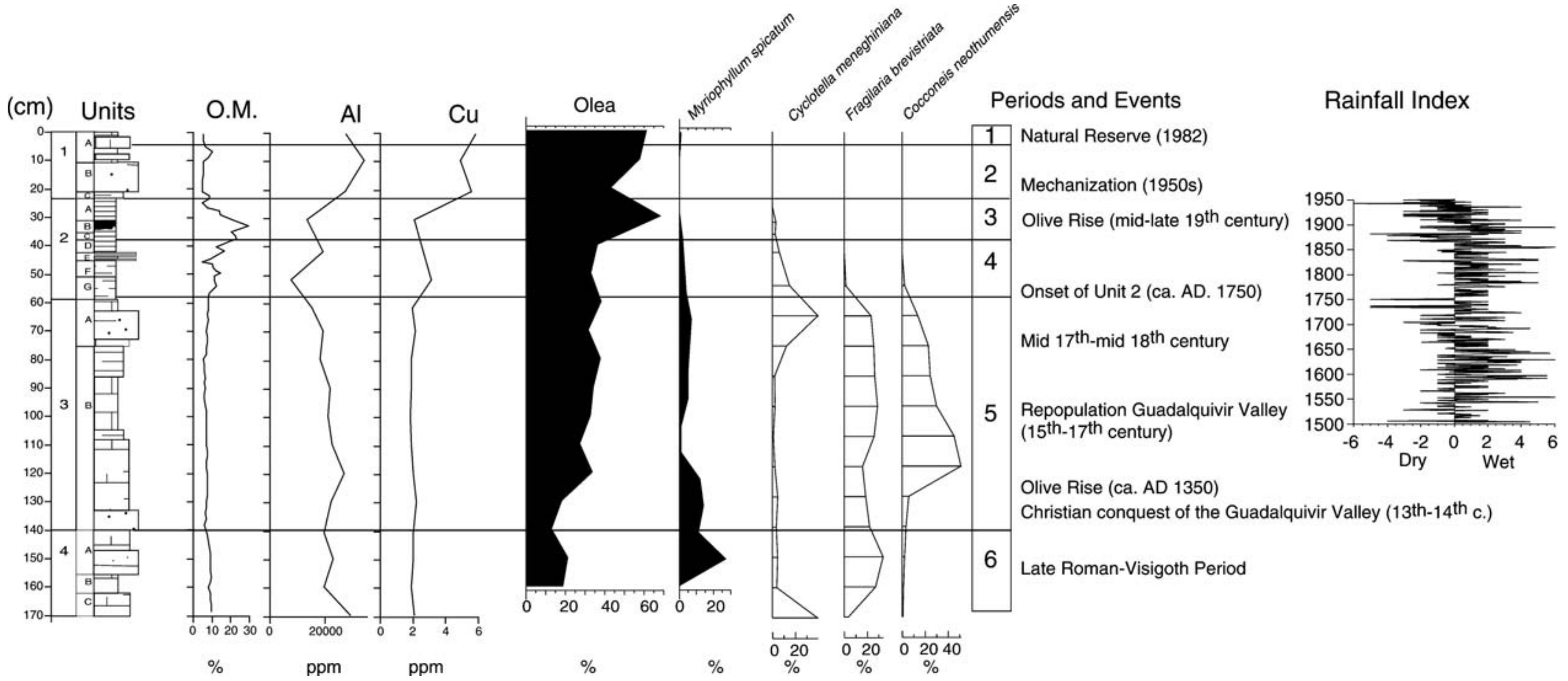

Figure 8. Summary of the environmental and climate changes reconstructed from several proxy records in the Zoñar cores and correlation with the main historic events in the watershed. Sedimentary facies and Units as in Figure 4. The rainfall index (Rodrigo et al. 1999, see text) is also indicated.

3000 yr BP onwards in the western Mediterranean (Davis 1994; Sadori and Narcisi 2001; Pantaleón-Cano et al. 2003). In Central Italy, cultivation of *Castanea, Juglans* and *Olea* started at 3000–2900 cal yr BP (Mercuri et al. 2002). The first significant spread of *Olea* in Lago di Pergusa (Sicily) occurs between 3300 and 3000 years BP and it could be interpreted either as the beginning of extensive cultivation or increasing arid conditions; however, the maximum expansion of *Olea* clearly related to human activities occurs between 2600 and 2400 years BP (Sadori and Narcisi 2001).

The Visigoth period (415–711 yr AD) is generally characterized by a progressive depopulation of urban areas and lower agricultural use of the land. However, some pollen records do not show changes in olive percentages, suggesting that areas already farmed during Roman times continued in production (Van den Brink and Janssen 1985; Riera et al. 2004). Changes in agricultural use of the land were more significant during the Arab period in southern Spain and particularly the Guadalquivir River Valley. Lagoa Comprida in Portugal (Van den Brink and Janssen 1985) shows a sharp rise in olive percentages up to 20% during this period. The city of Cordoba attained a population over 500,000, the largest and most prosperous city in Europe and the Mediterranean Basin. Although there is no sediment record from this period in the analyzed Zoñar cores, historical documents show that the agricultural landscape of the Campiña Cordobesa was dominated by olive tree orchards since the Roman times.

Period 5: From the Christian conquest till the end of the 'golden age' (13–18th centuries)

This period corresponds to sedimentary Unit 3 and it is characterized by two sequences (subunit 3B and 3A), both showing an upward trend towards lighter colors, and increasing lacustrine (authighenic and biogenic) component in the sediments: gray, massive carbonate mud (F 3), massive brown (F 2), and finely laminated brown sediments (F 1). These sedimentological features point to reducing fluvial input into the lake and the dominance of 'lacustrine' processes in the deepest area were the core was retrieved. The decrease in *Myriophyllum spicatum* and other aquatic plants and the generally low values during this unit suggest lower lake levels and more concentrated waters. A general trend to increased percentages of benthic diatoms of saline condition supports this interpretation.

A relatively small decrease in olive pollen occurs at the base of this unit that could be related to some of the events in the Guadalquivir Valley during the 13–14th centuries, although the interpretations must be cautious because the coarse pollen and chronological resolution. The city of Cordoba was conquered by the Christians in AD 1236, and the Guadalquivir River Valley was repopulated during the 13th and 14th centuries. However, till the conquest of the Kingdom of Granada (1492), the region was the border between Christian and Muslim Kingdoms and military incursions were frequent. The forest and fields were usually burnt during the military fights, and consequently, some farmland was abandoned and farming substituted by sheep and goat husbandry. The small decrease in pollen percentages at the base of pollen zone II could be a reflection of the agricultural regression during the 13th and 14th centuries in the Guadalquivir Valley.

Historical data show three periods of accelerated human impact on the landscape of the Cordoba Province characterized by increasing cultivated land (Ortega Alba 1975): (i) between the Christian conquest of the Guadalquivir River valley and the 18th century, (ii) the 19th century after Church-owned land was expropriated and more intensively cultivated, and (iii) the mid-20th century. The progressive increase in olive pollen in Unit 3 is a reflection of the intensification of agriculture in the Campiña Cordobesa since the 15th century. Once the border between Christian and Muslim kingdoms was more secure and particularly after the fall of Granada, the Campiña experienced a period of rapid transformation of the landscape due to the new structure of the land, the increase in agricultural exploitations, and a higher olive production. This would be the 'first' olive rise that occurs in the record at about 125 cm depth. Olive pollen doubled and maintained a slightly increasing trend throughout this period. Chemical profiles do not show an increase in soil erosion; aluminum concentrations slightly decline upcore as an evidence of smaller alluvial contribution to the lake sediments.

The rise in olive cultivation started in the 14th and 15th centuries throughout Spain, and continued during the 16–17th centuries characterized by an increased agricultural intensification. In northeastern Spain, when the Christian conquest was completed there are not references to olive groves, but later, in 1300 AD, vineyards were replaced by olive cultivations and the production of oil reached a peak in the 14th century (Riera et al. 2004). Many olive curves from Spanish pollen sites show the largest increase during the Holocene at about the 16th century, particularly in central and northeastern sites (Davis 1994; Riera et al. 2004). In spite of some unfavorable climatic conditions during the first part of the LIA, as frequent severe frost during the winter in Córdoba and periods when the Guadalquivir River froze over at the end of the 16th century (Font 1988), pollen record in Zoñar shows high values and a slight increase. The significant decline observed in Lagoa Comprida at about 500 yrs BP, interpreted as a decline in agricultural productivity (Van den Brink and Janssen 1985) and other periods of known social unrest and population crises as the 15th century do not show in the Zoñar record. However, the relatively low resolution of our sampling precludes any conclusion on the impact of such events on olive production in the Campiña Cordobesa.

The Modern Age Period (17–18th centuries) would correspond to subunit 3A (AD 1660–1760) composed of another fining upward sequence with gray, more clastic facies 4 at the base topped by brown facies 1 and finely laminated facies. A general decrease in fine particles (<2 microns) indicates a reduction in clastic input to the lake towards the top of this interval. Microscopic observations indicate that the higher percentages of large particles reflect the increase in diatom content and not of coarse clastic particles. This sequence represents another gradual transition from a clastic-dominated lake subenvironment with significant fluvial input, to a mixed clastic-authigenic subenvironment. Aluminum content, a chemical indicator of watershed erosion, decrease during this interval. Iron content also decreases although because of the higher chemical mobility of this element it is not a straightforward indicator of catchment erosion. Higher values of *Cyclotella meneghiniana* (DAZ ZON-IV) suggest another episode of relatively higher lake levels at the top of Unit 3.

Climate reconstructions in Andalucía based on documentary data and instrumental measurements show that changes in the rainfall regime have been more important than those in the temperature during the last centuries (Rodrigo et al. 1999). A rainfall index for the last 500 years has been calculated by Rodrigo et al. (1999, 2000) based on documentary and instrumental sources for the period 1791–1997 (Figure 8). Seasonal indexes derived from documentary sources were assigned as follows: −2 (*Very dry*, absence of rain together with information on drops in river and water spring levels), −1 (*Dry*, absence of rain without additional information), 0 (*Normal*, no news, no comments on impacts), +1 (*Wet*, hard and/or constant rainfall), +2 (*Very wet*, rain-induced flood). The index values derived from instrumental sources for the period 1791–1997 are expressed as follows (R = rainfall; Ri: ith-percentile of the instrumental series): *Very dry*: $R < R10$; *Dry*: $R10 < R < R25$; *Normal*: $R25 < R < R75$; *Wet*: $R75 < R < R90$; *Very wet*: $R > R90$. The Annual index is the sum of the four seasonal indices and its value ranges from −8 to +8, although lack of data relating to the summer prevents such extreme values to be reached. The results suggest a fluctuating evolution since the end of the Medieval Warm Period, with the wettest intervals during the late 16–mid-17th centuries (AD 1590–1650) and at the end of the 19th century. The driest periods occurred during the first half of the 16th century (AD 1501–1589) and during the AD 1650–1750 period, and a general trend to more arid conditions started in the early 20th century (Rodrigo et al. 1999, 2000).

The rainfall index must be interpreted as a measure of the behavior of weather anomalies or extreme phenomena, rather than average values, because it is based on historical documents reporting only exceptional socio-economical impacts. Although our chronology is not accurate enough to compare with these climatic fluctuations, some tentative correlations can be established. The wettest interval (late 16–mid-17th centuries; AD 1590–1650) could correspond to the top of Unit 3B and the transition to 3A. In subunit 3A, the presence of more clastic facies 4 at the base of a fining-upward sequence suggest increased fluvial activity in the creeks, although aquatic pollen and diatoms do not indicate a particularly high lake level phase. Sedimentological features, aquatic pollen and diatom assemblages mark the top of Unit 3 (subunit 3A) as a period of higher lake levels that could correspond to a secondary wet period between the late 17th and the early 18th century. In another Andalucian lake, the Laguna de Archidona (Málaga Province), a dry period during the mid-17th century dried out the lake and some weak soil formation processes took place (Luque et al. 2004); during the following period between AD 1650–1850 lake level rose, forest recovered, and agricultural practices were favored instead of grazing. Documentary sources also indicate the presence of larger shallow lakes in the Doñana National Park prior to the 19th century (Sousa and García-Murillo 2003).

Period 4: the late 18th–early 19th century period

A large limnological change occurred in the lake during the late 18th–early 19th century prior to the sharp increase in olive pollen. Better-defined lamination and progressive dominance of brown laminae in subunits 2G and 2F indicate that suitable conditions for the establishment of benthic bacterial and algal communities at the bottom of the lake were reached. These communities were disturbed by deposition of two cm-thick layers of fine sediments (Facies 5) that reflect two large flooding episodes in the lake (Subunit E). Thin (about 1 mm thick) clastic, gray laminae also occur at the base of subunit D, and consequently, fine grain percentages remain high. The mixture of diatoms of both freshwater and saline character in DAZ ZON-I could be an indication of the short-term changes in salinity as an effect of the freshwater flooding episodes. A brackish to saline lake, with anoxic bottom waters that prevented bioturbation and facilitated the development of bacterial and algal benthic communities was established during this time. The low clastic input and the higher salinity suggest generally lower lake levels than during previous units. Both, the decrease in *Myriophyllum* values and increase in *Sparganium* in Unit 2 point to a period of more concentrated waters and relatively lower lake levels with increasing littoral vegetation. This enhanced macrophytic development is also corroborated by the increase in benthic diatoms of an epiphytic condition. The lake probably experienced a significant siltation as indicated not only by the dominance of benthic diatoms but also by the increase in tube-dwelling diatom forms such as *Cymbella* (Figure 7).

Wet anomalies also dominated between AD 1750 and 1850 (Rodrigo et al. 1999, 2000) a period that, according to our chronological model would correspond to the deposition of the lower part of Unit 2 (G, F, E and D subunits) characterized by laminated sedimentary facies, biological evidence for decreasing lake levels, and the presence of clastic facies indicative of floods in the lake watershed (particularly in subunit E).

Period 3: 19th century (olive rise) till mid-20th century (introduction of modern farm machinery)

Subunit C contains the best-laminated, organic-rich facies of the core (Facies 7). During this period, lake level remained lower than present, fluvial input was low, and chemical concentration increased. Benthic diatoms dominate the assemblages (DAZ ZON-I), aquatic plants abundances decrease and the littoral vegetated area with *Sparganium* increases. Rainfall reconstructions during the 19th century show wet anomalies during the early and mid-decades, dry anomalies during the 1860–1880s, and the onset of a dry trend from the late 19th century (Figure 8). This period of more arid climatic conditions during the late 19th and the early 20th century corresponds to the deposition of the organic, finely laminated facies of subunit 2C to 2A indicative of the lowest lake level in the cores. Other wetlands and lakes in Andalucía show evidence of a more negative hydrological balance after the mid 19th century. Reduction of surface area occupied by shallow lakes in the Doñana National Park at the end of the LIA indicate an increase in aridity (Sousa and García-Murillo 2003) that could correlate with the onset of unit 2 in the Zoñar records. In the Laguna Archidona, located in the Málaga Province, a transition from laminated sediment to increasingly gypsum-rich sediments occurs after AD 1850 and it is interpreted as increasing aridity after the end of the LIA (Luque et al. 2004).

Since the end of the 19th century, a progressive decrease in rainfall took place, only interrupted by a relatively wet period during the 1960s (Figure 4). Increased human use of the water for irrigation could have also helped to lowering lake level during this period. Several historical documents provide some information on past lake level in Laguna Zoñar. In the mid-19th century Madoz

(1850) described Laguna Zoñar and reported two springs and one creek feeding the lake. He noted the depth of Laguna Zoñar as 34 'varas' (1 'vara' equals about 84 cm, so the depth was about 28.5 m). Although it seems unlikely that the lake was that deep, Madoz's description indicates that the lake level was high during the mid-19th century. Reconstructed rainfall for the late 19th century also shows some positive anomalies (Rodrigo et al. 1999). Dantin (1940) estimated the size as 2000 × 250 m and recorded that the surface outlet was functional and that Laguna Chica existed as a different lake.

The onset of an increasing trend in Fe and Al concentrations in the sediments marks the beginning of a period of significant soil erosion in the basin. Olive pollen sharply increases. All these indicators point to large human disturbance in the Zoñar watershed during the mid and late 19th century. The agrarian crisis of the 18th century did not have an impact on the continued expansion of olive in Spain. On the contrary, many records show that olive production in Spain peaked in the 18th and 19th centuries. Some regions were dedicated to specific crops required by industry, such as hemp, though there were large areas of olives and cereals and some regions expanded its olives groves and doubled their oil production (Davis 1994; Riera et al. 2004). Several factors may have helped: expropriation of church in 1837 brought more land for intensive cultivation, changes in the pattern of land ownership, and reduced frequency of winter frost at the end of the LIA. The sharp increase in olive pollen in Zoñar likely occurred during the late 19th century. Several laws signed by the Spanish Government during the late 19th and early 20th century favored the drainage of wetlands and most likely, the deepening and drainage of the Arroyo de las Salinas occurred at that time.

Subunit 2A is composed of variegated, laminated Facies 7 that become more irregular and dominated by gray laminae towards the top. It is a transitional interval between the laminated facies of Unit 2 and the massive facies of Unit 1. Organic matter values decrease towards the top, till values below 10%. Although the upper part of this subunit is still laminated, a clear change occurs in the composition of the sediments: higher clastic input is marked by the increase in finer particles and in magnetic susceptibility values. A decrease in large particles (bioclasts and diatoms) and the disappearance of green and brown laminae stresses another abrupt limnological change that anticipated the onset of Unit 1. Although lake levels remain low, conditions are not longer conducive to the development of bacterial mats.

Period 2: mid-20th century to declaration of the lake as protected area (1982)

The base of Unit 1 (Subunit 1C) still shows some faint lamination (Facies 2). Dark gray, massive sediments (Facies 4) with high magnetic susceptibility values and low organic content constitute subunit B. This period correlated with the introduction of machinery around the mid-20th century that provoked a rapid increase in soil erosion in the watershed. Aluminum and iron concentration sharply increase. Reworked marine diatoms dominate as a consequence of intense erosion of the Miocene marine bedrock in the watershed. Olive pollen maintains high values, and the decrease in Olea at the base of Unit 1 may be a reflection of increased littoral vegetation around the lake more than to changes in agricultural practices. Lake levels are still low as indicated by the extension of hygrophytes (high Cyperaceae and Poaceae values). Geochemical indicators show that this is the period of most intense human disturbance of the catchment and the lake hydrology. In the 1960s, the waters from the Zoñar and Escobar springs were diverted for human use to the nearby Aguilar de la Frontera town, lake level lowered, and the outlet creek Arroyo de las Salinas became nonfunctional. The width of the littoral vegetation zone surrounding the lake, increased. In the late 1970s water diversion for human consumption progressively stopped and lake levels begin to recover. Farming activities in the watershed remained intense, and consequently erosion as detected by Fe and Al profiles increased. The increase in copper reflects the increasing use of fertilizers since the 1960s. A general decreasing trend in precipitation is observed after 1960 (Rodrigo et al. 1999). A dry period during the early 1970s could correlate with the deposition of faintly laminated, brown sediments with higher organic matter content in subunit 1A. Increasing grain size at the top of the core is related to the abundance of large oxidized organic matter remains, soil particles and littoral plant remains, and it parallels a large increase in magnetic susceptibility.

Period 1: restoration (since 1982)

After the lake was declared a protected area in 1982, the spring waters were not diverted for human consumption and farming stopped in some fields bought by the regional government. Average lake level recovered and some littoral areas were submerged. The Laguna Chica was flooded again, and re-connected with the Laguna Zoñar, but the outlet creek did not reopen; currently, Laguna Zoñar does not have a surface outlet.

The top sample analyzed in the core is representative of the modern status of the lake system. The Al content is smaller compared to previous values and magnetic susceptibility also decreases, which suggest that reducing the surface of farming has helped a little to alleviate the erosion rate in the basin. Iron and phosphorous contents have also declined. Olive pollen maintains the same values. Copper remains high, which suggest that the total amount of fertilizers reaching the lake have not substantially changed. *Myriophyllum spicatum* appears again as an indicator or relatively higher lake levels and fresher waters. The decrease in *Poaceae* pollen seems to reflect the decrease of the littoral vegetation, now partially submerged.

Since 1989 the Andalucian Environmental Agency has started a restoration program with autochthonous species as *Quercus ilex*, *Quercus coccifera, Olea europaea* var. *sylvestris*, *Ceratonia siliqua*, *Populus alba*, *Tamarix gallica*, *Ficus carica*, *Celtis australis*, *Crataegus monogyna*, *Pistacia lentiscus*, *Arbutus unedo*, *Viburnum tinus*, *Retama sphaerocarpa*, *Myrtus communis*, etc. The shoreline of the Laguna Zoñar is vegetated with *Phragmites australis* and *Typha dominguensis* while *Juncus maritimus* and *Tamarix canariensis* develop in the waterlogged littoral areas. Dry shorelines are covered with *Polypogon maritimus* and Plumbaginaceae as *Limonium echioides*. *Zannichellia palustris* is the main submerged plant. All these species appear in the modern pollen rain samples and also at the top samples of the cores. The natural vegetation would be characterized by sclerophyllous formations with some patches of mesohygrophytic vegetation very restricted spatially and altered in their composition, although some taxa are present in the Zoñar area.

Conclusions

The study of two sediment cores from Laguna Zoñar (Andalucía, Spain) provides a detailed record of environmental, climatic and anthropogenic changes in a Mediterranean watershed since Medieval time. The direct relationship between rainfall and lake level observed during the last decades suggests that climate variability is a main controller of lake level in the past. Sedimentological and biological proxies indicate that higher lake levels dominated prior to the 13th century. Enhanced fluvial influence at the end of the Medieval Warm Period (ca. AD 1300) could be responsible for some erosion at the coring site and the generation of an erosive hiatus. There is not a direct correlation between rainfall anomalies reconstructed for the last 500 years from documentary records and the inferred lake level changes in Zoñar (Figure 8). This may be due to the fact that the rainfall index only reflects extreme events and the lake filters and smooth the climatic signal and also to the uncertainty of our chronological model. The most significant limnological change started in the late 18th century where more finely laminated facies deposited and it corresponds to a period of dominant wet anomalies. A dry period at the end of the 19th century corresponds to the onset of deposition of finely laminated, organic – rich facies during a low lake level stage. This dry phase at the end of the LIA has been identified in historical documents and also in other lake records in the region. The Zoñar record shows fluctuating lake levels since the end of the Medieval Warm Period till the late 19th century and a more acute dry period during the late 19th century – early 20th century, after the end of the Little Ice Age. This is in agreement with historical records document high climate variability during the 14–19th century in the Iberian Peninsula, with periods of intense rainfall and droughts (Rodrigo et al. 1999, 2000) and with dendroclimatic reconstructions that show outstanding oscillations during the LIA (Manrique and Fernández-Cancio 2000). Although the onset to lower lake levels characteristic of Unit 2 does not correlate with a dry rainfall anomaly, the deposition of finely laminated, organic-rich facies correlate with the arid period during the late 19th century (end of the LIA) identified in documentary records and also in several other sites in the region. Water consumption for human use and farming during the late 19th and early-mid-20th century likely intensified this trend.

Two main periods of increased human activities in the watershed are recorded in the sediments. The first started with the Christian conquest and colonization of the Guadalquivir River Valley (13th century) particularly after the fall of the Granada Kingdom (15th century). The second one corresponds to the late 19th century when more land was cultivated after expropriation of the Church. Intensification of soil erosion occurred in the mid-20th century, after farm machinery was introduced. The ^{137}Cs chronology indicates a very large increase in sedimentation rate during the last decades, when massive calcite mud deposited (Unit 1) on top of the variegated, laminated mud of Unit 2. Human activities may have played a role in Zoñar hydrology changes since the late 19th century, when the outlet was drained, and particularly in the mid-20th century (till 1982) when the waters were diverted for human use.

The end of deposition of laminated facies started at about 1960 and does not correlate with a significant change in rainfall. Increased farming activity may have played a major role in this limnological change in the lake. Once the lake was declared a protected area in the early 1980s, the average lake levels increased. Pollen indicators reflect this limnological change during the last few decades. Geochemical indicators show a relative decrease in soil erosion during the last decades, but no change in the amount of fertilizers reaching the lake. Our study also provides an opportunity to evaluate the relative significance of human versus climatic factors in lake hydrology and watershed changes during historical times. These paleolimnological reconstructions can be used by natural resources agencies to better define the lake management policies and to assess the results of the restoration efforts started two decades ago.

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