Quaternary Science Reviews 262 (2021) 106963

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

A 1400-years flood frequency reconstruction for the Basque country (N Spain): Integrating geological, historical and instrumental datasets

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A R T I C L E I N F O

Article history:
Received 19 October 2020
Received in revised form
12 April 2021
Accepted 14 April 2021
Available online 12 May 2021

Handling Editor: Yan Zhao

Keywords:
Paleofloods
Lake
Historical floods
Late Holocene
Multi-archive integration

A B S T R A C T

We present the first reconstruction of past flood events variability in the Basque Country and Western Ebro Basin (Northern Spain) integrating instrumental hydrological datasets (last 20 years), documentary archives (last 700 years) and Lake Arreo (655 m a.s.l.) sedimentary paleoflood record (last 1400 years). In this lake, allochthonous coarse and fine detrital layers (CDL and FDL respectively) intercalated within endogenic laminites were identified and interpreted as high- and moderate-energy flood events. The interplay between human activities and hydroclimate variability has controlled the deposition of these flood layers. Gauged data for the last 20 years suggest that floods are typically generated by heavy rainfall events on saturated soils after several days of continuous rainfall. These events occur mostly during the cold season (Oct–May). The reconstructed frequency of high-magnitude flood events from the lake record is coherent with the historical cold-season floods from Basque rivers. The lowest flood frequency took place during the 6–7th and 10–15th centuries, while higher flood frequency occurred during the 8–9th centuries and the last 500 years. Fluvial and lacustrine paleoflood records and documentary evidence show abrupt and large increases in extreme flood frequency during the termination of the Little Ice Age (1830–1870 CE) and mid to late 20th century, both periods of Rapid Climate Change (RCC). The significant increase in flood frequency observed during RCC suggests that a similar pattern could be expected in the near future with the ongoing global warming.

1. Introduction

Recent global warming seems to have directly affected timing and magnitude of European floods (Blöschl et al., 2017, 2019). However, the long-term impact of climate change on flooding and its regional variability is difficult to assess, mainly due to the geographically sparse flood records from catchments with natural flow regime and the shortness of instrumental datasets (Blöschl et al., 2020; Hall et al., 2014). In addition, there is not yet a clear understanding of flood trends in small catchments where the expected increase in local convective storms (Ban et al., 2015) may have a larger impact on flood frequency and magnitude than global changes in atmospheric patterns (Blöschl et al., 2019).

Geological, botanical and historical archives of past flooding events (i.e. paleofloods) overcome the limitations derived from the scarcity of instrumental information. They extend our knowledge of past flood occurrence beyond the instrumental record and also provide information where gauged data are absent (Wilhelm et al., 2019). Among paleoflood archives, lake sediments are particularly

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https://doi.org/10.1016/j.quascirev.2021.106963

valuable paleohydrological records due to its temporal continuity and the good preservation of flood layers (Gilli et al., 2013; Schillereff et al., 2014; Wilhelm et al., 2018, 2019). On the other hand, documentary flood archives fill the gap between instrumental and paleoflood records providing a wealth of spatio-temporal paleohydrological information including precise flood dates, number of affected watersheds and/or the socio-economic impacts (Benito et al., 2005a). Nevertheless, the integration of historical and paleoflood records at the local and regional scale is complex due to the comparison of non-homogeneous data with various uncertainties (e.g. geochronological, record completeness), coming from heterogeneous watersheds, among other factors (Schulte et al., 2019). Thus, a detailed and critical assessment of the different flood archives should be made to adequately integrate the different sources of information.

In the Iberian Peninsula, floods are considered as the most damaging natural hazard in social and economic terms (Ferrer, 2002). In Spain, more than 20 floods per 10,000 km^2 were registered between 1980 and 2015 accounting for 652 casualties (EEA, 2016) and annual average losses > 100 million Euros (Barredo et al., 2012). The Basque Country (Northern Spain) is one of the most vulnerable Spanish regions. Flood risk in this mountainous region is related to northern and western atmospheric flows leading to intense rain, that together with the concentration of socio-economic activities at valley bottoms, result in a high flood exposure and vulnerability. The costliest flood in Spain's recent history (i.e. the August 1983 flood in the Nervión River) resulted in 34 fatalities and >620 million euros economic losses (Barredo et al., 2012; Piserra et al., 2005). Unfortunately, the instrumental flood record in the Basque Country is limited to the last decades, which makes difficult to disentangle the flood response to climate variability and other forcings such as land use and vegetation changes.

In Spain, annual to decadal scale flood frequency changes have been obtained from karstic lakes in the Southern central Pyrenees (Corella et al, 2014b, 2016, 2019) and the Iberian Range (Barreiro-Lostres et al., 2017; Moreno et al., 2008). These karstic lakes are excellent systems to reconstruct past flood variability due to the high sedimentation rates and sensitivity of the relatively small watersheds to flooding events (Valero-Garcés et al., 2014). All these paleoflood series document events under Mediterranean influence. The determinant role of large atmospheric modes of climate variability in lake-watershed dynamics - particularly North Atlantic Oscillation (NAO) and Western Mediterranean Oscillation (WeMO) - has been assessed in several sites from the Central System (Corella et al., 2016; Hernandez et al., 2015, 2018; Sánchez-López et al., 2016). Flood variability at millennial scale has also been identified in Sanabría Lake sedimentary sequence (NW Iberian Peninsula) and related to changes in NAO-like patterns and vegetation cover during the Holocene (Jambrina-Enríquez et al., 2014). In this study, we reconstruct the first high-resolution lacustrine paleoflood record for the last 1400 years in a region under Atlantic influence in the Iberian Peninsula based on the sedimentary record of Lake Caicedo Yuso-Arreo (hereafter Lake Arreo), the only deep natural lake in the Basque Country. The wealth of instrumental and documentary data from the lake and its catchment, the multiproxy characterization of the flood layers and the known vegetation history of the watershed allow us to assess the long-term interplays between large-scale climate variability, land use, vegetation changes and flood frequency patterns. The results are compared with compiled documentary archives of catastrophic floods occurring in rivers from Northern Spain (Basque Country and Western Ebro basin) to assess the centennial-scale flood variability in Northern Spain.

2. Study site

2.1. Geographical and geological context

Lake Arreo is located in the northwestern limit of the Ebro Basin (Basque Country, Northern Spain) (42° 46′ N, 2° 59′ W; 655 m a.s.l.) (Fig. 1). The lake is located on the southwestern edge of the Añana saline diapir. The Lake Arreo watershed (491.5 ha) lies on Triassic gypsiferous and mudstone formations (Keuper facies). Hypo-volcanic ophite rocks are cropping out forming scarps associated to an ENE-WSW fault at the northern shore of the lake (Martín-Rubio et al., 2005). The origin of the lake is attributed to interstratal evaporite dissolution and subsequent subsidence.

2.2. Lake's morphology and hydrology

Lake Arreo (6.57 ha, 24 m maximum depth) has a funnel-shaped morphology, with an almost circular perimeter and bounded to the north by a steep scarp (Figs. 1d and 2a). Before 1993, the lake was meromictic with a chemocline between 12 and 16 m deep that delimited an anoxic monimolimnion of more saline water in the deep zone (Corella et al., 2011a; Chicote, 2004; González-Mozo et al., 2000; Rico et al., 1995). However, the synergetic effect of lower rainfall during the last two decades and intensive water extraction in the lake brought the meromictic conditions to an end (Corella et al., 2011a). Thus, Lake Arreo is currently monomictic - holomictic, with a strong summer thermal stratification and anoxic conditions in the hypolimnion, and a mixed period during autumn-winter.

A temporary stream (*Arroyo de lago*) drains the eastern area of the watershed providing water and sediments to the lake during flood events (Fig. 1c). The hydrological balance is controlled by surface and groundwater inputs and by an outlet in the south-western shore that controls the maximum lake level. Regional authorities have conducted a monitoring program since early 1990s including water chemistry, biology and limnological parameters showing that lake level fluctuates less than 1 m during the annual cycle (www.uragentzia.euskadi.eus). Only two extraordinary lake level drops (>2 m) have been documented during the last 30 years due to illegal water extraction in 1995 and 2002 (Corella et al., 2011a).

2.3. Land use and vegetation in the watershed

Catchment land cover (Fig. 1b) consists on crops and pastures in the lowlands (38% of the total area), while the higher elevation areas are occupied by sub-humid mountain trees (mainly *Quercus faginea* and *Pinus sylvestris* on the north-facing slope) and ever-green oaks (*Quercus ilex*) on drier south-facing exposures. Shrublands occupies 15% of the total area mostly composed of *Juniperus communis*, *Aphyllantes monspeliensis*, *Lavandula latifolia* and *Thymus vulgaris*. The lake is surrounded by a broad palustrine vegetation belt, with *Scirpus lacustris* communities in the deeper areas, and reed beds with *Phragmites australis*, *Typha latifolia*, *Typha angustifolia*, *Sparganium erectum*, etc in the shallower ones. In the east and south-eastern areas those reed beds are replaced by communities of *Cladium maríscus* with *Scirpus marítimus*, *Juncus acutus* and *Puccinellia fasciculata*, species linked to brackish environments. Characteristic elements of the vegetation developed on drier soil

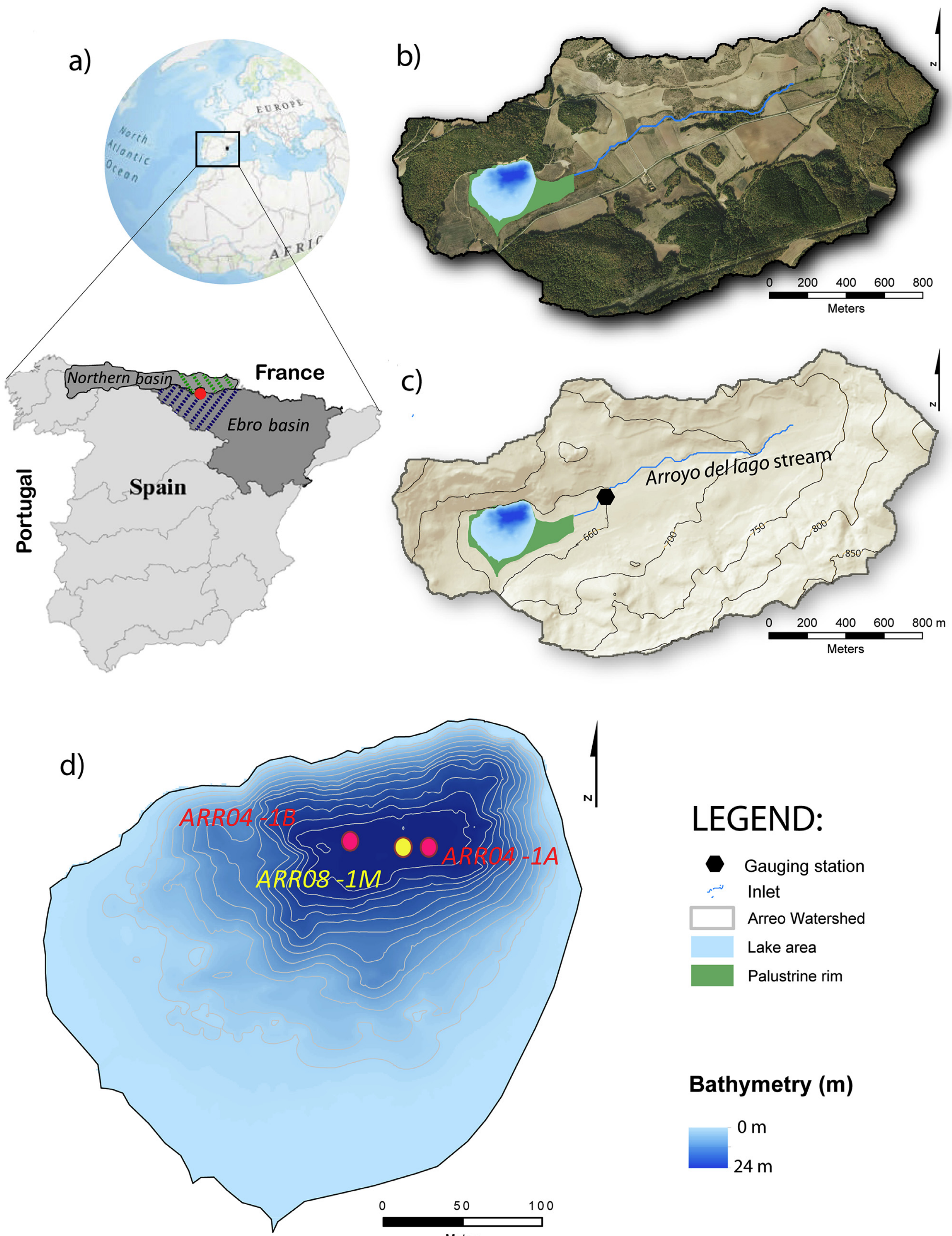

Fig. 1. a) Location of the studied area. Blue and green dotted lines represent the study areas with historical river floods in the spanish Northern and Ebro basins. Red dot indicates the location of Lake Arreo; b) Aerial photograph of Lake Arreo watershed; c) Digital Elevation Model (DEM) of Lake Arreo watershed and location of the gauging station in Arroyo del lago stream; d) Bathymetric map of Lake Arreo and location of the coring sites (contour intervals = 2 m) (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article).

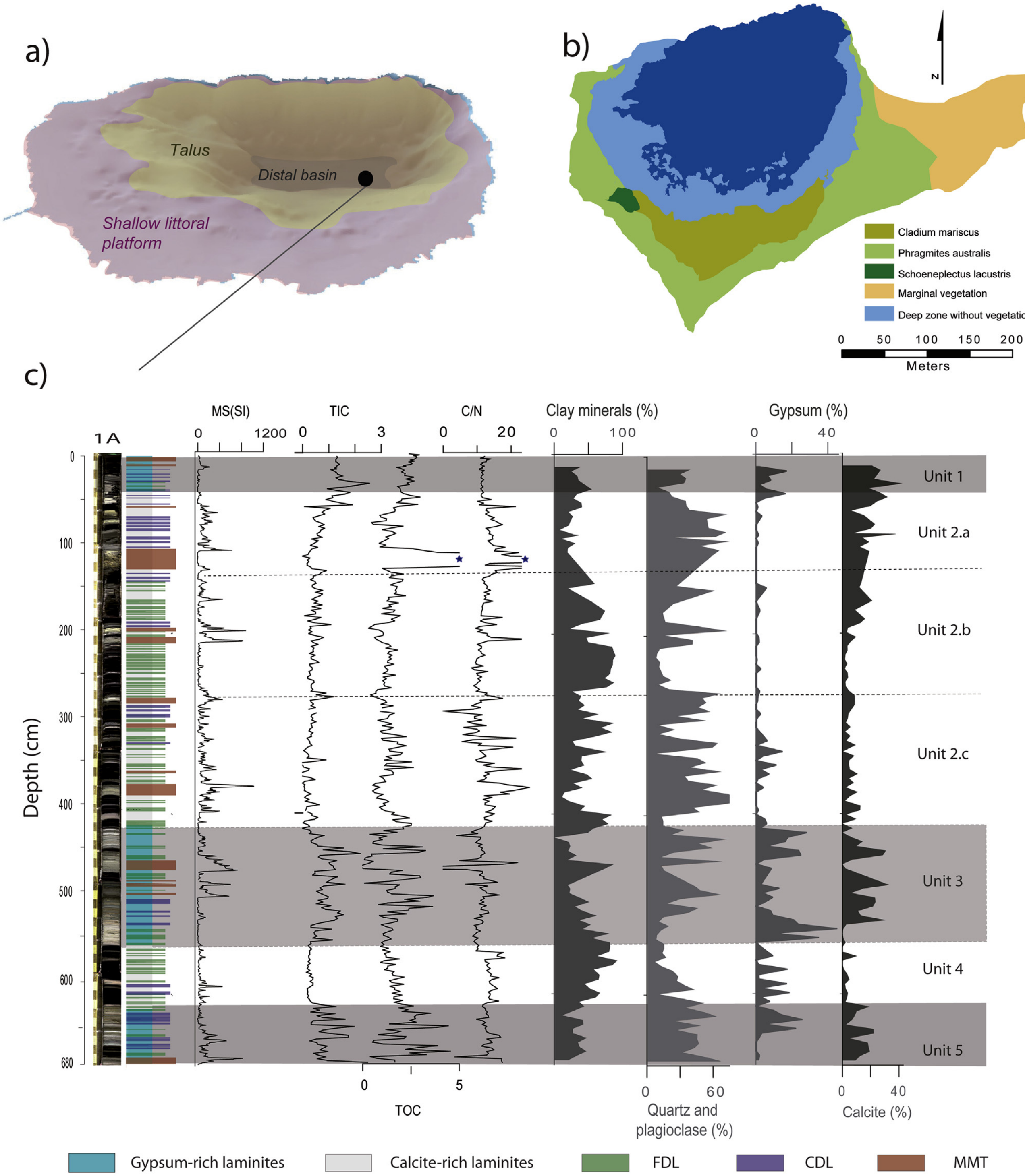

Fig. 2. a) 3-D bathymetric map showing the main depositional environments described in the text; b) Vegetation map of the main helophythic communities; c) Core image, sedimentary sedimentological column, magnetic susceptibility, Total Organic Carbon (TOC), Total Inorganic Carbon (TIC), carbon-nitrogen ratio (C/N) and mineralogical proxies (from Corella et al., 2013). Maximum TOC and C/N values indicated by the blue star are 21,8% and 70,7 respectively. Core images and lithostratigraphic units from ARR04-1A1K sediment core are also shown. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

are *Carex* spp, *Althaea officínalis* and *Epilobium hírsutum*. The submerged and floated leaf aquatics are presented by *Chara hispida* var. *hispida*, *Chara hispida* var. *major*, *Myriophyllum verticillatum*, *Polygonum amphibium*, *Potamogeton coloratus*, *P. lucens*, *P. pectinatus*, *P. pusillus*, *Ranunculus trichophyllus*, *Utricularia australis* and *Zannichellia pedunculata*.

2.4. Climate

The regional climate is of Atlantic-Mediterranean transitional type. The coldest and warmest months have average temperatures of 4.7 °C (January) and 19.8 °C (July). Mean annual rainfall in the area is 670 mm. November is the wettest month with a mean rainfall of 82.5 mm. Extreme one-day precipitation events (EPEd) (>70 mm) usually associated with convective storms mainly occur in summer (JJA) (with the highest intensities). A second period of EPEd occurs during the cold season (October–April) but with lower precipitation intensity. Precipitation during the cold season for the period 1961–2010 yr CE is positively correlated with Western Mediterranean Oscillation (WeMO, 76.5% of the cases) (Ríos-Cornejo et al., 2015). A positive WeMO phase often brings northern air flow to the Spanish northern coast, carrying wet air and abundant precipitation in the inner reliefs (Ríos-Cornejo et al., 2015).

3. Methods

3.1. Fieldwork: bathymetric, mapping and coring surveys

A hydroacoustic survey was carried out using a 200 kHz split-beam transducer and echo sounder (Biosonics DT-X) synchronized to a Differential Global Positioning System (DGPS). A digital bathymetric model was obtained by kriging interpolation showing a similar morphology than the first bathymetric map carried out by Rico et al. (1995) although improving the spatial resolution. Lake shoreline was adapted from Rico et al. (1995). Detailed imaging of lake floor was obtained by a SSS survey (high resolution Sonar-beam-150 A, 400–1250 kHz), combined with continuous geo-referenced video-recording for ground-truthing, using by an Intova Connex Action Camera featuring a waterproof housing and tethered to an underwater control cable for operation, powering, and monitoring at the surface. The video settings are Full HD 1080p at 30 fps. The submerged vegetation mapping was carried out using an unsupervised classification method implemented in SonarWiz acquisition and post-processing Software from Cheasepake Technology (Ecohydros, 2015). Sediment cores ARR04-1A1K (679 cm-long) and ARR04-1 B–1K (503 cm-long) were retrieved in May 2004 at 24 and 23.2 m water depth, respectively) using a Kullenberg coring platform from the University of Minnesota (USA) (Fig. 1). A short UWITEC gravity core (ARR08-1 A-1U) was retrieved in 2008.

3.2. Event layers' characterization

Sediment cores were split lengthwise and imaged with a DMT core scanner. Physical properties (density and magnetic susceptibility) of sediment cores were measured at a 5 mm resolution with a Geotek multi-sensor core logger (MSCL). Identification of discrete detrital layers (>5 mm thick) punctuating the sedimentary sequence were carried out i) by direct visual observations of sediment cores and smear slides and ii) by detailed inspection of thin sections. Lake clastic layers are deposited by direct runoff from the watershed related to major flooding episodes and/or by mass movement from slope failures as seen in other lake records (Corella et al., 2014a,b; Czymzik et al., 2010; Kremer et al., 2015; Moernaut et al., 2014; Noren et al., 2002; Santos-Gonzalez et al., 2021; Wilhelm et al., 2012, 2018; Wilhelm et al., 2016). Discerning the triggers of each single clastic layer is required to avoid over- or underestimations in the frequency of either floods and/or mass-movements. For this purpose, thin sections with dimensions of 120 mm × 35 mm were prepared after freeze-drying and impregnation with epoxy resin (Araldite) under vacuum conditions following (Brauer and Casanova, 2001). Thin-section inspection allowed us to characterize internal structure, texture and compositional features of detrital microfacies, and lastly identifying the process trigger.

Mineralogical and geochemical compositions of clastic layers were carried out in the core ARR04-1 A-1K providing compositional information of clastic layers. Mineralogical analyses (X-ray diffraction, XRD) were carried out in selected clastic facies using an automatic X-ray diffractometer SIEMENS-D500, Cu-Kα, 40 kV, 30 mA and graphite monochromator (Corella et al., 2013) (Fig. 2c). Total (TC), organic (TOC) and inorganic (TIC) carbon, as well as Total Sulphur (TS), were analyzed using a LECO 144DR elemental analyzer. Total nitrogen (TN) was analyzed using a VARIO MAX CN elemental analyzer (Corella et al., 2011a, 2013) (Fig. 2c). The base sublayers of 44 detrital layers were analyzed for grain size determination. Grain size distributions were measured on between 12 and 19 layers of each event type. Grain size of all fractions ranging from 3.9 μm to 217 mm was analyzed by Coulter laser grain sizer after destruction of organic matter with 10% H_2O_2 at 80 °C, stirred 24 h to facilitate particle dispersion and subjected to ultrasound during the analyses.

The flood record was reconstructed only in sediment core ARR04-1 A-1K (Fig. 2c) because i) the geochemical, mineralogical and dating analyses used to characterized the event layers were performed in this core and ii) it is closer to the Arroyo del Lago river mouth. We consider that this core, is representative of the depositional dynamics in the distal basin given i) the reduced area of the profundal sub-basin (Fig. 2a), and ii) the similar facies variability and sedimentation rates in distal cores previously reported in Corella et al. (2013).

3.3. Age-depth model

The original depth-age model, published in Corella et al. (2011a, 2013) was based on varve counting, ^{137}Cs radiometric dating for the uppermost 52 cm and 5 radiocarbon dates (2 more dates were rejected because of stratigraphic reversal), and it was constructed using the mixed regression method of Heegaard et al. (2005). Here we revise the age model using Bacon software for Bayesian age modeling in R (Blaauw and Christen, 2011). All dates were included in the model, including the two obvious outliers at 510.5 cm and 570 cm (Fig. S1; Table S1). Because Bacon assumes stratigraphic ordering of dates and a linear sedimentation process, it rejects age models that violate these assumptions, so the presence of an outlier date affects model uncertainty but not the maximum likelihood estimates for the age model. For the upper part of the core the onset of *Pinus radiata* in the palynological sequence dated at 1870 yr CE was added as an additional chronological tie point. The age model output from Bacon is based on the probability density function for each calibrated radiocarbon age and a prior estimate of the mean sedimentation rate throughout the core set at 2 cm/yr, and section length of the piece-wise-calculated spline, set to 20 cm (thick = 20). According to the model, the 6.78 m composite depth sedimentary sequence covers the period 620–2008 CE.

3.4. Precipitation and water discharge instrumental datasets

Characterization of the precipitation patterns over the lake basin was carried out using a composition of the climatic series of precipitation corresponding to two open-access AEMET stations (Spanish meteorological service). The 9087 (Vitoria/Aeródromo) and 9091O (Foronda/Txokiza) meteorological stations, (~24 km from the lake), have been combined for the periods 1943–1980 CE and 1980–2019 CE respectively in order to get a continuous daily precipitation record. The quality of the data has been ensured following protocol control that checked possible erroneous data and guarantees the homogeneity of the series (Brunet et al., 2008) and was carried out using RClimDex-extraqc (freely available at http://www.c3.urv.cat/softdata.php along with the user manual (Aguilar, 2010)). Dataset homogeneity has also been tested with the ACMANT software (Domonkos, 2015) (also available at http://www.

c3.urv.cat/softdata.php), using precipitation series from six nearby stations as reference. The daily water discharge series was obtained from a gauge station installed a few meters upstream the river mouth entering Lake Arreo (Fig. 1c). Hydrological data are based on continuous monitoring of flow and lake level by the Basque Water Agency (www.uragentzia.euskadi.eus) for the period 2001–2020 CE. Calibration of the sedimentary record and the hydrological dataset was not possible due to i) the lack of sediment for the period 2008–2020 CE due to poor recovery of the top sediments; ii) the poor sediment preservation of the upper sediments in Lake Arreo for the period 1990–2008 CE due to the presence of two disrupting event layers related to documented slope failures in 1993 CE and 2002 CE respectively. Until data sets are available for a calibration, the reconstructed paleoflood archive should be interpreted with caution in quantitative terms.

3.5. Documentary flood data

Regional documentary flood data include Basque rivers and the western part of the Ebro basin, namely the catchment draining the uppermost 150 km of the Ebro River (Fig. 1a). Historical flood datasets were obtained from: (1) written documents, scientific and technical reports, local history books and non-systematic compilations by historians such as the works by Font (1988); Fontana-Tarrats (1976); Masachs (1948); (2) published historical flood compilations (e.g. Barriendos and Rodrigo, 2006; Benito et al., 1996a, 1996b), and (3) available datasets, namely the National Catalogue of Historical floods (Protección Civil, 2014), which completed flood records and damages over the 20th century. Archival flood information provides direct (e.g. flood date, duration, inundation extent) or indirect (e.g., economic damage and repair works) data of individual flooding (Barriendos et al., 2019; Brázdil et al., 2006). Reported floods correspond to overbank inundation in urban areas (streets, bridge, mills) and overflow to agricultural fields. Floods are classified in terms of severity impact (Barriendos and Martín-Vide, 1998) as catastrophic (channel overflow with major damage) and extraordinary (channel overflow with some damage). The Basque rivers dataset comprises 144 units of information on floods from 18 rivers, which corresponds to 86 flood events over the period 1400–2011 CE (Table S2). Some flood events have been reported in multiple locations particularly in recent times when documentary data is abundant, which support the assumption to infer past regional flood conditions from point sources. The Ebro River basin dataset (1330–2010 CE) contains 188 entries from 23 rivers, and 161 flood events (Table S3).((

4. Results and discussion

4.1. Lake Arreo morphometric analyses and depositional environments

The bathymetric analyses, video-recording and aquatic vegetation mapping carried out in Lake Arreo (Fig. 2) have revealed a complex morphometry with four distinctive depositional and ecological subsystems:

1) A hygrophyte vegetation belt mostly developed in the eastern and southern flat area over 39,000 m^2. This area can be largely flooded when there is an increase in the water discharge of Arroyo de Lago stream. Communities of helophytes (mainly *Phragmites australis*) dominate in the eastern area at the river mouth (13,212 m^2) and the larger extension of the outer southern rim (25,791 m^2). *Cladium mariscus* and *Schoenoplectus lacustris* are colonizing the southern area occupying 10,676 and 640 m^2 respectively (Fig. 2b). The surface area covered by these plant communities has been stable during the last years due to the protection protocols implemented by the regional government since this site was included in the "Nature 2000 Network – Special Areas of Conservation (ZEC)" (ES2110007). Palynological studies of lake sediment cores have revealed that this vegetation belt has been present for the last 1400 years and the changes in its composition and surface area have been strongly related to variations in the lake level and land uses (Corella et al., 2011a, 2013).
2) A palustrine area (shallow waters), mainly in the southern and western areas (18,000 m^2, 35% of the lake area, 0–3 m depth with slopes <20°), with lake waters mixed throughout the year. This area is covered with remains of helophytes and submerged macrophytes coated with biogenic carbonates (Fig. 2b). Indeed, the sedimentary record shows high rates of biogenic carbonate precipitation in this sub-environment (~1 cm/year) mainly associated with *Chara* macrophyte incrustations (Martín-Rubio et al., 2005; Corella et al., 2013). Currently submerged vegetation has been strongly reduced by the collateral effects of invasive species (Haubrock et al., 2018).
3) A step talus >3 m deep with slopes >20° dominated by sediment transport and with limited deposition. The southern and western talus has a rocky substratum and presence of abundant submerged dead tree trunks. Slopes are particularly steep in the northern margin where echo-sounding and video recording have showed numerous mass-wasting deposits. Scarp-failure deposits in the northern littoral areas of the lake were already described by Martínez-Torres et al. (1992).
4) A deep basin covering a flat area at 24 m depth. Finely laminated sediments are preserved in the deep basin favored by the anoxic conditions prevailing during most of the annual cycle that impeded bioturbation activities in the lake bottom (Corella et al., 2011a, 2013). These laminated sediments mostly consist on alternating gypsum-rich rhythmites and biogenic varves punctuated by mm to cm thick event layers; similar laminated successions have been described in other Iberian karstic lakes (Corella et al., 2011b, 2012; Martín-Puertas et al., 2009; Trapote et al., 2018b).

4.1.1. Deep basin lithostratigraphical units

The sediment sequences in both cores ARR04-1A-1K and ARR04-1B–1K in the distal deep basin show alternating finely laminated endogenic calcite-rich and gypsum-rich facies punctuated with event layers. Corella et al. (2013) described five lithostratigraphic units: three of them - 5 (635–900 CE), 3 (1300–1615 CE) and 1 (1965 CE-Present-day) - are mostly composed of finely laminated calcite and gypsum laminae (>gypsum contents; Fig. 2) punctuated by event layers, while units 4 (900–1300 CE) and 2 (1615–1965 CE)- consist of alternating calcite-rich laminites and event layers.

4.2. Event layers in Lake Arreo

Lake Arreo sedimentary sequence in the distal basin includes 142 event layers (Figs. 2, 3 and 5) Table 1. The sedimentological, textural and geochemical analyses of the layers provide insight into the depositional processes operating in the lake during the last 1400 years and tools to ascribe them to mass-movement turbidites and/or flood events.

4.2.1. Mass-movement turbidites

Event layers deposited as mass-movement turbidites (MMT) have been identified in the distal cores based on sedimentological, textural and compositional features. Sixteen MMT layers have been

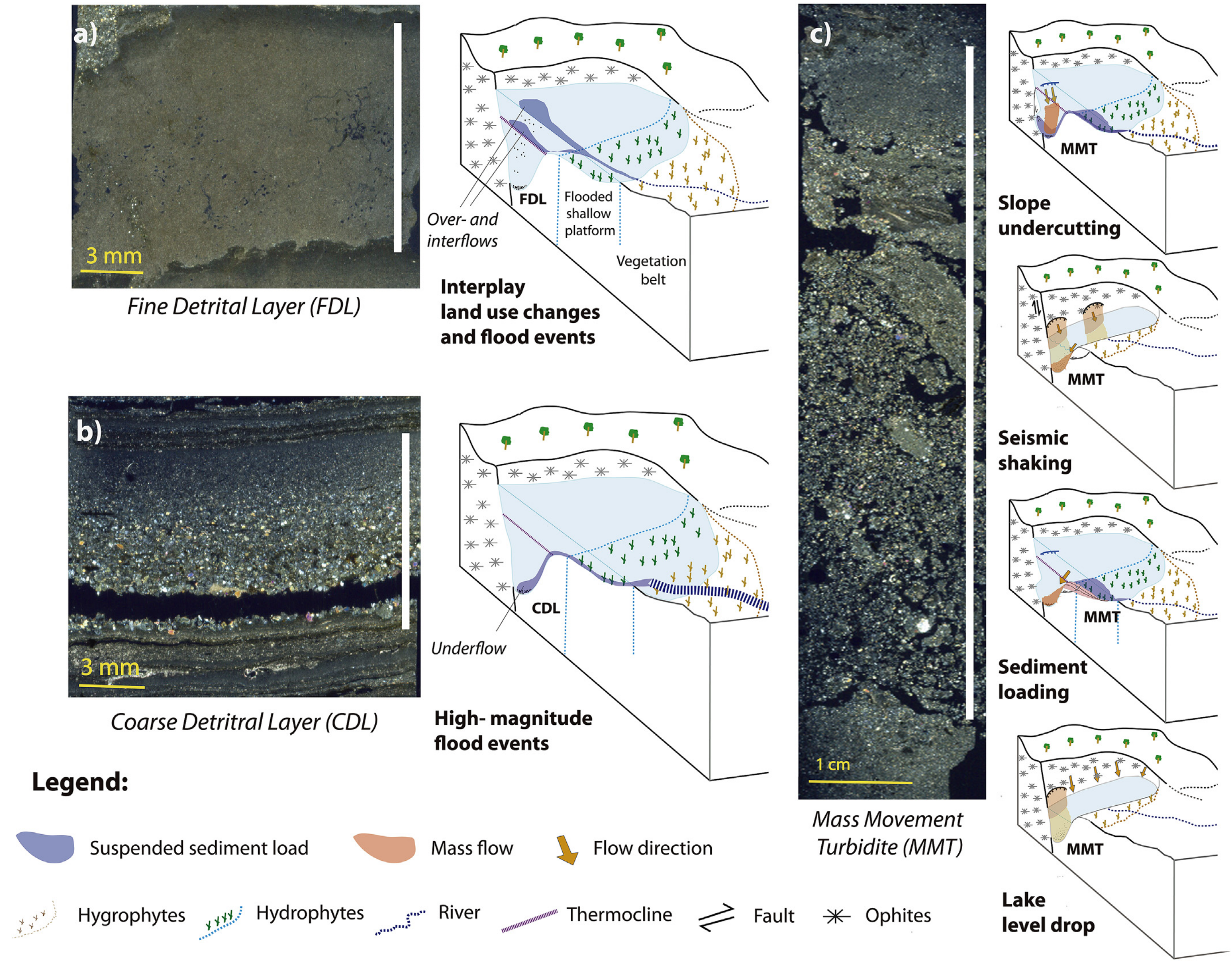

Fig. 3. Polarized microscope photos of the three types of event layers identified in Lake Arreo and sketches of their respective deduced depositional models. A) Fine Detrital Layer (FDL); B) Coarse Detrital Layer (CDL); C) Mass Movement Turbidites (MMT). White vertical lines represent the event layer thickness.

identified. They consist on centimetre-thick detrital layers with a sandy, non-graded coarse basal sub-layer and an erosive basal surface, followed by finer sediments with several fining upward pulses (Fig. 3c). The thick and homogeneous basal sub-layer as well as the multiple coarse grain-size pulses occurring during individual events found in Lake Arreo's MMTs are all common features of mass-movement-induced gravity flows (Gorsline et al., 2000; Mulder and Alexander, 2001; Mulder et al., 2003; Wirth et al., 2011). These individual flood laminae are the thickest observed in the sedimentary sequence ranging between 1 and 26 cm (mean thickness of 6.9 cm). Grain-size of MMT bases minimal and maximum values ranges between 17 and 217 μm (mean = 91.4 μm) (Fig. 5). MMT in Lake Arreo are mostly composed of siliciclastic material with abundant plagioclase, quartz and pyroxene crystals. Reworked hydrophyte fragments and/or littoral carbonates are also frequent. MMT show very high Magnetic Susceptibility (MS) values, while TIC and TOC values are very low, ranging respectively from 0.1 to 0.2 and 0.4–0.8 % wt. The carbon-nitrogen ratio is high (C/N 12.8 and 17.4).

The abundant plagioclase and pyroxene crystals as well as the high MS values in the MMT deposits point out to the ophitic body from the northern cliff (with significant presence of ferromagnetic minerals) as the main source of the slope failures. Indeed, scarp-failure deposits in the northern littoral areas of the lake were described by Martínez-Torres et al. (1992). Nevertheless, the presence of reworked carbonates and hydrophytes in the MMTs also demonstrate that they incorporate sediment from the southeastern littoral platform with high carbonate production and hydrophytes communities.

According to the age model, the two most recent MMTs in Lake Arreo sequence occurred in 2002 and 1995, and they have been attributed to documented slope failures that triggered 2 and 4.7 m lake level drops respectively due to illegal water extraction (Corella et al., 2011a). These lake level drops would have increased shear stress and strain as well as decrease pore water pressure in slope sediments, leading to scarp failure. Nevertheless, such lake level changes are not expected to occur under natural lake dynamics (0.5–0.7 m variability; Fig. 6). Thus, the fourteen MMT occurring before the instrumental and observational period were likely caused by other mechanisms such as rapid sediment loading, earthquakes, underwater seepage or slope undercutting and over-steepening (Fig. 3c) as seen in other lacustrine and marine settings (Girardclos et al., 2007; Hampton et al., 1996; Locat and Lee, 2002; Strasser et al., 2007; Sultan et al., 2004). Local or regional

Table 1
Mean characteristics of the different event layers identified in Lake Arreo.

Event layer type	Nº layers	Layer thickness	Grain-size	TIC (%)	TOC (%)	C/N	Magnetic susceptibility (MS)	Mineralogy	Sedimentological features	Depositional processes
Mass-movement turbidites (MMT)	16	1–26 cm	17–217 μm (91.4 μm)	0.1–0.2	0.4–0.8	12.8–17.4	Very high	Plagioclase, quartz and pyroxene crystals. Frequent calcite (littoral, reworked)	Sandy, non-graded coarse basal sub-layer with several fining upward pulses. Erosive basal contact	Mass-movement-induced gravity flows
Fine detrital layer (FDL)	76	2.4–9.1 cm	3.9 –19.2 μm (8.1 μm)	0.1–0.3	0.8–1.8	10–10.5	Moderately high	Dominant clay minerals (>80%)	Non-graded fine silt layers. Occasional thin basal coarse-silt sublayers. Non-erosive basal contact	Flood-related low-density currents. Overflows and/or interflows
Coarse detrital layer (CDL)	50	2–7.2 cm	6.3 –86.2 μm (37.2 μm)	0.4–0.5	1.1–2.3	9.5–15.1	High	Quartz and carbonates with abundant clay minerals (>60%)	Graded silty layers with a thin coarse sub-layer. Fining upwards texture. Micro-erosive basal contact	Flood-related high-energy density currents. Underflow events

earthquakes could be a likely trigger of some of these MMTs since the northern margin of Lake Arreo is bounded by an ENE-WSW fault (Martín-Rubio et al., 2005) that could be reactivated during seismic shaking.

4.2.2. Flood layers

In Lake Arreo, two types of flood layers have been identified based on different textural characteristics (Fig. 3a and b).

4.2.2.1. Fine detrital layers (FDL). FDL consist on mm to cm-thick blackish, non-graded fine silt layers mainly composed of clay minerals (>80%) with minor contributions of terrestrial and aquatic organic matter (i.e. planktonic diatoms). Thin basal coarse-silt sublayers sometimes occur without any clear micro-erosion features (Fig. 3a). Elemental geochemistry shows TIC and TOC values ranging between 0.1-0.3% and 0.8–1.8 % wt (C/N = 10–10.5). Textural analyses of the basal part of the flood layers show a grain size range from 3.9 to 19.2 μm (min and max values respectively, mean = 8.1 μm) (Fig. 5). 76 FDL have been identified with maximum and mean thicknesses ranging between 9.1 and 2.4 cm, respectively. The non-graded structure of the fine material and the lack of micro-erosion features suggest low-density currents as the depositional process for these layers. In these conditions, the sediment plumes from the currents are not sufficiently dense to pervade the thermocline formed by the permanent water stratification so that suspended matter is distributed within the lake basin through overflows and/or interflows (Wilhelm et al., 2015). The thin silty basal sublayer (mean grain-size of 8.1 μm, Fig. 5) and the faintly grading towards finer clayish material on top of the layers suggest the differential settling of suspended particles according to their grain size.

4.2.2.2. Coarse detrital layers (CDL). CDL are characterized by mm to cm-thick greyish graded layers with a thin coarse sub-layer and a well-developed fining upwards bed (Fig. 3b). They are mostly composed by quartz and carbonate-rich silty mud with abundant clay minerals (60%), plagioclase (20%) and gypsum (5%). Micro-erosion and irregular basal surfaces as well as plant remains, and reworked littoral carbonates are also present in the basal sub-layer. They display relatively high MS and density values. TIC and TOC values are low ranging between 0.4-0.5% wt and 1.1–2.3 % wt, respectively, while C/N values ranges from 9.5 to 15.1 (terrestrial origin). Fifty CDL have been identified in the sequence with maximum and mean thickness of CDL layers varies between 7.2 and 2 cm respectively. The basal parts of the CDL layers have grain-size ranging from 6.3 to 86.2 μm (mean = 37.2 μm) (Fig. 4). Grain-size of the thinnest CDL might appear similar to the one of FDL. This may, however, result from the limited sampling resolution (≥5 mm minimum) that makes not possible to sample only the mm-scale basal layer. Deposition of CDLs are interpreted to occur when major flooding episodes trigger high-energy density currents, penetrating through the lake stratification as underflows as previously described in stratified lakes elsewhere (Corella et al., 2014a; Giovanoli, 1990; Sturm and Matter, 1978; Wilhelm et al., 2015). The higher grain-size of CDL layers might reflect higher flood magnitudes since grain-size may be a proxy for flow energy and discharge (Lapointe et al., 2012; Schillereff et al., 2016; Wilhelm et al., 2012, 2013).

4.2.2.3. Influence of climate variability and land use on FDL and CDL deposition. Lake Arreo paleoflood record should be carefully interpreted in terms of reconstructing past hydroclimate since sediment supply may vary as the result of a complex interplay between natural and anthropogenic processes. Flood layers in Lake Arreo (both FDL and CDL) remained low during the High and Late Middle Ages (10–15th centuries) concomitant with the most

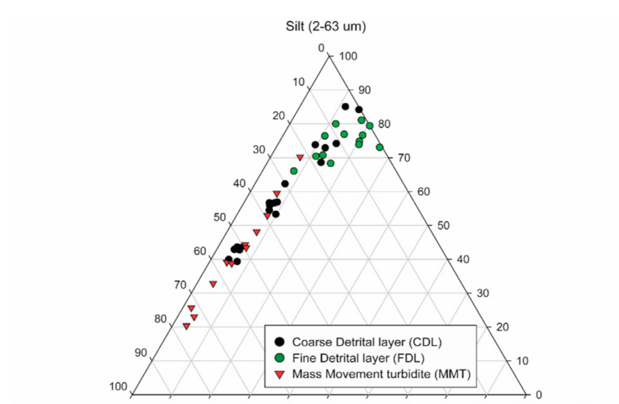

Fig. 4. Ternary plot showing the textural composition of the basal parts of analyzed flood and mass-movement layers.

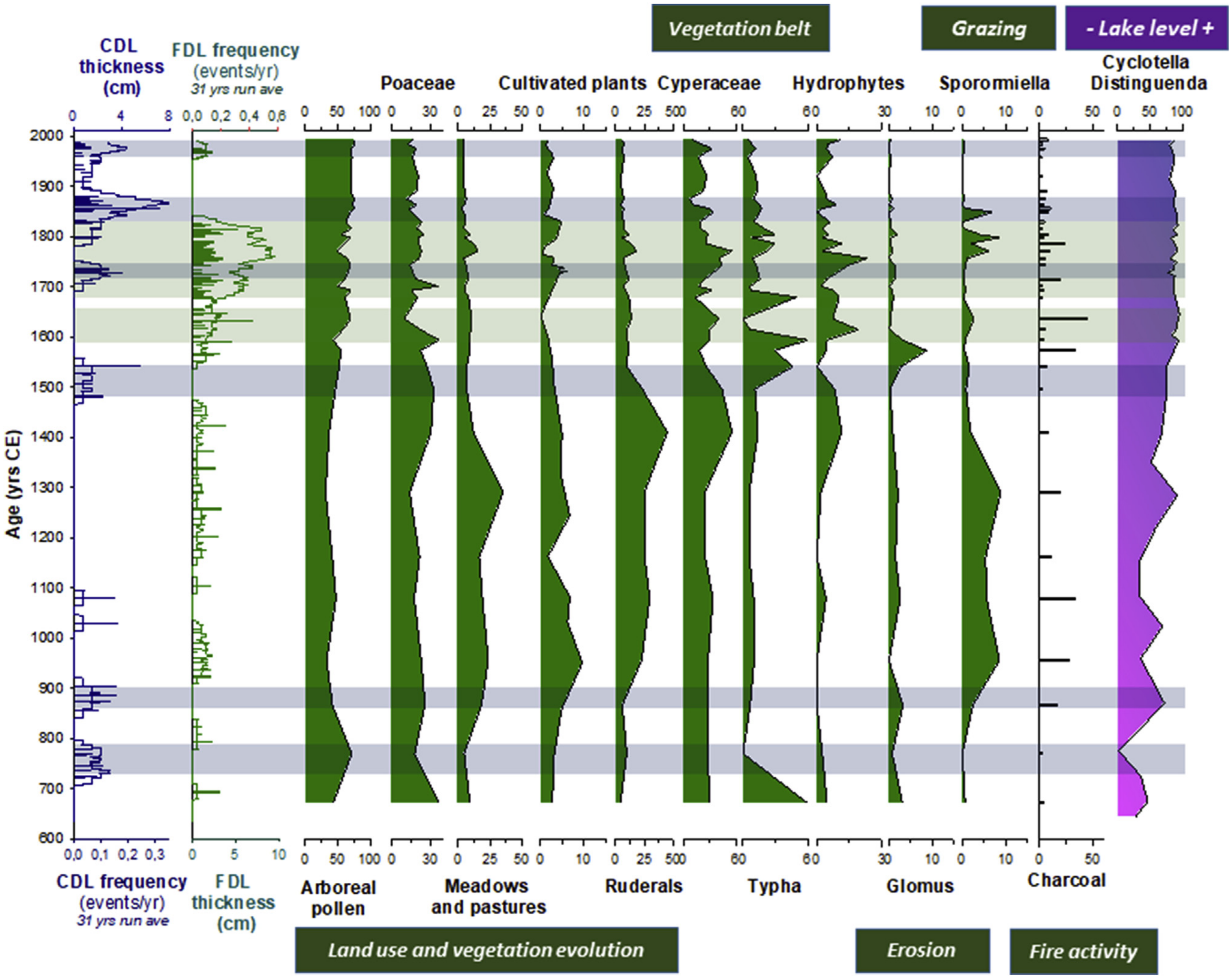

Fig. 5. From left to right: Flood frequency variability (green FDL; blue: CDL); Main palynological indicators of land use and vegetation changes: AP – arboreal pollen (trees and shrubs); Cultivated taxa - *Triticum/Avena*, *Secale*, *Cerealia*, *Cannabis*-type, and *Polygonum aviculare*-type; Ruderals - *Artemisia*, Chenopodiaceae, *Plantago major*, *P. media*, and *Urtica*; Meadows and pastures - *Aster*-type, *Cirsium*, Chichorioideae, Apiaceae, *Heracleum*, *Campanula*-type, *Filipendula*, *Potentilla*, *Gallium*-type, *Lathyrus*, *Trifolium*-type, *Lotus*-type, Ranunculaceae, *Ranunculus acris*-type, *Hypericum*, *Lotus*-type, *Rumex acetosa*, *R. acetosella*, *Plantago lanceolata*. Hydrophytes - *Potamogetom*, *Utricularia*, *Myriophyllum, Lemna;* Diatom-based Lake level reconstruction from Lake Arreo (from Corella et al., 2013). Blue and green horizontal bars represent periods with increase in CDL and FDL frequencies respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

intense land use in the watershed reflected by the elevated pollen anthropogenic indicators in Lake Arreo sediments and during the late MCA and beginning of the LIA (Fig. 5). On the other hand, more frequent deposition of flood layers occurred during periods of forest recovery and reduced anthropogenic pressure in the watershed (the 8th century and some intervals during the last five centuries) suggesting that flood layers are closely controlled by hydroclimate variability. Thus, heavier rainfall triggering high-magnitude floods would probably lead to CDL deposition while moderate events would result in FDL layers.

Nevertheless, we cannot rule out the role of human pressure on the watershed on run-off generation. We observe a major increase in FDL frequency during the 18th century coinciding with a peak in *Sporormiella* dung spores a proxy for grazing activities (Etienne et al., 2013; Montoya et al., 2018; Trapote et al., 2018a). FDL layers also increased during the 1960s concomitant with a smallholding concentration process that affected the vegetation belt around the lake and the sediment availability in the watershed (Corella et al., 2011). Thus, flood layer occurrence depends on the interplay between heavy rainfall variability and human impact at catchment scale, which is in agreement with observations from other Iberian karstic lakes (Barreiro-Lostres et al., 2017; Corella et al., 2019).

4.3. Flood record in the Lake Arreo watershed

Instrumental data can bring information about the hydrometeorological processes generating floods and, thereby, about the type of flooding recorded in historical and geological archives. Flood generation in Lake Arreo watershed was analyzed by comparing daily water discharge with precipitation over the period 2001–2020 CE. Annual floods do not always correspond to the maximum daily precipitation, pointing to the combination with other hydro-meteorological processes and/or catchment conditions. Daily discharge data reveal that extreme floods mostly occur in winter (DJF) and spring (MAM), while the most severe annual maximum daily heavy rainfall events occur in summer (Fig. 6). Interestingly, direct runoff during summer heavy rainfalls, characterized by high intensity and short duration, is limited due to high infiltration capacity and permeability of soils (infiltration coefficient ~0.4) developed on ophyte/diabase bedrock (cambisols and

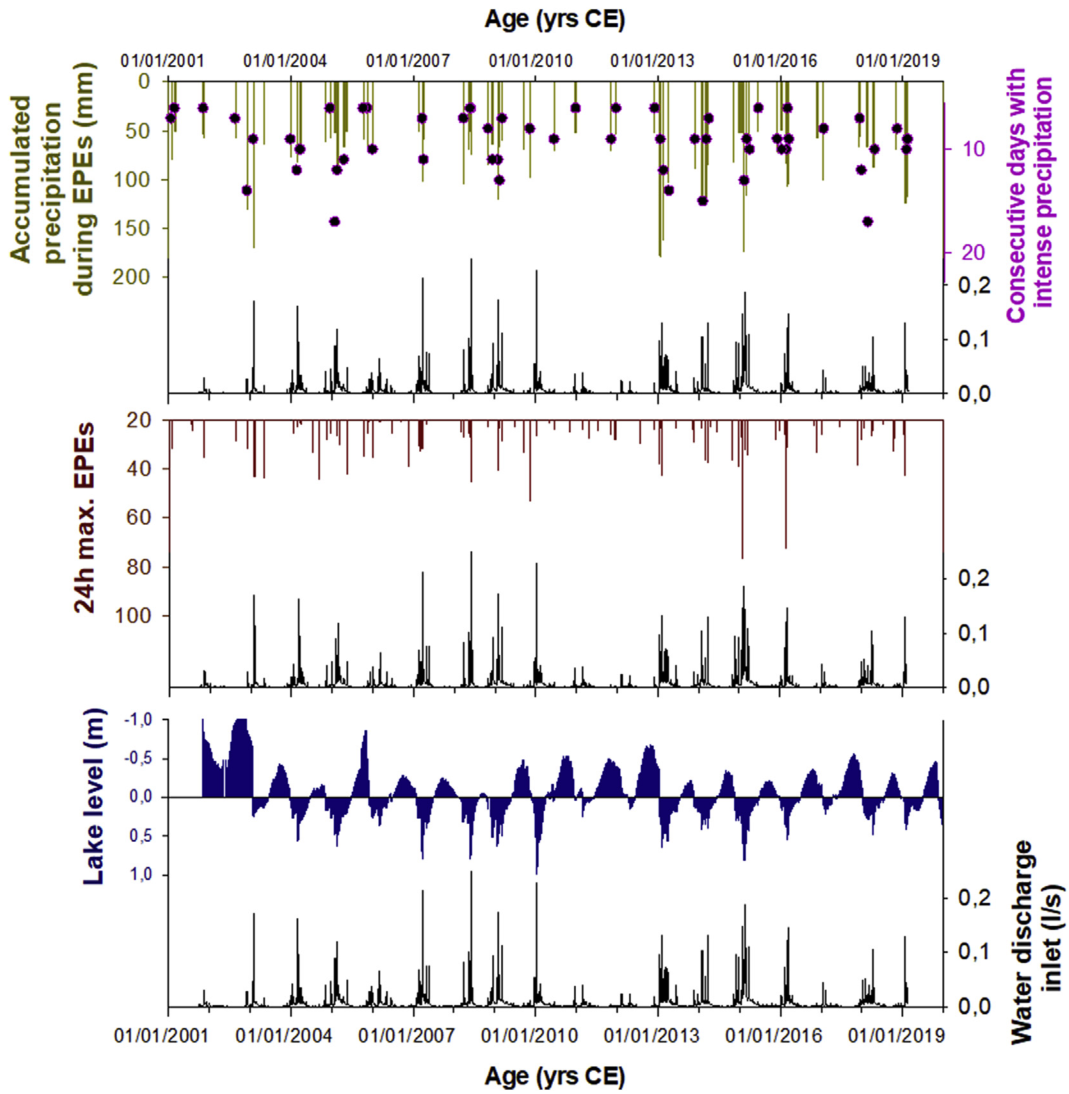

Fig. 6. Daily water discharge recorded on Lake's Arreo inflow compared with (from top to bottom); accumulated precipitation during extreme precipitation events (EPE) and consecutive days before EPE; Monthly daily maximum precipitation; daily lake level variability; (Precipitation data obtained from meteorological station at Vitoria airport).

regosols) (Iñiguez Herrero, 1980). Only saline soils and lithosols developed on clayish material (16% in surface area) are producing hortonian flows during summer rainfalls. On the other hand, water discharge measurements at the gauge station reveal that 75% of the largest floods can be explained by heavy rainfall episodes (>20 mm/day) preceded by long rainfall episodes (accumulated rainfall >80 mm in 6–13 days). Thus, both heavy rainfall and high antecedent moisture conditions (i.e. saturated soils) are needed to trigger floods in the Lake Arreo watershed. Thus, CDL layers of Lake Arreo sequence are interpreted as high energy flood events occurring during the cold season (Oct–May). The record spans since the onset of the Middle Ages (Fig. 7) with moderate increase in the frequencies between 720 and 780 CE, 850–900 CE, 1480–1540 CE, 1720–1740 CE and the largest increase in frequencies occurring between 1830-1880 CE and 1950–1990 CE.

Water inflows to the lake correlates well with lake level variability. Thus, the water table can increase between 0.5 and 0.7 m during periods of maximum river discharge, while lake level regularly decreases from 0.2 to 0.3 m during summer droughts (Fig. 6). A relation between flood variability/sediment delivery and lake level changes is further observed in the longer term. Thus, lower flood frequency during the Middle Ages coincided with lower lake levels (Fig. 5), coherent with lower rainfall and run-off. On the other hand, the highest flood frequency occurred during the last five centuries in agreement with the highest lake level and a shift from a brackish lake to a meromictic lake with reduced salinity in Lake Arreo (Fig. 5) (Corella et al., 2013).

4.4. Historical floods of the western Ebro Basin and the Basque Country

The compiled historical flood datasets from rivers of the Western Ebro Basin and the Basque Country reports a total of 200 historical floods since 1330 CE. The level of flood risk perception by the riverine population was relatively high due to frequent damages triggered by the Ebro River overflows into major villages. Typically, documentary flood registers describe economic impacts caused by flood water inundation (mostly in urban areas), and social disruption as consequence of damages in irrigation canals, roads and bridges. The analysis of regional documentary data indicates flood-rich and flood-poor periods over the last 700 years. High flood frequency in rivers from Western Ebro basin occurred between

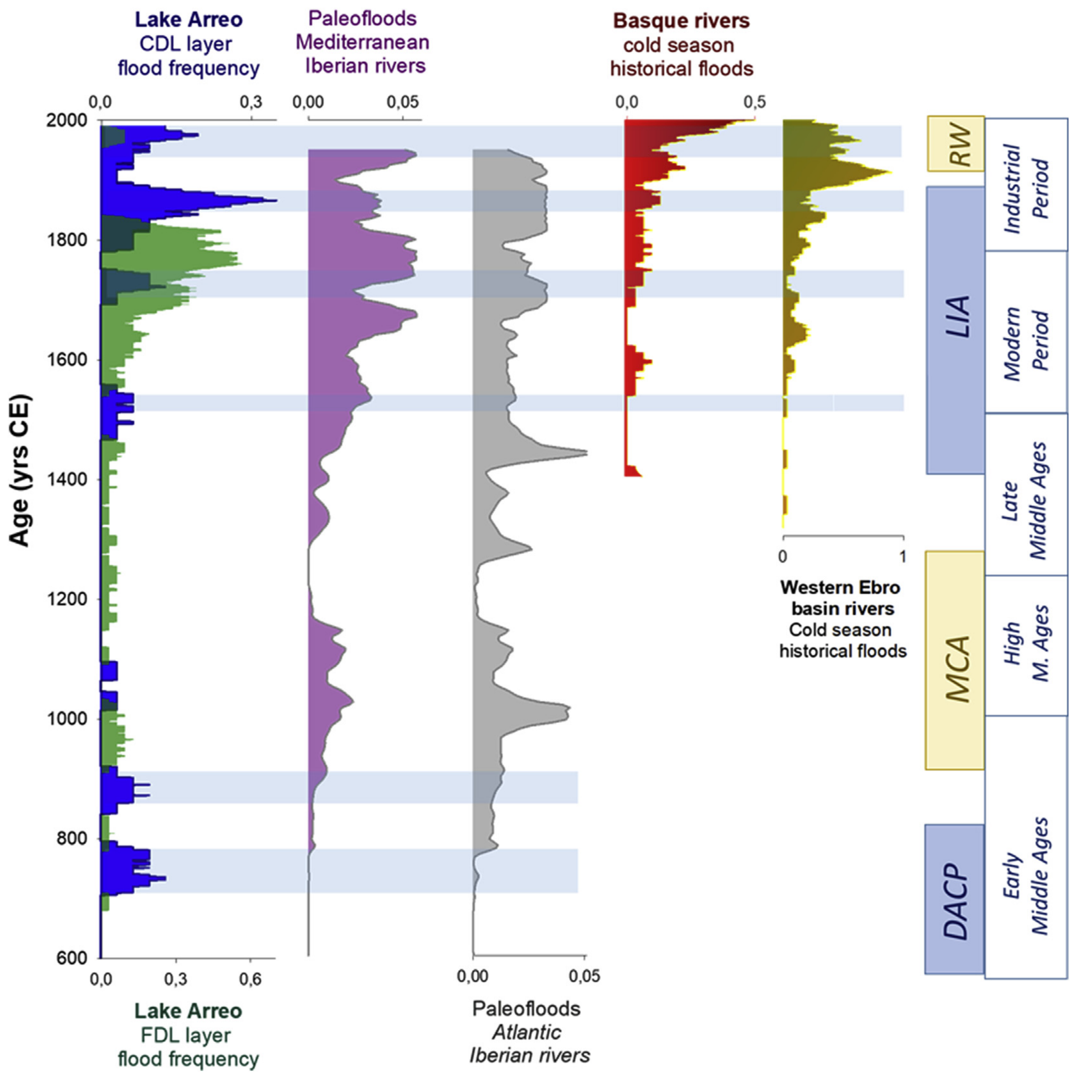

Fig. 7. From left to right: CDL (blue) and FDL (green) flood layer frequency variability (horizontal blue bands represent periods with increased CDL flood frequency); Paleoflood occurrence probability in Mediterranean (pink) and Atlantic (grey) rivers (Benito et al., 2015); Cold-season (Oct–May) normalized historical floods from Basque rivers and Western Ebro basin tributaries (from Tables S1 and S2); . All curves represent the 31 yr running average. Main climatic and historical periods are also indicated. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

1625-1670, 1830–1850, 1900–1940 and 1950–1980 yr CE while Basque rivers show high flood frequency between 1580-1600, 1820–1840, 1860–1880, 1910–1930 and 1970–2010 CE (Fig. 7, Tables S1 and S2). In contrast, periods between 1410–1530 and 1610–1690 CE and between 1300-1580 CE were characterized by few reported floods in the Basque rivers and Western Ebro basin respectively.

4.4.1. Comparison between historical and paleoflood records

In the Iberian Peninsula, compiling historical flood information at a regional scale results in a mixed population of flood types due to the spatial diversity of flood-producing hydro-meteorological conditions, and variety of geomorphology, catchment size and vegetation cover. Thus, multi-archive, regional flood reconstructions should be carried out with care.

The historical flood records of the Ebro basin headwaters and the Basque rivers show a regular increase of floods towards modern times (Fig. 7), which may result from i) increase in reported floods during the last centuries and ii) an increasing vulnerability/exposure of population associated to demographic growth since second half of the 19th century. As a result, flood frequency during the Pre-Industrial Period is most likely underestimated as highlighted when comparing with the paleoflood record from Lake Arreo (Fig. 7).

As instrumental data and documentary evidence show, the Arreo record is mostly a cold-season flood archive. Thus, we have decoupled the flood seasonality from the historical flood archives to provide an adequate comparison with the lacustrine records (Fig. 7). The Lake Arreo and Basque rivers cold-season flood time series variability shows a higher agreement suggesting a similar hydroclimate driver. Winter rainfalls in the Basque Country mainly result from atmospheric fronts coming from the north and north-west, a pattern clearly different from central and eastern Iberian Peninsula, more strongly influenced by Mediterranean dynamics (Capel, 1981; Esteban-Parra et al., 1998; Serrano et al., 1999). The evolution pattern of extreme one-day precipitation events (EPEd) that cause major winter floods in the Basque Country also follows this same behavior (Benito et al., 1996b). The relief also plays a major role because the Cantabrian Mountains, parallel to the coast, forces the air masses to ascend (orographic forcing), producing

EPEd on the windward side (northern slopes), very close to the location of Lake Arreo. When air masses reach the southern slopes, they are drier and warmer because of the rain shadow effect, and for this reason, the Ebro Valley is isolated from the winter Atlantic moisture fluxes (Beguería et al., 2009). This behavior has been verified for precipitation events above the 90th percentile in autumn and spring, mainly associated with two specific synoptic situations (Fernandez-Montes, 2014). One, a steep gradient between the Azores High and much lower pressure in the Western Mediterranean and Northern Africa, significantly conducive to a strong North flow converging over the northern mountain chains and promoting the ascent of air and precipitation in north-facing slopes at high altitude. Another, the Azores anticyclone in the Atlantic and low pressure extended in Central Europe with a through over the Western Mediterranean, driving a humid northern-westerly flow to Northern Iberia. This SLP configuration produces extreme precipitation in the north/northwest facing slopes and rain-shadow effect leeward of Cantabrian, Iberian and Pyrenees Mountains. Atmospheric synoptic situations driving the largest cold season water discharge in Lake Arreo correspond to these atmospheric reorganization patterns (Fig. S2). Therefore, the agreement between historical floods series of the Basque rivers and the reconstructed paleoflood series of Lake Arreo stream suggests that the lacustrine record represent a long-term, regional hydroclimatic proxy of floods induced by winter Atlantic atmospheric flows.

4.5. Flood variability during the last 1400 years in northern Spain

Combining instrumental, historical and geological flood records is a valuable approach to understand the flood evolution at a regional scale since each archive contains complementary hydrological information (Wilhelm et al., 2019). The Arreo multi-archive dataset provides a reconstruction of cold-season flood variability since the 7th century for Northern Spain.

Low flood frequency was recorded up to 7th century (Fig. 7), corresponding to the end of the Migration period, characterized by a strong hydrological deficit in the Mediterranean and scarce paleoflood events in both fluvial and lacustrine archives in the Iberian Peninsula (Benito et al., 2015b; Corella et al., 2016; Currás et al., 2012). Overlapping this period, central Spain lake records suggest warm temperatures and arid conditions and low flood frequency (Sánchez-López et al., 2016). Similar reduced flood frequency and lower lake levels during this period have been also reported in the southern and western European Alps (Magny, 2004; Sabatier et al., 2017; Schulte et al., 2015; Wirth et al., 2013). Flood frequency variability remained low during the Middle Ages except for two periods during the 8th and the late 9th centuries (Fig. 7) that corresponds to i) the termination of the Dark Ages Cold Period (DACP; 460−775 CE), a cold and humid episode in Europe (Helama et al., 2017) and ii) the transition to the Medieval Climate Anomaly (MCA; 900−1300 CE). Lower flood frequency reconstructed in Lake Arreo during the MCA is concomitant with the warmer and more arid conditions reconstructed in the Iberian Peninsula during this period (Moreno et al., 2012; Sanchez-Lopez et al., 2016). Increased aridity might have increased sediment availability in the watersheds that could be easily eroded and re-mobilized during moderate rainfall events as documented in other Iberian lakes (i.e. Cimera lake (Sanchez-Lopez et al., 2016)). Nevertheless, we infer the opposite pattern in Lake Arreo with more floods occurring during the LIA, characterized by colder and more humid conditions in NE Spain (González-Sampériz et al., 2017; Morellón et al., 2012; Oliva et al., 2018). This is coherent with our hydrological interpretation of flood-generating mechanisms needing preconditioning humid (i.e. saturated) conditions in the watershed' soils to trigger large floods.

The last five centuries stand out as the period with the largest flood variability of the last 1400 years in agreement with historical floods from Northern Spain, fluvial paleoflood records of Iberian rivers (Benito et al., 2015) (Fig. 7) and paleoflood records from lakes of the Iberian Range (Moreno et al., 2008). And abrupt increase in FDL frequency occurred during the 17th and the 18th centuries while higher CDL frequencies have intermittently occurred since the early 17th century (Fig. 7). A marked abrupt increase in floods in the mid-19th century occurred in both paleoflood records and historical floods from Basque rivers (Fig. 7). The late LIA also correspond to periods with high flood frequency and magnitude in historical records of NE Iberia and western Mediterranean (Barriendos and Rodrigo, 2006; Llasat et al., 2005; Rodriguez-Lloveras et al., 2017). Interestingly, the highest increase in flood frequency before the onset of the current global warming coincides with the termination of well-known cold and humid periods (i.e. DACP and LIA). Increased flood frequency during intervals of rapid climate changes has also been described in European flood records from fluvial archives (Benito et al., 2015a; Macklin et al., 2006) suggesting changes in atmospheric circulation patterns resulting in increased hydroclimate instabilities (Knox, 2000).

The second largest increase in flood frequency recorded in both lacustrine and documentary archives occurred during the second half of the 20th century (Fig. 7). This period coincides with the Great Acceleration (1950 CE- Present day) and the intensification of the global warming. Several studies suggest changes in the characteristics of precipitation in the study region throughout the 20th century with i) an increase in the number of days of intense or very intense precipitation in summer and winter; ii) a general increase in the number of rainy days throughout the year and iii) an increase in rainfall above the 90th and 98th percentiles in the study area (Gallego et al., 2011; Moberg et al., 2006). An increase in flood magnitude and frequency of floods in Atlantic basins between 1960 and 1980 CE and a subsequent decrease in peak discharge of extraordinary floods has also been reported by a comprehensive assessment endorsed by the Spanish Ministry of Environment (Benito et al., 2005b) which agrees well with our multi-archive reconstruction from the Basque Country. Flood events in Northern Spain increased over the last decades of the 20th century characterized by warming conditions and dry anomalies in Iberia (Brunet et al., 2007; Coll et al., 2017). Such weather conditions are an indication of higher frequency of persistent anomalous atmospheric circulations associated to warm sea surface temperature anomaly in the Northern Atlantic Ocean (Ballesteros-Cánovas et al., 2019; Blöschl et al., 2020). At the European scale, documentary gauged flood records showed a similar increase in flood frequency since 1960 under warm climate (Blöschl et al., 2019).

Our research demonstrates a high sensitivity of flooding to climate variability over the last 1400 years, in particular during periods of climate transition including the current global warming. Whereas most flood projections under different climate change scenarios uses a top-bottom down approach sometimes not adapted to local conditions, paleoflood hydrology provides a local approach to better understand long-term flood hydrology and thus improve our adaptation capacity to future flood hazard and risk analysis.

5. Conclusions

The integration of instrumental, historical and paleoflood datasets as well as the comparison with other available paleohydrological records have allowed us i) to depict the large spatio-temporal heterogeneity of extreme floods in Northern Spain and; ii) to highlight the complexity of comparing different flood archives. This study also exemplifies the need to carefully interpreted paleoflood and historical records before establishing comparisons between the different sources of paleohydrological information.

The exceptional morpho-sedimentary and catchment conditions of Lake Arreo makes it an ideal setting to record and preserve long-term paleoflood information in the Basque Country (Northern Spain). A total of 126 flood layers were identified over the last 1500 years. A subsequent textural and geochemical characterization of clastic lake sediments classified 50 layers as coarse detrital laminae (CDL) and 76 fine detrital laminae (FDL). The paleoflood record was completed with daily gauged flow records at the lake major stream for the 2001–2020 CE period and documentary flood records from the Basque Rivers (1400–2000 CE) and Ebro headwater tributaries (1300–2000 CE). The multiproxy analyses of event layers indicates that:

- FDL were generated by moderate-magnitude floods, caused by an interplay between hydroclimate and land use.
- CDLs were generated by high-magnitude floods mainly controlled by regional hydroclimate.

Instrumental data indicate that floods in Lake Arreo are generated during the cold season by heavy rainfall events after several days of continuous Atlantic frontal rainfalls, leading to soil moisture saturation as a catchment precondition for flood generation. Historical data suggest that the Lake Arreo flood record represent regional, long-term changes in flood occurrence, given the similarities with changes in winter floods in the Basque Country over the last centuries. Thus, the lacustrine flood layers archive has been interpreted as a reconstruction of cold-season flood variability in the region. The highest flood frequencies occurred between the 8–9th centuries and during the last 500 years.

Long-term paleoflood records demonstrated a high sensitivity of flooding to anomalous atmospheric circulation patterns occurring during climate transitions. It also provides a robust and viable approach to improve our understanding future changes on flood hazards to enhance climate change adaptation.

Author contribution

JPC, GB, BVG and BW designed the research. JPC and GB carried out the paleohydrological research and compilation of historical archives respectively and analyzed the resulting data. AM and ER provided bathymetric and limnological data. All authors interpreted the results. JPC wrote the paper with contributions from all authors

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement Nº 796752 (FLOODARC). Additional support has been obtained by the Spanish Ministry of Science, Innovation and Universities (MICINN) projects LIMNOCAL (CGL 2006–13327. C04-01/CLI), MEDLANT (CGL2016-76215-R), MEROMONT (CGL2017-85682-R) and EPHIMED (CGL2017-86839-C3-1-R) (co-financed with European FEDER funds). The Basque Water Agency facilitated access to its hydrological data.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2021.106963.

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