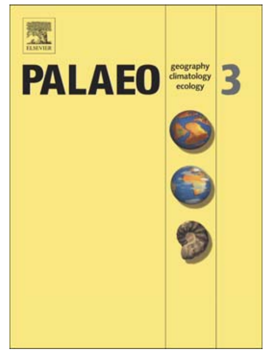

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MULTI-PROXY PALAEOECOLOGICAL RESPONSES TO WATER LEVEL FLUCTUATIONS IN THREE SHALLOW TURKISH LAKES

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Abstract

Natural or human-induced water-level fluctuations influence the structure and function of shallow lakes, especially in semi-arid to arid climate regions. In order to reliably interpret the effect of water-level changes from sedimentary remains in the absence of historical data, it is crucial to understand the variation in sedimentary proxies in relation to water level measurements. Here, we took advantage of existing water surface elevation data on three large shallow lakes in Turkey to elucidate the impact of lake-level changes on benthic-pelagic primary production over the last 50-100 years. Sub-fossil cladocerans, diatoms, plant remains and pigments were investigated as biological variables; X-ray fluorescence (XRF) and loss on ignition (LOI) analyses were conducted as geochemical-physical variables on a set of ^{210}Pb and ^{137}Cs dated cores. Dating of the cores were robust, with the exception of uncertainties in Lake Marmara littoral core due to low unsupported ^{210}Pb activities and high counting errors. Results indicated that Lake Marmara was dominated by benthic species throughout the sediment record, while Lakes Beyşehir and Uluabat shifted from a littoral-dominated system to one with increased pelagic species abundance. In all cores there was a stronger response to longer-term (decadal) and pronounced water-level changes than to short-term (annual-biennial) and subtle changes. It was also noted that degree of alteration in proxies differed between lakes, through time and among pelagic-littoral areas, likely emphasizing differences in depositional environments and/or resolution of sampling and effects of other stressors such as eutrophication. Our results highlight lake-specific changes associated with water-level fluctuations, difficulties of conducting studies at required resolution in lakes with rather mixed sediment records and complexity of palaeolimnological studies covering recent periods where multiple drivers are in force. They further emphasise the need to include instrumental

records when interpreting effects of recent water-level changes from sediment core data in large shallow lakes.

Keywords: Diatom sub-fossil, Plant macrofossil, Cladocera sub-fossil, Pigment, Sediment geochemistry, Mediterranean

1. Introduction

The hydrology and ecosystem dynamics of shallow Mediterranean lakes respond to the natural cycle of seasonal dry and wet periods of variable annual and inter-annual periodicity and intensity. Along with intense seasonality and climatic change, long term anthropogenic impacts of irrigation, damming, soil erosion and groundwater drawdown have greatly affected lake water levels and their continued variability in the Mediterranean region (Coops et al., 2003).

Lake ecosystems respond to water-level change, as their inter-linked habitats adjust to dynamic environmental parameters. Prediction of future ecological patterns and trajectories of change due to lake water-level change is therefore difficult, but can be assisted by assessment of recent palaeoecological and sediment evidence from lakes with documented water-level records. Individual lakes will respond to water-level changes in a unique way, depending on their basin morphometry, climate, duration and magnitude of change and resilience of ecological communities, but some general processes can be identified. Water-level fluctuations expand and contract spatial patterns of sedimentation and determine edaphic–hydrological conditions that control the zonation of littoral vegetation (Harrison and Digerfeldt, 1993). A significant rise in lake level causes transgressive overlap of fine-grained muds (low energy, deep water) on top of shoreline sediments (high energy, shallow water), expanding the area for aquatic and marginal plants. Conversely, a regressive fall in lake level will reduce the areal extent of littoral habitats and may generate a hiatus in deposition due to erosion of previously deposited high lake-level fine mud. This simple model is of course complicated by basin morphology; i.e. a fall in level, revealing a wide shallow margin that may increase littoral habitats. Reduced water depth may also cause a greater proportion of catchment-derived matter to be transported towards the centre of the lake basin. Equally, a fall in water depth can extend the photic zone to the bottom of shallow, turbid lakes, increasing the potential area of aquatic plant growth and organic sedimentation. Periods of water-level stability allow development of marginal wetland peats, carbonate benches and chemical precipitates depending on water chemistry (Jones and Jordan, 2013).

Indirect effects of water-level change on biological communities include changing nutrient availability, turbidity (water clarity) and fish predation (Jeppesen et al., 2015). Reduced water levels in shallow lakes can cause a decrease or increase in water clarity depending on the morphometry and amplitude of water-level reduction (e.g. proportion of sediment exposed to the resuspension), thus, either negatively or positively affecting aquatic macrophyte and benthic/epiphytic diatom growth (Jones and Jordan, 2013). Furthermore, increased water levels reduce light penetration to the lake bottom, having a negative impact on the growth of light-demanding species. The direction of water-level change can have dual effect on fish, zooplankton and phytoplankton numbers. Where macrophytes expand, small planktivorous fish can take refuge in macrophyte beds, especially in warmer climates (Meerhoff et al., 2007), causing an increase in small-bodied zooplankters (e.g. rotifers and small cladocerans) and in phytoplankton due to the enhanced fish predation on large-bodied zooplankton (Amsinck et al., 2005). Conversely, very low water levels can induce fish kills (Nõges et al., 2007), expectedly resulting in higher abundance of large-bodied zooplankters (e.g. *Daphnia* spp.) and lower phytoplankton biomass (Iglesias et al., 2011).

Lake ecosystems in Turkey are subject to annually variable water volumes, depths and salinities due to the Mediterranean climate of extreme summer heat with high evaporation and variable autumn/winter precipitation (Beklioğlu et al., 2006; İyigün et al., 2013). As in many other parts of the world where arid to semi-arid climates predominate, lake catchments in Turkey have been heavily modified by human activities, especially in the last century due to agricultural and population demands on water usage.

Climate change projections indicate that catchments in arid and semi-arid Mediterranean regions are likely to show an approximate decrease of 25-30% in precipitation and enhanced evaporation accompanied by an even stronger reduction in runoff by the end of the 21st century (Giorgi and Lionello, 2008). This would magnify seasonal and multiannual water-level amplitudes and enhance hydrological stresses and thus cause prolonged hydraulic drought periods.

Developing adaptive management plans in order to protect lake environments and their ecosystem services is therefore a necessity. However, to develop suitable adaptive strategies, it is essential to investigate the response of lakes and resilience of ecological communities to past water-level fluctuations as a key to understanding current and future conditions. Multi-proxy palaeolimnological techniques can contribute to such an understanding, especially where there is no long-term biological monitoring data. To elucidate this further, a range of palaeolimnological techniques was employed on dated sediment cores from three lakes (Lakes Beyşehir, Marmara and Uluabat) for which long-term instrumental water-level monitoring records (50-100 years) were available. This paper addresses three key questions:

1) Do recent sedimentary (biological/non-biological) records accurately reflect known water level changes?
2) Do measured proxies respond in synchrony to known water level changes?

3) If relationships between proxy data and known water-level changes are complex or poorly-correlated, what factors might account for this?

2. Materials and methods

2.1. Study sites

The three study lakes are located in the mid-western part of Turkey (Table 1, Fig. 1). According to Köppen-Geiger Climate classification Lake Beyşehir is located in the Warm-summer Mediterranean climatic zone (Csb), while Lakes Marmara and Uluabat are located in Hot-Summer Mediterranean zone (Csa). The instrumental water-level data from these lakes were compiled by the General Directorate of State Hydraulic Works (DSI) and the General Directorate of Electrical Power Resources (EIE) of Turkey (here onwards DSI-EIE Database). The three lakes have been classified as important bird areas (IBA) since 2004 (BirdLife International, 2015). Moreover Lake Beyşehir is one of the most important plant areas (IPA) in Turkey (PlantLife International, 2015) and since 1991 it has been classified as a 1st degree Natural Site protection area (a site protection status defined by the Turkish Ministry of Culture) (Nas et al., 2009), while Lake Uluabat has been listed as a Ramsar site since 1998 (Salihoğlu and Karaer, 2004).

2.1.1. Lake Marmara

At the beginning of the 20th century, Lake Marmara was endorheic, saline and around 50% smaller than at present (Girgin, 2000). Inflow (17 hm^3 yr^{-1}) to the lake was originally derived from temporary streams and fault-generated springs (Altınayar et al., 1994). The water level and area of the lake increased in the early-mid 20th century, after converting the lake to a reservoir for irrigation purposes between 1932 and 1953 (Girgin, 2000). The construction of the first canal network south of the lake, which is used to divert the surplus lake water to the Gediz River, was completed in 1945. In the north a diversion canal and a regulator were built to divert river water to the lake (completed in 1952), and in the south another regulator was constructed to control the outflow from the first drainage canal and to ensure a lake level of 79 m.a.s.l (completed in 1953). Another canal on the eastern side carrying the water from a dam to the lake was completed in 1955. An impoundment was also made in the eastern part (finished in 1963) to prevent flooding (Girgin, 2000). Maximum water storage capacity was reached around 1960, with a level of 79.2 m.a.s.l and area of 6800 ha (Arı and Derinöz, 2011). Prior to the early-mid 20th century, the lake level was measured as ca. 73-74 m.a.s.l (Girgin, 2000). Downstream irrigation demands are probably the most significant control on water loss from the lake (Altınayar et al., 1994).

Turkish State Meteorological Service data (available at http://mgm.gov.tr/) indicated that the months with higher precipitation had been between November and March for the 1980-2012 period. Pronounced intra-annual, spring/summer low water-level periods and inter-annual water-level fluctuations have subsequently been recorded (Beklioğlu et al., 2006; DSI-EIE Database).

During very shallow periods, previously flooded areas of the lake and surrounding wetlands have been cultivated (Arı and Derinöz, 2011). Agricultural data retrieved from the Turkish Statistical Institute (TÜİK) (available at http://tuik.gov.tr) shows that between 1995 and 2012 there has not been a significant change in the area of cultivated land around the lake. Conversely, the area of artificial land use, such as continuous urban areas and industrial units, increased from 1995 to 2006 (available at http://aris.ormansu.gov. tr/csa/). In addition, increased nutrient inputs due to population growth and agricultural intensification has led to hypertrophic conditions in the lake, especially in the last 20 years (Arı and Derinöz, 2011; Gülersoy, 2013). A study conducted in Gediz River Basin showed that the mean annual total phosphorus concentration of the lake decreased from 0.6 to 0.2 mg L^{-1} at 2001-2002 period (Gündoğdu and Kocataş, 2006).

Several fish species have also been introduced; piscivorous *Sander lucioperca* was introduced in 1955, followed by omnivorous *Carassius carassius* and herbivorous *Ctenopharyngodon idella* (Innal and Erk'akan, 2006). Massive fish kills occurred in the lake in the mid-1990s corresponding with extreme drought, thus reduced water levels and eutrophication (Arı and Derinöz, 2011).

2.1.2. Lake Beyşehir

Rivers, streams and groundwater from the Anamas and Sultan mountains in the western and eastern catchments feed Lake Beyşehir (Beklioğlu et al., 2014; Nas et al., 2009). Annual and intra-annual precipitation totals fluctuate in accordance with the North Atlantic Oscillation (NAO)/Mediterranean oscillation (Türkeş and Erlat, 2003). The main water loss from the lake occurs via evaporation, with an average of around 570 hm^3 yr^{-1} for the years 1971-2010, and through the controlled outflow (average ca. 300 hm^3 yr^{-1} between 1950 and 2010) that was built between the years 1908-1914 for downstream catchment irrigation (Altınayar et al., 1998; DSI-EIE Database).

Within the lake catchment, agriculture dominates with c. 50% dry and c. 30% irrigated farming (Çiftçi et al., 2010). Data from the Turkish Statistical Institute (TÜİK) (available at http://tuik.gov.tr) indicate that, at the nearby cities there has been a decrease, in the area of the cultivated lands between the years 1995-2012, while there was an increase in artificial lands during 1990-2006 (available at http://aris.ormansu.gov. tr/csa/). Despite intensive land use, monthly data gathered between the years 2010 and 2012 show that the lake is oligo-mesotrophic, with minimum and maximum chlorophyll *a* (Chla), total nitrogen (TN) and total phosphorus (TP) concentrations between 0.6-9.9 μg L^{-1}, 0.0-0.7 mg L^{-1} and 0.01-0.04 mg L^{-1}, respectively (Beklioğlu et al., 2014).

The introduction of piscivorous *Sander lucioperca* in 1978 (Çubuk et al., 2006) has changed the fish community in the lake and contributed to the extinction of the omnivorous endemic fish species *Alburnus akili* (Yeğen et al., 2006), possibly due to predation. Omnivorous *Carassius gibelio* and benthivorous species *Tinca tinca* (from 1990s onwards) and *Atherina boyeri* (in 2002) have also been introduced to the lake (Innal and Erk'akan 2006; Yeğen et al., 2006). *Carassius gibelio* has been considered as invasive in Turkey (Aydın et al., 2011), and unfortunately is a widespread species recorded in many lakes (Boll et al., 2016). Futhermore, Beklioğlu et al. (2014) found that the invasive benthivorous *Pseudorasbora parva* was the dominant fish species in Lake Beyşehir in 2010 and 2011.

2.1.3. Lake Uluabat

Lake Uluabat is fed by groundwater and the Mustafakemalpaşa River. The main outflow connects the lake to Susurluk (Simav) River and eventually to the Sea of Marmara. Water loss from this outflow is compensated by the main inflow. Historical lake and catchment data are fragmentary, though most authors agree that a progressive reduction in lake area has occurred over recent decades (Reed et al., 2008), from c. 160 km^2 with a maximum depth of 7.5 m.a.s.l. to c. 120 km^2 with depths now ranging between c. 5.5 m.a.s.l. in winter/spring to c. 3 m in summer/autumn (Aksoy and Özsoy, 2002; Salihoğlu and Karaer, 2004; DSI-EIE Database). Water levels have been regulated since 1990 (Kazancı et al., 2010) with the construction of a weir at the outflow to raise minimum water levels (Tağıl, 2007). Precipitation data for the city close to the lake indicates that for the period 1973-2012 higher precipitation occurs around November-March (available at http://en.tutiempo.net/). The Mustafakemalpaşa River has carried a significant amount of suspended sediment to the lake during the late Holocene (Aksoy and Özsoy, 2002; Tağıl, 2007) and formed a large delta at the river-mouth on the lake, being very important for maintenance of the lake's RAMSAR status.

Diatom based reconstruction of lake water phosphorus indicated that the lake has been eutrophic (>0.1 mg L^{-1} TP) since prior to the 19th century, showing a trend of increased anthropogenic eutrophication since the start of the 20th century (Reed et al., 2008). Multiple sources of domestic and industrial effluent (including tanneries, slaughterhouses) and fertilizers from the predominantly agricultural catchment area have contributed to the current eutrophic status (Salihoğlu and Karaer, 2004). Aksoy and Özsoy (2002), further showed that between 1974 and 1998 the agricultural land in the delta had increased three times in size, as a result of transforming the reed areas to cultivated lands. This is supported by statistical data from the nearby cities, which indicates an increase in the area of cultivated land from 1995 to 2012 (available at http://tuik.gov.tr). Furthermore an increase in artificial land cover from 1990 to 2006 was recorded (available at http://aris.ormansu.gov. tr/csa/).

Fish populations in the lake have been manipulated by introductions (e.g. omnivorous *Carassius gibelio* after 2000s) (Aydın et al., 2011), overfishing and variable connectivity of the lake to the sea (Çınar et al., 2013). Salt-water/euryhaline fish species (piscivorous *Alosa maeotica*, *Anguilla anguilla*, zooplanktivorous *Mugil cephalus* and *Syngnathus* sp.) were recorded in the lake in 2006 (Çınar et al., 2013). A crustacean (*Astacus leptodactylus*) fishery was extensive in the lake in the 1980s. However, due to plague, which was peaked around 1986, and overfishing their numbers have declined and fish have become economically more important (Baran and Soylu, 1989).

2.2. Field methods

Sediment cores from Lakes Beyşehir, Marmara and Uluabat were retrieved with a Livingstone piston corer from littoral and pelagic locations in October 2011 (Fig. 1, Table 2). The length of the cores were c. 0.6 m and 0.7 m from Lake Marmara, c. 0.9 m and 1.6 m from Lake Beyşehir, and 0.9 m and 1.1 m from Lake Uluabat for littoral and pelagic locations, respectively. For the expediency of the current study, however, only the lengths corresponding to instrumental or known water level data are presented, and not the whole cores. It should also be noted that, due to the bad weather conditions in Lake Uluabat, it was not possible to reach the mid-lake location, therefore the core was retrieved from the nearest deep area, 1.0-1.5 km from the vegetation.

Cores were sliced into 0.5 cm thick layers for the first 20 cm (30 cm for Lake Beyşehir) and at 1 cm intervals to the base of the cores. Before chemical, biological and micro/macrofossil analyses samples were refrigerated at 4°C, while for pigment analysis, they were stored frozen.

2.3. Laboratory methods

A range of geochemical and physical proxies were analysed in radiometrically dated (using ^{210}Pb) littoral and pelagic cores. However, diatom valve preservation was low in the pelagic cores of all three lakes. Therefore, to obtain a comparable dataset, diatoms, sub-fossil cladocerans and plant macrofossils were analysed in the littoral cores and when possible in the pelagic ones. Conversely, pigment analysis was carried out only on the pelagic cores due to their better preservation here than in the littoral cores.

Freeze-dried sediment samples from the littoral and pelagic cores of each lake were analysed for ^{210}Pb, ^{226}Ra, ^{137}Cs and ^{241}Am by direct gamma assay in the Environmental Radiometric Facility at University College London using ORTEC HPGe GWL series well-type coaxial low-background intrinsic germanium detectors. Corrections were made for the effect of self-absorption of low energy gamma rays within the sample (Appleby et al., 1992). For all the lakes, ^{210}Pb chronologies were calculated using the constant rate of supply (CRS) dating model (Appleby and Oldfield, 1978).

Sediment water (dry weight: DW), organic matter (loss-on-ignition: LOI550) and carbonate content (LOI950) were measured at 105°C, 550°C and 950°C, respectively, following Heiri et al. (2001). Wet density measurements were undertaken on every fourth sample by weighing a 2 cc vial of wet sediment.

Sediment samples were analysed for geochemical and selected trace elements using a Spectro XLAB2000 X-ray fluorescence (XRF) spectrometer at University College London. Freeze-dried sediments were milled to a fine powder. Approximately 1 g (weighed to 4 d.p) sediment was placed in nylon cups with a base of prolene foil (4 μm thickness). Reference sediment samples (Buffalo River Sediment, National Institute of Standards and Technology (NIST) - RM8704; Canadian Certified Reference Materials Project (CCRMP) - LKSD-2) were included in each sample batch run to identify any machine drift error and assess measurement accuracy.

The diatom analysis was conducted according to the method described by Battarbee (1986). Identification and counting of the diatom slides were conducted with a Leica DMI4000B inverted microscope at Middle East Technical University at 1000x magnification. From each sample approximately 500 valves were counted. Diatom taxa were grouped into two categories, planktonic and non-planktonic, according to their habitat classes.

The method for taxonomic analysis and enumeration of cladocerans was an adaptation of the techniques described by Korhola and Rautio (2001) and the method of Jeppesen et al. (1996, 2001) with heating ca. 3 g sample in 10 % KOH. Identification and counting of the samples were carried out using a stereo microscope (LEICA MZ 16) and an inverted light microscope (LEICA DMI 4000) at Middle East Technical University. Identified cladoceran species were classified into four habitat groups, as planktonic, macrophyte-associated, macrophyte and sediment-associated, and sediment-associated (Flößner, 2000; Hann, 1989).

Plant macrofossil sample preparation was carried out from sediment samples of 3 to 25 cm^3 (depending on the sample size) following the method described by Brodersen et al. (2001). Identification and counting were conducted at Middle East Technical University using a

LEICA MZ 16 stereo-microscope at 10x – 110x magnification. Haas (1994) was used for the identification of charophyte oospores.

Sedimentary pigment analysis samples were stored frozen until pigment extraction. The analysis was performed using the system described by Buchaca and Catalan (2007), except the filtration was done through 0.2 µm syringe filters. Pigment analysis was carried out at the Department of Bioscience and the Arctic Centre (ARC) of Aarhus University, Denmark. Pigment groups were ascribed to different algal groups according to the information given in Leavitt and Hodgson (2001), and Buchaca and Catalan (2007).

2.4. Numerical analysis

To reveal the timing of major changes in the sediment records and to be able to compare these changes with the instrumental water level records from all three lakes, principal curves analysis (PCs) was employed for the geochemical, physical and biological variables in all the cores using the pcurve package (Hastie et al., 2011) in R version 3.1.2 (R Core Team, 2015). Prior to analysis, geochemical and physical variables were log-transformed. Since there is a high variability in the numbers of plant remains (e.g. low versus high seed producing species), plant macrofossil data were square-root transformed, centered and standardised and the values which were zero before this were returned to zero (Davidson et al., 2013). Moreover, diatom and cladoceran data were converted to relative abundances and subsequently square root or Hellinger transformed depending on the dissimilarity measures used (Davidson et al., 2013).

For biological variables, Nonmetric Multidimensional Scaling (nMDS) axis scores using Bray-Curtis dissimilarities (Legendre and Legendre, 1998) or Principal Component Analysis using Euclidean dissimilarities (with Hellinger transformed species data) (Legendre and Gallagher, 2001) were used as the starting curves. The choice between these two matrices was made according to the species response curves and the variation explained after PC analysis. For environmental variables Euclidean distance matrix was employed (Legendre and Gallagher, 2001). The smoothing function used for all the variables was LOESS and the optimal degree of smoothing was determined by a generalised cross validation procedure.

3. Results

3.1. Lake Marmara

3.1.1. Water-level change

Instrumental water-level data from Lake Marmara covered the period from 1970 to 2011. The mean water level for this period was 75.7 m.a.s.l and varied between 73.2 and 77.7 m.a.s.l. A period of higher water levels was observed around the 1970s to the 1980s, followed by a very significant decline from the late 1980s until the mid-1990s. The lowest level occurred in 1992-3 (ca. 2.0 m decrease from the mean) when most of the lake dried out. Another large, but short-term, water-level drop was in 2007-2008. After 2008 with the construction of a dam (1998-2012), the water level in the lake has increased.

Calculated local water depth at the pelagic core site ranged between 0.7 and 5.0 m, while at the littoral core site it was between -0.9 and 3.4 m, indicating that the littoral core site has been regularly exposed.

3.1.2. Chronology

In the littoral core of Lake Marmara ^{210}Pb activities are low (Supplementary Fig. 1.A, Supplementary Table 1). The equilibrium depth of total ^{210}Pb activity with the supported ^{210}Pb occurs deeper than 20 cm. Unsupported ^{210}Pb activities decline irregularly with depth , and the maximum activity appears at c. 8.3 cm while the surface sediment activity is very low (Supplementary Fig. 1.B). Sedimentation rates in the core have varied in the last 70 years and disturbance to sedimentation has occurred in recent years. As unsupported ^{210}Pb activities are low and counting errors are relatively high, there is some uncertainty with interpretation of the chronology for this core.. However, the 1963 depth derived from the ^{210}Pb CRS model was placed at c. 14.3 cm, which was in reasonable agreement with the depth suggested by the ^{137}Cs record (Supplementary Figs. 1.C and 4.A). The sedimentation rate showed some regular increases and decreases, ranging between 0.05-0.50 g cm^{-2} yr^{-1}, with a marked increase towards the surface of the core.

^{210}Pb activities in the pelagic core are also low. The equilibrium depth of total ^{210}Pb activity with the supported ^{210}Pb occurred at a depth of c. 38 cm (Supplementary Fig. 1.D, Supplementary Table 2). Unsupported ^{210}Pb activities decline irregularly with depth with the maximum activity at c. 6.3 cm (Supplementary Fig. 1.E), suggesting changes in sedimentation rates and an increase in recent years. The ^{137}Cs activity versus depth shows a peak at 28.5 cm, which is almost certainly derived from the 1963 fallout maximum from the atmospheric testing of nuclear weapons (Supplementary Fig. 1.F). However, the CRS dating model placed the 1963 depth at 18.5 cm (Supplementary Fig. 4.B), which was not in agreement with the depth suggested by the ^{137}Cs record. Corrected chronologies and sedimentation rates were calculated by the CRS model using the ^{137}Cs peak at 28.5 cm for 1963 as a reference level.

Corrected chronologies showed that 15.3 cm was dated to 1986. Also, a distinct peak in the sedimentation rate, with an increase of 0.27 g cm^{-2} yr^{-1} at 20.5 cm (dated 1976±5) in the pelagic core agreed with the peak rate at 11.3 cm (dated to 1978±11) in the littoral core.

3.1.3. Sediment composition (LOI) and bulk sediment geochemistry

The DW and LOI profiles of the littoral core were more variable than the pelagic core (Figs. 2.A and 2.B). Prior to the constructions, during lower water-level periods (40-23 cm, pre 20th century), LOI950 and LOI550 were low with less than 10% and 5%, respectively, while DW was relatively high, being c. 80% (Fig. 2.A). The distinct low LOI950 in this period (ca. 34-24 cm) is visible in the Ca element profile but was more evident by the concomitant increase of Ti and erosion resistant Zr (more sand silt). DW showed a significant shift, decreasing to c. 40-50% above 24 cm, indicating a change in the hydraulic properties of the sediment (less compact and higher silt content). Around 20-22 cm, coinciding with the construction period, a fall in mineral (Rb:Sr, Ti, Zr) indicators and a rise in LOI950 from c. 5% to c. 12% was observed. There was a change in sediment composition around 12 cm (1973 ±13), with a 1% decline in Fe, 20 µg g^{-1} drop in Rb and a noticeable c. 0.5% decrease in Mg, Al and K. Between 8-9 cm (c. 1990-1995), LOI550 values show a marked c. 3.5% decrease. PC-XRF scores also indicated that the main changes in the core were above 24 cm coinciding with the construction period, also around the long-term drought in 1990s with a significant and sudden change.

Before water-level regulation in Lake Marmara, XRF and LOI measurements of the pelagic core suggest a stable carbonate-/lithogenic-mixed mud system (Fig. 2.B). LOI550 values were low (<10%) throughout the core, indicating low organic matter content and/or preservation.

The principal geochemical change in the pelagic core followed the compositional changes measured by LOI950 with a significant decrease of Ca by c. 5% and Sr by c. 500 µg g^{-1} above 40 cm during the last half century (after c. 1950 AD). Also, more non-carbonate/soil mineral-associated elements (Rb:Sr, Ti) gradually increase during this time. This soil input phase appeared to finish around 23 cm (c. 1975) (Fig. 2.B). LOI950 showed some variability, with a peak of c. 3% increase, in carbonate deposition at 14 cm (late 1980s), coinciding with low water levels. From c. 1995, especially after 1997, water levels increased and the lake refilled with soil/mineral matter continuing to be deposited in the pelagic area. The short-term water level decrease in 2007-2008, however, was not registered in the core, with the exception of a slight increase in LOI950.

3.1.4. Biological variables

Before constructions began in 1932 (likely below c. 23 cm), notwithstanding the possible low water levels, dominant cladocerans were planktonic *Bosmina longirostris*, with c. 25-90% and *Daphnia* spp. with 2-4%, but the abundance of benthic species such as *Leydigia* spp., with c. 5-10% was also relatively high (Fig. 2.A). Moreover, short-growing, low turbidity-tolerant macrophyte species, Characeae and *Ranunculus*, comprised the dominant macrophyte remains. At around 26 cm cladocerans shifted to benthic dominance, and both the abundance and diversity of macrophyte remains was sparse. Diatom preservation was poor in the lower core (below 18 cm), preventing species identification.

The change in PC at c. 23 cm indicates a significant alteration in both cladoceran and plant macrofossil records during the construction period (1932-1953), which culminated with maximum water levels in c. 1960 (around 15 cm depth) (Fig. 2.A). *Daphnia* spp. and short-growing plant remains disappeared and remains of tall-growing plants, tolerating lower light availability, such as *Potamogeton* spp., appeared, along with macrophyte-associated cladoceran *Graptoloberis testudinaria*.

Following the construction period (14-0 cm; c. 1970-present), changes in the pelagic-benthic diatom ratio associated with water level were muted, though a slight increase in pelagic species abundance (e.g. *Aulacoseira granulata*) can be distinguished during high levels. In contrast, the variation in the relative abundance of pelagic and benthic cladocerans (excluding cosmopolitan *B. longirostris* and *Chydorus sphaericus*) was more coherent with water-level fluctuations, with an increase in pelagic benthic species ratio, with an increase of 0.3 (note that the excluded *B. longirostris* have the highest abundance) (Fig. 2.A). Despite higher water levels, remains of short-growing plants (Characeae) were abundant. The long-term low water-level period from c. late 1980s to mid-1990s likely led to the notable increase in macrophyte remains at this time, and the coincident very slight decrease in pelagic-benthic ratio of diatoms and cladocerans, by c. 0.10 and 0.04, respectively.

In the pelagic core, through the construction period (c. 40 to 30 cm), there is a decrease in all the pigment concentrations, with c. 0.5-1.5 nmol g^{-1} organic matter (OM), except Cryptophyta markers, and an increase in the alloxanthin/diatoxanthin (Cryptophyta/diatom) ratio (Fig. 2.B). A significant change was also observed in the PC scores. After the 1960s pigment concentrations increased. However, in the upper part of the core PC scores did not show any significant change until around long-term drought period in the 1990s (ca. 15-10 cm), where a significant increase (twice the previous concentration) in cyanobacteria and Chlorophyta markers was also observed.

3.2. Lake Beyşehir

3.2.1. Water-level change

The instrumental water-level data between 1905 and 2012 showed that mean water level was c. 1123.3 m.a.s.l (Figs. 3.A and 3.B), and included four low and four high water-level periods. High levels were around 1905-1927, 1940-1956, 1966-1973 and 1977-1988, being 1.0- 2.2 m higher than the mean level. There were two relatively long- and one short-term water level drops in c. 1928-1939, 1957-1965 and 1974-1976, by approximately 2.0 m (for the first) and 1.0 m (for the latter two) from the mean level. A longer-lasting low water-level period occurred in 1989-2011, reaching its lowest level in the mid-90s with a 2.0 m drawdown.

Water-level calculations based on the water depth at the core sites in October 2011 compared to the instrumental lake-level value, indicated that lowest local water depth at the pelagic site was 5.7 m and the highest was 9.5 m, while at the littoral core site the water depth ranged from 1.5 to 5.0 m.

3.2.2. Chronology

In the littoral core from Lake Beyşehir total ^{210}Pb activity reaches equilibrium with the supported ^{210}Pb at around 20 cm (Supplementary Fig. 2.A, Supplementary Table 3). Unsupported ^{210}Pb activities, calculated by subtracting ^{226}Ra activity from total ^{210}Pb activity, declines irregularly with depth suggesting changes in sedimentation rates (Supplementary Fig. 2.B). Maximum unsupported ^{210}Pb activity is at c. 5 cm, indicating a recent increase in sediment accumulation rates. The ^{137}Cs activity versus depth shows a broad peak between 17 and 10 cm, which is likely to be derived from the 1963 fallout maximum from the atmospheric testing of nuclear weapons (Supplementary Fig. 2.C). The relatively high ^{137}Cs activities in the surface might be due to soil in-wash from the catchment and re-suspension of ^{137}Cs-labile sediment in the littoral zone. The 1963 depth derived from the ^{210}Pb constant rate of supply (CRS) model was placed between 11.8 and 13.3 cm (Supplementary Fig. 4.C), which was in agreement with the depth suggested by the ^{137}Cs record. Because of low unsupported ^{210}Pb activities and relatively high counting errors in the sediments deeper than 17.0 cm, ^{210}Pb dates were not ascribed to depths below 16.8 cm (pre-1900s). The data showed that sedimentation rates increased greatly since the 1900s from 0.03 to 0.30 g cm^{-2} yr^{-1} at present.

In the pelagic core, the equilibrium depth of total ^{210}Pb activity with the supported ^{210}Pb is at around 6 cm (Supplementary Fig. 2.D, Supplementary Table 4). Like the littoral core from the same lake, unsupported ^{210}Pb activities also decline irregularly with depth indicating recent change in sedimentation rates (Supplementary Fig. 2.E). The ^{137}Cs activity versus depth curve has a shoulder between 3 and 5 cm that may be derived from the 1963 fallout (Supplementary Fig. 2.F). ^{137}Cs activities increase in the upper core sediments, due to soil in-wash from the catchment in recent years as also observed in the littoral core. Because of the low accumulation rate in the pelagic zone, this surface increase may also indicate some bioturbation – an intact bivalve was found in the surface mud of the core and diffusion in the slowly accumulating sediment. The CRS dating model placed the 1963 depth between 3.8 and 4.3 cm, which was also in agreement with the depth suggested by the ^{137}Cs record (Supplementary Fig. 1.D). Sedimentation rates of the core showed a gradual increase from the 1930s to the 1970s, from 0.02 to 0.05 g cm^{-2} yr^{-1}, followed by fluctuations in recent years (ranging between 0.03 and 0.09 g cm^{-2} yr^{-1}).

3.2.3. Sediment composition (LOI) and bulk geochemistry

In the littoral core, LOI950 and DW decreased gradually, by c. 10 % and 15%, from 15 cm (1932 ±12 AD, drought period) to present (Fig. 3.A). LOI550 mirrors this change. The shift in sediment composition recorded post 14-15cm (mid 1930s – early 1940s) emerged with increased values of terrigenous/mineral indicators (i.e. Ti, Zr) and a fall in autochthonous Ca with 4% and Sr with 140 $\mu g\ g^{-1}$.

The pelagic core is formed of homogenous low organic (<6% LOI550, mean 4% sd 0.48) silt-clay/carbonate mud (Fig. 3.B). DW remained at approximately 46-50% throughout the core. The small surface increase in LOI550, by c. 1.5%, coincided with a c. 2% decrease in Ca and a small increase in organic matter-associated elements (P, S, As and Br). The small but fluctuating nature of Al, Si, Ti, K, Zr, Rb and Sn (mineral in-wash) suggested a conservative sub-decadal record of catchment sediment inputs contrasting with chemical precipitation in the lake (Ca, Mg, Sr).

3.2.4. Biological variables

During the 1905-1988 period (c. 20- 7 cm), water level was fluctuating between high and low, though was dominated by high levels. Benthic diatoms, (e.g. *Navicula subrotundata* and *Amphora pediculus*), and littoral cladoceran taxa were dominant. Short growing plants, such as *Chara* spp. (mostly *C. contraria* type oospores) and *Ranunculus* sect. *Batrachium*, were also present (Fig. 3.A). Above 15 cm, after the 1930s drought (the most pronounced in this period), the abundance of sediment-associated cladocerans decreased from c. 35% to 1%, while the abundance of the small-bodied pelagic taxon *Bosmina longirostris* increased from c. 3% till 70% to the sediment surface, becoming the dominant species around early-1990s. This change was also reflected in the PCs of cladocerans which increased above 15 cm (Fig. 3.A). Conditions following this drought led to the first appearance of the planktonic diatom *Aulacoseira granulata*, which is a typical species of eutrophic and turbid environments (Wolin and Stone, 2010).

Above 7 cm, during the lower water-level period c. 1989-2011, planktonic diatom taxa, such as *A. granulata* and *Cyclotella ocellata*, increased and reached together a maximum abundance of around 50% at the surface sediment (Fig. 3.A). Moreover, during this period an increase in plant remains, especially of tall-growing, low-light tolerant species such as *Ceratophyllum* sp., was observed, and oospores of Characeae mostly belonging to *C. hispida*- and *C. globularis* types appeared. Furthermore, the PC scores of macrophytes, cladocerans and diatoms either increased or decreased above 7 cm indicating synchronous compositional shifts in all three groups (Fig. 3.A).

Pigment preservation indicated by the chlorophyll *a*:phaeophytin *a* ratio in the pelagic core was not stable and relatively low, causing the interpretation to be unclear or misleading (Fig. 3.B). Therefore, pigment data are not interpreted further in the study. Cladoceran remains, on the other hand, were in agreement with the change in the littoral core, with a shift from benthic species dominance towards more pelagic associated species (Fig. 3.B).

3.3. Lake Uluabat

3.3.1. Water-level change

Repeated annual water-level changes of approx. 1 m, have been a regular feature of Lake Uluabat since c. 1960. A long-term high water-level period occurred around 1960-1984 and a long-term low water-level period has lasted from around 1985 until the present. In the former, a few short-term decreases were observed, while short-term (one to two years) increases have occurred in the latter. The largest water-level drop was recorded in 2001, with a 1 m drop from the mean (3.96 m.a.s.l).

Local water depth indicate that water levels at the pelagic core site fluctuated between 1.0 m and 2.7 m, while at the littoral core site it varied between 0.8 m and 2.4 m.

3.3.2. Chronology

^{210}Pb activities in the Lake Uluabat littoral core are low and most counting errors are higher than the unsupported ^{210}Pb activities in the sediments greater than 20 cm, hence the depth where total ^{210}Pb activity reaches equilibrium with supported ^{210}Pb is uncertain (Supplementary Fig. 3.B, Supplementary Table 5). Low unsupported ^{210}Pb activities that decline irregularly with depth indicate significant changes in the magnitude and regularity of sedimentation (Supplementary Fig. 3.B). The ^{137}Cs activity versus depth shows a broad peak between 26 and 35 cm, which is almost certainly derived from the 1963 fallout maximum from the atmospheric testing of nuclear weapons (Supplementary Fig. 3.C). The 1963 depth derived from the ^{210}Pb CRS model is placed at 18.5 cm, which is not in agreement with the depth suggested by the ^{137}Cs record (Supplementary Figs. 3C and 4.E). Corrected chronologies and sedimentation rates were calculated by the CRS model using the ^{137}Cs peak at 34.5 cm for 1963 as reference level. Sedimentation rates showed two peaks in the 1960s and the 1970s, respectively, and since then sedimentation rates were relatively uniform with a mean of 0.28 g cm^{-2} yr^{-1}. A similar break around 1960s in the sedimetation rate of a core retrieved from the North-Eastern part of the lake, was also observed by Reed et al. (2008), but they did not observe a second peak around 1970s, as in the current study. This difference might be a result of a higher accumulation rate found in the core we collected from a diffrent location (western part of the lake near outflow).

In the pelagic core of Lake Uluabat, the equilibrium depth of total ^{210}Pb activity with supported ^{210}Pb occurs at an approximate depth of 41 cm (Supplementary Fig. 3.D, Supplementary Table 6). Unsupported ^{210}Pb activities in the sediments are low, and they decline irregularly with depth (Supplementary Fig. 3.E), indicating significant changes in sedimentation rates. Sedimentation rates in this core are relatively high. The ^{137}Cs activity versus depth shows a peak between 22 and 25 cm, which is certainly derived from the 1963 fallout maximum (Supplementary Fig. 3.F). In the pelagic core of Lake Uluabat, the CRS dating model places the 1963 depth at 32 cm (Supplementary Fig. 1.F), which was considerably deeper than the depth suggested by the ^{137}Cs record. Corrected chronologies and sedimentation rates were calculated by the CRS model using the ^{137}Cs peak at 23 cm for 1963 as reference level. Sedimentation rates varied with a mean of 0.22 g cm^{-2} yr^{-1}.

3.3.3. Sediment composition (LOI) and bulk sediment geochemistry

LOI550 was higher in the littoral core (up to 18%) than the pelagic core, most likely due to the proximity of littoral vegetation, and showed an almost linear increase from 20 cm to the surface (Fig. 4.A). In parallel, LOI950, Ca and Sr increased from c. 10 to 12%, c. 6 to 8% and c. 200 to 260 µg g^{-1}, respectively, while concentrations of the mineral indicators (i.e. K, Al) decreased slightly from 20 cm to the present (1975-2011). At around 4 cm, both LOI550 and LOI950 profiles indicate broader changes interspersed with a marked c. 1% increase and decline, respectively. DW also showed a steady decline from 45 to 35%, then to 18% between 20 cm (c. 1974) and present reflecting less compacted mud in the upper core (Fig. 4.A). LOI950 displayed two peaks at 10 cm with c. 10% (c. 1992) and 1 cm with c. 15% (c. 2009). The former peak appeared to coincide with a short-lived fall in the lake level (and deposition of carbonate/biogenic sediments). The latter peak coincided with a drop in Rb/Sr that indicates a recent decline in soil/mineral sediment and an increase in authigenic-organic mud (Fig. 4.A).

The homogeneous nature of the pelagic sediment core, consisting of silty mud, was apparent in the stable LOI and element profiles, also from the PC scores (Fig. 4.B). Less compact and slightly more organic mud occurs in the top 10 cm. The LOI550 profile showed little variation (mean 7.1 sd 1.1) except a very steady increase, between c. 7% and 11%, from the bottom to the top of the core. Br, which is often associated with organic matter (along with P), increased steadily up core, from c. 3 $\mu g\ g^{-1}$ to 7 $\mu g\ g^{-1}$, supporting an increase in organic carbon in the upper 20 cm. However, there was no evidence of significant organic matter accumulation, suggesting that the site was unlikely to have been colonised by aquatic/emergent plants during low-water phases. Additionally, the low LOI550 indicated that organic matter was quickly degraded and recycled rather than buried (Fig. 4.B). At around 7-8 cm a small shell-rich (*Hydrobia* sp.) peak in LOI950 (21.7%), Ca, Sr and As (arsenic) was observed and Rb reduced, suggesting an authigenic sediment depositional phase.

3.3.4. Biological variables

Between 20 cm to 16 cm of the littoral core (ca. mid-1970s until the mid-1980s), when the water level was high, remains of both short-growing (e.g. *Chara* spp.) and tall-growing (e.g. *Ceratophyllum* sp.) plant taxa were found (Fig. 4.A). Accordingly, macrophyte- and sediment-associated cladoceran taxa, such as *Graptoloberis testudinaria* were observed, along with the pelagic *Bosmina longirostris*. The diatom assemblage also contained a mixture of planktonic (e.g. *Aulacoseira granulata*, *Cyclostephanos dubius*) and benthic (*Cocconeis* spp., *Epithemia* spp.) taxa.

Coinciding with the long-term low water-level period from 1985 to 1996 (ca. 16-9 cm), an increase in submerged and floating leaved macrophyte taxa, namely *Najas minor, Chara* sp. and Nymphaceae was seen (Fig. 4.A). Accordingly, the abundance of *G. testudinaria* increased by c. 20% and planktonic diatom species *A. granulata* decreased by c. 26% from the 1990s. In the two consecutive short-term high water-level (ca. 8.5-7 cm and 6-5 cm; late 1990s and early 2000s respectively) periods a decline in macrophyte species richness was seen, and *Ceratophyllum* sp. remains were dominant (Fig. 4.A). This change can also be seen in the PC scores obtained from plant remains. From 5 cm to 1 cm (ca. 2007-2010), during the low water-level period, *B. longirostris* increased by c. 20% and *G. testudinaria* decreased by c. 10%. Plant remains indicated a possible increase in *Ceratophyllum* sp. abundance especially above 5 cm. Together with these changes, the rapid increase, from c. 2% to 20%, in planktonic and eutrophic-tolerant diatom species *C. dubius* suggested a possible increase in nutrient concentrations in recent years.

Marker pigment concentrations showed an increasing trend from 30 cm depth to the surface (approx. 80 years) in the pelagic core (Fig. 4.B). However, pigment preservation exhibited a parallel increase that lowers the confidence in their use for interpreting ecological changes.

During the higher water-level period from 1960 to1984 (ca. 22-12 cm), cyanobacteria pigment concentration was lower (0.5-1.0 nmol g^{-1} OM) than in the later low-water (1.0-5.0 nmol g^{-1} OM) periods. Accordingly, macrophyte- and sediment- associated cladoceran abundances were also higher by 50%, but benthic and planktonic diatoms were equally abundant (Fig. 4.B). In the upper part of the core, coinciding with low water levels (ca. 5-2 cm), cyanobacteria indicator pigments increased. Correspondingly, despite low water levels, a significant increase in the abundance of planktonic cladocerans occurred, along with remains of tall-growing plant species (Fig. 4.B).

4. Discussion

4.1. Responses in the cores to water level changes

Our results from the three lakes showed that longer term and more pronounced water-level changes were reflected in the sediment record, while short-term but distinct lake-level changes left little impression. Noisiness of short-term cyclical water-level changes, low temporal resolution, and additional anthropogenic impacts on these lakes have prevented close relationships between actual changes and those recorded in the sediment, highlighting the care is required in using recent sediment records from large shallow lakes for forecasting future patterns of water-level changes.

Contemporary water-level data showed that all the lakes had both longer lasting (more than 5 years) and short-term high- and low-level periods, with some being more intense (c. 2 m shift from the mean levels). Overall an increase in total submerged macrophyte remains was observed during more protracted water-level reduction periods, coinciding with higher macrophyte coverage as judged from the contemporary records (Altınayar 1998; Altınayar et al., 1994, 1998; Beklioğlu et al., 2006). However, the extent of changes (indistinct at times) in the relative abundance of benthic-pelagic cladocerans and diatoms and also in the composition of submerged macrophytes (tall- vs. short- growing) varied among the lakes and even within the same core. Moreover, the record of sub-decadal trends in the cores was somehow blurred by the interaction between timing and magnitude of lake response and mixing. Thus, slow rates of accumulation and resuspension occurring in the study lakes were not conducive to detecting sub-decadal trends. We further found that the geochemical and physical proxies in these lakes indicated better agreement of littoral cores with water-level alterations compared to pelagic cores, especially during periods of marked water-level changes as also suggested by Furey et al. (2004).

Before the water-level regulation in Lake Marmara, when the water level was low, the lake was endorheic (Altınayar et al., 1994). Geochemical and physical records, with reduced carbonate and higher mineral mater (Ti, Zr) suggested that the littoral core site consisted of more sand-silt material and was water covered but likely affected by mixing and sorting of the sediment as a result of profound seasonal water-level changes. The presence of *Ranunculus* sect. *Batrachium* remains (Birks et al., 2001) and desiccation-resistant Charophyte oospores (Soulié-Märsche and García, 2015) in the littoral core also confirmed fluctuating water levels. The conditions in the pelagic core were more stable with carbonate-lithogenic mixed sediment content, representing deposition in the pre-modified endorheic lake. The long-term low water-level period in the 1990s appears to have left its mark on the pelagic and littoral sediments, suggesting a return to depositional conditions not seen since before the water level regulation. Furthermore, biological proxies in the sediment with predominance of macrophytes, and slight increase in benthic/macrophyte associated taxa of cladocerans and diatoms concur with the high Secchi depth measurements of the 1990s (Beklioğlu et al., 2006), by showing relatively low phytoplankton indicator pigment concentrations and higher contribution of low-light intolerant species (e.g. diatom *Cocconeis placentula*, cladoceran *Graptoloberis testudinaria*).

Contrary to expectations, however, the pronounced water-level drops in Lakes Beyşehir (c. 1930s and 1990s) and Uluabat (1990s and mid-2000s), did not result in an increase in remains indicative of a benthic system, but rather a decrease in littoral species abundance (e.g. cladoceran *G. testudinaria*) and an increase in tall-growing plant remains (e.g. *Ceratophyllum* sp.). As other cores from these lakes also have suggested (Fethi et al., 2014; Kazancı et al., 2010; Reed et al., 2008), our geochemical and physical sedimentary records indicate sediment resuspension, especially during low water-level periods as the lake's wide open large surface area makes it susceptible to wind induced resuspension. Correspondingly, results of Oğuzkurt (2001), Dalkıran et al. (2006) and Beklioğlu et al. (2012) also revealed relatively low Secchi depths for these lakes. Therefore, this change towards a system with more pelagic species may reflect that the water-level decrease enhanced resuspension and thus turbidity in these two lakes, where coverage of submerged macrophytes and thus protection against resuspension typically have been lower than in Lake Marmara, which was completely covered with submerged plants during the 1990s low level period (Altınayar et al., 1994). A study conducted in large Lake Marsh (Minnesota) also showed significantly lower impact of wind, and thus lower resuspension, during the year with dense macrophyte beds, compared to a low plant covered period (James and Barko, 1994).

The effect of the deliberate water-level increase (c. 1930-1953/1960), of around 6 m (from c. 73 to 79 m.a.s.l.), in Lake Marmara shifted the lake from an endorheic to an open and deeper lake system used for irrigation (Gülersoy, 2013), occurring concomitantly with the input of water and soil materials as a result of river channelization. Corresponding with this water level increase, the littoral core sediment was compact with higher silt content while the pelagic core indicated lower light conditions at the pelagic water-sediment interface by the loss of carbonate and increased mineral input (Harrison and Digerfeldt, 1993). Accordingly, a change towards dominance of tall-growing macrophyte remains, such as *Potamogeton* sp, *Zannichellia. palustris*, and a decrease in all the pigment concentrations (except Cryptophyta) was also observed, likely indicating higher light attenuation (Bjerring et al., 2013; Nõges and Nõges, 1998) but relatively lower nutrient concentration. Despite water-level increase, however, planktonic cladoceran *Daphnia* spp. disappeared, indicating higher fish predation (Jeppesen et al., 2003). Even though there are no measurements from the pre-construction period the lake was defined as saline (Altınayar et al., 1994; Girgin, 2000) and it has been claimed that with increasing water levels the salinity of the lake has decreased (Gülersoy, 2013). However, the changes in the core could not be reliably interpreted as a change in salinity, since the possible biological indicators, such as *Zannichellia palustris*, have a wide salinity tolerance range (Greenwood and Dubowy, 2005; Heegard et al., 2001). Furthermore, the better preservation of the diatoms with higher water level may also be related to relatively lower alkalinity (Flower, 1993). The geochemical records indicated a new, but less distinct water level increase in Lake Marmara in the late 1990s, which may be a result of less significant increase in water level. However, unlike the previous water level increase the reaction of cladocerans was clearer, while the change in submerged macrophytes was more tentative. The observed higher pelagic/littoral cladoceran ratio, possibly draw attention to the lower fish predation pressure as a result of fish kills (Arı and Derinöz, 2011), allowing cladocerans to react as expected. Submerged macrophyte remains indicated a community with abundant short-growing plant remains (e.g. *Chara* sp.), which suggests a relatively good light climate (Blindow, 1992), notwithstanding the higher water levels. Furthermore, a community with higher macrophyte species richness may indicate relatively higher nutrient concentrations (Rørslett, 1991) compared to previous high water level period.

Various studies on the water level-biological proxy relationship have indicated a change towards pelagic species abundance with higher water depths (Moos et al., 2005; Riis and Hawes, 2003; Sarmaja-Koronen and Alhonen, 1999). In contrast, the high water level period (c. 1900s to mid-1980) of Lake Beyşehir coincided with increased abundance of benthic species, such as the diatom *Navicula subrotundata*, cladoceran *Monospilus dispar*, and more remains of short-growing plants (e.g. *Ranunculus* sect. *Batrachium*). Since this lake is defined as oligo-mesotrophic, this shift may indicate improved light conditions, owing to the possible lower turbidity, compared to low water-level periods (ca. 1990s-2011).

4.2. Possible Factors Leading to Poor Agreement

Lake water-level changes are clearly recorded in Quaternary-Holocene lake sediment sequences (e.g. Abbott et al., 2010; Shuman et al., 2009; Stone and Fritz, 2004). In our lakes, however, it would be difficult to attribute the complex shifts in the palaeo-records to water-level changes were it not for the presence of the instrumental water-level data. Even though water-level data used in this study cover extensive periods as instrumental records, compared with many palaeolimnological studies (Bjerring et al., 2013; Finkenbinder et al., 2014), these periods are still relatively short (longest being 100 years for Lake Beyşehir). A study, covering the Holocene period, from shallow Lake Juusa, Estonia, showed that diatom assemblage change in both littoral and pelagic cores were compatible with each other, also with c. 2-4 m water level fluctuations (Punning and Puusepp, 2007), though the much smaller size of this lake compared to our study lakes should be noted. It is also pointed out that the variation in the lake level or surface area of open basin lakes is less sensitive than closed ones, since water level in overflowing lakes depends not only on climate, but also on the outflow of the lake (Cheddadi et al., 1997). Nevertheless, the study conducted in large, shallow and open-basin Lake Võrtsjärv, Estonia, pointed to the good correlation between instrumental water level data and sedimentary pelagic diatom abundance (Heinsalu et al., 2008).

A stronger agreement of all the proxies with the water-level records in Lake Marmara compared to the other study lakes most likely reflects a higher amplitude of water-level change, with the difference between yearly maximum and minimum levels being highest, with an average of 2.1 m for this lake. Similarly, using at least 30 years of water level data, Evtimova and Donohue (2016) compared two sets of lakes in Ireland, which are exposed to high (mean annual >1m) and low (mean annual ≤0.65 m) amplitude water level changes on a monthly and yearly basis. This study showed more significant impact of high amplitude fluctuations than low level ones on the littoral area structure (Evtimova and Donohue, 2016). The flatter bottom profile of Lake Marmara than in the other lakes (Beklioğlu et al., 2006; Bulkan, 2009; Karaer et al., 2012; Mercan, 2006), may have contributed making the littoral zone more extensive with higher chances of shifting between benthic and pelagic dominated system (Vadeboncoeur et al., 2008). It is worth noting, however, that if the fluctuations are not around a "critical depth" (Sverdrup, 1953), the flatter bottom profile may also result in lower sensitivity depending on the proportion of lake area in or out of the photic zone.

In the other two lakes, the relationship between the sediment record and water-level fluctuations was more equivocal. Geochemical and physical proxies from Lake Beyşehir show that the littoral and pelagic cores have evolved in contrasting depositional environments.

It is apparent that these variables in the pelagic core, at the resolution of sampling, did not reveal a palaeolimnological record of water-level change during the last century. Moreover, even though an overall trend towards more pelagic conditions can be seen in the littoral core, due to the rather coarse temporal resolution (3-33 years and 6-42 years per sample, for littoral and pelagic cores, respectively) it was not possible to identify the effect of each water-level change period separately. A recent review (Andersen, 2014) also points out the problems with temporal variability, drawing attention to the loss of ecological information when the lifespan of aquatic organisms and coarser temporal resolution is taken into account. Indeed, Korhola et al. (2005) when estimating a 4-6 m Holocene lake level change in three small and shallow lakes, highlighted the high sample-specific error (± 2.4-2.6 m) and low temporal resolution, which complicated the noise-signal separation.

Similarly, geochemical and physical proxies analysed from Lake Uluabat cores were poorly related to changes in water level, although with high temporal resolution. The reason for this might be the cyclical pattern of seasonal water-level fluctuations (low in September/October and high in January-March) and the positioning of the cores near the outflow (transporting fine-grained particles out of the lake). While the former can cause high variation in ecological response of biological proxies (Osborne et al., 1987), leading to ambiguous interpretation, the latter can yield records reflecting suspended and re-worked sediment, thus smoothing geochemical and physical changes, resulting with homogenous records (Kazancı et al., 2010).

Studies have furthermore shown that Lake Beyşehir and Lake Uluabat are largely affected by wind turbulence (Fethi et al., 2014; Kazancı et al, 2010). Moreover, Karaer et al. (2012) pointed out the faster flow rates caused by higher wind speed at the western part of the lake, near the outflow, thus close to our coring location. Correspondingly, Nõges et al. (1999)

demonstrated the spatial variability of sediment composition in a large shallow lake, caused by wind impact. Woodbridge and Roberts (2010) also showed that even in varved sediments, analysed with high temporal resolution, core signals can be smoothed and aggregated through mixing at the surface sediment. Therefore, the impact of wind resuspension may also be a reason for poor agreement in these two Turkish lakes.

4.3. Multiple drivers of alterations

Interpretation of the palaeolimnological records with respect to changes in water level is also complicated by the occurrence of other anthropogenic pressures. Besides canal and regulator constructions, the study lakes have been, and are today, exposed to various human impacts, such as fish introductions, agriculture around the lakes and excessive destruction of reedbeds. Nevertheless the effect of such factors on the lakes differed.

In Lake Marmara, even though the biomass of bottom-feeding *Cyprinus carpio* rose following *Sander lucioperca* introduction in 1955, the drought period in the 1990s led to extensive fish kills and reduced carp abundance (Arı and Derinöz, 2011). This reduction might have resulted in lower sediment resuspension and higher zooplankton grazing on phytoplankton (Jeppesen et al., 2012), thereby maintaining a relatively high light penetration to the lake bottom even after the increase in water level. In turn, this, together with lower seasonal variation in water level towards present may have led to the higher abundance of low-light intolerant species. Moreover, contrary to communities seen prior to construction, endurance of high nutrient-tolerant species, such as macrophyte *Ceratophyllum* sp., during 1990s low water-level period can be related to the intensification of agricultural activities and thus enhanced nutrient loading to the lake (Arı and Derinöz, 2011). Similarly, higher abundance of diatom *Cocconeis* *placentula* and lower *Epithemia sorex* and *Fragilaria capucina* might point to higher nitrogen concentrations (Marks and Power, 2001). A study, covering around 160 years, from large-shallow Lake Võrtsjärv, Estonia, demonstrated that prior to human impact, pelagic diatom abundance was strongly related to water-level fluctuations, but this relation was masked following eutrophication (Heinsalu et al., 2008). Recent studies also draw attention to the difficulties of interpreting palaeolimnological proxies in sites with multiple drivers (Battarbee et al., 2012; Bennion et al., 2012).

Even though Lake Beyşehir currently is of low trophic status (oligo- mesotrophic) (Beklioğlu et al., 2014), the change in littoral and pelagic cores suggested a trend towards a decrease in littoral species during lower water levels. The significant increase in bottom-dwelling fish species such as *Tinca tinca* and *C. carpio* recorded following fish introduction to this lake (Çubuk et al., 2006), may have promoted greater resuspension of the sediments (Breukelaar et al., 1994) and reduced zooplankton grazing on phytoplankton (Jeppesen et al., 2012), possibly contributing to the indirect effect of reduced water levels. Furthermore, the study by Fethi et al. (2014) demonstrated that the sediment of Lake Beyşehir is dominated by silty clay, as also suggested by the geochemical records from this study. Therefore, the colloidal nature of clayey sediments, leading to slow settling out, may be another reason for the deterioration of the light climate in Lake Beyşehir.

Unlike Lake Beyşehir, studies suggest a major shift in the trophic state of Lake Uluabat from being first-second class (e.g. 0.2-1 mgNH_4 L^{-1}, 0.002-0.01 mgNO_2 L^{-1}, 5-10 mgNO_3 L^{-1}, 0.02-0.16 mgTP L^{-1}, 8-4 mgDO L^{-1}) (1970s) to second-fourth/worst class (e.g. fourth class; >2 mgNH_4 L^{-1}, >0.05 mgNO_2 L^{-1}, >20 mgNO_3 L^{-1}, >0.65 mgTP L^{-1}, <3 mgDO L^{-1}) (2000s) (Salihoğlu and Karaer, 2004; WPCR, 1988), possibly contributing to the disappearance of low-light intolerant Characeae species, also to the change towards higher amount of tall-growing plant remains (e.g. *Potamogeton* spp.) and lower abundance of benthic cladocerans (e.g. *Pleuroxus* spp.) during the lower water-level periods. Moreover, as for Lake Beyşehir suspended sediments in the water column might have been another reason for a higher light attenuation as the inflow of Lake Uluabat carries high amounts of suspended solids to the lake (Tağıl, 2007).

4.4 Conclusions

The major advantage of this study was to be able to use multi-proxy core data in comparison with the recorded water-level changes of the lakes. Since each proxy (biological and sedimentary) has a unique response to ecosystem changes, using multiple proxies facilitated the interpretations of changes in our cores. However, weaknesses of the proxies should not be overlooked, because the response of each proxy may vary depending on the nature and strength of the main stressors, leading to disagreement of the proxies with each other or with water level changes. Therefore, our results also showed that for this study none of the proxies could be used on their own. Correspondingly, our results highlight the lake-specific changes associated with water-level fluctuations and, once again the complexity of palaeolimnological studies covering recent periods where multiple drivers are in force (Battarbee et al., 2012; Bennion et al., 2012). The results also suggest muted responses in the proxies, especially when the lake-level change is small (as in Lake Uluabat) and/or when there is an effect from other drivers. Other plausible reasons for the muted response of the palaeo-records to water-level change are the mismatches between sampling resolution and sedimentation rates, and different depositional environments of pelagic and littoral cores (as seen in Lake Beyşehir). The inherent homogenised nature of lake sediments may result in low sensitivity of high frequency sediment data to record changes. Nonetheless, where instrumental records of lake changes are limited or do not exist, multi-proxy palaeolimnological data provides an essential long-term assessment of environmental change that can be incorporated into lake management.

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Fig. 1 Location map of Turkey and the three study lakes, showing the littoral (black stars) and pelagic (white stars) core locations and the main outflows (lines with black arrows) and inflows (black lines) of the lakes. The black rectangle on the south-east cost of Lake Marmara shows the impoundment

Fig. 2 Summary diagram of Lake Marmara (A) littoral and (B) pelagic cores with biological, geochemical and physical variables, showing low (light grey shading) and high (dark grey shading) water level periods, also the mean water level (dashed line in the water level graph) calculated from the instrumental data. Species names in bold indicate the pelagic environment. Only abundant sub-fossil cladoceran and diatom species are shown in the graph. It should be noted that, since there is no dating, the pre-construction period is an approximation according to changes in the cores.

Fig. 3 Summary diagram of Lake Beyşehir (A) littoral and (B) pelagic cores with biological, geochemical and physical variables, showing low (light grey shading) and high (dark grey shading) water level periods, also the mean water level (dashed line in the water level graph) calculated from the instrumental data. Species names in bold indicate the pelagic environment. Only abundant sub-fossil cladoceran and diatom species are shown in the graph

Fig. 4 Summary diagram of Lake Marmara (A) littoral and (B) pelagic cores with biological, geochemical and physical variables, showing low (light grey shading) and high (dark grey shading) water level periods, also the mean water level (dashed line in the water level graph) calculated from the instrumental data. Species names in bold indicate the pelagic environment. Only abundant sub-fossil cladoceran and diatom species are shown in the graph

Fig. 5 Synthesis diagram of the changes observed at the study lakes, showing principal curve (PC) axis-1 scores and water level data. Dotted line in the water level graphs shows mean water levels calculated from the instrumental data. Dark and light grey shading indicates high and low water-level periods, respectively. Horizontal dashed lines show the start and end of the main construction periods. Black diamond shapes in Lake Marmara indicate the period without dating. It should also be noted that, since there is no dating, the start of the construction period in Lake Marmara is an approximation according to changes in the core.

N
Black Sea
TURKEY
Mediterranean Sea
500 km
Uluabat
5 km
Marmara
5 km
Beyşehir
5 km

Figure 1

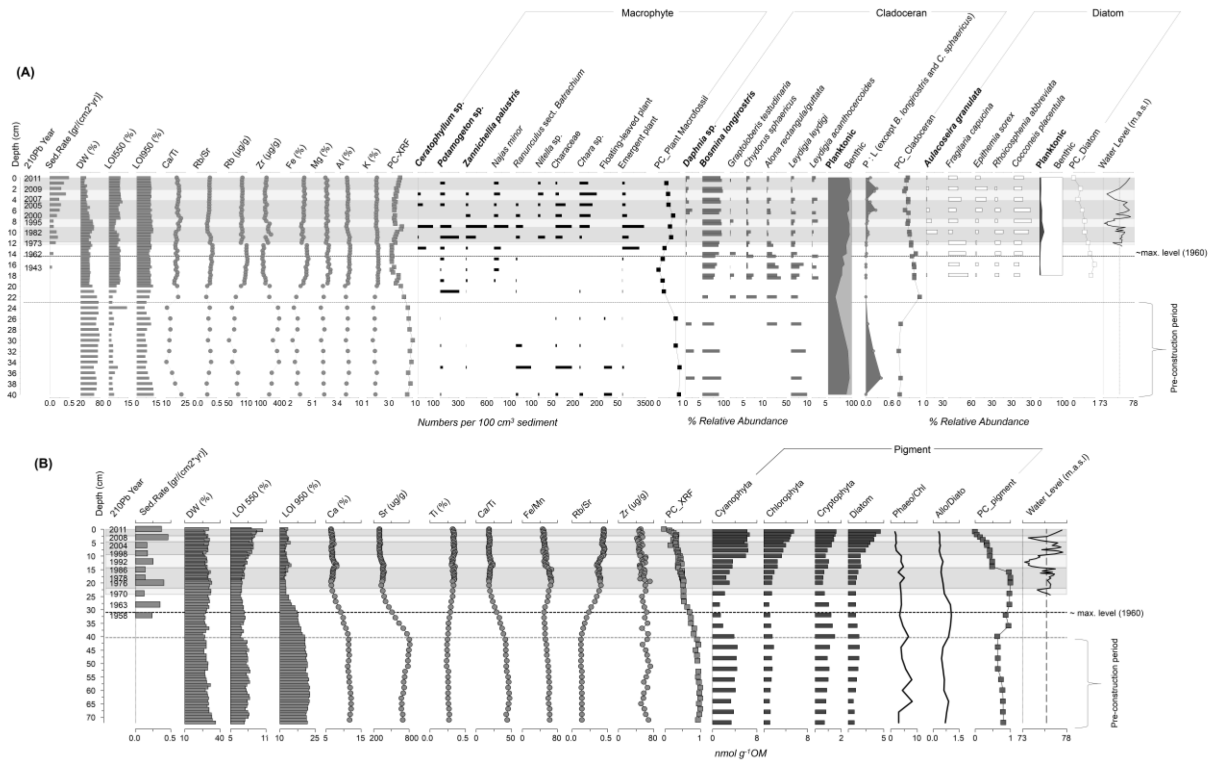


Figure 2

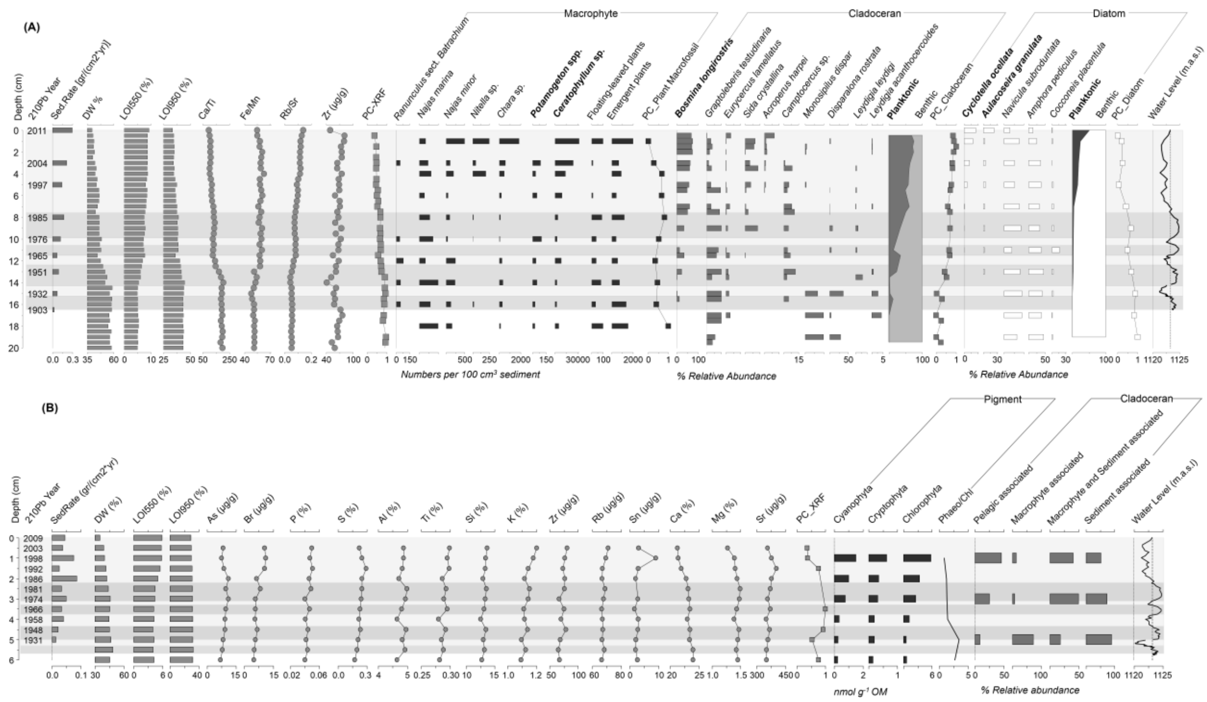


Figure 3

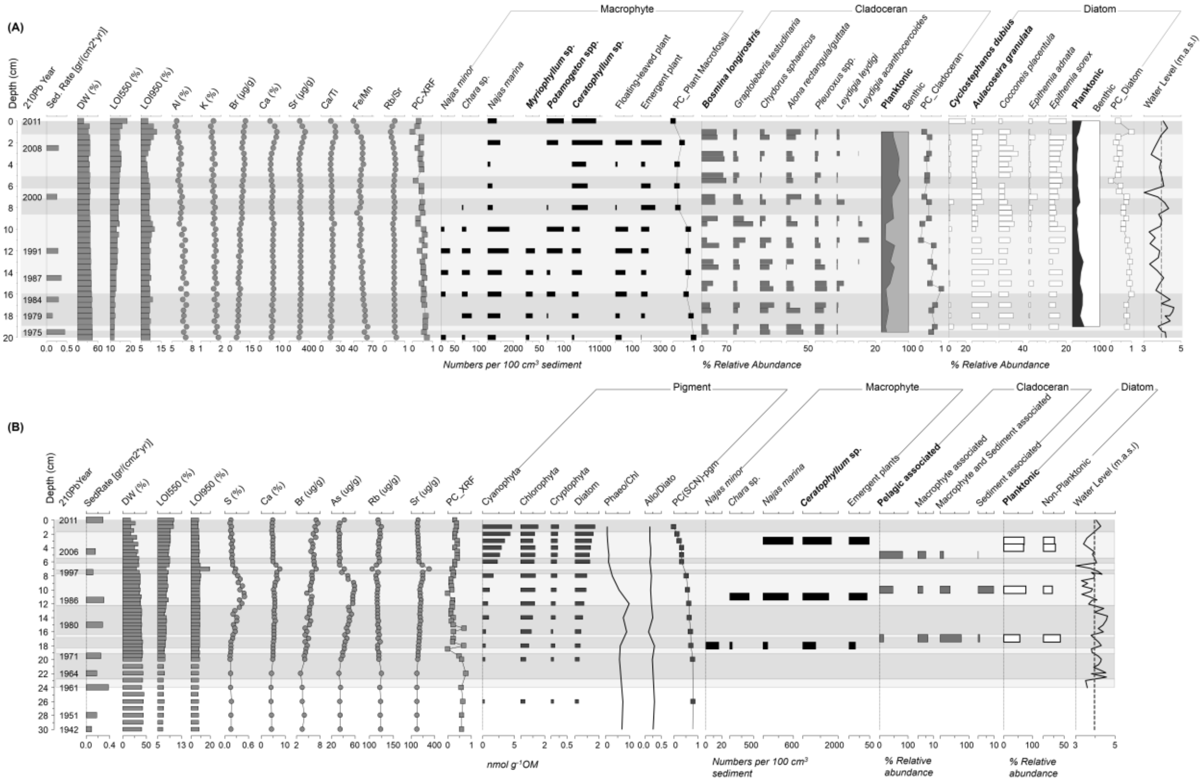
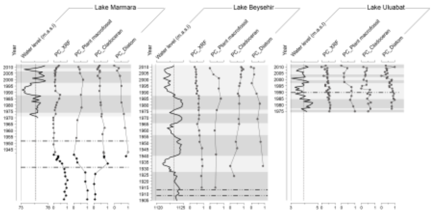


Figure 4



Lake Marmara
Lake Beysehir
Lake Uluabat
Year
Water level (m.a.s.l)
PC_XRF
PC_Plant macrofossil
PC_Cladoceran
PC_Diatom

Figure 5

Table 1 General characteristics of the study sites

Table 2 Summary of cores collected in October 2011

Table 1.

Lakes	Location		Surface Area (km^2)[a]	Maximum Depth (m)[b]	Trophic status
	N	E			
Marmara	38°36'50.0"	27°60'55.0"	68	5.0	Eutrophic
Beyşehir	37°45'10.0"	31°30'50.0"	730	9.0	Oligo-mesotrophic
Uluabat	40°10'45.0"	28°35'30.0"	240	4.5	Eutrophic

[a] Information on surface areas received from Beklioğlu et al. (2006)

[b] Information on maximum depths received from Bulkan (2009) for Lake Marmara, Beklioğlu et al. (2014) for Lake Beyşehir and Karaer et al. (2012) for Lake Uluabat.

Table 2.

Lake and Core Location		Water depth (m)	Core length (m)[c]	N (wgs84)	E (wgs84)
Marmara	Pelagic	4.1	0.73	38°36'31.8"	27°58'53.0"
	Littoral	2.5	0.64	38°35'59.5"	28°00'09.6"
Beyşehir	Pelagic	7.5	1.65	37°45'01.4"	31°30'48.9"
	Littoral	3.0	0.95	37°45'18.0"	31°37'34.5"
Uluabat	Pelagic	1.5	1.14	40°12'04.0"	28°29'08.5"
	Littoral	1.2	0.87	40°12'53.1"	28°29'06.2"

[c] The results from the cores presented in this study cover only the periods with instrumental or known (e.g. Lake Marmara) water level data, not the whole core.

Highlights

- Sediment record reflected longer-term (decadal), pronounced water level changes
- Short-term (1-10 years) water level changes left little impression in the cores
- Proxy response differed between lakes, through time, among pelagic-littoral areas
- Discerning water-level change effect can be hard in lakes subject to multiple pressures