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Water level fluctuations in Lake Baringo, Kenya, during the 19th and 20th centuries: Evidence from lake sediments

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This article presents a fossil diatom-based, semi-quantitative reconstruction of water level fluctuations for Lake Baringo over the past 200 years as a consequence of climatic variations. A 285 cm long sediment core sample was collected using a Rod-Operated Single-drive Stationary Piston corer. Lake level was inferred using indices based on the proportion of planktonic to benthic diatom taxa (P/B ratio). The sediment archive presented distinct zones dominated by planktonic and benthic diatom flora. An initial transgression in the early 19th century was characterised as a shallow water environment dominated by planktonic *Aulacoseira* spp. This was a response to extreme drought during the late 18th to early 19th century. Mid-19th century was defined by a high lake stand. The late 19th to early 20th centuries experienced low water level following the widely documented aridity at the time. The mid-20th century was marked by a spectacular rise in water level that coincided with remarkably wet years during the early 1960s and late 1970s. The first decade of the 21st century witnessed widespread changes in water level. The proxy records show that lake ramping and drawdown over the years follow approximately 50-year climatic cycles.

Keywords: climatic variations, fossil diatoms, P/B ratio, 200 year record

Introduction

East African lakes, including Lake Baringo, have been shown as sensitive to climatic variations (Verschuren 2003), owing to their arid/semi-arid location, lack of surface outlet, over-dependence on river inflow for recharge (Odada et al. 2003), and precipitation-evaporation control on water balance (Spigel and Coulter 1996). Climatic control over lakes is often reflected in water level fluctuations, particularly in endorheic lakes (Nicholson and Yin 2001; Magny et al. 2007). Recently, Cohen et al. (2006) investigated the link between climate variability and lake productivity.

Previous studies have already described a largely dry environment in the East African region that led to complete drying of Lake Baringo about 200 years ago (Bessems et al. 2008; Kiage and Liu 2009a). It is widely documented that over the years the climate of East Africa has been highly variable, with alternating wet and dry episodes (Nicholson 1999; Verschuren et al. 2000; Anderson 2002; Kiage and Liu 2009b; Cort et al. 2013). The response of some East African lakes to these changes in climate in terms of variations in water level has been investigated (Nicholson and Yin 2001; Verschuren 2001) and lake Baringo provides further information on this process that can have significant social and economic consequences (Conway 2002; Njaya et al. 2011). Drawdown can have devastating effects on lake fisheries, thereby affecting the economy of the riparian fishing communities. However, recession enhances lake productivity reflected in increased fish catches in the few years after recovery (Kabwezi and

Wilson 1998). This study focuses on reconstructing water level for Lake Baringo using fossil diatoms. Reconstructions made in this paper are semi-quantitative partly, because currently there are no diatom training data sets for quantitative lake level reconstructions for Lake Baringo. Nevertheless, interpretations of the diatom records are compared with published climate records (rainfall and drought patterns), other lake level reconstructions made in the region, as well as instrumental water level recordings in Lake Baringo where such data is available.

Materials and Methods

Study area

Lake Baringo is located within the semi-arid Eastern arm of the Great Rift Valley in Kenya, East Africa with a surface area of 130 km^2 (Omondi et al. 2014). It is a holomictic, endorheic lake situated between 0°30′ N to 0°45′ N and 36°00′ E to 36°10′ E, at an altitude of 970 m above sea level, with a catchment area of 6 200 km^2 (Figure 1).

The lake is pan-shaped, with maximum depth of 11.6 m (as at 2014), a mean temperature of 25° C and evaporation rates between 1 650 and 2 300 mm per year (Odada et al. 2006). Lake Baringo water remains fresh despite lack of a surface outlet, because some water is lost by ground seepage through the fractured lake floor (Gregory 1896). The islands located towards the south end of the lake are remnants of Pleistocene volcanic activity dating to about 1.8 million years ago (Gregory 1921). The lake derives
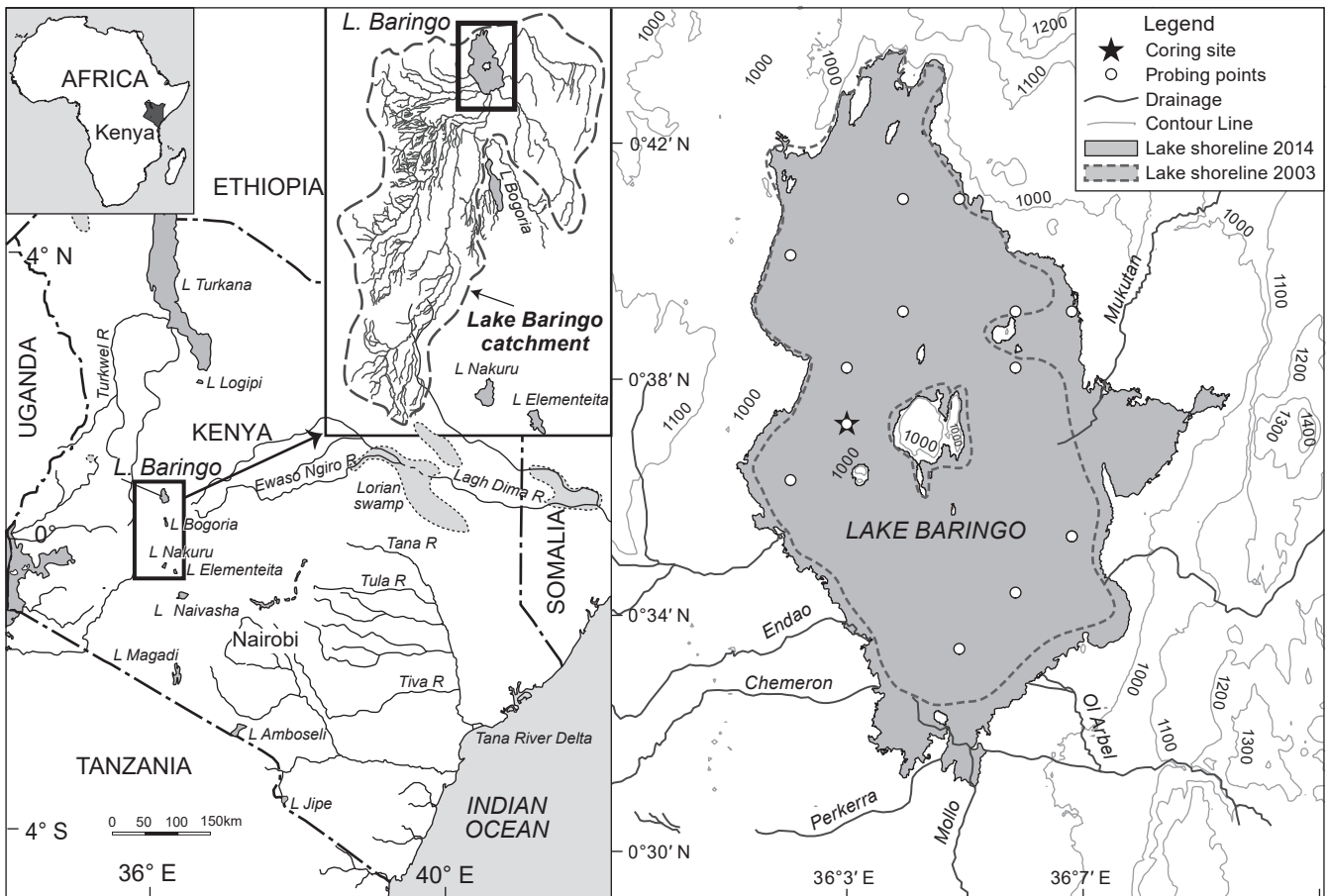
Figure 1: Map of Lake Baringo and its drainage basin in the Kenyan Rift Valley with a situation of its hydrographic network in relation to those of other rift lakes and lake shore position in 2003 (stippled line) and during the flooded situation of 2014.

water and sediments from seasonal rivers, including Ol Arabel, Mukutan, which drains the Laikipia Border Fault Escarpment, Endao and Chemeron, which drains the Tugen hills and perennial rivers, including Molo and Perkerra, the latter which flows Northwards from the Mau hills. All these rivers show significantly reduced discharge during dry months of the year and may at times dry out completely.

Coring

The sediment record was studied in a 285 cm core sample extracted from the deepest point of the lake (36°3′ E, 0°37′ N) in July 2014 using a Rod-Operated Single-drive Stationary Piston corer (Wright 1980) operated with push rods from the side of a stationary fishing boat. The core sample was transported intact in the core tube to Ghent University (Belgium) for chronology and Egerton University (Kenya) for fossil diatom analysis.

Preparation of sediment

Analysis of the core was carried out within four weeks of the coring. One gram of wet sediment was placed in a graduated 250 ml glass beaker and 10 ml of 30% H_2O_2 added and covered with a watch glass. This set up was then placed on a heating plate at 100 °C and boiled for one hour taking care not to dry the sample, in which case

distilled water was added. After this, 1–2 drops of 50% HCl was added to each beaker and left to settle for 24 hours. The resulting supernatant fluid was then removed with a pipette and the settled material (diatoms and inorganic material) re-suspended in distilled water. The washing process was repeated three more times, each time allowing the diatoms and inorganic material to settle. For the final wash, 1–2 drops of ammonia (NH_3) solution was added to help keep any remaining clay particles in suspension, which was then removed with the last supernatant fluid.

To each treated sample, 5 ml of concentrated HCL was added and covered with parafilm. The samples were mixed gently with the acid and left for 24 h. The samples were then shaken gently and centrifuged at 2 000 rpm. After decanting the supernatant fluid, the samples were washed with distilled water three times, each time centrifuging and decanting the supernatant fluid. After this, 5 ml of a digestion solution (a mixture of concentrated sulfuric acid and nitric acid in the ratio 3:1) was added to the sample and left standing for 24 h. Thereafter, the samples were centrifuged and the supernatant fluid was decanted. The samples were then rinsed four times with distilled water, each time centrifuging and decanting the supernatant fluid. The treated sediment samples were retained in their respective containers and stored.

Preparation of fossil diatom slides

Labelled glass microscope slides (ten per batch) were placed on the left side of a horizontal slide tray and cover glasses on the right side. With a pipette, a drop (as round as possible) of 200 µl distilled water was placed on a cover glass. The treated sediment sample above was whirled by hand and 50 µl of it placed onto the drop of water on the cover glass and dispersed equally across the drop with a pipette. A different pipette-tip was used for each sample to avoid cross-sample contamination. The cover glass was then left overnight to dry. The horizontal slide tray was taken to a fume hood and a drop of Naphrax, with a refraction index of 1.7, placed onto the labelled microscope slide. The cover glass with the dried diatoms was then placed upside down on the drop of Naphrax. The microscope slide + Naphrax + cover glass were placed on a warm heating plate and heated for 30–60 seconds. The slides were left for one night to cool and harden. The prepared slides were then observed and counted under light microscope with a phase contrast oil immersion objective at a magnification of ×1 000. The diatoms were identified following Gasse (1986) and grouped as planktonic or benthic. The ratio of obligate planktonic to benthic taxa was calculated according to Luo et al. (2013). The facultatively planktonic taxa were not included in the determination of this ratio.

Dating

The chronological framework for Lake Baringo sedimentation profile was determined using ^{210}Pb and ^{137}Cs technique. A detailed chronology is found in Degefa et al. (2015). To estimate the ages of the undated segments of the core, the average sedimentation rate between two dated points was calculated as the difference in depth over the difference in age.

P/B ratio (proportion of planktonic to benthic diatom taxa)

In freshwater lakes, variations in the ratio of planktonic to benthic diatom taxa have been used to infer water level fluctuations (Barker et al.1994; Hyvärinen and Alhonen 1994; Wolin 1996; Tapia et al. 2003; Bergner and Trauth 2004; Stone and Fritz 2004; Wilson et al. 2008).

The proportion of planktonic to benthic diatom taxa, or P/B ratio, was calculated as: P/B ratio = $\sum$planktonic taxa/$\sum$(planktonic + benthic taxa). In relatively deep clear water lakes and at high water levels, where planktonic diatoms dominate over benthic diatoms, the result will be a high P/B ratio in the total diatom flora (Stager et al. 2005). In contrast, at low water levels, increased light availability at the lake bed may in some cases result in benthic diatoms dominating over planktonic forms resulting in a low P/B ratio.

However, in shallow eutrophic lakes, such as Lake Baringo, the productivity of planktonic diatoms has been shown to exceed that of benthic forms (Wolin 1996; Vadeboncoeur 2008) especially at low lake levels when wave-driven turbulence disturbs the lake bed and results in turbidity-driven light limitation (Nõges and Nõges 1999; Jeppesen et al. 2000; Gattuso et al. 2006; Nõges et al. 2003). Under these conditions, a poor light climate will limit primary production to a surface layer comprising circulating phytoplankton (Odour et al. 2003). Furthermore, Turner et al. (2005) showed that benthic algae declined

following lake drawdowns, because of habitat disruption and loss of colonisable area. It may also be surmised that sediment resuspension at low water levels may increase nutrient availability in the water column, further enhancing phytoplankton production (Nõges and Nõges 1999) and increasing the P/B ratio.

In contrast, in shallow eutrophic lakes, when higher lake levels result in decreased turbulence and sediment resuspension at the lake bed, conditions may be favourable for benthic diatoms (increased light penetration). Furthermore, high lake levels will also increase benthic habitat, owing to flooding at the lake margins and increase the overall abundance of benthic taxa (Wilson et al. 2008) and hence a low P/B ratio will become apparent. Conversely, because these small shallow lakes depend on nutrient recycling from the bottom, increases in water level may also cause nutrient dilution (Ballot et al. 2003; Oduor et al. 2003; Swaine et al. 2006; Omondi et al. 2014; Okech et al. 2018), which in turn may reduce the production of planktonic taxa.

Results

Chronology

According to Degefa et al. (2015), the core profile was found to have ages of approximately AD 1800 at the base of the core, AD 1825 at 270 cm, AD 1943 at 200 cm, AD 1993 at 110 cm, AD 2003 at 30 cm and AD 2014 at the surface. The ages calculated using mean sediment accumulation rates (cm y^{-1}) for the undated segments of the core are shown in Table 1.

Fossil diatom stratigraphy (oldest to the latest time frame)

Diatom-based stratigraphy of Lake Baringo sediments revealed alternating patterns of benthic and planktonic diatoms abundance along the core (Figure 2). The sediment package was divided into six diatom zones depending on the dominance of either planktonic or benthic diatom taxa as reflected by the P/B ratio.

Zone 1 (AD 1790s to AD 1820s). This period was dominated by planktonic diatoms mostly *Aulacoseira granulata* (Ehrenb.) and *Thalassiosira faurii* (Gasse). Planktonic taxa contributed over 80% of total diatom count compared to <20% contribution by the benthic taxa. Among the planktonic taxa, *Aulacoseira* sp. represented 70%, whereas *Thalassiosira* sp. represented 10%. Benthic diatoms were represented by *Gomphonema* sp., *Eunotia* sp., *Synedra* sp., *Cymbella* sp. and *Cocconeis* sp. each representing less than 5%.

Zone 2 (AD 1830s to AD 1860s). A different pattern of diatom taxa abundance was observed where benthic taxa outnumbered the planktonic forms. Benthic forms contributed more than 74%, mostly represented by *Navicula* spp. at 63%, *Cymbella* spp.*, Fragilaria* spp.*, Hantzschia* spp. and *Synedra* spp. at <5%. *Aulacoseira* spp. were also observed, but contributed 9% of the relative abundance.

Zone 3 (AD 1870s to AD 1920s). This period also witnessed dominance of planktonic taxa that made up to 70% and was mostly represented by *Aulacoseira* spp. and *Thalassiosira faurii* (Gasse) Hasle. Benthic forms made less than 30%. Some of the benthic taxa observed were *Achnanthes inflata* (Kutz) Grun.*, Nitzschia amphibia* (Grun.), *Pinnularia gibba* (Ehrenb.) Ehrenb.*,

Table 1: Ages calculated for Lake Baringo sediments using mean sediment accumulation rates (cm y^{-1})

Depth (cm)	Depth difference (cm)	Age difference (years)	Estimated age (AD)	Sedimentation accumulation rate (cm y^{-1})
0–0.8	1	0.4	2014	2.7
1–1.8	1	0.4	2014	2.7
2–2.8	1	0.4	2014	2.7
3–3.8	5	1.8	2014	2.7
8–8.9	8	2.9	2012	2.7
16–16.8	8	2.9	2009	2.7
24–24.8	8	2.9	2006	2.7
32–32.8	8	1.0	2003	8.0
40–40.8	8	1.0	2002	8.0
48–48.8	8	1.0	2001	8.0
56–56.8	8	1.0	2000	8.0
64–64.8	8	1.0	1999	8.0
72–72.8	8	1.0	1998	8.0
80–81	8	1.0	1997	8.0
88–88.8	8	1.0	1996	8.0
96–96.8	8	1.0	1995	8.0
104–104.8	8	1.0	1994	8.0
112–112.8	8	0.0	1993	1.8
120–120.8	8	4.4	1983	1.8
128–128.8	8	4.4	1979	1.8
136–136.8	8	4.4	1975	1.8
144–144.8	8	4.4	1971	1.8
152–152.8	8	4.4	1967	1.8
160–160.8	8	4.4	1963	1.8
168–168.8	8	4.4	1959	1.8
176–176.8	8	4.4	1955	1.8
184–184.8	8	4.4	1951	1.8
192–192.8	8	4.4	1947	1.8
200–200.8	8	13.3	1943	0.6
208–208.8	8	13.3	1926	0.6
216–217	8	13.3	1913	0.6
224–225	8	13.3	1900	0.6
232–233	8	13.3	1887	0.6
240–241	8	13.3	1874	0.6
248–249	8	13.3	1861	0.6
256–257	8	13.3	1848	0.6
264–265	2	3.3	1835	0.6
266–267	2	4.0	1833	0.5
268–269	2	4.0	1829	0.5
270–271	2	4.0	1825	0.5
272–273	2	5.0	1820	0.4
274–275	2	5.0	1815	0.4
276–277	2	5.0	1810	0.4
278–279	2	5.0	1805	0.4
280–281	2	0.0	1800	0.4
282–283	2	5.0	1795	0.4
284–285	4	10.0	1790	0.4

AD: *Anno Domini*

Hantzschia amphioxys (Ehrenb.) Grun. and the facultative planktonic *Gomphonema clevei* (Fricke).

Zone 4 (AD 1930s to AD 2000). A shift in dominance occurred at sediments dated between AD 1930s and AD 2000, where benthic taxa contributed up to 98% to the total diatom assemblage. Among these, *Navicula* spp. contributed 70% abundance. Other taxa, including *Luticola cohnii* (Hilse) DG Mann, *Cymbopleura naviculiformis* (Auerswald) Krammer 2003,

facultative planktonic *Gomphoneis clevei* Cleve 1894, *Fragilaria rumpens* (Kütz.) GWF Carlson*, Cocconeis pediculus* Ehrenb. and *Synedra cunningtonii* (GS West) were also present, but contributed less than 5% each.

Zone 5 (AD 2001 to AD 2008). This zone had a poor diatom community structure. Frustules of centric diatoms, which could not be easily identified, possibly because of fragmentation and dissolution were observed. *Aulacoseira granulata* (Ehrenb.) Ralfs were easily identified and made up to 90% of the total diatoms counted. The facultativelly planktonic *Navicula gawaniensis* (Gasse), as well as benthic genera, such as *Cymbella* spp., *Synedra cunningtonii* (GS West), which contributed less than 10%, were also observed. However, no diatom frustules were observed in sediments dated AD 2009 (16 cm section of the core).

Zone 6 (AD 2010 to AD 2014). This zone comprises the top most section of the core and constitutes the most recently deposited materials. This zone was dominated by the benthic *Synedra cunningtonii* (GS West), which made up to 72% of the total diatom count. Other benthic taxa observed here were *Tabularia fasciculata* (Agardh) Williams and Round 1986*, Cymbella* spp. and *Fragilaria capucina* (Kutz) each representing less than 5% relative abundance. *Navicula* spp. had 9% abundance. *Aulacoseira* sp. was also observed and contributed 16% to the total diatom assemblage.

Discussion

Early 19th century (AD 1790s to AD 1820s)
The bottom of the core, dated between AD 1790 and AD 1800, was characterised by a high P/B ratio of between 0.8 and 0.9, implying the dominance of planktonic diatoms mostly represented by *Aulacoseira* spp., therefore implying a shallow and turbulent lake environment. *Aulacoseira* species are heavily silicified diatoms with high sinking rates. Their ecology requires turbulence to remain in the photic zone (Bradbury et al. 2002) and they are often found in shallow eutrophic lakes (Rioual et al. 2007). Increased turbulence and corresponding nutrient increase during low water stages in a lake can favour this genus over other planktonic species. The presence of *Thalassiosira faurii* also indicates periods of low lake level and increase in salinity, owing to evaporation, because this species has been shown as tolerant to high salinity (Gasse 1986). This is also the period when Lake Victoria experienced low water level (Stager et al. 2005) and Lake Naivasha was reduced to a puddle (Verschuren 1999). The Nile floods were extremely low and Lake Chad was desiccated (Nicholson 1995). According to Nicholson (2001), lakes, swamps, rivers and wet plains across Africa were left dry, with farmers and communities complaining of low rainfall. These observations are attributed to the wide spread drought of the late 18th century, which was probably most extreme during the early parts of the 19th century (Nicholson 1999; Nicholson and Yin 2001). Although the effects of this drought were severely felt in Eastern Africa, no instrumental rainfall data exists for this period (Figure 3a).

Mid-19th century (AD 1830s to AD 1860s)
After AD 1830s, there was a rapid increase in the lake level up to AD 1861, during which the P/B ratio remained
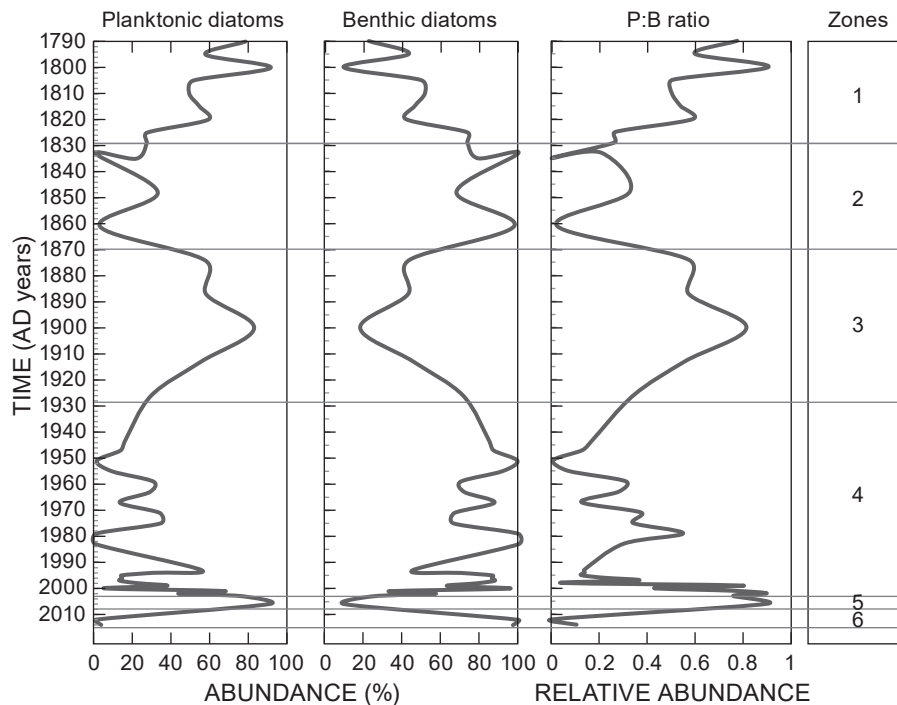
Figure 2: Profile diagram of percentage abundance for planktonic and, benthic diatom taxa and P/B ratio of Lake Baringo sediments.

below 0.5, because of dominance by benthic diatom taxa over planktonic forms. Similar transgression episodes were also observed in other lake of East Africa. Around AD 1858, Lake Rukwa covered a reasonably large surface area compared to the low stand of the early 19th century (Hobley 1914). Lake Malawi, Chad, Tanganyika, Victoria and Naivasha rose between 3 to 10 m above their early 19th century stands (Nicholson and Yin 2001). Nicholson (2001) reported that during the mid-19th century, most African lakes recovered from the low levels of the early 19th century, with some achieving very high stands. Although rainfall data during this period is sporadic, available data provides that wet conditions prevailed in East Africa at the time (Figure 3b).

Late 19th century to early 20th century (AD 1870s to AD 1920s)
The transgression of the mid-19th century was followed by a late 19th century lake level decline. During this time the P/B ratio was above 0.6, implying that planktonic diatom taxa contributed most to the total diatom abundance. The low stand observed during this time was a direct response to a series of climate related droughts that affected Baringo area during the late 19th century and the early 20th century (Anderson 2002). The existence of drought-induced shallow lake environment during this period is also confirmed by a number of lines of evidence.

The first line of evidence lies in oral tradition pre-colonial histories. According to Thomson (1887), before AD 1850, the Lake Baringo area was used by Arab traders and early European explorers as an important source of food for caravans moving from the East African coast towards the North and West of the African continent to trade ivory. However, in AD 1880s, European missionaries and

explorers found Baringo in the middle of a serious drought and traders could not find food for their caravans. Another expedition led by Gregory in AD 1893, encountered drought in the area characterised by dry river beds (Gregory 1896). Ambler (1988) recounted a series of droughts that occurred in the area towards the end of the 19th century leading to frequent wars between pastoralists and agriculturalists. The second line of evidence is provided by paleolimnological surveys of East African lakes. For example, Cort et al. (2013) described the late 19th to early 20th century drought as more severe than any other in recorded history in this region. This drought coincided with the worst known drought in Ethiopian history, which severely reduced the level of Lake Abiyata (Legesse et al. 2002).

According to other lake level reconstructions made in the region, this was also the period when Lake Tanganyika shifted from open to closed basin when surface outflow was cut, because of a negative shift in rainfall (Bootsma and Hecky 1993). Similarly, outflow from Lake Malawi through the river Shire ceased in approximately AD 1915 (Owen et al. 1990). Nicholson (1999) attributed the abrupt decline in lake levels during this time to drastic climatic dislocation. The 20th century started with below average rainfall (Figure 3c) signifying another period of aridity somewhat similar to the beginning of the 19th century. This caused severe and widespread droughts during the 1910s leading to a concern over a general desiccation across Africa (Nicholson 2001).

Mid-20th century (AD 1930s to AD 1980s)
The drought episode of the early 20th century was followed by an increase in water level during mid-20th century. Beadle (1932) recorded that Lake Baringo depth was approximately
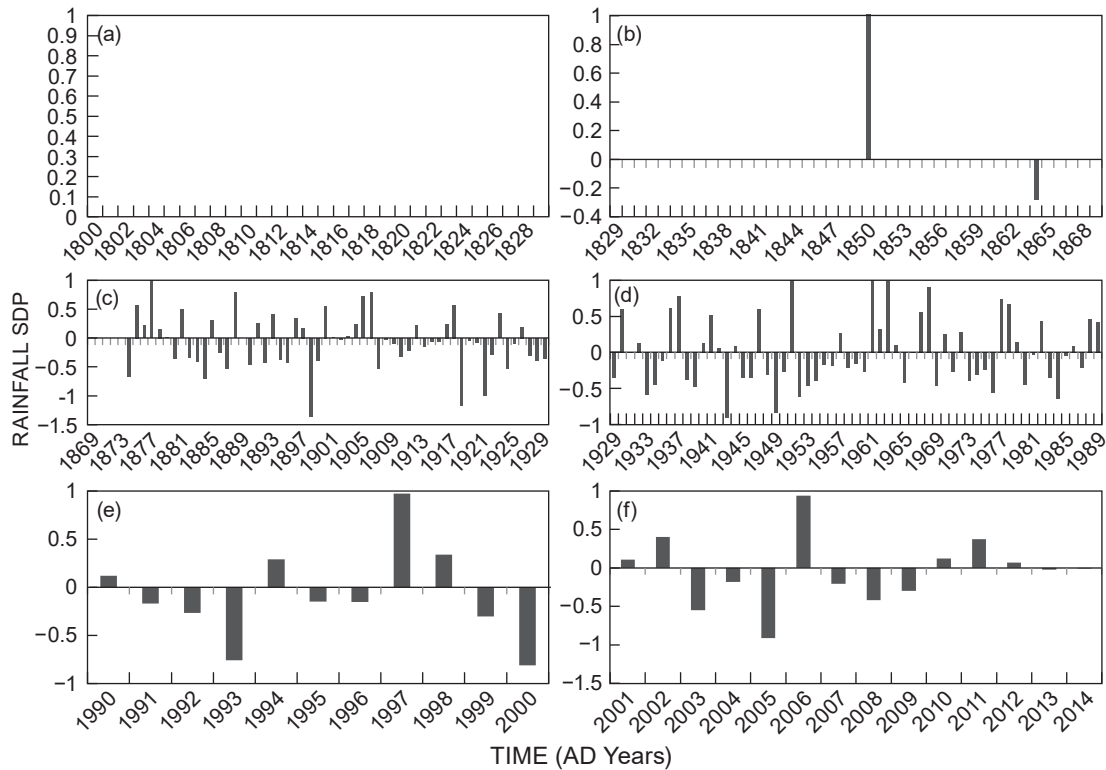
Figure 3: Rainfall fluctuations in east Africa (AD 1800 to AD 2014), expressed as standardised departures (departure from the long term mean divided by the standard deviation) ($X_{ij} = (r_{ij} - \bar{r}_i)/\sigma_i$). Where, X_{ij} is the annual rainfall departure, r_{ij} is the annual totals for station i in the year j, $\bar{r}_i$ is the long term mean for the station i and σ_i is the standard deviation of annual totals at station i (Nicholson 1986). In the resultant time series, a value of +1/−1 indicates an average positive/negative anomaly of one standard deviation from the mean (data used with permission of Sharon E Nicholson). (a) 1800 - 1828, (b) 1829 - 1868, (c) 1869 - 1929, (d) 1929 - 1989, (e) 1990 - 2000, and (f) 2001 - 2014; SDP = standardised departures.

7.5 m in AD 1932. Lakes throughout East Africa experienced spectacular rise in water level during the mid-20th century. According to Stager et al. (2005), this is the period when Lake Victoria experienced its highest level of the century and Lake Tanganyika rose more than two meters above the zero scale of the level gauge (Nicholson 1999). Outflow from Lake Malawi resumed when water level rose by 6 m (Beadle 1981). Lake Baringo water level dropped briefly during mid-AD 1950s following the relatively dry conditions that reoccurred after the extreme drought of the early 20th century (Nicholson 1996), but increased towards AD 1980, as a consequence of abnormally wet conditions in the early 1960s and late 1970s (Figure 3d; Nicholson 1996).

According to Nicholson (2001), a shift in climate occurred over equatorial Africa during the early 1960s when there was an increase in rainfall, which was about 20–40% above monthly means in magnitude (Nicholson 2000) followed by a consequent increase in the levels of East African lakes (Nicholson and Yin 2000), including lake Baringo. The stations at Wajir, Eldama and Lokitaung recorded abnormally high rainfall of 612, 402 and 302 mm, respectively, in November 1961, compared with monthly means of 58, 48 and 39 mm (Nicholson 1996). Similar conditions, but of a lesser magnitude, reoccurred in 1963. Based on Ssentongo (1995), the mean depth of Lake Baringo during the 1960s was 5.6 m. This trend continued

towards AD 1970s. Instrumental records show that in 1970s, the lake was more than 8 m (Kallqvist 1987) and 8.6 m deep in 1975 (Johansson and Svension 2002). However, this transgression was interrupted by a short regression episode during the late 1960s towards early 1970s following a period of a brief dry spell (Nicholson 1996).

Late 20th century (AD 1990s to AD 2000)

The period between AD 1990 and AD 1994 witnessed a shallow lake environment as a response to below average rainfall over East Africa (Figure 3e). Wilson (1989) recorded a mean value of 4 m in March 1989. According to Hickley et al. (2004), the depth of the lake in AD 1993 was below 3 m. From AD 1995, the water level increased towards AD 1998 through to AD 2000. Hickley et al. (2004) reported that in 1998, the mean lake level was 4.5 m. This transgression reflects the effects of El Niño rains of AD 1997–1998 (Figure 3e), which caused flooding (Birkett et al. 1999) and also affected other lakes in East Africa, including Lake Naivasha, whose water level rose by 2 m (Kitaka et al. 2002). These floods were accompanied by devastating economic, ecological, hydrological and agricultural impacts in East Africa (Conway 2002). Furthermore, these heavy rains were widespread and saw the levels of Lake Victoria, Tanganyika and Malawi rise by 1.7 m, 2.1 m and 1.8 m, respectively (Birkett et al. 1999).

Early 21st century (AD 2001 to AD 2014)

From AD 2001 to AD 2009, evidence for a shallow lake environment was observed during which the P/B ratio was ≥0.9, signifying the dominance of planktonic diatoms. In AD 2001, the lake was 2.1 m deep (Johansson and Svension 2002). Hickley et al. (2008), as well as Bessems et al. (2008), measured mean water depth of 2.65 m in 2003 and Kiage and Liu (2009a) measured the depth of Lake Baringo as 2.5 m in 2005. Between AD 2006 and AD 2009, the water level stayed low and was <4 m in 2006 (Corrine et al. 2006). We are not able to reconstruct lake level for the period AD 2009 (16 cm section of the core) using the diatom records, because no diatom frustules were observed at this point. However, instrumental records show that the lake was at 2.95 m in 2009 (Omondi et al. 2014). These low levels were a direct response to a series of droughts that affected most parts of Kenya in AD 2005 and 2008/2009 when rainfall was in the magnitude of 25–80% below monthly mean (Nicholson 2016) (Figure 3f). Lake Baringo levels rose towards AD 2011. Low P/B ratio provides a clear evidence to support a rising lake level towards AD 2014. This prediction is supported by Omondi et al. (2014), who recorded a depth of 9.55 m in 2012, as a consequence of heavy rainfall in approximately AD 2010 towards AD 2012, which was 50–150% above the 1998–2014 mean (Nicholson 2016) (Figure 3f). By AD 2014, the water level had risen to 11.6 m (authors' field observations). However, the lake was already receding by 2015 in direct response to below average rainfall observed in AD 2013–2014 (Figure 3f).

The lake level reconstructions made in this paper show a pleasing correspondence between the inferred lake levels from the P/B ratio and historical accounts. This provides a level of confidence that P/B ratio can be used to infer lake levels and appears a useful tool in describing history of shallow lakes.

References

Ambler CH. 1988. *Kenyan communities in the age of imperialism.* New Haven: Yale University Press.

Anderson D. 2002. *Eroding the commons: The politics of ecology in Baringo. Athens, Kenya: University of Ohio Press.*

Barker PA, Roberts N, Lamb HF, van der Kaars S, Benkaddour A. 1994. Interpretation of Holocene lake-level change from diatom assemblages in Lake Sidi Ali, MiddleAtlas, Morocco. *Journal of Paleolimnology* 12: 223–234.

Beadle LC. 1981. The Inland Waters of Tropical Africa: *An Introduction to Tropical Limnology.* 2nd edn. London: Longman.

Beadle LC. 1932. Scientific results of the Cambridge Expedition to the East African lakes. *Zoological Journal of Linnean Society* 38: 157–211.

Bessems I, Verschuren D, Russell JR, Hus J, Mees F, Cumming BF. 2008. Paleolimnological evidence for widespread late-18th century drought across equatorial East Africa. *Paleogeography, Paleoclimatology, Paleoecology* 259: 107–120.

Bergner AGN, Trauth MH. 2004. Comparison of the hydrological and hydrochemical evolution of Lake Naivasha (Kenya) during three highstands between 175 and 60 kyr BP. *Paleogeography, Paleoclimatology, Paleoecology* 215: 17–36.

Birkett CM, Murtugudde R, Allan JA. 1999. Indian Ocean climate event brings floods to East Africa's lakes and Sudd Marsh. *Journal of Geophysical Research Letters* 26: 1031–1034.

Bootsma HA, Hecky RE. 1993. Conservation of the African Great Lakes: A limnological perspective. *Journal of Conservation Biology* 7: 644–656.

Bradbury JP, Cumming B, Laird K. 2002. A 1500-year record of climatic and environmental change in Minnesota III: measures of past primary productivity. *Journal of Paleolimnology* 27: 321–40.

Cohen AS, Lezzar KE, Cole J, Dettman D, Ellis GS, Gonneea ME, Plisnier PD, Langenberg V, Blaauw M, Zilifi D. 2006. Late-Holocene and recent hydroclimatic variability in the central Kenya Rift Valley: The sediment record of hypersaline lakes Bogoria, Nakuru and Elementeita. *Journal of Paleolimnology* 36: 189–209.

Cort GD, Bessems I, Kappens E, Mees F, Cumming B, Verschuren D. 2013. Late Holocene and recent hydroclimatic variability in the central Kenyan Rift Valley: The sediment record of the hypersaline lakes Bogoria, Nakuru and Elmentaita. *Paleogeography, Paleoclimatology, Paleoecology* 388: 69–80.

Conway D. 2002. Extreme rainfall events and lake level changes in East Africa: recent events and historical precedents. In: Odada EO and Olago DO (Eds), *The East African Great Lakes: Limnology, Palaeolimnology and Biodiversity.* Advances in Global Change Research. pp 63–92. The Netherlands: Kluwer Academic Publishers.

Corrine T, Renaut RW, Tiercelin JJ, Herisse AL, Cotton J, Cabon JY. 2006. Geothermal evidence of hydrothermal recharge in Lake Baringo, central Kenya Rift Valley. *Journal of Hydrological Processes* 20: 2027–2055.

Degefa A, Bessems I, Tjallingii R, Cumming B, Verschuren D. 2015. *200 years of anthropogenic soil erosion in the Lake Baringo catchment, Kenya: exploratory evidence from lake sediment, presented at Our Common Future Under Climate Change conference, UNESCO Paris, July 2015.* Paris: UNESCO. [Accessed 30 January 2018]..

Gregory JW. 1896. The Great Rift Valley: Being the narrative of a journey to Mount Kenya and Lake Baringo. London: Frank Cass.

Gregory JW. 1921. Rift Valleys and geology of East Africa. London: Seeley, Service and Company Ltd.

Gasse F. 1986. East Africa diatoms: Taxonomy and ecological distribution. Berlin, Stuttgart, Germany: *Strauss Offsetdruck* GmbH.

Gattuso JP, Gentili B, Duarte CM, Kleypas JA, Middleburg JJ, Antoine D. 2006. Light availability in the coastal ocean: Impact on the distribution of benthic photosynthetic organisms and their contribution to primary production. *Journal of Biogeoscience* 3: 489–513.

Hickley P, Muchiri M, Britton R, Boar R. 2008. Economic Gain *versus* Ecological Damage from the Introduction of Non-native Freshwater Fish: Case Studies from Kenya. The *Journal of Open Fish Science* 1: 36–46.

Hickley P, Muchiri M, Boar RR, Britton JR, Adams C, Gichuru N, Harper D. 2004. Habitat degradation and subsequent fishery collapse in Lakes Naivasha and Baringo, Kenya. *Journal of Ecohydrology and Hydrobiology* 4: 503–517.

Hobley M. 1914. The Alleged Desiccation of East Africa. *The Journal of Geography* 44: 467–470.

Hyvärinen H, Alhonen P. 1994. Holocene lake-level changes in the Fennoscandian tree-line region, western Finnish Lapland: diatom and cladoceran evidence. *The Holocene* 4: 251–258.

Jeppesen E, Jensen JP, Sondergaard M, Lauridsen T, Landkildehus F. 2000. Trophic structure, species richness and biodiversity in Danish lakes: changes along a phosphorus gradient. *Journal of Freshwater Biology* 45: 201–218.

Johansson J, Svensson J. 2002. Land degradation in the semi-arid catchment of Lake Baringo: A minor field study of physical causes with a socio-economic aspect. Sweden: Earth Sciences Centre.

Kabwezi HH, Wilson JGM. 1998. The fishery of Lake Chilwa. In: Van Zegeren K, Munyenyembe MP (Eds), *The Lake Chilwa Environment: a Report of the 1996 Ramsar Site Study*. pp. 91–108. Zomba: Chancellor College Publications.

Kallqvist T. 1987. Primary production and phytoplankton in Lake Baringo and Naivasha, Kenya. Norwegian institute for water research report. pp 59. Oslo: Blinden.

Kiage LM, Liu KB. 2009a. Paleoenvironmental Changes in the Lake Baringo Basin, Kenya, East Africa since AD 1650: Evidence from the Paleorecord. *Journal of The Professional Geographer* 61: 438–458.

Kiage LM, Liu KB. 2009b. Palynological evidence of climate change and land degradation in the Lake Baringo area, Kenya, East Africa since AD 1650. *Paleogeography, Paleoclimatology, Paleoecology* 279**:** 60–72.

Kitaka N, Harper DM, Mavuti KM. 2002. Phosphorus input to Lake Naivasha, Kenya, from its catchment and the trophic state of the lake. *Journal of Hydrobiologia* 488: 73–80.

Legesse D, Gasse F, Radakovitch D, Vallet-Coulomb CC, Bonnifille R, Verschuren D, Gibert E, Barker P. 2002. Environmental changes in a tropical lake (Lake Abiyata, Ethiopia) during recent centuries. *Palaeogeography, Palaeoclimatology, Palaeoecology* 187**:** 233–258.

Luo W, Mackay AW, Leng MJ, Rioual P, Panizzo VN, Lu H, Gu Z, Chu G, Han J, Kendrick CP. 2013. Influence of the ratio of planktonic to benthic diatoms on lacustrine organic matter δ13 C from Erlongwan maar lake, Northeast China. *Journal of Organic Geochemistry* 54: 62–68.

Magny M, De Beaulieu JL, Drescher-Schneider R, Vanniere B, Walter-Simonnet AV, Miras Y, Millet L, Bossuet G, Peyron O, Bruglapaglia E, Leroux A. 2007. Holocene climate changes in the central Mediterranean as recorded by lake-level fluctuations at Lake Accesa (Tuscany, Italy). *Journal of Quaternary Science Reviews* 26: 1736–1758.

Nicholson SE. 2016. An analysis of recent rainfall conditions in eastern Africa. *International Journal of Climatology* 36: 526–532.

Nicholson SE. 2001. Climatic and environmental change in Africa during the last two centuries. *Journal of Climate Research* 17: 123–144.

Nicholson SE. 2000. The nature of rainfall variability over Africa on time scales of decades to millennia. *Journal of Global and Planetary Change* 26: 137–158.

Nicholson S E. 1999. Historical and Modern Fluctuations of Lakes Tanganyika and Rukwa and their Relationship to Rainfall Variability. *Journal of Climate Change* 41: 43–71.

Nicholson SE. 1996. A review of climate dynamics and climate variability in Eastern Africa. In: Johnson TC, Odada EO (Eds). *The limnology, climatology and paleoclimatology of the East African lakes*. pp 25–56. Amsterdam: Gordon and Breach Publishers.

Nicholson SE. 1995. Environmental Change within the Historical Period. In: Goudie AS, Adams WM, Orme A (Eds.). *The Physical Geography of Africa*. pp. 60–75. Oxford: Oxford University Press.

Nicholson SE. 1986. The special coherence of African rainfall anomalies: Interhemispheric Teleconnections. *American Meteorological Society* 25: 1365–1381.

Nicholson SE, Yin X. 2001. Rainfall conditions in equatorial East Africa during the 19th Century as inferred from the record of Lake Victoria. *Journal of Climate Change* 48: 387–398.

Njaya F, Snyder KA, Jamu D, Wilson J, Howard-Williams C, Allison EH, Andrew NL. 2011. The natural history and fisheries ecology of Lake Chilwa, southern Malawi. *Journal of Great Lakes Research* 37: 15–25.

Nõges T, Nõges P. 1999. The effect of extreme water level decrease on hydrochemistry and phytoplankton in a shallow eutrophic lake. *Hydrobiologia* 408/409: 277–283.

Nõges T, Nõges P, Laugaste R. 2003. Water level as the mediator between climate change and phytoplankton composition in a large shallow temperate lake. *Journal of Hydrobiologia* 506–509: 257–263.

Odada EO, Onyando JO, Obudho PA. 2006. Lake Baringo: Addressing threatened biodiversity and livelihoods. *Lakes & Reservoirs: Research & Management* 11: 287–299.

Odada EO, Olago DO, Bugenyi F, Kulindwa K, Karimumuryango J, West K, Ntiba M, Wandiga S, Obudho PA, Achola P. 2003. Environmental assessment of the East African Rift Valley Lakes. *Journal of Aquatic Science* 65: 254–271.

Oduor SO, Schagerl M, Mathooko JM. 2003. On the limnology of lake Baringo (Kenya), I. Temporal physico-chemical dynamics. *Journal of Hydrobiologia* 506–509: 121–127.

Okech EO, Kitaka N, Oduor SO, Verschuren D. 2018. Trophic state and nutrient limitation in Lake Baringo, Kenya. *African Journal of Aquatic Science* 43: 169–173.

Omondi R, Kembenya E, Nyamweya C, Ouma H, Machua SK, Ogari Z. 2014. Recent Limnological changes and their implications on fisheries in Lake Baringo, Kenya. *Journal of Ecology and the Natural Environment* 6: 154–163.

Owen R, Crossley R, Johnson T, Tweddle D, Kornfield I, Davison S, Eccles D, Engstrom D. 1990. Major low levels of Lake Malawi and their implications for speciation rates in cichlid fisheries. *Proceedings. Biological Sciences* 240: 519–553.

Rioual P, Andrieu-Ponel V, de Beaulieu JL, Reille M, Svobodova H, Battarbee RW. 2007. Diatom responses to limnological and climatic changes at Ribains Maar (French Massif Central) during the Eemian and Early Würm. *Quaternary Science Reviews* 26: 1557–1609.

Spigel RH, Coulter GW. 1996. Comparison of hydrology and physical limnology of the East African Great Lakes: Tanganyika, Malawi, Victoria, Kivu and Turkana (with reference to some North American Great Lakes). In: Johnson TC, Odada E (Eds), *The Limnology, Climatology and Paleoclimatology of East African Lakes*. pp. 103–139. Toronto: Gordon and Breach.

Ssentongo GW. 1995. Report on the present fisheries situation of Lake Baringo. Rome: FAO.

Stager JC, Ryves D, Cumming BF, Meeker L, Beer J. 2005. Solar variability and the levels of Lake Victoria, East Africa, during the last millennium. *Journal of Peleolimnology* 33: 243–251.

Stone JR, Fritz SC. 2004. Three-dimensional modeling of lacustrine diatom habitat areas: Improving paleolimnological interpretation of planktic:benthic ratios. *Limnology and Oceanography* 49: 1540–1548.

Swaine MD, Adomako J, Ameka G, De Graft-Johnstone KAA, Cheek M. 2006. Forest river plants and water quality in Ghana. *Journal of Aquatic Botany* 85: 299–308.

Tapia PM, Fritz SC, Baker PA, Seltzer GO, Dunbar RB. 2003. A Late Quaternary diatom record of tropical climatic history from Lake Titicaca (Peru and Bolivia). *Paleogeography, Paleoclimatology, Paleoecology* 194: 139–164.

Turner MA, Huebert DB, Findlay DL, Hendzel LL, Jansen WA, Bodaly RA, Armstrong LM, Kasian SEM. 2005. Divergent impacts of experimental lake-level drawdown on planktonic and benthic plant communities in a boreal forest lake. *Canadian Journal of Fisheries and Aquatic Sciences* 62: 991–1003.

Thomson J. 1887. *Through Masai land: A journey of exploration among the snow-clad volcanic mountains and strange tribes of Eastern equatorial Africa: Being the narrative of the Royal*

Geographical Society's expedition to Mount Kenya and Lake Victoria Nyanza, 1883–1884. London: S. Low, Marston, Searle and Rivington.

Verschuren D. 2003. Lake-based climate reconstruction in Africa: Progress and Challenges. *Hydrobiologia* 500: 315–330.

Verschuren D. 2001. Reconstructing fluctuations of a shallow East African lake during the past 1800 yrs from sediment stratigraphy in a submerged crater basin. *Journal of Paleolimnology* 25: 297–311.

Verschuren D, Kathleen RL, Cumming BF. 2000. Rainfall and drought in equatorial East Africa during the past 1,100 years. *Journal of Letters to Nature* 403: 410–414.

Verschuren D. 1999. Sedimentation controls on the preservation and time resolution of climate-proxy records from shallow fluctuating lakes. *Journal of Quaternary Science Reviews* 18: 821–837.

Vadeboncoeur Y, Peterson G, Vander Zanden MJ, Kalff J. 2008. Benthic algal production across lake size gradients: Interactions among morphometry, nutrients and light. *Journal of Ecology* 89: 2542–2552.

Wilson KK. 1989. Phytoplankton and physicochemical dynamics of Lake Baringo. MSc Thesis, Kenyatta University. Nairobi, Kenya.

Wilson GP, Reed JM, Lawson IT, Frogley MR, Preece RC, Tzedakis PC. 2008. Diatom response to the last glacial-interglacial transition in the Ioannina basin, northwest Greece: Implications for Mediterranean *paleo*-climate reconstruction. *Journal of Quaternary Science Reviews* 27: 428–440.

Wolin JA. 1996. Late Holocene lake-level and lake development signals in Lower Herring Lake, Michigan. *Journal of Paleolimnology* 15: 19–45.

Wright HE. 1980. Coring of soft lake sediments. *Boreas* 9: 107–114.