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ORIGINAL PAPER

Environmental variability in Lake Naivasha, Kenya, over the last two centuries

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Abstract Lake Naivasha, Kenya, is one of a number of freshwater lakes in the East African Rift System. Since the beginning of the twentieth century, it has experienced greater anthropogenic influence as a result of increasingly intensive farming of coffee, tea, flowers, and other horticultural crops within its catchment. The water-level history of Lake Naivasha over the past 200 years was derived from a combination of instrumental records and sediment data. In this study, we analysed diatoms in a lake sediment core to infer past lacustrine conductivity and total phosphorus concentrations. We also measured total nitrogen and carbon concentrations in the sediments. Core chronology was established by ^{210}Pb dating and covered a ~186-year history of natural (climatic) and human-induced environmental changes. Three stratigraphic zones in the core were identified using diatom assemblages. There was a change from littoral/epiphytic diatoms such as *Gomphonema gracile* and *Cymbella muelleri*, which occurred during a prolonged dry period from *ca.* 1820 to 1896 AD, through a transition period, to the present planktonic *Aulacoseira* sp. that favors nutrient-rich waters. This marked change in the diatom assemblage was caused by climate change, and later a strong anthropogenic overprint on the lake system. Increases in sediment accumulation rates since 1928, from 0.01 to 0.08 g cm^{-2} year^{-1} correlate with an increase in diatom-inferred total phosphorus concentrations since the beginning of the twentieth century. The increase in phosphorus accumulation suggests increasing eutrophication of freshwater Lake Naivasha. This study identified two major periods in the lake's history: (1) the period from 1820 to 1950 AD, during which the lake was affected mainly by natural climate variations, and (2) the period since 1950, during which the effects of anthropogenic activity overprinted those of natural climate variation.

Keywords Lake sediments · Diatoms · Conductivity · Lake Naivasha · Human impact · Eutrophication

Introduction

Lake sediments are frequently analysed to make paleoenvironmental inferences regarding changes in

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lake hydrology and surrounding ecosystems. These environmental changes can be caused by climatic fluctuations, by geomorphological and geological processes within the catchment area, and by human activities. The most recent climate records in lake-sediment archives are frequently overprinted by a local anthropogenic signal, confounding interpretation of environmental changes that were due to solely natural processes (Hausmann et al. 2002; Lotter and Birks 1997). Lake sediments may also fail to reflect past climate changes accurately in cases where non-climatic factors such as geomorphic and hydrologic setting influence the system (Fritz 2008). In the Naivasha basin, the last 100 years have been characterized by intense anthropogenic influence within the catchment, such as the damming of input rivers and the farming of coffee, tea and flowers around the lake (Verschuren 1996).

Diatoms in lake sediments are frequently used as bioindicators to infer ecological changes that have occurred within a lake and its surrounding catchment (Osborne 2000). This is possible because diatoms are remarkably sensitive to variations in water nutrient content, conductivity and pH. Past lake-water chemistry can be inferred from diatom valves in a sediment core, using transfer functions (Gasse et al. 1995). Such transfer functions have been developed from regional-scale studies in Africa (Gasse et al. 1995) and from combined, worldwide datasets (European Diatom Database Initiative, EDDI 2009).

Lake Naivasha was listed as a Ramsar site in 1995 (Ramsar 2010) and its 1-million-year history has been investigated over various timescales. Studies of its most recent history indicate the increasing importance of human influences, in addition to natural factors, on ecosystem changes (Verschuren et al. 2000; Trauth et al. 2003, 2005, 2010). The human population in the town of Naivasha and the area around the lake has increased 50-fold over the past three decades, to ~120,000 (Edeghonghon Jimoh et al. 2007). Consequently the aquatic health of the lake has become increasingly important for the people who depend on it. It is particularly important to protect the lake against increasing eutrophication (Hubble and Harper 2001). Anthropogenic influence since the beginning of the twentieth century is reported to have caused major changes in nutrient input, plankton composition and macrophyte abundance (Ballot et al. 2009; Hubble and Harper 2001). Published data on the floral shift, however, cover only the period between 1929 and 2005 AD, and because data collection was relatively patchy, the data do not provide a clear picture of the timing of species changes (Ballot 2009; Hubble and Harper 2001).

This study refines the temporal resolution of the environmental record of Lake Naivasha, using a continuous and well dated sediment record from the lake, covering about the last 200 years. The record reveals substantial changes in sedimentation rate and diatom assemblages, which were caused by human activities rather than by climate-driven processes.

Study site

At 1,889 m a.s.l., Lake Naivasha (0°55′S 36°20′E) is the highest closed-basin lake in the East African Rift System (Fig. 1). The modern lake covers an area of about 180 km^2 and has a water volume of ~0.85 km^3 (Bergner et al. 2003), a catchment area of 3,400 km^2 and an average depth in 1983 of 8 m (Verschuren 1999). Crescent Island Crater (CIC) is a partially submerged crater in the eastern part of the lake that represents the area of greatest water depth, 16 m in 1983 (Verschuren 2001). At low water levels, the crater becomes increasingly isolated from the main lake, and as a result, becomes chemically distinct (Hubble and Harper 2001).

The regional climate of this equatorial lake basin is influenced by the seasonal migration of the Inter-tropical Convergence Zone (ITCZ), causing a strongly bimodal annual cycle, with rains in March/April and October/November (Nicholson 1996). The area receives additional rainfall from the "Congo air boundary", with westerly to south-westerly airflow during August and September, the so-called September rains (Nicholson 1996). Average rainfall in the vicinity of the lake is ~650 mm $year^{-1}$, whereas the Aberdare Range in the eastern part of the catchment receives up to 2,400 mm $year^{-1}$. Interannual variations in precipitation are linked to E-W adjustments in the zonal Walker circulation associated with the Indian Ocean Dipole and the El Niño/Southern Oscillation (Saji et al. 1999; Moy et al. 2002). There is considerable variation in rainfall, temperature and vegetation throughout the catchment area as a result of large differences in altitude.

Lake Naivasha is the second-largest freshwater lake in Kenya. It has a pH of ~8.1 (Åse 1987), which

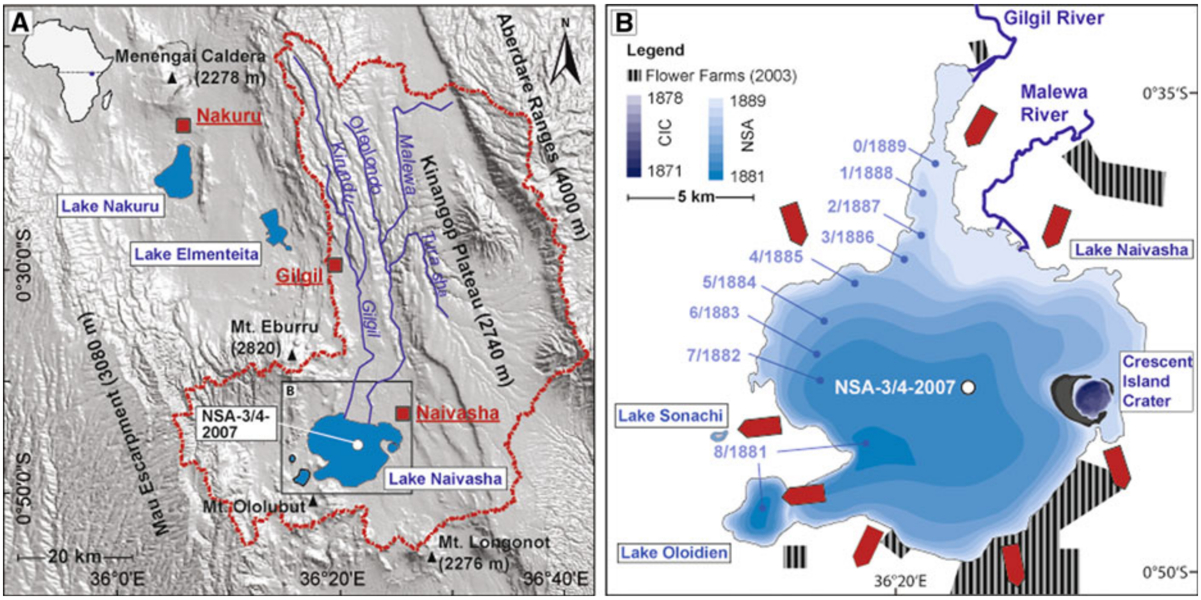

Fig. 1 **a** Location map for Lake Naivasha within the highest basin of the Kenyan Rift System, together with the catchment area and sites discussed in the text. **b** Bathymetry of the Lake Naivasha main lake, and its satellite basins Crescent Island Crater and Lake Oloidien (1983), and Lake Sonachi (1990) (modified from Åse et al. 1986; Verschuren 1999). Coring locality shown as *white circle*; *arrows* show the direction of groundwater flow, taken from Gaudet and Melack (1981)

makes it unique in the semi-arid climate zone of the eastern arm of the Rift Valley, where other lakes are both alkaline and saline. Because potential evapotranspiration in the lake area is about 1,900 mm year^{-1} (Clarke et al. 1990), the relatively low pH is attributed to high freshwater inflow from the Malewa and the Gilgil Rivers, which enter from the north. These two rivers drain the high-elevation Kinangop Plateau, and the Aberdare Range to the north and north-east, which receive high amounts of precipitation (Bergner et al. 2003). It is estimated that about 15% of the river input leaves the lake by underground seepage through porous volcanic material (Bergner et al. 2003). An understanding of this subsurface outflow process is fundamental to explaining the hydrochemical budget and solute export from the lake (Gaudet and Melack 1981; Ojiambo and Lyons 1996).

A major threat to Lake Naivasha is sediment pollution caused by human activities. The most important impacts are clearance of natural vegetation for agriculture, especially horticulture, and removal of the fringing papyrus swamps along the main inflow rivers, the Malewa and Gilgil, as these swamps buffer the lake from excess sediment input (Melack 1976; Harper et al. 1995). Consequences of sediment pollution are a reduction in water transparency and changes in the input and recycling of nutrients (Golterman 1977). Additional factors that influence the health of the lake are the growing human population's activities in the upper catchment, which require increasing water abstraction from the lake and catchment (Jimho 2007). Since the 1920s, several exotic invasive species have been introduced into the lake, resulting in changes to the structure and dynamics of the food web. Despite these recent anthropogenic impacts, Lake Naivasha is still considered to be reasonably healthy (Hubble and Harper 2001).

Materials and methods

Core sampling

Parallel sediment cores (NSA-3 and NSA-4) were collected from the centre of Lake Naivasha (0°45′47.30″S, 36°21′58.31″E) in August 2007 with a KC Kajak sediment core sampler (KC-Denmark A/S) (Fig. 1). A transparent coring tube was used and the core was extruded in the field. The core lengths (37.8 cm for NSA-3 and 35.4 cm for NSA-4) were limited by our inability to penetrate deeper into the compacted sediment. Both cores were sampled at 2.1-cm intervals and samples were stored in the dark in Whirl-Pak® plastic bags. Once in the laboratory, samples were kept in the dark at 10°C. Samples from the NSA-4 core were used for ^{210}Pb dating, while the NSA-3 samples were analysed for sediment type, organic content, and diatoms.

^{210}Pb chronology

Oven-dried subsamples from the Lake Naivasha NSA-4 sediment core were analysed for ^{210}Pb, ^{226}Ra and ^{137}Cs by direct gamma assay in the Liverpool University Environmental Radioactivity Laboratory using Ortec HPGe GWL series well-type, coaxial, low-background intrinsic germanium detectors (Appleby et al. 1986). ^{210}Pb was determined via its gamma emissions at 46.5 keV, and ^{226}Ra by the 295 keV and 352 keV γ-rays emitted by its daughter radionuclide ^{214}Pb following 3 weeks of storage in sealed containers to allow radioactive equilibration. ^{137}Cs was measured by its emissions at 662 keV. The absolute efficiencies of the detectors were determined using calibrated sources and sediment samples of known activity. Corrections were made for the effect of self-absorption of low energy γ-rays within the sample (Appleby et al. 1992).

Sedimentology and geochemistry

Total carbon (TC) and total nitrogen (TN) were analysed concurrently by IR spectroscopy and heat conductivity detection after burning weighed aliquots in an oxygen gas flow at 1,350°C, using a LECO CHN-2000 Elemental Analyzer. The TOC was determined after release of CO_2 in carbonates by reaction with hot 4 and 25% HCl, followed by analysis with the LECO CHN-2000 system. Total inorganic carbon (TIC) was obtained by subtracting TOC from TC. Mass accumulation rates (MARs) of sediment components were calculated from the bulk sediment accumulation rate (SAR) × %M/100, where %M is the percent mass of TIC, TOC or TN.

Prior to sedimentological analysis, mineral assemblages in samples from NSA-3 were determined by X-ray diffraction (XRD) analysis of powdered bulk samples, without further treatment, using a Siemens D5000 diffractometer. In addition, sediment samples NSA-3-1 to NSA-3-18 were examined with an optical microscope to semi-quantitatively cross-check the mineral content as well as the abundance of sponge spicules, macrophyte fossils, and other constituents.

Diatom counts and transfer functions

Between 0.25 and 0.35 g of sample material was processed for 90 min in 15-ml Falcon tubes containing 4 ml of 30% H_2O_2, which were placed in a water bath at 80°C. This was done to remove organic matter. After adding 10 µl of 2N HCl, sample tubes were filled with VE water and incubated overnight at 10°C. The supernatant was then discarded and samples were washed with VE water before being centrifuged at 3,000 rpm for 4 min. This washing step was repeated four times, after which 1:4 and 1:10 solutions were prepared and samples were settled on coverslips and dried overnight before being mounted on glass slides using Naphrax™. Diatom species identification was carried out using a Leica DM 4000B optical microscope at 1,000× magnification. A total of 300–500 valves were counted per slide. The diatom species were determined following Hustedt (1949), Gasse (1986) and Krammer and Lange-Bertalot (1986, 1988, 1991a, b). Diatom percentages were zoned using stratigraphically constrained cluster analyses with ZONE, an unpublished software tool provided by S. Juggins, University of Newcastle.

Major changes in the diatom assemblages over the last two centuries were determined by a detrended correspondence analysis (DCA) with CANOCO 4.5 software (ter Braak and Šmilauer 2002). The DCA also provided information about whether the species distribution was uniform or Gaussian with a single mode. The data were log-transformed to stabilize the variance and rare species were down-weighted. A gradient length of 1.8 indicated a uniform species distribution. The main trends in diatom variations down-core were subsequently analysed using a principal component analysis (PCA) of the log-transformed species percentages.

Salinity, as represented by conductivity (log 10 µS cm^{-1}), was reconstructed using the East African Salinity dataset included in the European Diatom Database (EDDI, http://craticula.ncl.ac.uk/Eddi/jsp/index.jsp). This dataset includes 579 diatom species identified from 187 samples which came from 98 sites between latitudes 19°N and 14°S and longitudes 27°N and 43°E. The sites range from Afro-alpine bogs at altitudes of up to 4,000 m to hypersaline lakes below sea level. The conductivity in these lakes ranges from 40 to 50,000 μS cm^{-1} and the pH from 5 to 10.9. In this study, results were back-transformed into μS cm^{-1} and classified according to the ecological habitats of the species: planktonic, planktonic/littoral, littoral and littoral/epiphytic diatoms. The total phosphorus (TP) was reconstructed using the EDDI combined TP dataset, including 347 samples from various European lakes. Finally, the results were back-transformed to total phosphorus values in μg l^{-1}.

Diatom-based inference models based on weighted averaging with inverse deshrinking (WAinv) were used for the reconstruction of conductivity and TP, as this gives an overall lower root mean-squared error (RMSE) of prediction (Birks et al. 1990). We used modern analog technique (MAT) analysis to test how well fossil diatom assemblages were represented in the dataset. This analysis evaluates the sample of the dataset for the closest analogues of floristic match by means of a similarity index. An index value above 100–150 indicates a poor floristic similarity to any of the samples from the underlying dataset, while values below this threshold indicate a high similarity. The MAT analysis indicates whether or not the analysed samples are similar to those of the underlying datasets, thus providing a measurement of the validity of the reconstructed environmental features.

Results

^{210}Pb chronology

Total ^{210}Pb activity reached equilibrium with ^{226}Ra activity at a depth of about 33 cm (Fig. 2a). Unsupported ^{210}Pb (Fig. 2b) declined irregularly with depth. Concentrations in the top 15 cm were relatively constant, fluctuating around a mean value of 164 Bq kg^{-1}. Below 15 cm, there was a slow decline down to a depth of 22 cm, at which point there was a relatively abrupt change to a much steeper gradient. Concentrations below 30 cm were close to or below the detection limit. ^{137}Cs concentrations had a well defined peak between 20 and 25 cm depth, probably recording the 1963 fallout maximum from atmospheric testing of nuclear weapons (Fig. 2c).

Raw ^{210}Pb dates calculated using the CRS dating model (Appleby and Oldfield 1978) place 1963 at a depth of 20 cm, in relatively good agreement with the depth determined from the ^{137}Cs record (Fig. 2d). The mean, post-1963 SAR calculated from the ^{137}Cs stratigraphic date is 0.055 g cm^{-2} $year^{-1}$, compared to the mean pre-1963 value calculated from the gradient of the ^{210}Pb profile of 0.010 g cm^{-2} $year^{-1}$. Corrected ^{210}Pb dates were calculated by applying the CRS model in a piecewise way using the ^{137}Cs date as a reference level (Appleby 2001). Results suggest that the relatively slow SAR persisted until the middle of the twentieth century, but increased significantly thereafter (Table 1; Fig. 2). The mean SAR value during the past 10 years was 0.080 g cm^{-2} $year^{-1}$. Using the corrected ^{210}Pb chronology, the extrapolated age for the base of the NSA-3-18 core is 1820 AD, assuming a SAR of 0.01 g cm^{-2} $year^{-1}$ at the maximum core depth.

Lithology and geochemistry

Sediments of the core from the centre of Lake Naivasha consist of 37.8 cm of organic mud that shows layers of different colors in the lower part of the core (Electronic Supplementary Fig. 1). Macroscopic observation is not supported by the XRD results. The large amount of organic matter in the sediment, including diatoms, overwhelms any mineralogical signal. Therefore, XRD is inapplicable for sediment investigations of the NSA-3 core.

Diatom composition and geochemistry of the NSA-3 core, together with their paleo-environmental interpretations, are summarized in Figs. 3, 4 and 5. TOC accumulation rates vary between 1.2 and 6.2 mg cm^{-2} $year^{-1}$, with rates increasing towards the top of the core. The generally low TN accumulation rates show a similar trend, varying between 0.1 and 0.8 mg cm^{-2} $year^{-1}$. TOC/TN ratios range between 4 and 9 and tend to increase slightly down-core. The accumulation of organic (TOC, TN) and inorganic (TIC) matter is almost constant throughout the period between 1843 and 1947 AD. After 1947, TOC, TC and TN accumulation rates increase regularly, all reaching a maximum in the uppermost sample, except for the TN rate, which decreases slightly in 2006. TIC accumulation rates fluctuate at the beginning of the 1970s, but

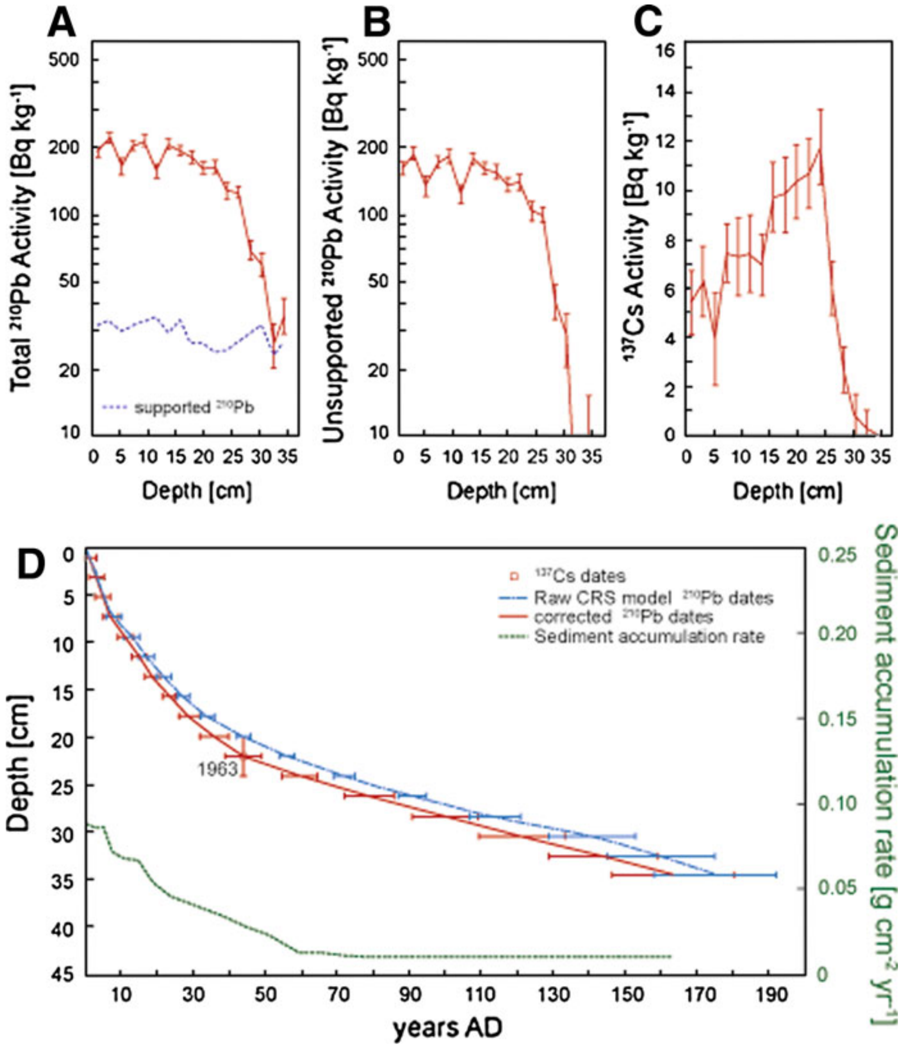

Fig. 2 Radiometric chronology of Lake Naivasha sediment core NSA-4. Fallout radionuclides in the NSA-4 Lake Naivasha sediment core, showing **a** total and supported ^{210}Pb, **b** unsupported ^{210}Pb, **c** ^{137}Cs concentrations versus depth. **d** The raw CRS model ^{210}Pb dates and the 1963 depth determined from the ^{137}Cs record, together with the corrected ^{210}Pb dates and sedimentation rates calculated using the ^{137}Cs date as a reference point

show an overall increasing trend. Since MARs are a direct function of the bulk sedimentation accumulation rate, all MAR values increase significantly after 1947 AD (Table 1; Fig. 4). TOC/TN ratios vary between 8 and 9 in the period between 1843 and 1990 AD, but then show a decreasing trend until 2004, dropping to a value of 4 before again increasing slightly towards 2006. The quantity of fine-grained minerals is constant throughout the sediment core, whereas the numbers of macrophyte fossils and sponge spicules increase sharply down-core from sample NSA-3-15 to sample NSA-3-18.

Diatom assemblages

Thirty-nine species were identified in the core, but only those with abundances >0.5% were plotted in Fig. 3. The species were grouped into four ecological types: planktonic, planktonic/littoral, littoral, and littoral/epiphytic, following Gasse (1986) and Gasse et al. (1995). Valve preservation was generally good throughout the core. Three diatom assemblage zones were identified in the core (Table 2a; Fig. 3).

Zone I, between 38.7 and 29.5 cm, corresponds to the time interval between *ca.* 1820 and 1896 AD (samples NSA-3-18 to NSA-3-15). The diatom assemblage of this zone is dominated by the littoral/epiphytic and littoral diatoms *Gomphonema gracile* Ehrenberg (up to 26%), *Epithemia adnata* Kützing (up to 11%), *Cymbella muelleri* Hustedt (up to 22%), and *Navicula elkab* Müller (up to 18%). Abundances of planktonic species, such as *Aulacoseira ambigua* (Grunow) Simonsen and *A. granulata* (Ehrenberg)

Table 1 ^{210}Pb chronology of the Lake Naivasha core NSA-4-2007

Depth (cm)	Chronology				Sedimentation rate		
	g cm^{-2}	Date AD	Age years	±	g cm^{-2} y^{-1}	cm y^{-1}	± (%)
0.00	0.00	2007	0	0			
1.05	0.10	2006	1	2	0.089	1.01	8.0
3.15	0.28	2004	3	2	0.086	1.09	7.8
5.25	0.43	2002	5	2	0.086	1.05	11.6
7.35	0.62	2000	7	2	0.073	0.67	7.5
9.45	0.89	1996	11	2	0.068	0.53	8.9
11.55	1.16	1992	15	2	0.066	0.56	11.0
13.65	1.39	1988	19	2	0.054	0.50	8.7
15.75	1.62	1984	23	2	0.046	0.41	9.5
17.85	1.87	1978	29	3	0.042	0.34	11.6
19.95	2.13	1971	36	4	0.036	0.31	12.5
22.05	2.41	1963	44	5	0.029	0.18	15.2
24.15	2.66	1947	60	5	0.013	0.12	13.6
26.25	2.88	1928	79	7	0.010	0.11	13.6
28.45	3.09	1907	100	9	0.010	0.10	13.6
30.45	3.31	1885	122	12	0.010	0.09	13.6
32.55	3.54	1863	144	15	0.010	0.10	13.6
34.50	3.74	1843	164	17	0.010	0.10	13.6

Simonsen, as well as the planktonic/littoral species *Synedra acus* Kützing, vary between 5 and 20%. In sample NSA-3-16 (33.6–31.5 cm, *ca.* 1863 AD), each of these planktonic species reaches a maximum abundance of only 5%, whereas *Cymbella muelleri* and *Navicula elkab* reach their maximum relative abundances within this zone, and reach similar abundances in samples NSA-3-18 to NSA-3-16. *Aulacoseira* sp. dominates in samples from NSA-3-15 to the top of the core. When *A. ambigua* is scarce, *A. granulata* is abundant, and vice versa.

Zone II ranges from 29.4 to 25.2 cm, corresponding to the time interval between *ca.* 1896 and 1938 AD (samples NSA-3-14 to NSA-3-13), and is transitional between zones *I* and *III*. Within this zone, the planktonic/littoral *Synedra acus* is dominant, with a mean abundance of 23%. The planktonic species *A. ambigua* and *A. granulata* increase rapidly to peak abundances of 38% and 57%, respectively. The littoral and littoral/epiphytic species of flora decline and reach their minima around 1930 AD, shortly before the start of *Zone III*.

Zone III is the core interval between 25.1 and 0 cm, corresponding to the time interval between *ca.* 1938 and 2007 AD (samples NSA-3-12 to NSA-3-1). The diatom assemblage within this zone is characterized by *A. ambigua*, *A. granulata* and *Synedra acus*. The uppermost sample shows very high numbers of *Synedra acus*, however, with less frequent *A. ambigua* and *A. granulata*. The abundance of macrophytes and sponge spicules decreases within

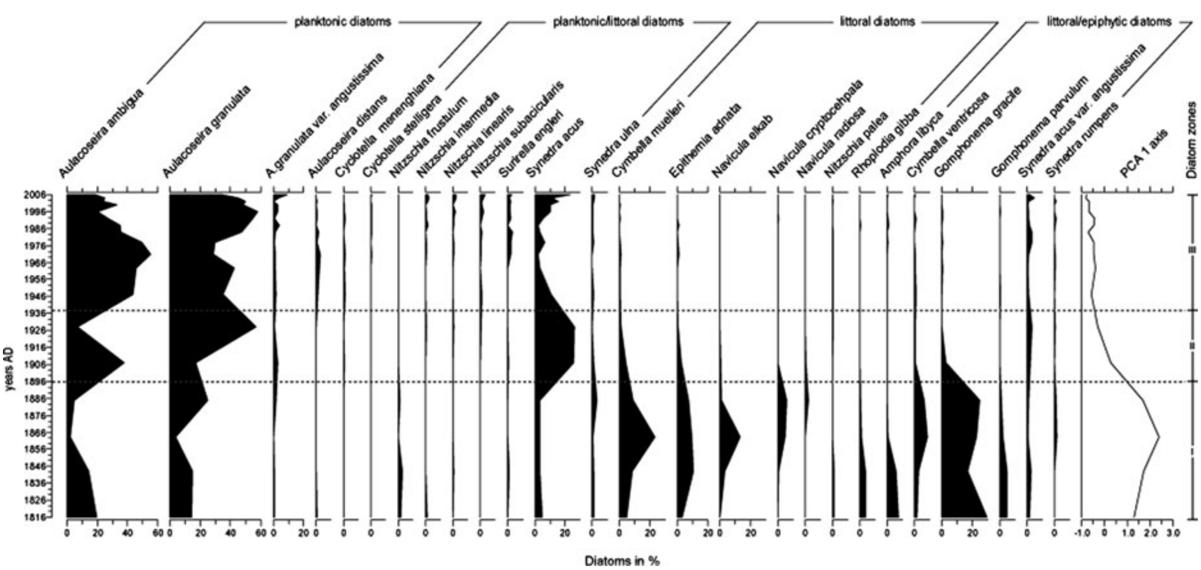

Fig. 3 Summary of the diatom assemblages from Lake Naivasha core NSA-3, PC1 scores, and diatom-based zonation

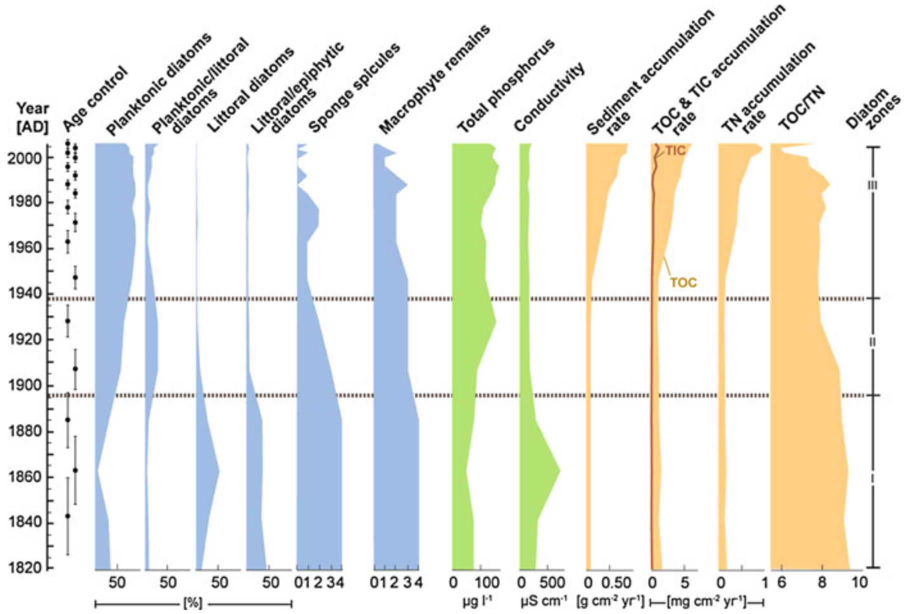

Fig. 4 Down-core variations in diatom habitat preferences, diatom-based zonation, diatom-inferred conductivity and total phosphorus (TP) values, sediment accumulation rates (SAR) and mass accumulation rates for geochemical variables (*TN* total nitrogen, *TOC* total organic carbon, *TIC* total inorganic carbon and the *TOC/TN* ratio) based on the age model. Age control is provided with *error bars*

this zone, and they are almost absent between 1998 and 2004 AD (samples NSA-3-7 to NSA-3-2).

Statistical analysis and environmental reconstruction

The PCA of the data matrix of samples and the diatom percentages show that the first two principle components (PC) account for 72% of the total variance (PC1 63%, PC2 9%). The PC1 scores are plotted in stratigraphic order, together with the distribution of diatom species (Fig. 3). Species and samples from the underlying dataset are plotted on the PC1 axis, with the inferred diatom zones marked in red ellipses (Electronic Supplementary Fig. 2). The grouping of samples in this plot suggests that PC1 serves as an indicator for the ratio of planktonic diatom species (negative PC1 scores) to epiphytic/littoral diatom species (positive PC1 scores). Moving up-core, the PC1 scores change from −0.8 to 2.4 with the change from littoral/epiphytic to planktonic assemblages in transitional *Zone II*.

The modern analogue technique (MAT) analysis for the conductivity dataset indicates a good floristic match by comparing species composition of the analysed samples with those of the underlying samples in the dataset. All identified species are included in the East African salinity dataset. Because the East African conductivity dataset contains several samples from Lake Naivasha, it shows good agreement with the analysed samples. Samples NSA-3-18 to NSA-3-15 (*ca.* 1816–1885 AD), and in particular sample NSA-3-16 (*ca.* 1863 AD), perform relatively poorly because they show a high abundance of littoral and littoral/epiphytic species, which may not typically occur in any of the dataset samples. Sample NSA-3-16 has the highest similarity to a mud sample from Lake Kamuru in Uganda. Most of the analysed samples, however, correlate best with either a sediment sample from Lake Rugwero in Rwanda or a core-top sample from Lake Naivasha (Crescent Island Crater site). All three modern analogue samples are from freshwater lakes.

Results of the conductivity and TP reconstructions are shown in Fig. 4. Reconstructions indicate the highest conductivity values in *Zone I*, about 731 µS cm^{-1} in sample NSA-3-16—*ca.* 1863 AD, driven mainly by the occurrence of littoral species *Cymbella muelleri* and *Navicula elkab*. In particular, *N. elkab* favors highly saline (∼13 mS cm^{-1}) and

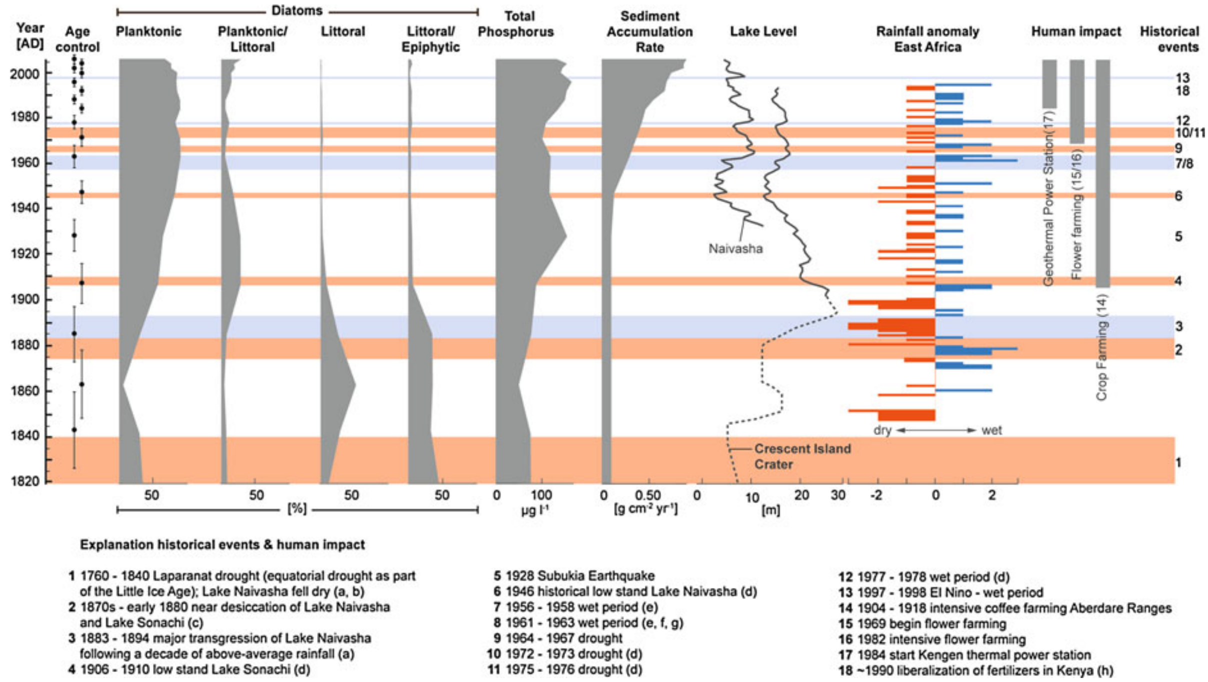

Fig. 5 Compilation of diatom assemblage variations, sediment accumulation rate (SAR), total phosphorus (TP) and historical records of environmental and land use data. Water levels for the main Lake Naivasha (NSA) are instrument-based while those for the Crescent Island Crater Lake (CIC) are a combination of instrumental (*solid line*) and sediment proxy (*dashed line*) (Åse et al. 1986; Verschuren et al. 2000). Rainfall anomaly for Eastern Africa (EA): data combined from rainfall proxy indicators for the nineteenth century and instrumental data for the twentieth century, from Nicholson (2001). References to historical events: **a** Nicholson (1995); **b** Verschuren (2001); **c** Sikes (1935); **d** Verschuren (1999); **e** Nicholson et al. (1988); **f** Vincent et al. (1979); **g** Gaudet and Melack (1981); **h** Ariga and Jayne (2006); *blue bars* indicate historical highstands of CIC/NSA or Lake Sonachi; *red bars* indicate historical lowstands of CIC, NSA or Lake Sonachi. Age control is provided with *error bars*

Table 2 Stratigraphic zonation inferred by diatoms, their dominant and subdominant diatom taxa (a) and the performance of the conductivity and TP models used for diatom-inferred reconstructions (b)

Zone	Core depth (cm)	Age (years AD)	Dominant taxa	Subdominant taxa
(a)				
III	0–25.14	2006–1938	*Aulacoseira ambigua*, *Aulacoseira granulata*	*Synedra acus*
II	25.14–29.45	1938–1896	*Aulacoseira granulata*, *Synedra acus*	*Aulacoseira ambigua*, *Cymbella muelleri*, *Gomphonema gracile*
I	29.45–37.8	1896–1820	*Gomphonema gracile*, *Cymbella muelleri*	*Epithemia adnata*, *Aulacoseira granulata*, *Aulacoseira ambigua*

Gradient	Method	r^2	RMSE	r^2_{jack}	RMSEP
(b)					
Conductivity	WAinv	0.86	0.32	0.78	0.41
TP	WAinv	0.71	0.30	0.36	0.33

WAinv, Weighted averaging with inverse deshrinking; RMSE, root mean squared error of prediction; RMSEP, jackknifed RMSE; r^2, jackknifed coefficient of determination alkaline ($\sim$pH 9) waters (Gasse 1986). Apart from this sample, *Zone I* is characterized by an average reconstructed conductivity of 300 µS cm^{-1}. Conductivity values for zones *II* and *III* are almost identical, generally varying between 150 and 185 µS cm^{-1}. The uppermost core sample (*Zone III*) shows a slightly higher conductivity value (215 µS cm^{-1}).

The TP dataset includes only 34 of the 39 diatom species identified in our study. The MAT analyses for TP reconstructions were therefore of poorer quality than the conductivity reconstructions. The uppermost sample and samples NSA-3-18 to NSA-3-15 have the least similarity to the dataset samples, which relates to the fact that *Navicula elkab* and *Cymbella muelleri* are completely absent from the dataset. The diatom-inferred TP reconstruction yields lowest values in *Zone I*, including a minimum of 49 µg l^{-1} in sample NSA-3-16. Moderate TP values of $\sim$ 80 µg l^{-1} are indicated for *Zone II*. After $\sim$1938, the reconstructed TP values increase briefly to 155 µg l^{-1} and then decline to 100 µg l^{-1} at around 1970 AD. The reconstructed TP values subsequently increase to a maximum of 164 µg l^{-1} in 1996 (sample NSA-3-5) before once again decreasing slightly to 132 µg l^{-1} at present.

Discussion

The radiometric chronology of the Naivasha core is thought to be quite reliable for the time between 1907 and 2007 AD, showing a low, ±2–5 year error range. The raw ^{210}Pb dates place 1963 at a depth of 20 cm, which is in relatively good agreement with the depth determined from ^{137}Cs.

The ^{137}Cs peak appears to preclude mixing as a cause of the irregular ^{210}Pb record. Before 1907 AD, errors on dates are greater, from ±9 years (sample NSA-3-14) to ±17 years (sample NSA-3-17). This section of the core also displays an apparent lower in sedimentation rate, which must be interpreted with caution.

Sedimentation rates and geochemical data, together with the environmental reconstructions of conductivity and total phosphorus, conform with the three diatom assemblage zones (Fig. 5). *Zone I* covers the time from 1820 to the end of the nineteenth century and was influenced mainly by natural climate variations, in particular by long periods of drought. *Zone II* represents a transition zone characterized by a shift from primarily climate-driven influences to a period when human increasingly altered the environment of Lake Naivasha. In *Zone III*, which covers the period from 1938 to 2007 AD, natural conditions in the lake are overprinted by anthropogenic influences, which are mainly reflected by high sedimentation rates and a rapid shift in the diatom assemblage.

Zone I (*ca.* 1820–1896 AD): natural climatic variations—minor human activity

Relatively low and constant bulk sediment accumulation rate (0.01 g cm^{-2} $year^{-1}$) and mass accumulation rates for TN (0.2 mg cm^{-2} $year^{-1}$) and TOC (2 mg cm^{-2} $year^{-1}$) indicate low sediment input from the catchment into Lake Naivasha during this period. The influence of human activity was minor because nomadic tribes only made sporadic use of the lake and its surroundings for water supply and food. The diatom-inferred TP values are relatively low, but increase slightly from 50 to 88 µg l^{-1} between 1863 and the end of *Zone I*. According to the classification scheme for warm-water tropical lakes, TP values serve as an indication of the shift from mesotrophic to eutrophic conditions (Salas and Martino 1991). A growing predominance of littoral and/or epiphytic diatom assemblages is indicative of rising conductivity values ranging between 290 and 731 µS cm^{-1}, suggesting low water level in the lake, presumably caused by a drier climate. Low TN values and TOC/TN ratios $\sim$9 reflect organic matter contributions from epiphytic and/or benthic diatoms and abundant aquatic macrophytes, both indicative of low water levels related to drier conditions (Meyers 2003). This interpretation is consistent with the large numbers of sponge spicules in the sediments, and the historically documented Laparanat-Mahlathule drought that caused low lake stands between 1760 and 1840 (Verschuren et al. 2000). Reconstructed lake levels for the Crescent Island Crater (CIC) indicate two major lowstands during this period (Verschuren et al. 2000), whereas East African rainfall anomalies reconstructed by Nicholson (2001) indicate a prolonged dry period with rare events of pronounced rainfall. *Zone I* contains only one peak in inferred conductivity around 1863 ± 15 AD, during the identified long dry period. This may have been a consequence of erosion and dissolution of salts formed during the long drought that occurred before 1840 AD, and perhaps lasted even longer, as suggested by the records of Verschuren et al. (2000) and Nicholson (2001). Lake Naivasha is particularly sensitive to such declines in lake stage in that a small drop in lake level exposes a large area of lake bottom due to the shallow slope of the littoral area, particularly along the north shore. Declining lake level caused by a dry climate may have desiccated lake sediments where evaporites accumulated (LNROA 1993). Thus, conductivity rises, rather than falls, with the onset of rains, as dissolved ions increase in the system with greater precipitation (Fig. 3). A rise in water level dissolved accumulated salts in the previously exposed sediments, which led to a brief increase in conductivity, with a peak of 731 µS cm^{-1} about 1863 ± 15 AD (sample NSA-3-16). Thereafter, the Naivasha basin was persistently filled with water and the lake displayed lower conductivity. Considering the age error on sample NSA-3-16, it is not possible to identify exactly which precipitation event led to this early conductivity peak. It could have been the short wet period around 1850 AD (Verschuren 2000), or alternatively 1860 or 1870 AD, years for which Nicholson (2001) inferred enhanced rainfall events.

Another explanation for the single conductivity peak is that lake level had decreased considerably after a long drought, which led to higher conductivity values in the lake. Because sample NSA-3-16 represents ~20 years of lake history, and thus the average conductivity during that time, it is very difficult to infer the short-term environmental changes that occurred during that period, though there may have been high variability. It is difficult to compare our diatom record from the main basin of Lake Naivasha with lake level changes in the Crescent Island Crater. Although the basins are hydrologically connected from time to time, their bathymetries differ, and consequently, they may display differences in sedimentation patterns and sensitivity to climate changes.

In general, high conductivity is indicated by the presence of two littoral species, *Cymbella muelleri* and *Navicula elkab*, and the littoral/epiphytic species *Gomphonema gracile*, which is very sensitive to pollution in modern lakes (Kelly et al. 2005). All three species favor water with moderate to high ionic strength, from 1,000 to 30,000 µS cm^{-1} (Gasse 1986). The conductivity values decrease up-core from ~1863 until the beginning of the 20th century, and remain constant at ~170 µS cm^{-1} thereafter. This change in water chemistry corresponds to a decrease in littoral and epiphytic diatom frequencies. After a generally dry period from 1820 to 1882 (Nicholson 2001) during which Lake Naivasha was nearly desiccated and its groundwater reservoirs emptied, a wetter period occurred from 1883 to 1894 (Nicholson 1995).

Zone II (*ca.* 1896–1938 AD): transition zone—increased human activity

From about 1883 to 1894 AD, Naivasha experienced a wetter period, indicated by a lake level highstand in the Crescent Island Crater (Verschuren et al. 2000), although sedimentation rates during that time were still low (0.01 g cm^{-2} $year^{-1}$). An increase in commercial farming of tea and coffee in the early 20th century had no discernible effect on sedimentation rate in the lake. Such large catchments are known to store sediments in sinks within the basin for many years before they are transported to the lake. Nutrients, however, reach the lake much more quickly, as they are transported rapidly in dissolved form after rainfall events (Phillips 2003). This may explain the rapid increase in total phosphorus from around 1900 AD. Since the 1930s, the diatom-inferred TP values have exceeded 111 µg l^{-1}, indicating progressive eutrophication of the lake (Salas and Martino 1991). The arrival of the British colonists at the end of the 19th century and the intensive tea and coffee farming that followed coincide with nutrient enrichment of Lake Naivasha. Nutrient input favored planktonic species *A. ambigua* and *A. granulata*, both of which increased in abundance within this zone and maintain high abundance in *Zone III*. A slight decline in TOC/TN ratios towards values ~8, indicative of planktonic diatoms, parallels the rising TP values (Meyers 2003). This implies a direct link to increased nutrient input to the lake from intensive coffee, tea and pyrethrum farming in the highland areas of the catchment.

Following this wet episode of the late nineteenth century, climate became drier beginning around 1910 AD, as indicated by a shift to a negative water balance (Nicholson 2001). Nevertheless, the large aquifers that filled during the wet period continued to provide groundwater to the lake, contributing to the low salinity in Lake Naivasha.

Zone III (*ca.* 1938–2007 AD): human activity overprints natural climatic variation

At the beginning of *Zone III*, the sediment accumulation rate increased to a maximum of 0.08 g m^{-2} $year^{-1}$. The most likely reason for this higher sediment accumulation rate was human activity within the catchment. Conversion of natural sediment traps such as papyrus swamps to horticulture and intensively farmed landscapes in the upper catchment fostered soil erosion and consequent sediment delivery to the lake. Anomalously high rainfall between 1962 and 1964 and a relatively wet period that continued through 1990 AD contributed to further degradation of the loose upper soil layers. The Ba/Ca ratios of marine corals off the East African coast (Fleitmann et al. 2007) support our interpretation of increasing erosion within *Zone III* since the year 1908 ± 5 AD due to human activities in the Kenyan Highlands.

Eutrophication in *Zone III* was caused by an increased supply of phosphorus and nitrogen to the lake (Osborne 2000). The steady rise of *Aulacoseira* sp., which prefers nutrient-rich waters, coincides with a reduction in species that are more sensitive to pollution, such as *Gomphonema gracile*, and indicates the continuing eutrophication of Lake Naivasha. The diatom-inferred total phosphorus values show a positive trend since *ca.* 1963, increasing to 165 µg l^{-1} in 1996. This trend in TP is probably attributable to the increasing numbers of *Aulacoseira* within *Zone III*. *Aulacoseira* species occur commonly in eutrophic European and American lakes (Kilham et al. 1986; Karst and Smol 1998; Anderson et al. 1990), and this genus is therefore regarded as an indicator of eutrophic conditions. Ballot et al. (2009) found TP values between 70 and 200 µg 1^{-1} in Lake Naivasha from 2001 to 2005, and noted that the eutrophication of the lake was marked by changes in the phytoplankton community, including a decrease in species richness. Modern Lake Naivasha is dominated by *Cyanocatena planktonica* (Cyanobacteria), *Pediastrum simplex* (Chlorophyceae) and *A. granulata*.

Along with rising SARs, TOC and TN accumulation rates rise between 1947 and 2007 AD. The TOC/TN ratios are fairly stable around 8 until 1990 AD. According to Meyers (2003), TOC/TN values between 4 and 8 reflect the abundance of a nitrogen-rich proteinaceous organic matter source such as phytoplankton. Diatoms account for a large proportion of the algae in Lake Naivasha, and TOC/TN values around 9 drop even lower towards the top of the core. This may have been due to TN enrichment. An increase in TN could be attributed to the use of fertilizers in Kenya after 1990, when the fertilizer market was liberalized in the early 1990s (Ariga and Jayne 2006).

Total nitrogen and phosphorus are minor contributors to the conductivity of lake waters, as is silicate. These constituents, however, are important in biological cycles. They are often the drivers of productivity in continental waters and are incorporated into living organisms. Because of their contribution to the ionic strength of waters, it is not surprising that diatom-inferred conductivity remained relatively constant (~170 µS cm^{-1}) during the eutrophication process.

The growing human population and intensive flower farming on the southern shore of the lake brought fertilizers into the lake and further promoted eutrophication. Despite inputs of sediments and nutrients, as well as dam construction and removal of water in the catchment areas, and water consumption by the Olkaria geothermal power station, Lake Naivasha remains a freshwater system. Even the documented lowstand of Lake Naivasha between 1944 and 1955 (~5 m lowering) did not increase the conductivity, according to the diatom flora. The hydrological balance of the lake is highly dependent on groundwater flow, which may explain the lack of a conductivity response to arid intervals (Telford and Lamb 1999; Ayenew et al. 2007). A recent study on Lake Beseka in the Ethiopian Rift Valley suggests a close relationship between tectonic activity and expansion of the lake due to enhanced groundwater discharge (Goerner et al. 2008). This model may also apply to Lake Naivasha, which is also situated within a highly tectonically active region.

In summary, this study has shown that over the last ~200 years, Lake Naivasha's water chemistry and biology have been influenced by natural climatic variations and anthropogenic activities. Lake Naivasha's water level responded to natural rainfall variations, as occurred in the period between 1820 and 1882 AD, when long dry periods led to low water levels and/or complete desiccation (Verschuren et al. 2000). The enduring Laparanat drought (1760–1840 AD) caused slightly saline conditions in the lake and favored the abundance of saline-tolerant diatoms such as *Navicula elkab* and *Cymbella muelleri*. In the generally wetter period from 1883 to 1894 AD, the lake received more freshwater from the catchment and groundwater reservoirs, which helped maintain the freshwater nature of the lake. These freshwater conditions favor diatoms such as *Synedra* sp. and *Aulacoseira* sp. that prefer waters with low conductivity. After 1900 AD, shorter wet and dry periods alternated and the lake level fluctuated in response to these variations. This is documented by instrumental lake level data since 1932 and by both proxy and instrumental rainfall data since 1850 (Nicholson 2001). The sediment accumulation rate increased from 1947 to 2007 AD, due to higher rates of soil erosion from cultivated areas within the lake catchment, rather than as a consequence of intense rainfall. Higher erosion rates caused greater inputs of nutrients and pollutants to the lake. Nutrient-rich waters favored eutrophic diatoms such as *Aulacoseira* sp. and led to displacement of pollution-sensitive diatom species such as *Gomphonema gracile*.

Since the middle of the twentieth century, intense anthropogenic activity around Lake Naivasha has led to cultural eutrophication, which has overprinted the influence of natural climate variation on the lake. Several previous studies have suggested that human activity, in particular agriculture, is the main reason for higher sediment fluxes into lakes (Mannion 1995; Bookman et al. 2010). In addition to inputs of soil and nutrients, transport of fertilizers, pesticides, and other pollutants resulting from intensive land use, has far-reaching implications for the future of Lake Naivasha and numerous other lakes (Plater et al. 2006). This study demonstrated that Lake Naivasha is highly sensitive to changes in catchment activities. It will therefore be important to monitor variables in the lake that are influenced by anthropogenic activities, to be able to manage the lake wisely. The human population around the lake, as well as numerous other species, depend on the health of Lake Naivasha.

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References

Anderson NJ, Rippey B, Stevenson AC (1990) Change to a diatom assemblage in a eutrophic lake following point source nutrient re-direction: a paleolimnological approach. Freshw Biol 23:205–217

Appleby PG (2001) Chronostratigraphic techniques in recent sediments. In: Last WM, Smol JP (eds) Tracking environmental change using lake sediments. Volume 1: Basin analysis, coring, and chronological techniques. Kluwer Academic, Dordrecht, pp 171–203

Appleby PG, Oldfield F (1978) The calculation of ^{210}Pb dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. Catena 5:1–8

Appleby PG, Nolan PJ, Gifford DW, Godfrey MJ, Oldfield F, Anderson NJ, Battarbee RW (1986) ^{210}Pb dating by low background gamma counting. Hydrobiologia 141:21–27

Appleby PG, Richardson N, Nolan PJ (1992) Self-absorption corrections for well-type germanium detectors. Nucl Inst Methods B 71:228–233

Ariga J, Jayne TS (2006) Can the market deliver? Lessons from Kenya's rising use of fertilizer following liberalization. Policy brief, Tegemeo Institute for Agricultural Development and Policy, vol 7, pp 1–4

Åse LE (1987) A note on the water budget of lake Naivasha, Kenya. Geografiska Annaler 69A:3–4

Ayenew T, Becht R, van Lieshout A, Gebreegziabher Y, Legesse D, Onyando J (2007) Hydrodynamics of topographically closed lakes in the Ethio-Kenyan Rift: the case of lakes Awassa and Naivasha. J Spatial Hydrol 7(1):1–20

Ballot A, Kotut K, Novelo E, Krienitz L (2009) Changes of phytoplankton communities in Lakes Naivasha and Oloidien, examples of degradation and salinization of lakes in the Kenyan Rift Valley. Hydrobiologia 632:359–363

Bergner AGN, Trauth MH, Bookhagen B (2003) Paleoprecipitation estimates for the Lake Naivasha basin (Kenya) during the last 175 k.y. using a lake-balance model. Glob Planet Change 36:117–136

Birks HJB, Line JM, Juggins S, Stevenson AC, ter Braak CJF (1990) Diatoms and pH reconstruction. Philos Trans R Soc Lond B 327:263–278

Bookman R, Driscoll CT, Effler SW, Engstrom DR (2010) Anthropogenic impacts recorded in recent sediments from Otisco Lake, New York, USA. J Paleolimnol 43:449–462

Clarke MCG, Woodhall DG, Allen D, Darling G (1990) Geological, volcanological and hydrogeological controls

on the occurrence of geothermal activity in the area surrounding Lake Naivasha, Kenya. Ministry of Energy, pp 1–138
EDDI (2009) http://craticula.ncl.ac.uk/Eddi/jsp/, 12 Sept 2009
Edeghonghon Jimoh H, Vogler C, Waters JJJ (2007) Perceived and real sources of pollution in Lake Naivasha. http://www.pdf-searcher.com/Perceived-and-real-sources-of-pollution-in-Lake-Naivasha.html, 01 Dec 2010
Fleitmann D, Dunbar RB, McCulloch M, Mudelsee M, Vuille M, McCanahan TR, Cole JE, Eggins S (2007) East African soil erosion recorded in a 300 year old coral colony from Kenya. Geophys Res Lett 34:L04401. doi:10.1029/2006GL028525
Fritz SC (2008) Deciphering climatic history from lake sediments. J Paleolimnol 39:5–16
Gasse F (1986) East African diatoms—taxonomy, ecological distribution. Bibliotheca diatomologica 11. Cramer, Stuttgart, 202 pp
Gasse F, Juggins S, Ben Khelifa L (1995) Diatom-based transfer functions for inferring hydrochemical characteristics of African palaeolakes. Palaeogeogr Palaeoclimatol Palaeoecol 117:31–54
Gaudet JJ, Melack JM (1981) Major ion chemistry in a tropical African lake basin. Freshw Biol 11:309–333
Goerner A, Jolie E, Gloaguen R (2008) Non-climatic growth of the saline Lake Beseka, Main Ethiopian Rift. J Arid Environ 73(3):287–295
Golterman HL (1977) Sediments as a source of phosphate for algal growth. In: Golterman HL (ed) Interactions between sediments and fresh water. Proceedings of an international symposium held at Amsterdam, 6–10 September 1976. The Hague, Dr W Junk Publishers, Wageningen, PUDOC, pp 286–293
Harper DM, Adams C, Mavuti K (1995) The aquatic plant communities of the Lake Naivasha wetland, Kenya: pattern, dynamics, and conservation. Wetlands Ecol Manage 3(2):111–123
Hausmann S, Lotter AF, van Leeuven FN, Ohlendorf C, Lemcke G, Grönlund E, Sturm M (2002) Interactions of climate and land use documented in the varved sediments of Seebergsee in the Swiss Alps. Holocene 12:279–289
Hubble DS, Harper DM (2001) What defines a healthy lake? Evidence from Lake Naivasha, Kenya. Aquat Ecosyst Health 4:243–250
Hustedt F (1949) Süßwasserdiatomeen aus dem Albert-Nationalpark in Belgisch Kongo. In: Damas H (ed) Exploration du Parc National Albert (1935–1936). Hayez, Bruxelles
Karst TL, Smol JP (1998) Tracking the cultural eutrophication history of Collins Lake (Southeastern Ontario, Canada) using paleolimnological techniques. Lake Reservoir Manage 14:456–465
Kelly MG, Bennion H, Cox EJ, Goldsmith B, Jamieson J, Juggins S, Mann DG, Telford JR (2005) Common freshwater diatoms of Britain and Ireland: an interactive key. Environment Agency, Bristol
Kilham P, Kilham SS, Hecky RE (1986) Hypothesized resource relationships among African planktonic diatoms. Limnol Oceanogr 31:1169–1181
Krammer K, Lange-Bertalot H (1986–1991) Süβwasserflora von Mitteleuropa, vols 2/1–2/4. Gustav Fischer Verlag, Stuttgart
LNROA—Lake Naivasha Riparian Owners Association (1993) A three-phase environmental impact study of recent developments around Lake Naivasha. Phase I, an assessment of current information on the lake, relevant to a management plan, and recommendations for phase II of the study. LNROA, Naivasha, 109 pp
Lotter AF, Birks HJB (1997) The separation of the influence of nutrients and climate on the varve time-series of Baldeggersee, Switzerland. Aquat Sci 59:362–375
Mannion AM (1995) Agriculture and environmental change: temporal and spatial dimensions. Wiley, Chichester
Melack JM (1976) Limnology and dynamics of phytoplankton in equatorial African Lakes. PhD thesis, Duke University, USA
Meyers PA (2003) Applications of organic geochemistry to paleolimnological reconstructions: a summary of examples from the Laurentian Great Lakes. Org Geochem 34:261–289
Moy CM, Seltzer GO, Rodbell DT, Anderson DM (2002) Variability of El Niño/southern oscillation activity at millennial timescales during the Holocene epoch. Nature 420:162–165
Nicholson SE (1995) Environmental change within the historical period. In: Goudie AS, Adams WM, Orme A (eds) The physical geography of Africa. Oxford University Press, Oxford, pp 60–75
Nicholson SE (1996) A review of dynamics and climate variability in Eastern Africa. In: Johnson TC, Odada EO (eds) The limnology, climatology and paleoclimatology of the East African Lakes. Gordon and Breach, Amsterdam, pp 25–56, 63–75
Nicholson SE (2001) Climatic and environmental change in Africa during the last two centuries. Clim Res 17:123–144
Nicholson SE, Kim J, Hoopingarner J (1988) Atlas of African rainfall and its interannual variability. Florida State University, Florida
Ojiambo BS, Lyons WB (1996) Residence times and major ions in Lake Naivasha, Kenya, and their relationships to lake hydrology. In: Johnson TC, Odada EO (eds) The limnology, climatology and paleoclimatology of the East African Lakes. Gordon and Breach, Amsterdam, pp 267–278
Osborne PL (2000) Tropical ecosystems and ecological concepts. University Press, Cambridge, pp 177–182
Phillips J (2003) Alluvial storage and the long-term stability of sediment yields. Basin Res 15:153–163
Plater AJ, Boyle JF, Meyers C, Turner SD, Stroud RW (2006) Climate and human impact on lowland lake sedimentation in Central Coastal California: the record from c. 650 AD to the present. Reg Environ Change 6:71–85
Ramsar (2010) www.ramsar.org, 29 Nov 2010
Saji NH, Goswami BN, Vinayachandran PN, Yamagata T (1999) A dipole mode in the tropical Indian Ocean. Nature 401:360–363
Salas HJ, Martino P (1991) A simplified phosphorus trophic state model for warm-water tropical lakes. Water Res 25:341–350
Sikes HL (1935) Notes on the hydrology of Lake Naivasha. J East Afr Uganda Nat Hist Soc 13:74–89
Telford RJ, Lamb HF (1999) Groundwater-mediated response to Holocene climatic change recorded by the diatom

stratigraphy of an Ethiopian crater lake. Quat Res 52:63–75

ter Braak CJF, Šmilauer P (2002) CANOCO references manual and user's guide to Canoco for windows: software for canonical community ordination version 4.5. Microcomputer Power, Ithaca

Trauth MH, Deino AL, Bergner AGN, Strecker MR (2003) East African climate change and orbital forcing during the last 175 kyr BP. Earth Planet Sci Lett 206:297–313

Trauth MH, Maslin MA, Deino A, Strecker MR (2005) Late Cenozoic moisture history of East Africa. Science 309:2051–2053

Trauth MH, Maslin MA, Deino A, Junginger A, Lesoloyia M, Odada EO, Olago DO, Olaka LA, Strecker MR, Tiedemann R (2010) Human evolution in a variable environment: the amplifier lakes of Eastern Africa. Quat Sci Rev 29:2981–2988

Verschuren D (1996) recent and late Holocene paleolimnology of lakes Naivasha and Sonachi, Kenya. PhD thesis, University of Minnesota, USA

Verschuren D (1999) Influence of depth and mixing regime on sedimentation in a small, fluctuating tropical soda lake. Limnol Oceanogr 44:1103–1113

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

Verschuren D, Laird KR, Cumming BF (2000) Rainfall and drought in equatorial east Africa during the past 1, 100 years. Nature 403:410–414

Vincent CE, Davies TD, Beresford AKC (1979) Recent changes in the level of Lake Naivasha, Kenya, as an indicator of equatorial Westerlies over East Africa. Clim Change 2:175–189