Palaeoenvironmental Reconstruction of the Recent History of Lake Chiuta Wetland, South Malawi

Zuze Dulanya[1, 2] & Martin H. Trauth[2]

[1]Geography and Earth Science Department, P.O. Box 280, Zomba, Malawi
[2]Universität Potsdam, Karl-Liebknecht-Str. 24, D-14476 Potsdam, Germany

Abstract

Understanding the environmental trajectory over the recent (ca. 200 years) of shallow inland water bodies is key to sustainable management of the fisheries industry that is facing severe challenges. Paleolimnological techniques using multiple proxies provide valuable insights into the drivers and responses of these delicate systems currently threatened by environmental degradation and climatic extremes. Until the latter part of the 20th Century, Lake Chiuta used to be an important ground for fisheries. The cause of the collapse of the fisheries industry is mostly assumed to be overfishing although there are pointers of water quality change and environmental degradation within the riparian catchment of the lake. This study used a multiple proxies such as LOI, grain size analyses and diatoms for mapping recent environmental changes of Lake Chiuta. Results of the study indicate that the lake is periodically affected by near decadal variability of climate in the short term but is on a medium to long term trajectory of declination affected by a shrinking lake and rapid incursion of marshland onto the open water. These may pose serious challenges not only to the fishery, but long term survival of the water body for other uses. It is recommended that integrated watershed management programs be used as a medium to long term solution to the water quality problems that impact the lake at various scales.

Keywords: Diatoms, Lake Chiuta, Marshland, Palaeolimnology.

1.0 Introduction

Wetlands are unique ecosystems characterised by hydrology, soils, and vegetation seasonally or perennially wet and occupying some 7million km^2 of the world's landmass (Aselmann and Crutzen, 1989). They are important sources of water and economic activities such as agriculture, fisheries and conservation e.g. water fowls. They also play a significant role in biogeochemical cycles such as moderation and production of methane, greenhouse gases and water nutrients.

Wetlands offer the potential for the application of multi-proxy palaeolimnological analysis in order to reconstruct the timing, magnitude and drivers of environmental change (Battarbee, 2000; Smol, 2008). This is partly because of their geomorphometric and hydrological characteristics, which make wetlands good at sediment preservation and thus form important archives for past environmental changes. However, as with other forms of aquatic ecosystems, wetlands are faced with various threats such as eutrophication, clearing for agricultural activities and other forms of environmental degradation. Due to buffering effects, nutrients that go in wetland ecosystems can remain for hundreds or thousands of years thereby causing a lot of damage to the ecosystems. For example, it was demonstrated in the Netherlands that P remained in the water system for up to 150-1700 years (Schippers et al, 2006). Climate change poses an added dimension to these threats due to shrinkage and/ or inundation as a result of increasing or decreasing aridity respectively with consequences of diminished biodiversity or overall disappearance of the wetlands. Wetlands have often been regarded as marginal lands and clearly a sound knowledge about these ecosystems is lacking in most areas of the world. With concerns over widespread environmental impact in terrestrial and aquatic ecosystems, environmental monitoring and restoration have become a major focus for environmental research over the past few decades (Lotter et al, 1999; Barbour et al, 2000; European Community, 2000; Keller and Cavallaro, 2008).

Diatoms (Bacillariophyceae) are one of the most commonly used in palaeoenvironmental reconstruction owing to their rapid response to environmental change, their ease of identification and preservation in a wide range of lacustrine habitats (Stoermer and Smol, 1999; Bellinger et al, 2006). A sound knowledge of diatom ecology is necessary to disentangle diatom response to a variety of environmental forcing functions. On the one hand, diatoms are sufficiently diverse (species richness being estimated as ranging from 10^4 to 10^5 species; Stoermer and Smol, 1999) that their taxonomy is not yet fully understood, particularly for regions, which have not been the object of sustained research. On the other hand, the issue of equifinality may arise, and it may be difficult to interpret the ecological response in terms of a single environmental parameter (Digerfeldt, 1986). Development of organic sediment accretions from macro-vegetation and very productive sessile periphytic microflora can cause shift in lake response from the littoral zone to the open waters (Wetzel, 1990). Presence of macrophytes in the littoral zone tends to buffer nutrients from the catchment making the littoral zone very productive. This response may mask the overall lake response to nutrient loading and other environmental signals like climate and hydrology. A classic example is the ambiguity of a relative increase in planktonic diatoms, which may arise either from increased productivity, or from increased lake level (Wilson et al 2008). For reasons such as this, it is well recognised that the multi-proxy approach has greater potential to generate reliable palaeo-environmental reconstructions than undue reliance on a single proxy, however powerful it may be (Sayer et al., 1999; Annadotter et al., 1999; Ryves et al., 2011).

Despite the Lake Chiuta's importance to the riparian community, the lake is faced by the twin problem of environmental degradation and climate variability (Dulanya et al., 2013). The lake is surrounded by a marshy wetland and is a source of livelihood to the artisanal fishermen, bird hunters and rice farming communities. It is known to be responsive to decadal climate variability while its upper catchment basin is widely used for agriculture including tobacco, maize and rice cultivation. Different hypotheses are proposed for the collapse of the fisheries industry in Malawi including the Lake Chiuta region (GOM/FAO/UNDP, 1993; Msiska and Lwanda, 2008). One hypothesis is overfishing; others are eutrophication and climate change. The study tests the multi-proxy technique using diatoms, loss-on-ignition and sediment characteristics to disentangle the recent environmental history of Lake Chiuta. The lake occupies a very flat pan-shaped basin and located in a rain-shadow area. Therefore, understanding its overall response to various cultural and natural forcing factors is necessary for sustainable management and projection of future environmental trajectories (Dearing et al., 2007).

2.0 LOCATION

The study region covers Lake Chiuta in Malawi which is situated between latitudes 14°42'S and 14°53'S and longitudes 34°47'E and 34°55'E (Figure 1a).

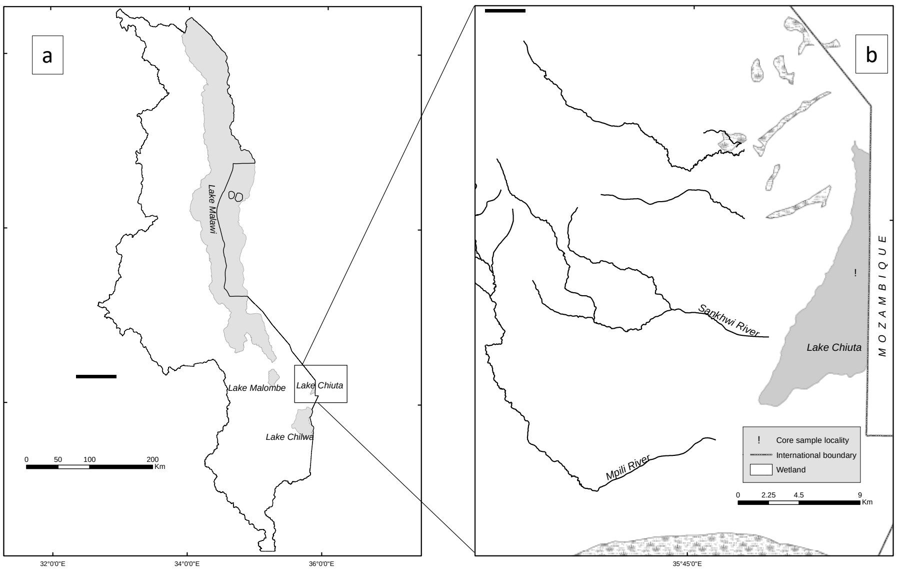

Figure 1: Location map of the study area (a), the hydrology around Lake Chiuta and core location (b)

2.1 Geology and geomorphology

The study area lies within the Mozambique mobile belt (~700-500 my BP) within the Malawi rift, which forms part of the western branch of East African Rift System (EARS). The geology is dominated by Precambrian to lower Palaeozoic metamorphic gneisses of (semi-)pelitic parentage with intercalations of calc-silicate rocks and marbles (Kroner et al, 2001; Carter and Bennett, 1973). A suite of intrusive alkaline rocks and granitoids of upper Jurassic to Cretaceous age ascribed to the Chilwa Alkaline Province are also found (Garson, 1960; Manyozo et al, 1984). The lake lies within the broad Phalombe-Chilwa plain of Miocene age covered by alluvium and residual soils of varying compositions (Pike and Rimmington, 1965; Dill et al, 2005).

2.2 Climate, hydrology and limnology

Malawi has two main seasons namely the cool dry season between May and October with mean temperatures of around 13°C in June and July and the hot wet season between November and April with temperatures between 30°-35 °C. The climate of the region is largely influenced by the seasonal migration and intensity of the Intertropical Convergence Zone (ITCZ), a low pressure belt within the Congo basin caused by tropical high pressure belts over both the Indian and Atlantic Oceans (Nicholson, 2001) and the Congo Air Boundary (CAB), that is controlled by sea-surface temperature (SST) anomalies such as the Indian Ocean Dipole (IOD) and El Niño/Southern Oscillation (ENSO) system (Abram et al, 2007; Saji et al, 1999). Local differences in rainfall are caused by complex topography causing deflections of moisture-bearing winds that are responsible for precipitation and rain-shadow effects in various areas. The study area lies near the southeastern end of the ITCZ belt and therefore sensitive to climate variability (Castañeda et al, 2007). The study area lies within one of Malawi's low rainfall belts with means between 600-800mm per annum making the lake sensitive to climate variability over both short (decadal) and long-time scales (Dulanya et al., 2013; Msiska, 2001; Thomas et al., 2009). The lake is also affected by similar climatic forcings that impact the nearby Lake Chilwa, which dries up despite the former being classified as a fresh water lake (Garson, 1960; Msiska, 2001).

Lake Chiuta is at an altitude of 620 m a.s.l., with a mean depth of 5m and a surface area of around 200 km^2, of which about 49 km^2 lie in Mozambique (Greboval et al, 1994). It is the northerly extent of the Lake Chilwa wetland with which it is separated by a sandbar since ca. 44 Ka BP Lake Chilwa ceased to have an outlet (Lancaster, 1981; Nicholson, 1998; Thomas et al, 2009). On the Malawian side, Lake Chiuta is fed by a number of seasonal streams that rise from its western highlands whose primary perennial source is Mpili River (Figure 1b). Most of these rivers disappear into a broad flat plain and marshes before getting into the lake. The lake formed due to crustal warping thus the lake may also be influenced by neotectonics (Pike and Rimmington, 1965). The lake basin is open, flowing northwards into Lake Amaramba in Mozambique and eventually into the Indian Ocean. Little is known about the hydrological balance of this lake related to groundwater flow.Similarly, very little work has been done in terms of fisheries and palaeolimnology compared to other lakes (Dobson and Lynch, 2003; Njaya et al, 1999; Greboval et al, 1994).

2.3 Vegetation

The open waters of Lake Chiuta are dominated by macrophytes such as *Nymphaea* spp. that float on the open water in this area. The lakebed is covered by a dense mat of *Utricularia* spp., which forms the substratum of the lake. A distinct lateral zonation of vegetation types is observed. *Typha domingensis* covers an area tens of metres wide on the western shore of Lake Chiuta followed by a zone of *Cyperus alopecuroides* and *Vossia cuspidata,* with the occasional occurrence of *Aeschynornene pfundii* and *Cyperus papyrus.* Other vegetation species include *Ceratophyllum demersum, Nymphaea* spp. and *Ottelia ulvifolia* and these are common in canoe channels (Njaya et al, 1999). The southern area of the lake supports a diverse community of emergent vegetation.

3.0 Methodology

3.1 Sediment Coring and water quality assessment

A sediment core was obtained during the calm, dry season, in August 2009 from Lake Chiuta. A plank boat hired from the artisanal fishermen at the lake's shores for navigation. Due to absence of lake bathymetry data, the core sample sites were identified with the help of a hand-held echo sounder used for measuring the water depth. Geographic coordinates were recorded using a Garmin Etrex GPS receiver and turbidity was estimated using a Secchi disk . After anchoring the boat, the soft sediment was retrieved from the lakebed by coring using an Uwitec gravity corer with 1m-tube attachment (http://www.uwitec.at/). Samples were extruded in the field into 1 cm thick subsamples except for the topmost 1cm, which was sampled at 0.5cm resolution for investigation of modern ecological changes. Samples were stored in sterile Whirlpak bags, and kept refrigerated during most of the field season prior to storage at 4^{o}C in the UK.

Various water quality parameters were also measured as to understand the modern limnological conditions of the lake (Table 1).

Table: Physico-chemical parameters and instrumentation used in water quality assessment

Parameter	Measuring Instrument	Unit	Purpose of measurement	Manufacturer
EC	conductivity meter model HI 98311	µS cm^{-1}	Conductivity	Hanna Instruments
pH	a pH meter DiST model HI98127		Acidity/ alkalinity	Hanna Instruments
Temperature	Thermometer	^{o}C	Water temperature	
Dissolved Oxygen	Hanna instruments test kit HI 3810	mg/L	Amount of Oxygen	Hanna Instruments

Images and optimum environmental conditions for Eastern Africa diatom samples (Gasse et al, 1995) obtained from the European Diatom Database (EDDI, http://craticula.ncl.ac.uk/Eddi/jsp/) were used for comparison and inferring environmental conditions that have prevailed in the study region.

3.2 Sediment stratigraphy and grain size analyses

Stratigraphy was described in terms of colour, grain size, mineralogy and structure which included layering (bedding), contacts, texture and inclusions within the sediment. These were useful in deciphering the form and nature of depositional regimes such as water energy, sediment provenance and the depositional environment in terms of sediment facies to reconstruct the geography and processes affecting the sediment and environment.

Dry sediment colour was described using Munsell colour charts. Sediments samples taken at an interval of every second centimetre were weighed in crucibles before and after oven drying overnight (approx. 12hours) and lightly crushed to loosen the crumbs. The loose sediments were sieved using sieves of 212 and 63-micron apertures. The hydrometer method was used for the residual fine particles that passed through both sieves. The grain sizes were converted to the phi-scale because grain-size hydraulics is a function of the diameter (*d*) squared (Krumbein, 1936) as follows:

$$phi\ (\varphi) = -\log_2 d \qquad (1)$$

where *d* is the diameter in mm.

The three main grain size classes (based on the sieves used in this work) in Wentworth scale are related to the phi-unit scale (Table 2). The results of the analysis were used for plotting grain size-depth profile for the core.

Table 2: Grain sizes description using two different classification schemes

Size range (µm)	Size Range (φ units)	Wentworth classification
31-63	4-5	Coarse silt
63-125	3-4	Very fine sand
125-250	2-3	Fine sand

3.3 Loss-on-ignition (LOI)

LOI analyses were carried out in the laboratory by weighing subsamples of ca 0.5 g wet weight. The subsamples were placed in weighed crucibles and re-weighed to three decimal places. Weight loss was measured after heating at 105ºC overnight to remove water. For carbon and carbonate estimation, the dried subsamples were oxidized at 500-550ºC and 900-1000ºC respectively (Dean, 1974; Heiri et al, 2001). Percent organic content was estimated by dividing the difference between the mass of dry sediment sample mass and the sediment heated sediment by the weight of the dry sediment (Dean, 1974; Heiri *et al*, 2001). Carbonate content was estimated by dividing percent LOI at 950ºC by 0.44 assuming a CO_2 molar weight of 44g mol^{-1} (Dean, 1974; Heiri et al, 2001).

3.4 Diatom preparation, identification and counting

Diatoms were prepared using standard techniques according to Battarbee (1986) from approximately 0.2g of wet sediments. Hot 30% hydrogen peroxide and 10% hydrochloric acid were added to the sample in order to remove organic matter and carbonates respectively. The remaining sample was neutralised and cleaned with de-ionised water and centrifuged 3-5 times at 1200rpm. Residues were dried on cover slides and microscope slides were prepared using Naphrax©. The diatom taxonomy used followed Krammer and Lange-Bertalot (1986-1991a, b) and Gasse (1986), with updated nomenclature. An Olympus BX45 light microscope was used with oil immersion and magnification at 1000x for counting diatom assemblages along a transect; 500 valves per slide were counted where preservation permitted. Diatom data were presented using Tilia and TgView (Grimm, 1991). Stratigraphic zone boundaries were defined using constrained incremental sum of squares (CONISS) software (Grimm, 1987).

3.4.1 Estimation of Diatom Dissolution Indices (DDI)

Poor diatom preservation can cause a bias in species assemblage composition towards more robust, heavily silicified valves, affecting the reliability of paleo-ecological reconstruction (Barker, 1992). The degree of dissolution can also be useful in deducing environmental conditions during sediment transportation and deposition.

In this work, diatoms valves were categorized into different groups depending on the state of dissolution using different criteria for centric and pennate diatoms. For the centric diatoms, valves with dissolved centres were counted as one valve while for the pennate diatoms, dissolved long ends with preserved centres were counted as half of a valve. DDI (F) was calculated from ratios between dissolved and pristine diatom frustules (Ryves et al, 2001*)* as follows:

$$F_i = \frac{\sum_j^m n_{ij}}{\sum_j^m N_{ij}} \qquad (2)$$

where F_i = F index of sample i, n = pristine valves of species j in sample i, N = sum of pristine and dissolved valves (girdle views are excluded)

Values range from 0 to 1 where a 0-value signifies complete dissolution and a value of 1 means that the values are pristine. Dissolution index values above 0.5 were interpreted as good preservation.

3.5 Dating

Due to the extensive marshes that cover the lake and the huge volumes of organic matter present, it was difficult to date the core and make estimates on the sediment accumulation rates and ages for the core. Therefore, the timing of the major events that have affected the lake can only be speculated based on some episodic events that have affected the region from time to time. Therefore the age on the core should be treated as tentative subject to further confirmation after reliable dates are obtained. The hard dry surface at the base of the core may be related to a major drought that affected the region. From historical droughts and lake level records, sediment accumulation rates, and the nature of the dessication in the sediment record, the 1920-30 drought may perhaps have been the closest (Nicholson, 1998; 2001; Owen et al, 1990). Although there have been other dessication events post-1930's, the part of the lake where the core was obtained still contained some water and so could not register this dessication event (Dulanya et al, 2013). Based on this assumption therefore, the base of the core is assumed to be in the 1920/30's.

4.0 Results

4.1 Stratigraphy and Grain Size

The stratigraphy of Lake Chiuta is dominated by brown and dark clay soil (Munsell colours Gley1, 2.5/N) at the bottom and partly-decomposed and decomposed organic matter at the upper sections. The depth to pure dark grey clays varies from one core to the other and the contacts between the two are not clearly defined. The following sequence is observed: dark plastic clay (Munsell colours Gley1, 2.5/N) from depths greater than 25cm (lithology d); a mixture of decomposed organic and minerogenic matter from 25–14cm depth (lithology e); and partly decomposed greenish yellow plant matter at the topmost parts of the core (lithology f).

Three main zones (I, II and III) have been demarcated based on the grain sizes analyses (Figure 2). Zone I lies at the bottom of the core from depths greater than 25cm. Zone III is shallower than 15cm with the major transition in grain sizes taking place around the 15-25cm depth interval and designated Zone II. Results of grain size analysis indicate a decreasing trend for the coarser ($<2.5\varphi$) and a corresponding increase for the finer ($>4\varphi$) sediment fractions from the bottom of the core. In Zone I fine sand is the most dominant compared to silty material accounting for 40-60% of the sediment. In Zone III silty sediment becomes the most dominant accounting for 60-80% of the sediment in the upper part of the sequence. The results from the intermediate sieve indicate rather stable values for the greater part of the lower core except for the top 10cm. Apart from these major changes in grain sizes, there are other notable changes in the core at about 32cm and 10 cm for all the curves.

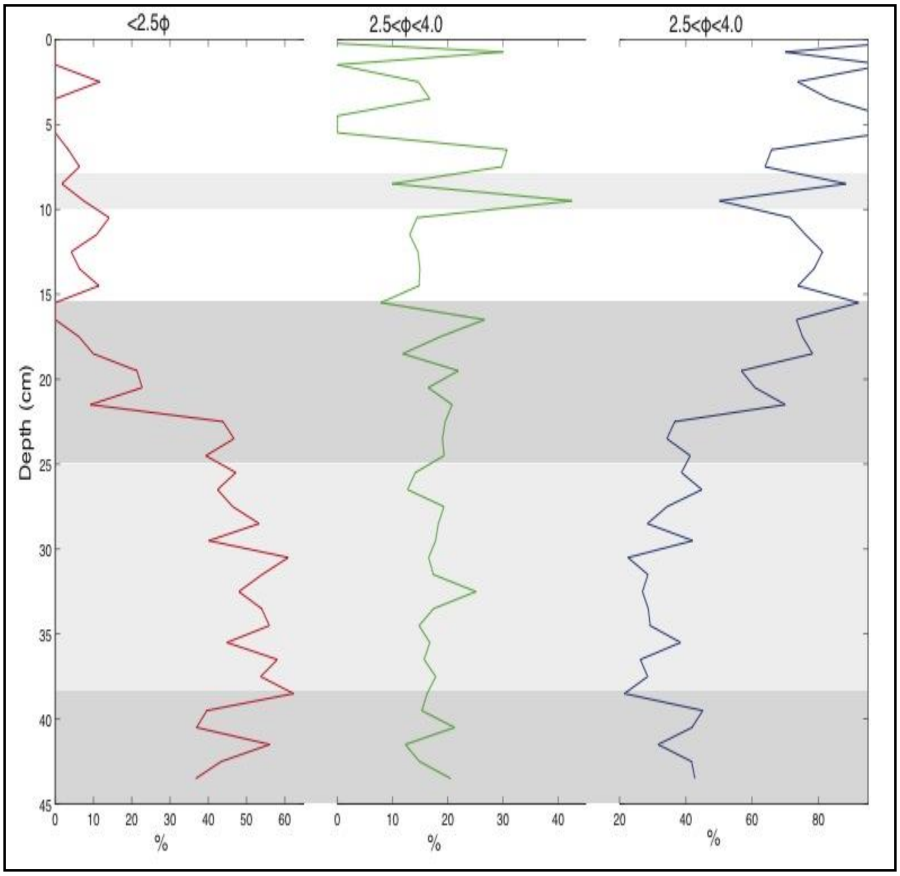

Figure 2: Downcore variations of sediment grain sizes (grey tones are used to highlight areas where major variations exist)

4.2 Loss on Ignition

Three main zones (I, II, and III) can be observed clearly based on the water, carbon and carbonate content in the sediment (Figure 3). The main changes are observed in the curves are consistent with the ones observed in the stratigraphy and grain size curves i.e. Zone I at > 25cm depth, Zone II between 14 and 25cm and Zone III below 15cm. Some minor fluctuations are observed at depths of about 33cm. In Zone I, water comprises about 65% of the core and about 30% carbon. In Zone II and III, water content increases to over 80% with carbon content of over 60%. Carbonate contents are generally stable throughout the core with values of less than 7% and small peaks at 41, 38, 34, 16, 8 and 2cm. These results indicate that the upper parts of the core are in general saturated with water and have higher carbon content than the lower parts.

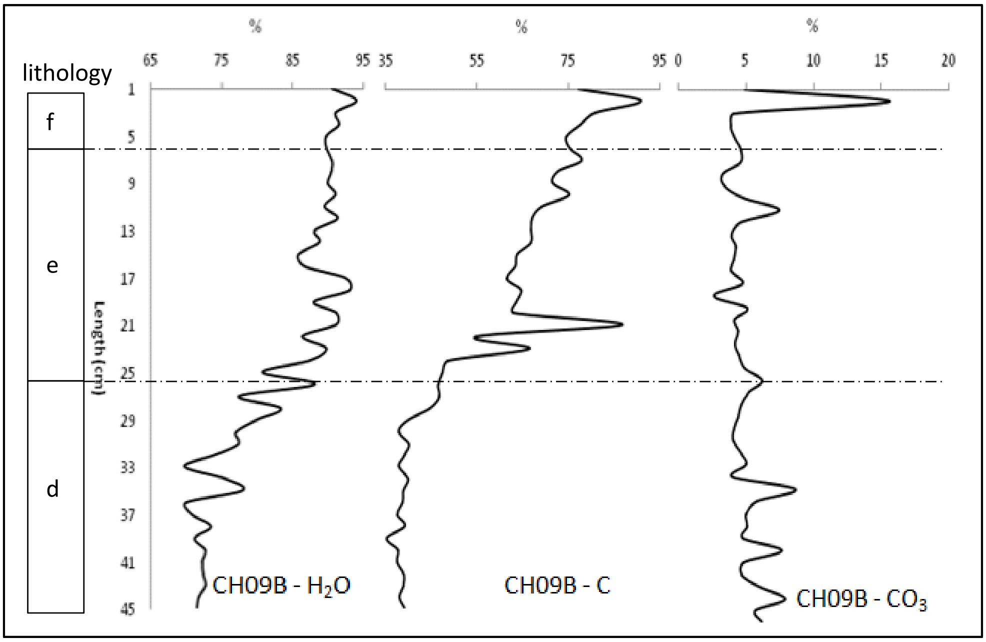

Figure 3: LOI results compared to the main lithological units

4.3 Modern limnology

Basic limnological data obtained from the study are presented in Table 3.

Table 3: Some physico-chemical characteristics of lake water

Core length (cm)	**Water Depth (m)**	**Secchi Depth (m)**	**Temp (ºC)**	**pH**	**Ec (µS cm^{-1})**	**Dissolved Oxygen (mg/L)**
44	2.7	2.4	30.2	8.9	334	9

These results indicate that the lake is shallow (ca. 3m deep) generally dipping in a northerly direction, very alkaline with mean pH of 8.9, fresh to mesotrophic (compare Dobson and Frid, 2009) based on EC and Secchi disk measurements respectively. The pH and water clarity is lowest near the littoral zone.

4.4 Diatom Stratigraphy

A total of 26 different diatom species were counted from Lake Chiuta (Figure 4). In general benthic diatom taxa are the most abundant compared to cosmopolitan and planktonic taxa. *Staurosirella pinnata* is the only cosmopolitan species that was observed in the lake. *Aulacoseira distans* O. Muller are by far the most abundant species in the lake comprising over 70% of all the diatom species counted in the core. Other *Aulacoseira* species observed in Lake Chiuta were *A. granulata* Ehr and *A. italica*. *Stephanodiscus hantzschii* and *Cyclotella meneghiniana* Kutz are the only other planktonic taxa observed apart from the *Aulacoseira* species. Zones I (with subzone d1 and d2) and II (subzones e1, e2i and e2ii) were defined using CONISS and are described as follows:

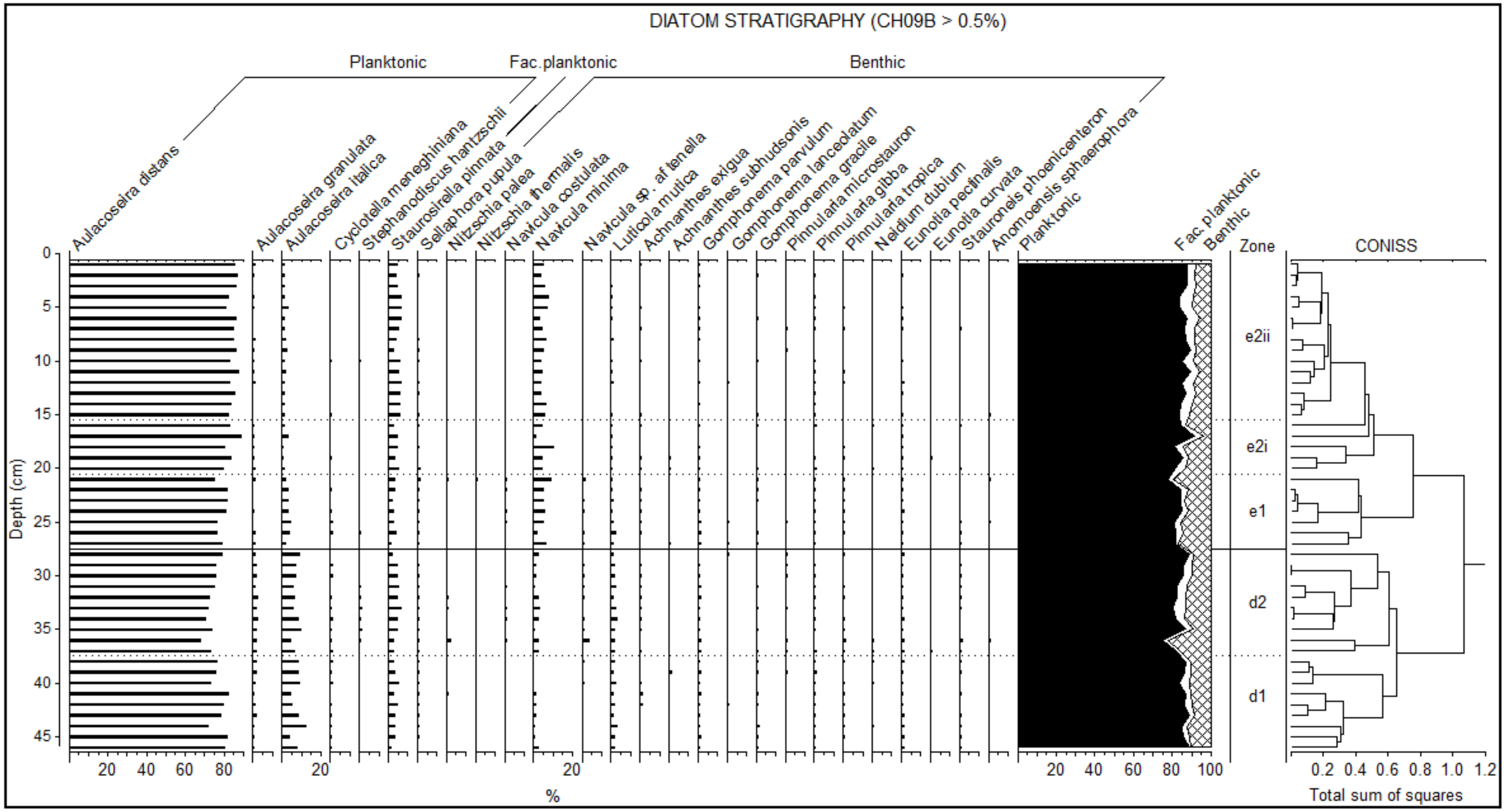

Figure 4: Zoned diatom stratigraphic diagram

Zone I

The zone is characterised by the presence of *Aulacoseira distans* (70-80%), *A. italica* (10%), *A. granulata, S. pinnata* (5%) *Luticola mutica* (<5%) and small *Navicula* species (identified as *Navicula minima* in this work < 5%). Also present in smaller amounts (0.5-2%) in this zone are *Stauroneiss phoenicenteron, Eunotia pectinalis, Cyclotella meneghiniana, Sellaphora pupula, Pinnularia gibba, P. maior, P. Microstauron, P. tropica, Gomphonema augur, G. gracile, G. parvulum, G. lanceolatum* and *Achnanthes* species which increase towards the upper part of the zone. *Hantzschia amphioxys* and *Nitzschia palea* are restricted to the bottom part of the zone. Other species present in the core include *Neidium* species *(N. iridis and N. dubium), E. curvata, E. tchirchiana, E. soleirolii, E. flexuosa* and *E. subarcuatoides*. Presence in the upper part of *Stephanodiscuss hantzschii* is also noted.

Zone II

Aulacoseira distans O. Muller is still the dominant species (~80%). There is a decrease in *A. italica* to about 5% with a corresponding increase in the small *Navicula* species to about 10% together with a persistent but gradual decrease in *E. pectinalis* and *Stauroneiss phoenicenteron* up the zone and sporadic presence of *Luticola mutica*. *S. pinnata* decreases to about 5% at the lower part gradually increasing to about 10% at the upper part of the zone. In general, variations in *Aulacoseira italica, Navicula minima* and *Luticola mutica* have been used as the main marker horizons for this core.

4.5 Diatom preservation and Diatom Dissolution Index (DDI)

The dissolution diagram for the same core shows good preservation of the valves (>0.9) and a repetitive cycle of high and low dissolution but with a generally decreasing dissolution trend (Figure 5). Due to their overall dominance in the core, the planktonic species make up the bulk of dissolved species. Considering the low dissolution indices obtained in this study, no attempts have been made to compare the dissolution of the planktonic from the benthic diatoms.

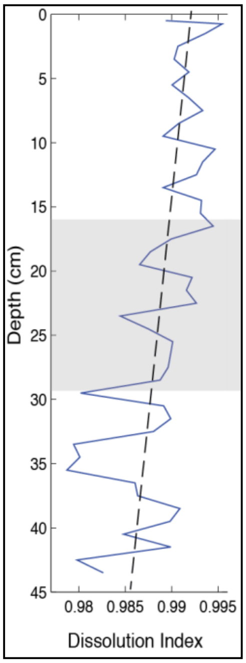

Figure 5: Diatom dissolution indices with trend line (dotted)

5.0 Discussion

Palaeolimnological reconstructions from Lake Chiuta have highlighted various processes and mechanisms responsible for environmental conditions prevalent nearly a decade ago. As stated earlier, lack of dates is a major flaw which fails to constrain the specific environmental changes observed to time periods. Among the notable changes observed are the expansion of the wetland (denoted by higher organic carbon content at the upper parts of the core), siltation and the roles and responses of the marsh in climatic, hydrological conditions of the lake and water quality in general. Comparison of some of the proxies used is shown in Figure 6.

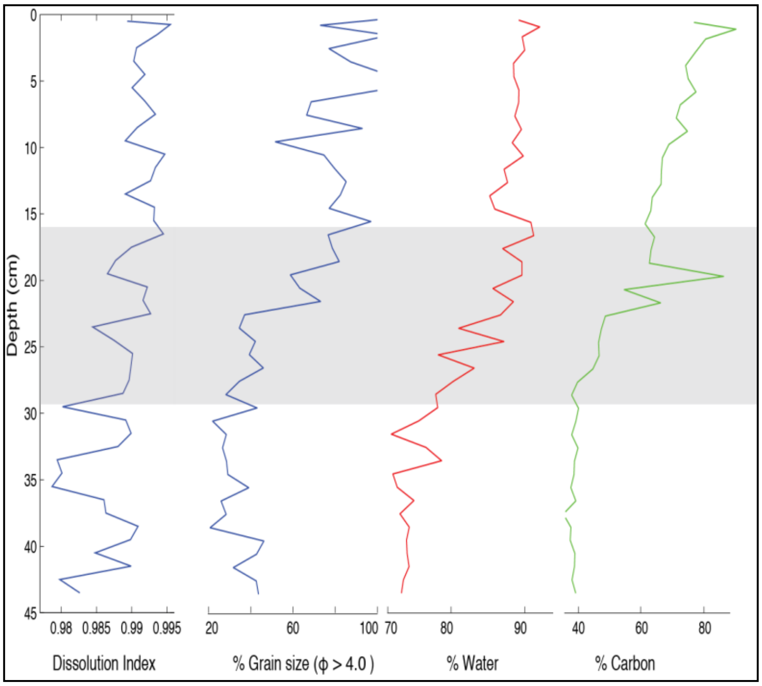

Figure 6: Comparison of diatom dissolution indices, grain sizes and LOI (grey tones are used to highlight areas where major variations exist)

5.1 Stratigraphy, Grain size analyses and LOI

The stratigraphy of the sediments indicates dark minerogenic clays at the bottom with less carbon content. These observations reflect anoxic conditions prevalent at the bottom part of the core. These conditions have persisted for a large part of the lake's recent (<100 years) environmental history.

Grain sizes from the lake indicate an increase of the coarse silt and clay (>4φ) with a corresponding decrease of the fine sand (<2.5φ) at the upper parts of the core and the vice versa for the lower parts. This is probably a reflection of a basin, which was deprived from sediment influx for some time as a result of the advancement of the marsh. Only the smaller grain sizes (very fine sand and silt fractions), which move as suspended solids probably, get deposited within the basin at the expense of the coarser material This observation is supported by increasing carbon content from LOI data, which seems to suggest that the lower parts of the core were relatively more stable having less carbon and water than the upper parts. These two pieces of evidence imply reduced levels of interaction between the catchment and the lake during the period represented by the upper part of the core (Zone III). Due to the stability of water and C values at the base of the core it is suggested that the incursion of and expansion of the marsh in the Lake Chiuta wetland had stalled earlier in the core sequence probably reflecting a major dry episode when most of the marsh dried up.

5.2 Diatom dissolution and stratigraphy

Diatom dissolution may be related to the physico-chemical conditions in the water body e.g. salinity, pH, conductivity, sediment texture and accumulation rate species related resistance to wear, water depth and permanence (Flower and Nicholson, 1987; Flower and Ryves, 2009). Considering that the water in Lake Chiuta is fresh to mesotrophic, the repetitive cycles seen on the diatom dissolution diagram probably indicate short-term high and low water stands. High stands were associated with a lot of wear of the diatom frustules thus higher dissolution indices compared to the low stands. In general, an increasing dissolution trend can be regressed through the dissolution curve. This is probably a reflection of the marsh progression in the long term in general which effectively is cutting off the diatom fossil interference from water currents and other possible agents which could destroy the frustules. This interpretation is supported by grain size and LOI data presented above.

Diatom assemblages have indicated presence of diatom flora that are acidophilous, epipelitic or epiphytic such as *Pinnularia* spp. *Eunotia pectinalis* (Krammer, 1991a). These floras are also common in swampy environments and rivers (Nguestsop et al, 2004). These assemblages probably reflect lateral habitat variations that occur across the wetland. For example, acidity tends to increase within the marshes, which are less oxygenated together with the release of humic acids from decaying plants. Acidity might also increase along the edges of the swamp due to lack of buffering due to the hard basement complex rocks that surround the Lake Chiuta catchment area as erosion takes place. Thus species within these habitats might be acidophilous. As a further adaptation to this, the diatom flora requires to have attachments to the macrophytes or slowly moving water. This is different to the open water area of the lake where water is oxygen-rich and lotic.

Associated with these lateral species composition, downcore variations are also apparent in the core. Apart from the dominance of *Aulacoseira distans*, the lower part of the core is dominated by *A. italica* and *Luticola mutica* an aerophilous and alkaliphilous species (Gasse, 1986). *A. italica* is littoral in the large African lakes, neutral to pH indifferent species (Nguetsop et al, 2004). The presence of *Stephanodiscuss hantzschii* towards the upper parts of Zone I, which is a phosphate-tolerant species, might signify a period when phosphate enrichment probably related to agriculture activities in the lake's catchment started to take place. This enrichment might also have been responsible for the expansion of the marshland which is evident though LOI in Zone II. In terms of downcore variability, there is a change from sediments with few *Navicula minima* at the bottom of the core (with occasional presence of brackish species such as *Anomoensis sphaerophora* and *Cyclotella meneghiniana* and dissolved fragments of *Achnanthes granulata*) to an increase in *Navicula minima* towards the upper part of the core. *Navicula minima* is an epipelitic and alkaliphilous species, gives the TP optimum and tolerant to organic pollution (Kelly and Wilson, 2004; http://craticula.ncl.ac.uk/EADiatomKey/html/taxon13521610.html). These observations may indicate that water became more polluted and silted up (presence of *C. meneghiniana*, *N. minima*, *etc*) probably due to an expanding population and water usage for both agricultural and sanitary use within the catchment. Taken together with other flora from the lower part of the core e.g. the presence of *A. italica* and *A. granulata* at the bottom, the sediment record suggests a lake, which has evolved from being a brackish to being organic-polluted (*N. minima and C. meneghiana*) before the encroachment of the marshes or indeed that the marsh growth around the lake might have been aggravated by pollution. These observations support the proposition of a lake once open to its catchment system but slowly being secluded due to an advancing marshland possibly as a result of human impacts of nutrient enrichment, which led to growth of macrophytes even at lakebed.

5.3 Lake limnology and turbidity

The sample site near the centre of the lake has less turbid water (secchi disk of 2.4) than the other two sites possibly due to throughflow which brings fresh, less turbid water from the input rivers during the dry season and might be more turbid during the rainy season. The modern conditions of the lake indicate that the lake could be classified as freshwater to mesotrophic based on EC and turbidity measurements. This classification is supported by botanical evidence such as the presence of *Nymphaea* spp. and *Ultricularia* spp., which have been described as are characteristic of mesotrophic conditions (Sayer et al, 1999). However, the marshes might also be playing the role of filters of the water system thus maintaining is status as fresh/ mesotrophic. Together with the contribution of marshes to water purification, the open waters probably tend to be more alkaline.

6.0 Conclusions

Apart from temporal variability associated with downcore changes of the proxies within the core, disentangling environmental changes in Lake Chiuta is challenging because of multiple habitats present within the wetland environment ranging from marshes to open water. This implies that both lateral and vertical variations of fossil diatom flora are to be expected. The lateral variations would reflect habitat variability and are difficult to disentangle as they are likely to exist together with temporal variations in a particular sample.

These deductions are supported by the sediment record (grain size analyses and LOI) as discussed in this study. Geological evidence from the Phalombe/ Lake Chilwa plain point towards a silted-up palaeo-Lake Chilwa which eventually split into two to have Lakes Chilwa and Chiuta (Thomas et al, 2009; Garson, 1960). The interpretation is consistent with the theory of lake ontogeny as discussed in various areas of the world where lakes are formed, mature and eventually die (Whiteside, 1983; Axford *et al*, 2009). The above therefore implies that Lake Chiuta might be in waning stages of its evolution.

Paleo-environmental reconstructions in Lake Chiuta area have highlighted a complex environmental history of the lake related to both temporal and spatial heterogeneities driven by both climate and ecological changes within the area and the necessity of using the multiple proxies in disentangling this variability. Short term cyclicity observed in the diatom dissolution indices is driven by climate fluctuations whereas long term ecological changes are largely influenced by anthropogenic disturbances which once led to organic pollution and later by the advancement of the marshes to cover a wide region of the lake's littoral habitats.

Acknowledgements

The study was supported by a Commonwealth split-site PhD scholarship award (Hull, UK) to the first author and by the Graduate School of the University of Potsdam (Germany). We also would like to extend our gratitude to Dr. Jane Reed for the guidance on diatom taxonomy and to Mark Anderson both from the University of Hull for laboratory technical support.

References

Abram, N., Gagan, M., Hantoro, W., McCulloch, M., Chappell, J. & Suwargadi, B. (2007). Seasonal characteristics of the Indian Ocean Dipole during the Holocene epoch. Nature, **445**: 299–302.

Annadotter, H., Cronberg, G., Aagren, R., Lundstedt, B., Nilsson, P. & Strobeck, S. (1999). Multiple techniques for lake restoration. Hydrobiologia **395/396:**77–85.

Aselmann, I. & Crutzen, P.J. (1989). Global distribution of natural freshwater wetlands and rice paddies, their net primary productivity, seasonality and possible methane emissions. Journal of Atmospheric Chemistry **8**: 307–358.

ASTM (1987). Annual Book of ASTM Standard, **11.01** Water **1**:29-638.

Axford, Y., Briner, J.P., Miller, G.H. & Francis, D.R. (2009). Paleoecological evidence for abrupt cold reversals during peak Holocene warmth in Arctic Canada. Quaternary Research **71**:142–149.

Barbour, M.T., Swietlik, W.F., Jackson, S.K,, Courtemanch, D.L., Davies, S.P. &Yoder, C.O. (2000). Measuring attainment of biological integrity in the USA: a critical element of ecological integrity. Hydrobiologia **422/423:** 453–464.

Barker, P. (1992). Differential diatom dissolution in Late Quaternary sediments from Lake Manyara, Tanzania: an experimental approach. Paleolimnology **7**:235–251.

Barttarbee ,R.W. (1986) Diatom analysis. In: Handbook of Palaeoecology and Palaeohydrology. John Wiley and Sons, Chichester.

Barttarbee, R.W. (2000) Palaeolimnological approaches to climate change, with special regard to the biological record. Quaternary Science Reviews **19**:107–124.

Bellinger, B.J., Cocquyt, C. & O'Reilly, C.M.(2006). Benthic diatoms as indicators of eutrophication in tropical streams. Hydrobiologia 573:75–87.

Carter, G.S. & Bennett, J.D. (1973).The geology and mineral resources of Malawi. Bulletin of the Geological survey of Malawi, Bulletin **6**.

Castaneda, I.S., Werne, J.P. & Johnson, T.C .(2007). Wet and arid phases in the southeast African tropics since the Last Glacial Maximum. Geology **35** (9): 823. DOI:10.1130/G23916A.1.

Dean, W.E. (1974). Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods. J. Sedim. Petrol. **44**:242–248.

Dearing, J.A., Jones, R.T., Shen, J., Yang, X., Boyle, J.F., Foster, G.C., Crook, D.S.& Elvin M.J.D. (2007). Using multiple archives to understand past and present climate–human–environment interactions: the lake Erhai catchment, Yunan Province, China. Journal of Palaeolimnology. doi:10.1007/s109033-007-9182-2.

Digerfeldt, G. (1986). Studies on past lake-level fluctuations. In Berglund BE (ed). Handbook of Holocene Palaeoecology and Palaeohydrology 127–143.

Dill, H.G, Ludwig, R.R., Kathewera, A.& Mwenelupembe, J. (2005). A lithofacies terrain model for the Blantyre Region: Implications for the interpretation of palaeo-savanna depositional systems and for environmental geology and economic geology in southern Malawi. Journal of African Earth Sciences **41:**341-393.

Dobson, M.& Frid, C. (2009). Ecology of Aquatic Ecosystems. Oxford, London.

Dobson, T.A. & Lynch, K.D. (2003). As nearshore stocks drop, Malawi begins to return to local fisheries management. Journal of Great Lakes Research **29(** 2): 232-242.

Dulanya, Z., Reed, J.M. & Trauth MH (2013) Mapping changing shorelines in the Malombe and Chiuta lakes of Malawi - environmental effects of recent climatic variations. Catena **104**, 111-119.

EDDI (EUROPEAN DIATOM DATABASE) (2012). European Diatom Database. URL: http://craticula.ncl.ac.uk/Eddi/jsp/ (Accessed 15 April 2012).

European Community Directive 2000/60/EC of October 23, 2000 of the European Parliament and of the Council establishing a framework for community action in the field of water policy. Official Journal of European Commission L327: 1-72.

Flower, R.J. & Nicholson, A.J (1987). Relationships between bathymetry, water quality and diatoms in some Hebridean lochs. Freshwater Biology **18(1)**: 71 – 85.

Flower, R.J. & Ryves, D.B. (2009). Diatom preservation: differential preservation of sedimentary diatoms in two saline lakes. Acta Botanica Croatica 68:381-399, ISSN: 0365-0588.

Garson, M.S. (1960). The geology of the Lake Chilwa Area. Bulletin of the Geological survey of Malawi, Bulletin 12.

Gasse, F. (1986). East African diatoms: Taxonomy, ecological distribution. Bibliotheca Diatomologica, Band 11. ISBN: 978-3-443-57003-3.

Gasse, F., Juggins, S. & Ben Khelifa, L. (1995). Diatom-based transfer functions for inferring past hydrochemical characteristics of African Lakes. Palaeogeography, Palaeoclimatology, Palaeoecoogy **117:** 31–54.

GOM/FAO/UNDP (1993). Fisheries management in south-east Lake Malawi, the Upper Shire River and Lake Malombe. CIFA Technical Paper 21. FAO, Rome.

Greboval, D., Bellemans, M. & Fryd, M. (1994). Fisheries characteristics of the shared lakes of the East African Rift. CIFA technical paper 24, FAO, Rome.

Grimm, E.C. (1991). TILIA and TILIA GRAPH. Illinois State Museum, Springfield, IL. 90.

Grimm, E.C. (1987). CONISS: A fortran 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Computers and Geosciences **13(1):**13–35.

Heiri, O., Andre, F.L. & Lemcke, G. (2001). Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. Journal of Paleolimnology **25:**101–110.

Keller, A.A. & Cavallaro, L. (2008). Assessing the US Clean Water Act 303(d) listing process for determining impairment of a waterbody. Journal of Environmental Management **86:** 699–71.

Kelly, M. & Wilson, S. (2004). Effects of phosphorus stripping on water chemistry and diatom ecology in an eastern lowland river. Water Research **38:**1559-1567.

Krammer, K., Lange-Bertalot, H. (1986). Bacillariophyceae. 1 Teil: Naviculaceae. In: Ettl. H., Gerloff, J., Heynig, H., Mollenhauer, D. (eds) Susswasserflora von Mitteleuropa. Gustav Fischer Verlag, Stuttgart. 886 pp.

Krammer, K. & Lange-Bertalot, H. (1988). Bacillariophyceae. 2 Teil: Bacillariaceae, Epithermiaceae, Surirellaceae. In: Ettl. H., Gerloff, J., Heynig, H. & Mollenhauer, D.(eds) Susswasserflora von Mitteleuropa. Gustav Fischer Verlag, Stuttgart. 596 pp.

Krammer K. & Lange-Bertalot, H. (1991a). Bacillariophyceae. 3 Teil: Centrales, Fragilariaceae, Eunotiaceae. In: Ettl. H., Gerloff, J., Heynig, H. & Mollenhauer, D. (eds) Susswasserflora von Mitteleuropa. Gustav Fischer Verlag, Stuttgart. 576 pp.

Krammer, K. & Lange-Bertalot, H.(1991b). Bacillariophyceae. 4 Teil: Achnanthaceae Kritische Erganzungenzu Navicula (Lineolatae) und Gomphonema. In: Ettl. H., Gerloff, J., Heynig, H. & Mollenhauer, D. (eds) Susswasserflora von Mitteleuropa. Gustav Fischer Verlag, Stuttgart. 437 pp.

Kroner, A., Willner, A.P., Hegner, E., Jaeckel, P. & Nemchin. A. (2001). Single zircon ages, PT evolution and Nd isotopic systematics of high grade gneisses in southern Malawi and their bearing on the evolution of the Mozambique belt in southeastern Africa. Precambrian Research **109:** 257-291.

Krumbein, W.C. (1936). Application of logarithmic moments to size frequency distribution of sediments. Journal of Sedimentary Petrology **6(1):**35–47.

Lancaster, N. (1981). Formation of the Holocene Lake Chilwa sandbar – Southern Malawi. Catena **8**(3/4):369–382.

Lotter, A.F., Pietnitz, R. & Schmidt, R. (1999). Diatoms as indicators of environmental change near artic and alpine treeline. In Stoermer, E.F. , Smol, J. (eds). The Diatoms: Applications for Environmental and Earth Sciences. Cambridge University Press, London.

Manyozo, D.M., M'ndala, A.T. & Phiri, F.R. (1984). The Geology of Lake Malombe Area. Bulletin of the Geological survey of Malawi **33**.

Msiska, O. (2001). A Review of limnology of Malawi. In R.G. Wetzel and B. Gopal (Eds.), Limnology in Developing Countries **3:**121-189.

Msiska, O.V. & Lwanda, A.G. (2008) .Trophic fluctuations in Lakes Malawi and Malombe. In: Proceedings of the 2008 Annual Research Conference. National Research Council of Malawi. Lilongwe, Malawi.

Njaya, F.J., Donda, S.J. & Hara, M.M. (1999). Fisheries co-management in Malawi: Lake Chiuta re-visit case study. Presented at the International Workshop on Fisheries Co-Management, Berjaya Georgetwon, Hotel Penang, Malaysia 23-28 August 1999. URL: http://www.co-management.org/download/chiuta.pdf

Nguetsop, V.F., Servant-Vildary, S. & Servant, M. (2004). Late Holocene climatic changes in West Africa, a high resolution diatom record from equatorial Cameroon. Quaternary Science Reviews **23:**591–609.

Nicholson, S.E. (1998). Fluctuations of rift lakes Malawi and Chilwa during historical times: a synthesis of geological, archaeological and historical information. In: Lehman, J.T. (Ed.), Environmental Change and Response in East Africa. Kluwer Academic Publishers, The Netherlands.

Nicholson, S.E. (2001) Climatic and environmental change in Africa during the last two centuries. Climate Research **1:**123–144.

Olaka, L.A., Odada, E.O., Trauth, M.H. & Olago, D.O. (2010). The sensitivity of East African lakes to climate variations. Journal of Paleolimnology **44**:629–644.

Owen, R.B., Crossley, R., Johnson, T.C., Tweddle, D., Kornfield, I., Davison, S., Eccles, D.H. & Engstrom, D.E. (1990). Major low levels of Lake Malawi and their implications for speciation rates in cichlid fishes. Proceedings of the Royal Society of London **B240:**519-553.

Pike, J.G., Rimmington, G.T. (1965).Malawi: A Geographical Study. Oxford Univ. Press, London.

Reed, J.M. (1998). Diatom preservation in the recent sediment record of Spanish saline lakes: Implications for palaeoclimate study. Journal of Paleolimnology **19:** 129–137.

Ryves, D.B., Battarbee, R.W., Juggins, S., Fritz, S.C.& Anderson, N.J. (2006). Physical and chemical predictors of diatom dissolution in freshwater and saline lake sediments in North America and West Greenland. Limnology & Oceanography **51: 1**355-1368, ISSN: 0024-3590.

Ryves, D.B, Juggins, S., Fritz, S.C. & Battarbee, R.W. (2001). Experimental diatom dissolution and the quantification of microfossil preservation in sediments.

Palaeogeography, Palaeoclimatology, Palaeoecology **172(1-2):** 99-113, ISSN: 0031-0182. DOI: 10.1016/S0031-0182(01)00273-5.

Ryves, D.B., Mills, K., Bennike, O., Brodersen, K.P., Lamb, A.L., Leng, M.J., Russell, J.M.& Ssemmanda, I. (2011). Environmental change over the last millennium recorded in two contrasting crater lakes in western Uganda, eastern Africa (Lakes Kasenda and Wandakara). Quaternary Science Reviews **30**(5–6):555–569.

Saji, N.H., Goswami, B.N., Vinayachandran, P.N. & Yamagata, T. (1999). A dipole mode in the tropical Indian Ocean. Nature **401:**360–363.

Sayer, C.D. & Roberts, N. (2001). Establishing realistic restoration targets for nutrient-enriched shallow lakes: linking diatom ecology and palaeoecology at the Attenborough Ponds, UK. Hydrobiologia **448:** 117–142.

Sayer, C.D., Roberts, N., Sadler, J., David, C. & Wade, P.M. (1999). Biodiversity changes in a shallow lake ecosystem: a multi-proxy palaeolimnological analysis. J. Biogeogr. **26:** 97–114.

Schippers, P., van de Weerd, H., de Klein, J., de Jong, B. & Scheffer, M. (2006). Impacts of agricultural phosphorous use in catchments on shallow water quality: About buffers, time delays and equilibria. Science of the Total Environment **369:** 280-294.

Smol, J.P. (2008). Pollution of Lakes and Rivers: A Palaeoenvironmental Perspective. Blackwell Publishing, U.S.A.

Stoermer, E.F. & Smol, J.P.(ed.) (1999). The Diatoms: Applications for the Environmental and Earth Sciences. Cambridge University Press, Cambridge.

Talling, J. (1992). Environmental regulation in African shallow lakes and wetlands. Rev. hydrobiol. Trop. **25:**87–144.

Thomas, D.S.G., Bailey, R., Shaw, P.A., Durcan, J.A., Singarayer, J.S. (2009). Late Quaternary high stands at Lake Chilwa, Malawi: Frequency, timing and possible forcing mechanisms in the last 44 ka. Quaternary Science Reviews **28:**526–539.

Trewin, N.H., Davidson, R.G. (1999). Lake-level changes, sedimentation and faunas in a Middle Devonian basin-margin fish bed. Journal of the Geological Society **156(3):**535 DOI: 10.1144/gsjgs.156.3.0535

Tweddle, D. (1983). The fish and fisheries of Lake Chiuta. Luso: Malawi J.Sci. Technol. Malawi **4(2):**55-83.

Wetzel, R.G. (1990). Land-water interfaces: Metabolic and Limnological Regulators. Internat. Ver. Limnol. **24:**6–24

Whiteside, W.C. (1983). The mythical concept of eutrophication. Hydrobiologia **103***:* 107–111.

Wilson, G.P., Reed, J.M., Lawson, I.T., Frogley, M.R., Preece, R.C., Tzedakis, P.C. (2008). Diatom response to the last glacial-interglacial transition in the Ioannina basin, northwest Greece: Implications for Mediterranean palaeoclimate reconstruction. Quaternary Science Reviews **27:**428–440.