PALEOLIMNOLOGICAL RECORDS OF ENVIRONMENTAL CHANGE IN LAKE BARINGO: CHANGES IN LAKE LEVEL AND TROPHIC STATE DURING THE 19TH AND 21ST CENTURIES

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A Thesis Submitted to the Graduate School in Partial Fulfilment for the Requirements of Master of Science Degree in Limnology of Egerton University

EGERTON UNIVERSITY

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DECLARATION AND RECOMMENDATION

Declaration

This thesis is my original work and has not, wholly or in part, been submitted for any award in any other University.

Signature _____ Date _____

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SM18/3702/13

Recommendation

This thesis is the candidate's original work and has been prepared with our guidance and submitted with our approval as supervisors for examination according to the Egerton University regulations.

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DEDICATION

This work is dedicated to all students who fight against financial odds to satisfy their academic ambitions. Keep pressing on, your efforts shall never go unrewarded.

ACKNOWLEDGEMENT

First I thank God for the gift of life. Secondly, am heartily thankful to my supervisors whose encouragement, guidance and support from the initial to the final level enabled me to develop an understanding of the subject. This research was conducted under Kenya government research permit MOES/001/11C to D.V. and sponsored by the Fund for Scientific Research -Flanders (Belgium) through LWM office Egerton University. We thank the county government of Baringo for allowing access to Lake Baringo. We also thank the department of Biological science, Limnology and Wetland Management programme (LWM) (Egerton University) for providing laboratory space and equipment. Special appreciation goes to Professor Sharon E Nicholson of Florida State University for providing us with rainfall data as well as East African Time Series for stations near Lake Baringo covering the period from AD 1874 to AD 2012. Lastly, I offer my regards and appreciations to all who supported me in during the completion of the project.

ABSTRACT

Paleolimnology is the reconstruction of historical conditions of lakes using information contained in the sediment proxies. Previous studies have provided evidence for climate variability in the East African region over the last 200 years. However, the response of Lake Baringo to shifts in climate over the years remains unknown. As a consequence this thesis presents a sediment based semi-quantitative reconstruction of water level fluctuations and trophic state variations for Lake Baringo for the period between 19th century and the first decade of the 21st century (214 years). Core samples were collected in June 2014 using a Hand-Driven Fixed-Piston corer and analysed for Fossil diatoms, Biogenic silica (BSi) and Magnetic susceptibility (MS). Inference for the historic trophic state was based partly on the abundance of different trophic level indicator diatom taxa and indices based on the ratio of Centric to Pennate diatoms (C/P ratio). Lake level was inferred using indices based on the proportion of planktonic to benthic taxa (P/B ratio) at respective depths. Current limnological characteristic of the lake including physical, chemical and trophic state were studied using water sample. The number of frustules did not show significant difference along length of the core (*One Way ANOVA, $F_{(46, 625)} = 0.76$, $p = 0.873$*). There was also no significant difference in the level of biogenic silica (*One Way ANOVA, $F_{(5, 41)} = 1.81$, $p = 0.133$*). However, significant difference was observed in the number of frustules counted for the individual genera (*One Way ANOVA, $F_{(18, 682)}$, $p = 0.000$*). The sediment archive presented distinct zones dominated by planktonic and benthic diatom flora. An initial transgression phase in the early 19th century was characterized as a shallow water environment dominated by planktonic *Aulacoseira* spp. This was a response to extreme drought during the late 18th to early 19th century. Mid-19th century was defined by a high lake stand. Late 19th to early 20th century experienced low water level following the widely documented aridity at the time. Mid-20th century was marked by a spectacular rise in water level which coincided with remarkably wet years during the early 1960s and late 1970s. The first decade of the 21st century witnessed widespread changes in water level. Further, the records show alternating patterns in the trophic state of the lake since AD 1800. The early 19th century was characterized as a eutrophic lake environment. The highest lake productivity occurred between AD 2001 and AD 2006. It is worth noting that drawdowns are accompanied by high nutrient concentrations while high lake levels coincide with low nutrient conditions. Carlson TSI show that today the lake is eutrophic and phosphorus limited regardless of the season with light limitation occurring during the wet season.

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LIST OF ACRONYMS AND ABBREVIATIONS

AD	Anno Dominni
APHA	American Public Health Association
BSi	Biogenic Silica
C/N	Carbon/Nitrogen ratio
CPOM	Coarse Particulate Organic Matter
CTSI	Carlson Trophic State Index
DIN	Dissolved Inorganic Nitrogen
DO	Dissolved Oxygen
DQ	Diatom Quotient
EARS	East African Rift System
GS	Grain Size
IAS	Inorganic Ash Spheres
ITCZ	Inter Tropical Convergence Zone
LMM	Light Microscope Micrograph
MS	Magnetic Susceptibility
OM	Organic Matter
P:B	Planktonic: Benthic ratio
SCP	Spheroidal Carbonaceous Particles
SD	Secchi Disk
TLI	Trophic level Index
TN	Total Nitrogen
TP	Total Phosphorus
TSI	Trophic State Index
WLF	Water Level Fluctuations

CHAPTER ONE

INTRODUCTION

1.1 Background information

Lakes are water filled basins surrounded by land on the earth's surface. They show remarkable time-based variations in their physical, chemical, biological and morphometric characteristics usually as a response to catchment management strategies such as land use pattern and natural vagaries such as climate change. One sign of anthropogenic influence to lakes is eutrophication which according to Art (1993) refers to a natural aging process by which water bodies accumulate nutrients mainly phosphates and nitrates. Usually, this process is exacerbated by human activities which cause faster and heavier in-wash of nutrients into these systems from the catchment areas. On the other hand, effect of climate change in lakes is often reflected in water level fluctuations (Nicholson and Yin, 2001; Magny *et al.* 2007) particularly in endorheic lakes. Recently, Cohen *et al* (2006) investigated the link between climate variability and lake productivity. Their results show that high productivity during the wet season was correlated with precipitation driven nutrient increase while productivity during drought conditions was associated with wind driven nutrient release from the sediments.

Paleolimnological studies occur worldwide. While some studies point out a daunting task in the delineation between anthropogic and climatic influences in lake systems (Mills *et al*. 2014), more recent work shows that these two drivers of change in lake systems are indeed distinct. For example, Makri *et al* (2019) used phytoplankton pigments to reconstruct the trophic status of Lake Morat in Switzerland. Their results show a consistent increase in lake phosphorus levels, hence trophic state in the face of accelerated campaigns to reduce phosphorus input into the lake. They explained this to be a consequence of nutrient recycling from the lake bottom. While this study attributes changes in lake trophic state to anthropogenic influence, more research have identified climate change as the major driver of eutrophication of lake systems. A glaring example is the work of Liao *et al* (2017) who established that hydrology (which is a climatic variable) played a significant role in controlling nutrient fluxes in Lake Poyang. With regard to lake level, several studies have been conducted. Some of these include, Baioumy *et al* (2010) in Lake Quran in Egypt, Quinn and Sellinger (2006) in Lake Michigan, and Laird and Cumming (2008) in Ontario.

Interest in paleolimnology is based on the idea that these water-filled basins accumulate sediments from the catchment in a chronological order. The study of such sediments is key in understanding the past condition of a lake (Smol, 2010). This information is critical in policy making and freshwater system management as it is of immense use in setting goals in restoration efforts.

Previous studies have already described a largely dry environment in the East African region that led to complete drying of Lake Baringo about 200 years ago (Bessems *et al.* 2008; Kiage and Liu, 2009a). This, according to Ashley *et al* (2004) was also the time when, Loboi Swamp that is located immediately south of Lake Baringo stood dry and Lake Naivasha further south in the Central Rift Valley experienced its most severe low-stand since the Medieval Warm Period (about AD 650 to AD 1250) (Verschuren *et al.* 2000).

It is widely documented that over the years, climate of East Africa has been highly variable with alternating wet and dry episodes (Nicholson, 1999; Verschuren *et al.* 2000; Anderson, 2002; Kiage and Liu, 2009b; Cort *et al.* 2013). The response of some East African lakes to these changes in climate has been investigated (Nicholson and Yin, 2001; Verschuren, 2001). However, there is still a paucity of such information for Lake Baringo basin.

1.2 Statement of the problem

The impacts of the widely documented climate variability on the ecology of Lake Baringo are not well understood. To understand the effects of these changes on the ecology of the lake over the past 200 years, an investigation on the paleolimnological characteristics of the lake is crucial. Furthermore, most previous studies of this nature in equatorial East Africa focused mainly on reconstruction of lake levels while the link between climate change and lake productivity remains neglected. As a consequence, this study investigated how the widely documented climate variability in East Africa might have affected Lake Baringo in terms of fluctuations in its water level and changes in trophic state. Reconstructions made in this research are semi-quantitative partly because currently there are no diatom training data sets for quantitative reconstructions for Lake Baringo. Nevertheless, interpretations of the diatom records are compared with published climate records (rainfall and drought patterns), other reconstructions made in the region as well as instrumental lake level recordings in Lake Baringo where such data are available.

1.3 Objectives

1.3.1 General Objective

To investigate water level fluctuations and changes in trophic state of Lake Baringo since AD 1800 using multi-proxy sediment records.

1.3.2 Specific objectives

i. To determine the differences in abundance and species composition of fossil diatoms in Lake Baringo since AD 1800.
ii. To determine the variations in Biogenic Silica concentrations in lake Baringo since AD 1800.
iii. To determine the current spatial and temporal variations in nutrient and Chlorophyll *a* levels in the lake.

1.4 Hypotheses

i. There are no significant differences in abundance and species composition of fossil diatoms in Lake Baringo since AD 1800.
ii. There are no significant variations in Biogenic Silica concentrations in Lake Baringo since AD 1800.
iii. The levels of nutrient and Chlorophyll-*a* in the lake show no significant spatial and temporal variations.

1.5 Justification

This research contributes towards understanding of how water level and trophic state have changed over the past 200 years in Lake Baringo as driven by climate change, hence fills the gaps of lake level and trophic state records which have remained fragmented over the years. A clearer understanding of the response of the lake to climate related processes will promote our understanding of the potential effects that climate exerts on lake level and productivity. This information is crucial for our understanding of its ecology and management. Further, understanding the link between climate and lake productivity have immediate implications in Kenya since inland fisheries provide a very large proportion of animal protein throughout the country. The ability to determine past water-level changes in freshwater is particularly important for reconstructing past climate variation and developing predictive models for future climate as well as lake level fluctuations.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Paleolimnology according to Whitmore and Riedinger (2013) is the science concerned with the reconstruction of past historical conditions of lakes based on information contained in sediment proxies. For this, it relies on interdisciplinary approaches to compensate for information loss (Koff *et al.* 2012). The interdisciplinary nature of paleolimnological studies is reflected in the frequent use of the term *multi-proxy*. The term *proxy* refers to an indirect measure of a variable that pertains to an applied question (Whitmore and Riedinger, 2013). Some of these variables (proxies) include Biogenic silica, fossil diatoms, grain size, Carbon/ Nitrogen (C/N) ratios, stable carbon isotopes, pollen grains, Zoobethos such as chironomids, fungal spores, macroscopic and microscopic charcoal.

2.2 Steps in paleolimnology

A paleolimnological study involves eight key steps which are followed with considerable care for the success of any research work. These steps are summarized in this thesis as described by Smol, (2002).

The first step involves choosing the study site. This is the choice of the lake to be studied. It depends on the question to be answered by the research. For example, contamination of a particular reservoir or a case in which one is interested in reconstructing the historic climatic conditions of a particular region over thousands of years. In the latter case, the deepest lake in the region should be selected since this most likely contains the longest sediment archive which can be used for this purpose. The second step is the selection of the coring site in the lake

The third step is sediment sample collection (coring). This is done using a variety of coring methods available (See section 2.3). The choice of the coring method will depend on the location of the sampling site, the nature of the sediment and the length of the core required. Maximum care should be taken during sample collection to avoid any disturbance that may interfere with the chronological order of deposited materials.

The forth step is sectioning the sediment core. This involves sub-sampling the sediment into appropriate temporal slices for the study at hand. For example, sub - sampling may be done every 2 cm, 5 cm, 10 cm or 20 cm along the core depending on the maximum

length of the core, labour, time, number of parameters to be analysed and the level of resolution required.

The fifth step is dating the sediment profile. The investigator needs to know when particular sediment was deposited and make inference hence being able to tell when the event took place. The sixth step is analysis of the sediment sample to collect data on a variety of environmental indicators which include physical, chemical and biological information. The seventh step involves interpreting the proxy data for environmental assessment. Here, inference is made on past condition based on the nature of proxy data that has been collected.

The last step is the presentation of the collected data and it concerns the process of making the interpreted information retrieved from the sediments available to interested parties such as managers, decision/policy makers, other scientists as well as the general public in a manner that is easily understood.

2.3 Types of coring methods for shallow sediment profiles

2.3.1 Open -Burrell gravity corers

These corers use the force of gravity to penetrate the sediment profile and the sediment is then collected in an open burrell usually a polycarbonate coring tube. The corer consists of a tube open at both ends that is driven vertically into the sediment. When the core drive is complete, the top of the tube is closed and the tube now filled with sediment is retrieved to the lake surface (Fig. 1a). They have one problem of being able to collect only sediments up to 1m depth hence not appropriate where longer sediment profiles are to be collected.

2.3.2 Freeze-crust corer

These according to Renberg, (1981) are designed to sample the watery sediments of the mud-water interface which contain gases that might disrupt the core profile during the coring process. They are made of either a wedge, cylindrical or box-shaped weighted chamber filled with a coolant such as dry ice immersed in alcohol. The chamber is lowered on a rope into the sediment. The super cooled apparatus is held in position by the sampling rope in the sediment for about 10 minutes as it freezes *in situ* a crust of sediment on the surface of the sampler (Fig. 1b). The device is then retrieved onto the lake surface and the frozen sediment crust is removed for subsequent sampling.

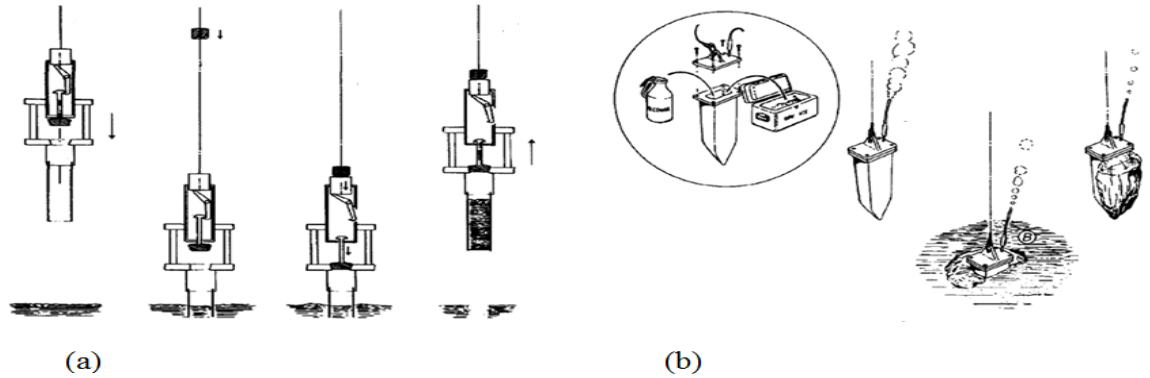

Figure 1. Operation of a messenger triggered Open –Burrell gravity corer (a) and freeze-crust corer (b) (Smol, 2002)

2.3.3 Rod driven fixed piston corers

A piston corer consists of a piston and cable assembly, the core tube, drive head and drive roads. The core tube is assembled with a close-fitting piston that can move the length of the core sample. In operation, the corer enters the sediment with the piston at the bottom of the tube, effectively preventing sediments entering the tube until the correct sampling depth is reached at which point the piston is held stationary and the core tube is pushed past it into the sediment using the drive rods (Fig. 2).

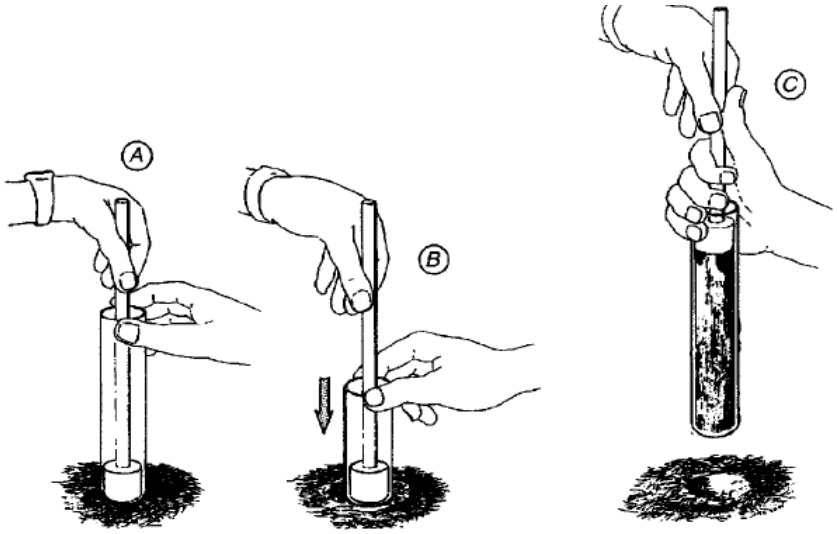

Figure 2. General operation of a rod-driven piston corer

Once the sample has been taken, the corer is recovered and the core tube containing the sediment sample is exchanged with a new empty core tube and then the coring of the next section can begin. Piston driven corers can collect sediment samples in lakes of up to 40 m. The sediments for this study were collected using this method.

2.4 Environmental proxy data in sediments and their implications

2.4.1 Water, Organic matter, Carbonate content, Percentage Organic Carbon (OC), Organic Nitrogen (ON) and Carbon/Nitrogen ratio (C/N)

The water content in a sediment is determined using the weight - loss techniques and is expressed as percentage of the total weight of the sediment sample. It is determined by weighing a known amount of sediment and drying it in an oven. By weighing the sample again after drying, the percentage of water is easily calculated by dividing the difference in weight by the wet sample weight. The results are represented either as percentage of the dry sample weight or of the wet sample weight. The water content of the sample provides information as to the amount of compaction (de-watering) the sediment has been subjected to, (Smol, 2002). Organic matter content is determined by ashing a known amount of dry sample in a muffle furnace set at 550^0C to combust any organic matter in the sediment. By cooling this ashed material in the desiccator, and then re-weighing it, the percentage of organic matter sometimes called, percentage loss on ignition (% LOI) is easily calculated by dividing the difference in weight by the dry sample weight. To determine the carbonate content, the ashed sample is returned to the muffle furnace and now heated to between 925^0C and 1000^0C. The carbonate will be converted to CO_2 during this process and so only the non-carbonate fraction comprising minerals such as feldspar and quartz etc. will be left in the sample. The percentage of carbonate is calculated dividing the difference in weight by the weight of the ashed sample.

Percentage of organic carbon, nitrogen and C/N ratio are important proxies for tracking changes in lake productivity as well as allochthonous inputs over time. An increase in the % OC of sediment can be indicative of an increase in the input of OM from the catchment or of the productivity of the lake (Koff *et al.* 2012). The ratio of percent C (%C) to the percent total nitrogen (% N) (C/N) in acidified samples indicates the source and type of OM deposited. During episodes of high lake productivity, more organic matter is generated within the lake in the form of algae and macrophytes hence autochthonous OM dominates the lake. This lowers the C/N ratios as compared to periods of low productivity when most of the organic matter is imported from the riparian habitat thus increasing the ratio due to allochthonous dominance (Koff *et al.* 2012).Vascular land plants have a relatively high C/N ratio of over 20 due to more carbon-rich (such as cellulose) and fewer nitrogen-rich compounds (such as protein) while, algae tend to have distinctly lower C/N ratios, typically

below 10 due to higher nitrogen-rich compounds and less carbon-rich compounds (Meyers and Teranes, 2001).

2.4.2 Biogenic silica (BSi)

Biogenic silica is the proportion of dissolved silica incorporated into the cell walls of silicified organism in lakes. It is a proxy used to estimate the abundance of diatoms i.e. algal groups that produce silica cell walls (frustules) (Smol, 2008). Eutrophic lakes tend to have abundant phytoplankton and therefore have elevated levels of biogenic silica. Low BSi values in lake sediments would suggest periods of lower aquatic productivity or silica limitation (Schelske and Stoermer, 1971). Levine *et al* (2011) associated high levels of biogenic silica with elevated lake productivity as a result of increased nutrient input in Lake Champlein.

Different authors have used different methods to determine the level of biogenic silica in lake sediments. However, the wet-alkaline digestion method is the easiest and therefore the most commonly used. It involves the digestion of the sediment sample using alkaline solution in a water bath shaking at 100 rpm and boiling at 85 ^{0}C. The method however has three modifications which are commonly used to correct for the dissolution of the mineral silicates.

The first one involves the use of a moderate strength base (2 M Na_2CO_3) where the sample is digested continuously for 5 hours after which the amount of Silica extracted is measured (Mortlock and Froelich, 1989). The second modification involves the use of a weak base (2 M Na_2CO_3) as the extraction solution and aliquot withdrawn at selected intervals (3, 4, and 5 h) and the amount of Silica extracted is measured on these sub-samples. In this procedure, the dissolution of diatom silica occurs during the first two hours and any increase after this time is due to the digestion of mineral silicates (DeMaster, 1979). Therefore to correct for the dissolution of mineral silicates and hence determine the concentration of biogenic silica in the sediment sample, a least-squares linear regression is made and the extrapolation to the y-intercept gives the BSi concentration. Another way of correcting for the dissolution of the minerals is by simultaneous measurement of Aluminium concentrations during the digestion (Kamatani and Oku, 2000).

2.4.3 Magnetic susceptibility (MS)

Magnetic susceptibiliy is a measure of the magnetic retention of a sample after exposure to a magnetic field and it is therefore an indication of the relative amounts of inorganic terrestrial sediment inputs versus organic matter. It is a fast, inexpensive measure of the relative concentration of magnetic minerals within the sediment (Nowaczyk, 2001).

Production of OM during periods of high lake productivity results in the deposition of materials which lack magnetic materials thus leading to a decrease in MS values. Periods of relatively low productivity will lead to higher MS values since the sediment becomes dominated by inorganic materials of higher magnetic content from the catchment. Cohen *et al* (2006) associated low MS values with high productivity in Lake Tanganyika.

2.4.4 Sediment grain size

This is an indication of the overall energy level of the lake environment and can record changes in lake level and large storm events (Noren *et al.* 2002). Redistribution of grain sizes is influenced by changes in lake level. Lake level decline leads to shoreline regression, where coarser sediments are deposited over finer sediments, while lake level rise (transgression) may deposit finer sediments on top of coarser ones. However, large storm events, which may lead to lake flooding, may also deposit significant amounts of coarser sediments in a lake system (Parris *et al.* 2009) particularly when the lake is relatively small. Koff *et al* (2012) found deposits of larger grain particles on top of finer sizes and interpreted it to be periods of high water level as a result of high stream discharge. This proxy is also used to trace the processes or sources of sediments (Smol, 2002; Degefa *et al.* 2015). For example, a high concentration of clay particles is often interpreted as erosion signal. An increased frequency of large sized particles such as sand grains, would suggest delivery of these materials in a high energy environment such as from a river flow. Degefa *et al* (2015) interpreted deposits of course materials in sediments recovered from Lake Baringo as episodes of high erosive power of rivers associated with wet conditions

2.4.5 Fly-ash particles

When fossil fuels such as coal and oil are burned at high temperatures to generate electricity or heat, or used for some industrial application, two types of particles are produced from the mineral component of the fuel. These include, porous spheroids of primary elemental carbon (Goldberg, 1985) also referred to as spheroidal carbonaceous particles (SCPs) and inorganic ash spheres (IASs). Collectively, SCPs and IASs are referred to as Fly-ash particles. These particles are used in paleolimnology to infer past industrial activities related to fossil fuel combustion e.g. lake acidification (Rose, 2001). Secondly, SCPs are used to provide additional geo-chronological control in sedimentary profiles. This is because SCPs are not produced by any natural process and so their first appearance in a dated sediment sample can be used to identify the start of industrial burning of fossil fuels.

2.4.6 Biological indicators

A central theme in ecology has been the attempts to classify ecosystems by the flora and fauna they contain. For example, presenting someone with a picture of cacti and camels will immediately suggest an arid and hot climate. Similarly, different living components of the lake can be used to infer past conditions based on their habitat preference. A good bioindicator must be able to leave easily identifiable fossil when it dies and also the ecology of the species must be well known to some level of certainty.

Pollen and spores (Fig. 3) are structures produced by angiosperm and gymnosperms, and lower plants such as mosses, ferns and fungi respectively as part of their reproductive and perrenation strategies. The outer layer of pollen grains contain the polymer sporopollenin which is one of the most inert organic substance known and this enables them to preserve well in lake sediments (Smol, 2002). Identification of pollen is based on the structure, sculpture and morphological features of this outer layer. By identifying and enumerating grains and spores in sedimentary profiles, palynologists can reconstruct past trends in terrestrial vegetation succession as well as past shifts in aquatic macrophytes and near shore vegetation. Since vegetation is closely linked to climatic variables, palynology is often used to reconstruct past climatic trends (Kiage and Liu, 2009b).

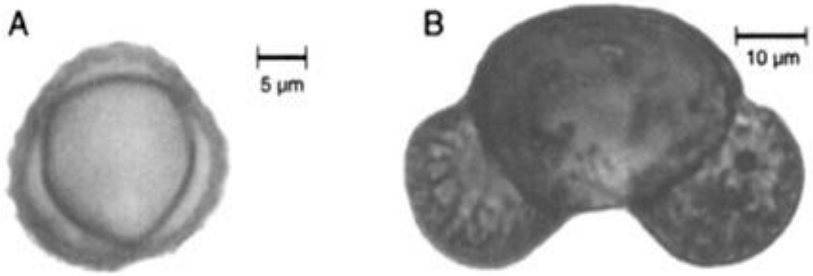

Figure 3. Light micrographs of pollen grains. (A) Ragweed (Ambrosia). (B) Pine (Source, Smol, 2002)

Plant macrofossils are defined as any identifiable plant remains that can be seen with the naked eye. However, some form of magnification is often needed for identification. Macrofossils include seeds, fruits, cones, needles, pieces of twigs and moss fragments. They have been used to reconstruct past aquatic macrophytes and near-shore vegetation (Birks, 2001). Because macrofossils are larger and heavier, they are not transported long distances and so are especially useful for describing local changes.

Charcoal represents burnt residues of past fires. They are <100µm in size and can be transported long distances by wind current and therefore provide information on regional fire

frequencies. They have been used to track different types of human activities such as industries that depend on wood burning and burn-agriculture (Smol, 2002).

Diatoms are microscopic algae that live suspended in the water column or attached to living or inert substrates. Their applicability in paleolimnology is because their frustules preserve well in lake sediments (Stoermer and Smol, 1999). Different taxa have different environmental optima and tolerance and so analysis of fossil species assemblages can be used to reconstruct a suite of environmental variables (Wang *et al.* 2012). Diatom-Based Statistical Models have been developed over the past decades and used to reconstruct specific environmental parameters from diatom assemblages. The method is based on developing a transfer function from a set of diatom assemblages from "modern lakes" and their relationships to select environmental gradients that independently explain the variation in species distribution. The transfer function is then applied to historical diatom assemblages in sediment cores to mathematically and quantitatively reconstruct specific environmental variables of interest to the researcher (Anderson, 1989; Fritz *et al.* 1991).

2.5 Sediment chronology

One important factor in interpreting lake records is accurate chronology of the sediment. Age can be estimated from the depth of the sediment assuming that the rate of sediment accumulation has been constant throughout the time and that there has been no compaction of the sediment (Frey, 1988). For accurate dating of the sediment, various techniques are used.

2.5.1 Lead dating

Lead - 210 (^{210}Pb) is a radioactive isotope of lead that is part of the Uranium-Lead decay series. Trace amounts of Argon - 222 (^{222}Ar) gas are produced from bedrock as part of this series, which then escapes into the atmosphere. Argon -222 (^{222}Ar) in the atmosphere then decays into ^{210}Pb, which is a solid and is deposited in known trace amounts on the earth's surface, including lakes (Walker, 2005). Lead (^{210}Pb) is consistently being deposited in lake sediments where it decays into Lead - 206 (^{206}Pb). Based on the activity of the unsupported ^{210}Pb in lake sediment, the sample age is calculated according to Appleby and Oldfield (1978)

$$T = (1/\gamma)\ln(\frac{A_o}{A_x}) \quad \text{.....Equation 1}$$

Where, T is the age of the fossil or the date of death, Υ is the ^{210}Pb radioactive decay constant (yr^{-1}), A_0 is the total unsupported ^{210}Pb activity in the sediment column, A_x is the total unsupported ^{210}Pb activity in the sediment column beneath particular depth.

2.5.2 Caesium dating

Caesium (^{137}Cs) is an artificial isotope manufactured by the nuclear industry which was released for the first time in the year 1945 with the dawn of the nuclear age (Pennington *et al.* 1973). Stratospheric testing of atomic weapons has been a major source of ^{137}Cs releases accelerated with the initiation of the nuclear arms race and the atmospheric weapon testing which began in November 1952. The radioactive debris injected into the atmosphere were transported around the world, but eventually re-deposited as fallout.

2.5.3 Radioactive carbon dating

Production of radioactive isotope of carbon occurs in the upper atmosphere as a result of cosmic rays which remove a proton from ^{14}N. This rapidly reacts with free oxygen, producing $^{14}CO_2$ which is then incorporated into plants and animals through their feeding levels (Bjorck and Wohlfarth, 2001). A consistent amount of ^{14}C is found in all living organisms as they continually take up $^{14}CO_2$ into their tissues. When the organism dies, the supply of ^{14}C to the tissues stops and it radioactively decays back to ^{14}N with a half-life of 5,730 ± 40 years (Bjorck and Wohlfarth, 2001). This method is ideal for dating organic deposits that are from about 500 to 40,000 years old (Smol, 2002). The age of the material can therefore be determined using the following equation.

$$T = \left[\frac{\ln(N/N_0)}{-0.693}\right] \times 5730\ years \quad \text{.....Equation 2}$$

Where, T is the age of the fossil (or the date of death), 5730 years is the half-life of ^{14}C isotope, N is the number of atoms left after time t (measured at sampling time) and N_0 is the number of atoms of the isotope in the original sample (at time $t = 0$, when the organism died). Since at any particular time all living organisms have approximately the same ratio of ^{12}C to ^{14}C in their tissues, the value of N_0 is equivalent to amount of ^{14}C contained in any living matter which is in continuous exchange of carbon with the atmosphere.

2.6 Effects of volcanic eruptions on lake level changes

Volcanic eruptions can affect water level in lakes by influencing flow of water in rivers. In a study to assess how volcanic eruptions affect water level changes in lakes, Carley and Hegerl (2015) found out that, eruptions are followed by reduced flow in rivers two years later, leading to decline in water level of lakes. Reduction in rainfall occurs because the aerosols released reduce the capacity of the atmosphere to hold water (Joseph and Zeng, 2011). They also noticed that the reduction in stream flow is also caused by reduction in rainfall which follows volcanic eruptions.

2.7 Past paleolimnological studies in Lake Baringo

Lake Baringo is an important natural resource that is heavily utilized by the bordering communities for water supply, fisheries, recreation and tourism. Climate-sensitive lakes of the East African Rift System (EARS) such as Lake Baringo offer some of the best sources for paleoenvironmental records (Verschuren, 2003). Such systems archive both short and long-term regional climate dynamics and integrate anthropogenic influences and other environmental signals in their sedimentary records (Russell *et al,* 2003). Palynological study of Lake Baringo sediments reveals a largely dry environment in the East African region since AD 1650 (Kiage and Liu 2009a). According to Bessems *et al* (2008), stratigraphic analysis of sediments collected from tropical African Lakes provides clear evidence of severe drought which led to complete drying of Lake Baringo about 200 years ago. This is the time when, Loboi Swamp that is located immediately south of Baringo stood dry (Ashley *et al.* 2004), and Lake Naivasha further south in the Central Rift Valley experienced its most severe low-stand since the Medieval Warm Period (Verschuren *et al*. 2000). Based on Degefa *et al* (2015), sedimentation rates increased five- to six-fold from the 19^{th} to the 20^{th} century, consistent with historical data on changes in demographic pressure, soil erosion and land degradation since the 1920s. Furthermore, mean offshore sediment accumulation in Lake Baringo over the past 60 years has been very high (from 0.5 g cm^{-2} yr^{-1} in the north to 1.2 g cm^{-2} yr^{-1} in the south). However, there results also show that siltation has had less influence on variation in mean water depth than climate-driven fluctuations of the lake's surface elevation, thus contradicting previous suggestions (Aloo, 2002) that siltation is the major cause of decline in water level of Lake Baringo. This opens up the desire for further investigations on the relationship between climatic variations and lake level fluctuations. This study therefore further explores climatic controls on water level of Lake Baringo using paleolimnological approach.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study area

Lake Baringo is one of the seven inland drainage lakes within the semi-arid (Le Houreou and Popov, 1981) Eastern Arm of the Great Rift Valley in Kenya, East Africa with a surface area of 231.6 km^2 (Onywere *et al.* 2013). It is a holomictic, endorheic lake lying between 0^o 30″ N – 0^o 45″ N and 36^o 00″ E – 36^o 10″ E at an altitude of 970 m above sea level with a catchment area of 6200 km^2 (Fig. 4). The lake is a RAMSAR site known for its high bird diversity, hippopotamus and crocodile populations.

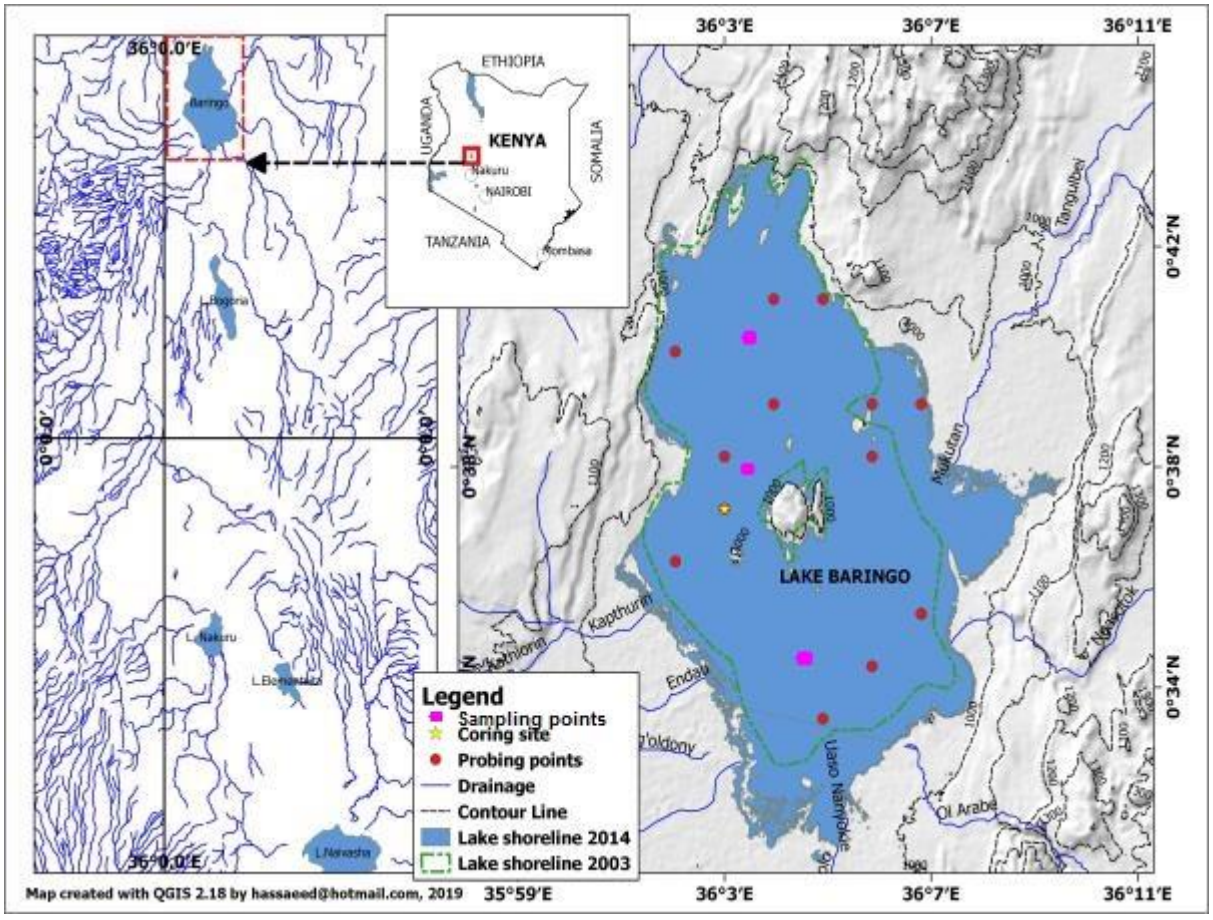

Figure 4**.** Map of Lake Baringo and its drainage basin in the Kenyan Rift Valley with a situation of its hydrographic network in relation to those of other rift lakes and lake shore position in 2003 (stippled line) and during the flooded situation of 2014

The lake has maximum depth of 11.6 m, mean temperature of 25^o C and high net evaporation of 1650 mm-2300 mm per year (Odada *et al.* 2006). Lake Baringo waters remain fresh despite the lack of surface outlet because some water is lost by ground seepage through the fractured lake floor (Gregory, 1896). Similar subsurface loss of water has been

demonstrated at Lake Naivasha, which also lies in a topographically closed basin, 160 km south of Lake Baringo (Ojiambo *et al.* 2003). The islands found in the lake towards the south are remains of volcanic activity which occurred during the Pleistocene Epoch and dates to about 1.8 million years ago (Gregory, 1921).

Lake Baringo water and sediments derive from seasonal rivers including Ol Arabel, Mukutan, which drains the Laikipia Border Fault Escarpment, Endao and Chemeron, which drains the Tugen Hills and perennial rivers including Molo and Perkerra which flows Northwards from the Mau Hills. The lake also gets water from rainfall directly on the water surface as well as several episodic streams from the surrounding hills. All these rivers show significantly reduced discharge during the dry months of the year since the area is prone to drought (Allen and Darling, 1989). The climate in this region is influenced by the biannual passage of the Inter Tropical Convergence Zone (ITCZ), which according to Nicholson, (1996) results in a bimodal precipitation pattern with the region experiencing higher than normal rainfall during El Nino years followed by lower than normal rainfall the year after El Nino (Indeje *et al.* 2000).

3.2 Sampling

3.2.1 Depth determination and Coring

The mean water depth was determined using an echo-sounder (Garmin 180 Fish Finder). The total depth of the water plus the sediment package was determined by the use of push rods forced down to the desiccation bottom i.e. probing at 13 random locations (Table. 1). The thickness of the sediment package was obtained by getting the difference between the depth of water plus the sediment and the sounding depth. The sediment record was studied in core samples extracted from the deepest point of the lake (36^o 3″ E, 0^o 37′N) using a Rod-Operated Single-drive Stationary Piston corer method (Wright, 1980) from a platform mounted between two boats.

Table 1. Location of core and probe sites in Lake Baringo

Site	Location	Water depth (m)
Core site	36^o 3″E, 0^o 37″N	11.6
Probe site 1	36^o 6″E, 0^o 34″N	9.1
Probe site 2	36^o 7″E, 0^o 35″N	8.9
Probe site 3	36^o 2″E, 0^o 36″N	10.9

Probe site 4	36° 3″E, 0° 38″N	10.5
Probe site 5	36° 4″E, 0° 39″N	11.1
Probe site 6	36° 2″E, 0° 40″N	10.9
Probe site 7	36° 5″E, 0° 41″N	11.0
Probe site 8	36° 6″E, 0° 39″N	9.9
Probe site 9	36° 7″E, 0° 39″N	10.7
Probe site 10	36° 4″E, 0° 41″N	11.0
Probe site 11	36° 6″E, 0° 38″N	9.5
Probe site 12	36° 5″E, 0° 33″N	9.0
Probe site 13	36° 7″E, 0° 35″N	8.8

Coring was started at about 20 cm above the sediment surface to avoid any disturbance of the top sediment layer and also due to sounding depth error. In case where the sediment thickness was beyond the maximum length of the coring tube (1.8 m), the next core was taken to complete the core but this started at an overlapping depth to ensure that no sample was missed between the end of the first core and the beginning of the second core (Fig. 5).

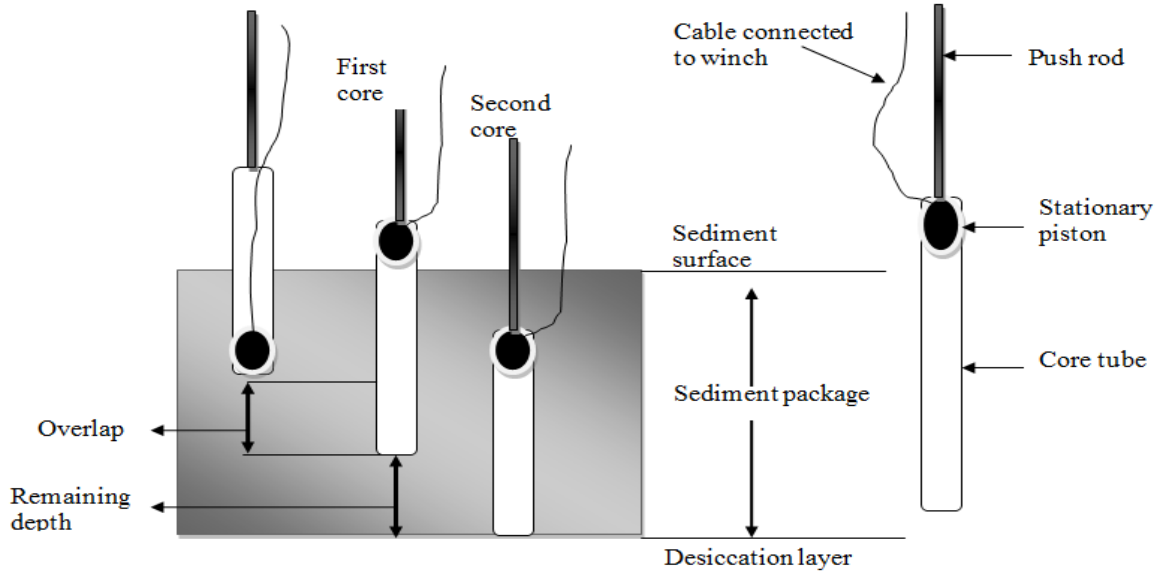

Figure 5. Operation of a Hand-Driven Fixed-Piston corer

The tubes were sealed on both ends at the field collection site using well-fitting cups and masking tape, labelled and transported to Ghent University (Belgium) for Magnetic

Susceptibility analysis and chronology, and Egerton University (Kenya) for fossil diatoms and Biogenic Silica analysis.

3.2.2 Whole core analysis of Magnetic Susceptibility

The cores tubes containing the samples were split into two sections lengthwise by cutting opposite sides of the PVC tubes with a circular saw. Along the entire length of the core, digital photos were taken and visual descriptions recorded. Macrofossils, when found, were collected for ^{210}Pb dating. High resolution (1-mm interval) measurements of value-specific Magnetic susceptibility (k, in 10^{-6} SI units) were performed for the entire length of the core using a Bartington Magnetic Susceptibility Meter (MS2E1 model) with an automated core-logging system according to Nowaczyk, (2001).

3.2.3 Biogenic silica analysis

Biogenic Silica was analysed according to Mortlock and Froelich, (1989). Powdered lake sediments (50 mg) were measured in 50 ml Nalgene bottles and 40 ml of 2 M Na_2CO_3 added. Sets of three sample bottles held together with rubber bands were placed in a hot water bath (85°C) and the sample digested continuously for 5 hours after which the amount of Silica extracted was measured in triplicates. A sub sample of 0.5 ml was extracted and mixed with 4.5 ml of 0.1M HCl in 15 ml centrifuge tubes and analyzed for silicates using ammonium molybdate method. Using plastic flasks, 2 ml of mixed solution (preparation: Ammonium heptamolybdate solution: Sulphuric acid = 1:1) was added to the sample. After 10 min 1 ml citrate solution was added. The treated samples were left standing for 6 min. The absorbance of each sample was then measured on a spectrophotometer (Genesys 10-S) at a wavelength of 810 nm and translated into a silica concentration using a best-fit line of absorbance versus silica concentration of five prepared standards with concentrations of 5, 10, 20, 40, and 60 mg Si l^{-1}.

3.3 Fossil diatom analysis

3.3.1 Preparation of sediment

One gram of wet sediment was placed in a graduated beaker and 10 ml of 30 % H_2O_2 added and covered with a watch glass. This set up was left standing for 20 minutes then placed on a heating plate at 100°C. The samples were boiled for 1 hour taking care not to allow the samples to dry in which case distilled H_2O was added. After 1 hour the beakers were removed from the heating plate and the watch glass rinsed into the beaker. After this, 1-

2 drops of 50 % HCl was added. The beakers were left to settle for 24 hours after which the resulting supernatant liquid was removed with pipette and the settled material (diatoms and inorganic material) re-suspended in distilled water. The washing process was repeated three times to remove all H_2O_2, each time allowing the diatoms and inorganic material to settle. For the final wash, 1-2 drops of ammonia (NH_3) solution was added to the sample to help keep any remaining clay particles in suspension, which was then removed with the last supernatant.

To each treated sample, 5ml of concentrated HCl was added and covered with parafilm. The samples were mixed gently with the acid and left standing for 24 hrs. The samples were then washed with distilled water three times through centrifugation at 2000 rpm and then decanting the supernatant. After this 5ml of digestion solution (mixture of concentrated sulfuric acid and nitric acid in the ratio 3:1) was added to the sample and left to settle for 24 hrs. Thereafter, the samples were rinsed again four times with distilled water through centrifugation and then decanting the supernatant liquid. The treated sediment samples were then retained in their respective containers and stored until analysed.

3.3.2 Preparation of fossil diatom slides

A standard glass microscope slide was labelled and placed on the left side of a horizontal storage tray and a cover glass on the right side. With a pipette, a drop of 200 µl distilled water was put on the cover glass. The treated sample in section 3.3.1 above was then whirled and 50 µl of it put into the drop of water on the cover glass and dispersed equally across the drop of water with a pipette. A different pipette-tip was used for each sample to avoid cross-sample contamination. The cover glass was then left overnight to dry. The horizontal slide tray (with microscope slide on the left and cover glass with dried sample on the right) was taken to a fume hood and a drop of Naphrax with a refraction index of 1.7 put on the labeled microscope slide, then the cover glass with the dried diatoms placed upside down on the drop of Naphrax. The microscope slide + Naphrax + cover glass were placed on a warm heating plate and heated for 30-60 seconds. The slides were left overnight to cool and harden. The prepared slides were then observed and counted under light microscope with phase contrast oil immersion objective at a magnification of ×1000. Photographs of valves were taken using Moticam camera.

3.3.3 Counting of fossil diatoms under optical microscope

The whole slide area containing the sample spread-out was observed and the valves counted. Enumeration of the diatoms was based on the number of valves obtained. Counts were made by scanning the slide across the field of view on a horizontal direction until 300 valves were counted. If more than half valve was found, it was counted as one valve. If a central fragment (containing the central nodule) of pennate diatom, was found and counted as one valve, then the ends were not counted. For centric diatoms, fragments were counted as one (N=1) when the central node was visible, and half (N= 1/2) valve when one fragment was observed. Very small fragments with no clear identity were ignored.

The results were presented in numbers of frustules (Number of valves/2) per unit dry weight. The diatoms were identified to genus/species level where possible using identification keys (Gasse, 1986). Percent frequency of occurrence was calculated for common species/ genera where the percentages were based on the total sum of the taxa. The ratio of centric to pennate diatoms (C/P) was calculated (equation 3). The values obtained were used to assign the trophic status according to Nygaard, (1949) (Table 2).

Additionally, inference on past lake productivity was based partly on the presence and abundance of different trophic level indicator taxa.

$$R = \frac{C}{P} \quad \text{Equation 3}$$

Where; C is the number of centric diatoms while P is the number of Pennate diatoms in the sediment sample.

Table 2. Algal quotient ratio used to assign Lake trophic level (Nygaard, 1949)

Trophic level	**C/P**
Dystrophic	0-0.3
Oligotrophic	<1
Mesotrophic	1-2.5
Eutrophic	3-5
Hypertrophic	5-20
Polytrophic	10-43

Water depths were assessed using known habitat preferences (Gasse, 1986). Diatom species were grouped into three habitat preferences: planktonic, facultative planktonic and benthic using taxonomic literature and comparison with previous studies (Gasse, 1986). This

was done for the purpose of calculating the ratio of planktonic to benthic taxa according to Luo *et al* (2013) as shown below:

$$P/B = \frac{\sum Planktonic\ taxa}{\sum Planktonic + Benthic\ taxa} \quad \text{..... Equation 4}$$

P is the number of planktonic forms and *B* is the number of benthic forms.

3.4 Chronology

The chronological framework for Lake Baringo sedimentation profile was determined using ^{210}Pb and ^{137}Cs technique. A detailed chronology of the sediment collected during the research work is found in Degefa *et al* (2015). In order to estimate the ages of the undated segments of the core, the average sedimentation rate between two dated points was calculated as the difference in depth over the difference in age assuming constant rate of sediment supply and negligible compaction by overlying materials.

3.5 Measurement of physico-chemical parameters and collection of water samples

Limnological characteristics of the lake were studied for 5 dry months (November 2014 to March 2015) followed by 4 wet months (July - October 2015). Dissolved oxygen (DO), temperature, pH and Conductivity were measured *in-situ* using HACH 40d Multi-meter probe at the Southern (00^o 34′ 28″N, 036^o 4′ 37″E), Central (00^o 37′ 37″N, 036^o 03′ 51″ E) and Northern (00^o 40′ 41″ N, 036^o 03′ 31″ E) parts of the lake. The degree of light attenuation was estimated using a black and white weighted Secchi disk. Using a 5-liter Schindler sampler, 500 ml water samples were collected from above locations in triplicates. Before sample collection, the sample bottles were rinsed with water from respective sites three times. The samples were kept in an ice-cool box and transported to Egerton University for analysis on arrival. Samples for dissolved nutrient were filtered through 0.45µm Whatman GF/C filters.

Dissolved nitrate was analyzed using the sodium-salicylate method. A stock solution was prepared by dissolving 6.067g of sodium nitrate ($NaNO_3$) in 1 litre of distilled water to make a stock solution with a concentration of 1000 mg l^{-1}. From this stock solution, a working solution with a concentration of 5 mg NO_3-N l^{-1} was made by taking 5 ml of the stock solution and diluting to 1 litre. A standard series with different concentrations of 0, 0.25, 0.5, 1, 2.5 and 5 mg NO_3-N l^{-1} was then made by taking 0, 1.0, 2.0, 4.0, 10. 0 and 20.0

ml of the working solution and diluting with distilled water to 20 ml. Triplicate samples for each concentration was made to make the calibration curve. To 20 ml of filtered water sample, 1 ml of sodium salicylate solution freshly prepared was added. The bottles were then put into the oven and the samples dried at a temperature of 95°C. The resulting residue was dissolved quantitatively by adding 1 ml of conc. H_2SO_4 and the bottles swirled carefully while still warm. Next, 40 ml of distilled water was added and mixed. Finally 7 ml of potassium-sodium hydroxide-tarterate solution was added, mixed and the absorbance determined at a wavelength of 420 nm.

Dissolved nitrite was determined using sulfanilamide and N-Naphthyl-(1) - ethylendiamin-dihydrochlorid method. Sodium nitrite salt ($NaNO_2$) with a molar weight of 69 g was used to make the standard calibration curve for the nitrite determination. A stock solution with a concentration of 1 g NO_2-N l^{-1}, was made by dissolving 1.2322 g of this salt in 250 ml distilled water. Five ml of this stock solution was diluted to 500 ml with distilled water to make an intermediate solution having a concentration 10 mg l^{-1}. Further, 5 ml of this intermediate solution was diluted to 1 liter with distilled water to give a working solution with a concentration of 50 µg l^{-1}. A series of standards with concentrations of 0, 2, 5, 10, 20 and 50 µg l^{-1} was made to determine the calibration curve by diluting 0, 1, 2.5, 5, 10 and 25ml of the working solution with 25, 24, 22.5, 20, 15 and 0 ml of distilled water respectively. To 25 ml of the filtered sample, 1 ml of Sulfanilamid solution was added. After 2-8 minutes, 1 ml of N-Naphthyl-(1)-ethylendiamin-dihydrochlorid solution was added and gently mixed. The solution was left standing for 10 minutes after which its absorbance was read from the spectrophotometer at a wavelength of 543 nm.

Ammonium nitrogen was measured through the hypochlorite method using nitroprusside as a catalyst. Standard calibration curve was made by dissolving 0.955 g NH_4Cl in a 250 ml volumetric flask, giving a stock solution with a concentration of 1g NH_4-N l^{-1}. Next, 10 ml of this stock solution was diluted further to 1 liter with distilled water, giving an intermediate solution with a concentration of 10 mg l^{-1}. From this solution, a working solution was made with a concentration of 250 µg l^{-1} by taking 25 ml of the intermediate solution and diluting it to 1 liter. The working volume for calibration curve used was 25 ml. Different concentrations of this standard working solution was made to determine the calibration curve by taking 0, 1.0, 2.0, 5.0, 10.0 and 25.0 ml of the working solution and diluting to 25 ml with distilled water. To 25 ml of the sample, 2.5 ml of reagent Sodium salicylate solution was added, followed immediately by the addition of 2.5 ml of Hypochlorid

solution. The samples were then placed in the dark for 90 minutes. Absorbance was determined at a wavelength of 655 nm.

Particulate phosphorus was measured on unfiltered water samples using persulphate digestion followed by measurement of SRP (APHA, 2004). Standard solution for the calibration of the standard curve was made by dissolving 5.623 g of potassium hydrogen phosphate (K_2HPO_4) (pre-dried in the oven for 24 hrs. at 70°C) in 1 liter of distilled water to make a stock solution with a concentration of 1g of PO_4-P l^{-1}. From this stock solution, 10 ml was diluted to 1 liter using distilled water to give an intermediate solution with a concentration of 10 mg L^{-1}. The intermediate solution was further diluted in a ratio of 1:20 to give a working solution with a concentration of 500 µg l^{-1}. The standard series was prepared by taking 0, 0.5, 1.0, 2.5, 5.0, 10.0, 20.0 and 25.0 ml of the working solution and diluting to 25 ml with distilled water. Ammonium molybdate solution, sulphuric acid, ascorbic acid and potassium-antimonyltartarate solutions were mixed in the ratios: A:B:C:D = 2:5:2:1. The resulting solution was added to the sample in a ratio of 1:10, e.g. 2.5 ml reagent added to 25 ml of the sample. The prepared sample's absorbance was measured after 15 minutes of adding reagents to the samples at a wavelength of 885 nm with distilled water as a reference. The factors limiting phytoplankton growth were determined using nutrient ratios (Axler *et al.* 1994), as well as TSI deviation concept according to Havens, (2000).

3.6 Estimation of chlorophyll *a*

Samples for chlorophyll *a* analysis were kept in the dark by wrapping the outer surface of the bottle containing the sample with aluminum foil. Analysis was done as acetone extract following (APHA, 2004). First, 25ml of the lake water sample was filtered through Whatman GF/C filters by gentle vacuum filtration. The filter together with the seston was folded and covered by aluminium foil and stored in a freezer overnight. The filter and the seston was then sliced into small pieces using a pair of scissor then homogenized in a tissue grinder at 5000rpm for 1 minute then covered with 5ml of 90% acetone.

The sample was adjusted to 10 ml with acetone and left for 8hrs in the dark at 4^0C. After incubation, the sample was centrifuged for 10 minutes at 2500rpm. The clarified extract was decanted into clean test tubes. Light absorbance of the extract was measured with a spectrophotometer with the sample placed in 1-cm cell cuvettes at 750 nm and 663 nm. The concentration of chlorophyll *a* was calculated according to Talling and Driver, (1961).

$$Chla(\mu g^{-l}) = \frac{[11.40(E_{663} - E_{750}) \times V_1}{V_2 \times L}$$ .....Equation 5

Where:

11.40 is the absorption coefficient for chl-a in µg l^{-1}, V_1 is the volume of extract in ml, V_2 is the volume of the filtered water sample in litre, L is the light path length of cuvette in cm, E_{663} and E_{750} are the optical densities of the sample.

3.7 Calculation of trophic state index

The trophic state of the lake was determined using the Carlson Trophic State Indices (CTSI) following Carlson, (1977) as shown in Table 3 below.

Table 3. Calculation of trophic state index

Trophic Index calculation
TSI_{CHL}= 30.6 + 9.81 ln (CHL)
$TSI_{(TP)}$=4.15 + 14.42 ln (TP)
$TSI_{(SD)}$ = 60 - 14.41ln (SD)

The Carlson Trophic State Index (CTSI) was then calculated as the mean of TSI_{CHL}, TSI_{TP} and TSI_{SD}. CTSI scale ranges from <40 Oligotrophic, 40-50 Mesotrophic, 50-70 Eutrophic and >70 hypertrophic.

3.8 Data analysis

Statistical analysis of the data from the cores was performed using MINITAB 14.0 statistical package (Meyer and Krueger, 2004). Raw data obtained from counts of fossil diatoms were normalized through square root transformation whereas raw data from the measurements of biogenic silica, nutrients and chlorophyll *a* were normalized through log-linear transformation before being subjected to statistical analysis. One-way analysis of variance (ANOVA) with pair-wise Tukey's comparison was used to identify differences for single proxies by testing the equivalence of the group specific means along the core ($P \leq 0.05$). Significant differences of individual physico-chemical and nutrient parameters between the months were tasted using One-Way ANOVA while the differences between the dry and wet seasons were tasted using Two Sample T-test.

CHAPTER FOUR

RESULTS

4.1 Chronology of core BAR14-2P

According to Degefa *et al* (2015), the core profile was found to have ages of AD 1800 at the base of the core (285cm), AD 1825 at 270 cm, AD 1943 at 200 cm, AD 1993 at 110 cm, AD 2003 at 30 cm and AD 2014 at the surface. The ages calculated using mean sediment accumulation rates (cm $^{-yr.}$) for the undated segments of the core are shown in Table 4.

Table 4. Chronology of core BAR14-2P

Depth (cm)	Depth difference (cm)	Age difference (yrs)	Estimated Age (AD)	Sedimentation Rate (cm/yr)
0-0.8	1	0.4	2014	2.7
1-1.8	1	0.4	2014	2.7
2-2.8	1	0.4	2014	2.7
3-3.8	5	1.8	2014	2.7
8-8.9	8	2.9	2012	2.7
16-16.8	8	2.9	2009	2.7
24-24.8	8	2.9	2006	2.7
32-32.8	8	1.0	2003	8.0
40-40.8	8	1.0	2002	8.0
48-48.8	8	1.0	2001	8.0
56-56.8	8	1.0	2000	8.0
64-64.8	8	1.0	1999	8.0
72-72.8	8	1.0	1998	8.0
80-81.0	8	1.0	1997	8.0
88-88.8	8	1.0	1996	8.0
96-96.8	8	1.0	1995	8.0
104-104.8	8	1.0	1994	8.0
112-112.8	8	0.0	1993	1.8
120-120.8	8	4.4	1983	1.8
128-128.8	8	4.4	1979	1.8
136-136.8	8	4.4	1975	1.8
144-144.8	8	4.4	1971	1.8
152-152.8	8	4.4	1967	1.8

Table 4 continued……

Depth (cm)	Depth difference (cm)	Age difference	Estimated Age (AD)	Sedimentation Rate (cm/yr)
160-160.8	8	4.4	1963	1.8
168-168.8	8	4.4	1959	1.8
176-176.8	8	4.4	1955	1.8
184-184.8	8	4.4	1951	1.8
192-192.8	8	4.4	1947	1.8
200-200.8	8	13.3	1943	0.6
208-208.8	8	13.3	1926	0.6
216-217	8	13.3	1913	0.6
224-225	8	13.3	1900	0.6
232-233	8	13.3	1887	0.6
240-241	8	13.3	1874	0.6
248-249	8	13.3	1861	0.6
256-257	8	13.3	1848	0.6
264-265	2	3.3	1835	0.6
266-267	2	4.0	1833	0.5
268-269	2	4.0	1829	0.5
270-271	2	4.0	1825	0.5
272-273	2	5.0	1820	0.4
274-275	2	5.0	1815	0.4
276-277	2	5.0	1810	0.4
278-279	2	5.0	1805	0.4
280-281	2	0.0	1800	0.4
282-283	2	5.0	1795	0.4
284-285	4	10.0	1790	0.4

4.2 Fossil diatom stratigraphy (Oldest to the latest time frame)

Diatom stratigraphy of Lake Baringo sediments revealed alternating patterns of benthic and planktonic diatoms abundance along the core.

Zone 1 (AD 1790s-AD 1820s). This period was dominated by planktonic diatoms *Aulacoseira granulata* (Ehrenb) and *Thalassiosira faurii* (Gasse). Planktonic taxa contributed over 80% of total diatom count compared to <20% contribution by the benthic taxa. Among the planktonic taxa, *Aulacoseira* spp represented 70% while *Thalassiosira* spp represented

10%. Benthic diatoms were represented by *Gomphonema* spp, *Eunotia* spp, *Synedra* spp, *Cymbella* spp and *Cocconeis* spp each representing less than 5%.

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

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

Zone 4 (AD 1930s-AD 2000). A shift in dominance occurred at sediments dated between AD 1926 and AD 2000, where benthic taxa contributed up to 98% to the total diatom counts. Among these, *Navicula* spp contributed 70% abundance. Other taxa including *Luticola cohnii* (Hilse) D.G.Mann, *Cymbopleura naviculiformis* (Auerswald) Krammer 2003, facultative planktonic *Gomphoneis clevei* Cleve 1894, *Fragilaria rumpens* (Kütz.) G. W. F. Carlson, *Cocconeis pediculus* Ehrenb and *Synedra cunningtonii* (G.S West) were also present but made less than 5% each.

Zone 5 (AD 2001-AD 2009). This zone had a poor diatom community structure. Valves of centric diatoms which could not be easily identified, possibly due to fragmentation and dissolution were observed. *Aulacoseira granulata* (Ehrenb.) Ralfs were easily identified and made up to 90% of the total diatoms counted. The facultatively planktonic *Navicula gawaniensis* (Gasse) as well as benthic genera such as *Cymbella* spp, *Synedra cunningtonii* (G.S West) which contributed less than 10% to the total diatom count were also observed.

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

diatom count. The vertical profile of the abundance of planktonic and benthic taxa is shown in figure 6.

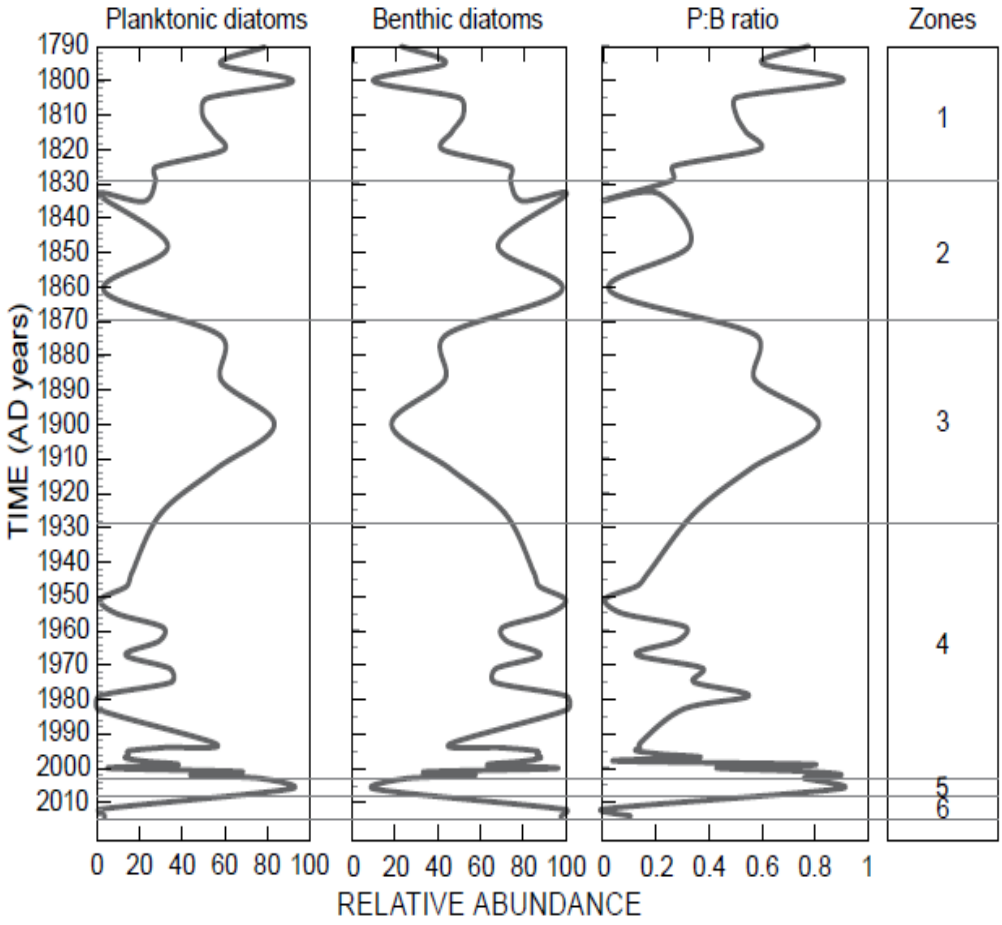

Figure 6. Profile diagram of Planktonic, Benthic diatoms, and P/B ratio of Lake Baringo sediments from the period between AD 1790 and AD 2014

4.3 Depth profile of diatom abundance and Biogenic silica

The 285 cm sediment package of Lake Baringo is characterized by varying levels of diatom abundance as shown by both biogenic silica and total diatom frustule count (Fig 7). The bottom most section of the core shows a gradual increase in diatom abundance and peaks to a mean of 125.33±342 at around 276 cm. This trend is also seen in the level of biogenic silica which starts at a lower level of about 40 mg l^{-1} at the base of the core and increases steadily to about 80mg/l at around 276 cm. This is followed by an irregular pattern of rising and falling of diatom abundance to about 224 cm as seen by both biogenic silica and diatom frustule count. A more uniform increasing trend in diatom abundance was seen at 216 cm where the number of frustules counted per gram of the dry sediment increased steadily towards 184 cm. However, the increase in biogenic silica at this point was not well

pronounced as that of the diatom frustule counts. A notable decline in diatom abundance as well as the level of biogenic silica was observed between 176 cm and 160 cm where the mean value of diatom counts was below 15 frustules while the level of biogenic silica was below 40 mg l^{-1}. This poor diatom abundance was followed by an increase towards 112 cm after which the abundance declined again to a mean value of less than 1frustule/gram of sediment around 48 cm.

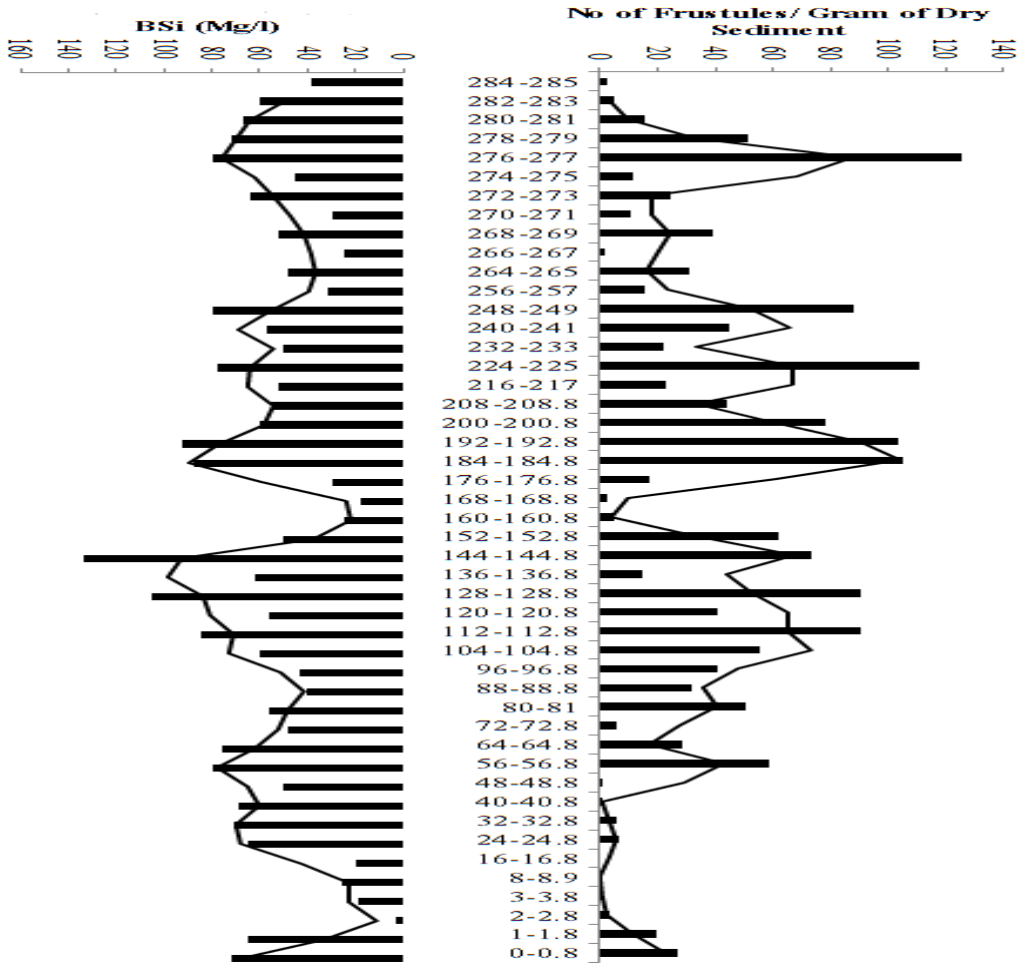

Figure 7. Vertical profile of diatom abundance and biogenic silica (BSI)

The figure further shows a declining trend of biogenic silica level from about 120 mg l^{-1} at 144 cm to about 60 mg l^{-1} at 48 cm. The diatom abundance remained low towards the top of the core until around 2 cm when it started to rise again to a mean value of 26.71±77.98 frustules at the sediment surface. The increase in biogenic silica observed at about 2 cm towards the sediment surface is directly related to the abundance of diatom frustules. However, there was no significant difference in the level of biogenic silica for the entire column of the core (One Way ANOVA, df = 46, p = 0.133).

4.4 High – resolution Magnetic Susceptibility (MS)

The Magnetic Susceptibility (MS) of the sediment profiles of BAR14-2P (Fig. 8) show a slight development from the base of the core, starting with low values around the desiccation layer to about 100×10^{-5} m^3/kg towards 280 cm. This is followed by a comparatively wider stretch from 280 cm to 272 cm where the level of MS declines to a value of about 50 $\times10^{-5}$ m^3/kg. Above this layer is a narrow stretch from 272 cm to 266 cm which is characterized by a fluctuating pattern in MS values with the highest peak occurring at around 268 cm and the lowest around 270 cm.

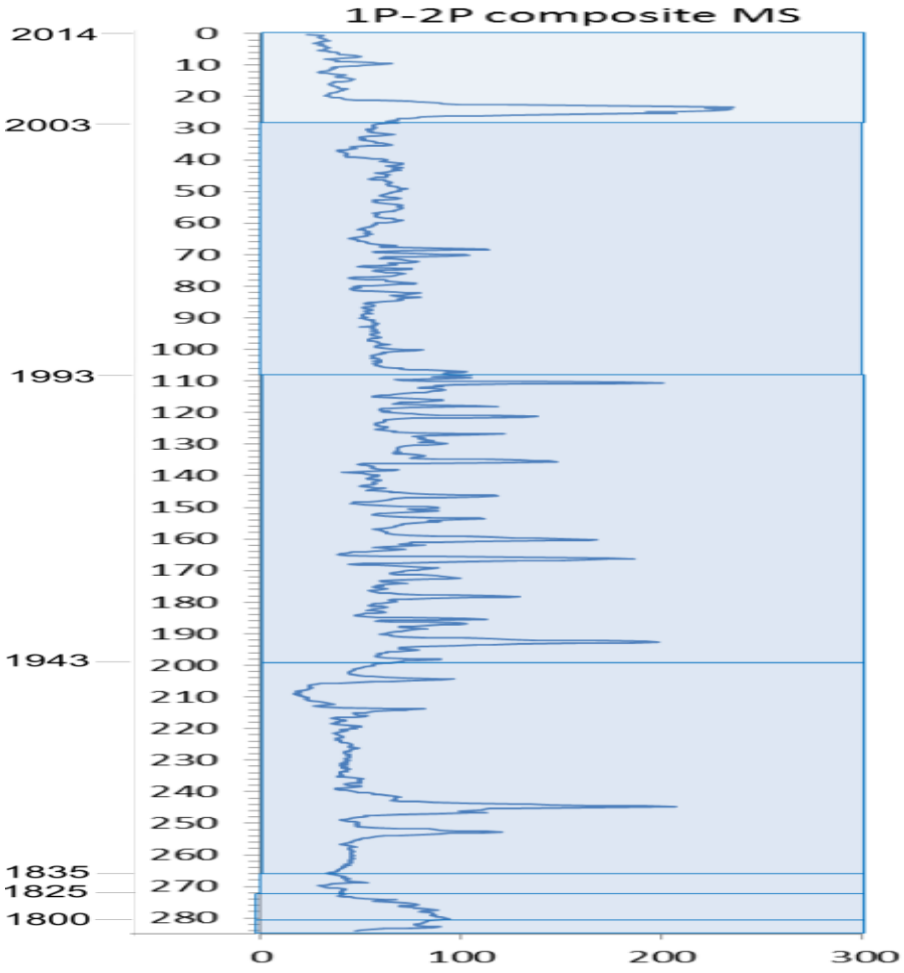

Figure 8. Trend in MS values of core BAR14-2P from Lake Baringo

From 266 cm, the MS profiles show increasing trends characterized by oscillating minor and major peaks with the major peaks extending over 200 $\times10^{-5}$ m^3/kg. The layer between 266 cm to 199 cm has one major peak with a value of slightly above 200×10^{-5} m^3/kg at around 245 cm and three minor peaks with MS value slightly above 100×10^{-5} m^3/kg around 254cm, 214cm and 204cm. In between the high MS peaks, the values remain relatively constant with a value of about 50×10^{-5} m^3/kg. However, the lowest value between 266 cm and

199 cm is below 50×10^{-5} m^3/kg and occurs at around 208cm. The next stretch extends from 199 cm to 108 cm which is characterized by elevated and unstable levels of MS values with several major peaks of over 200×10^{-5} m^3/kg and minor peaks of about 150 $\times10^{-5}$ m^3/kg. Between 108 cm and 28 cm there is a more uniform level of MS value of below 100×10^{-5} m^3/kg except for minor peaks at around 70cm with values slightly above 100×10^{-5} m^3/kg. The top-most section of the core extends from 28cm to the sediment surface. This has a major peak at about 26cm with a value of over 200×10^{-5} m^3/kg. At around 22cm, the MS values drops below 50×10^{-5} m^3/kg and this declining trend continues towards the sediment surface.

4.5 Spatial and Temporal variation in physico-chemical parameters

The average temperature of the lake during the entire study period was 27.39±1.19^{o}C. Spatially, the water became warmer towards the north during both seasons. The mean temperature during the dry season was 25.96 ±0.70^{o}C at the south, 26.62±0.29^{o}C between the islands and 27.58 ±1.40^{o}C at the north. During the wet season the mean temperature was 27.91±0.73^{o}C at the southern end, 28.03±0.50^{o}C at the central and 28.73±0.47^{o}C towards the north. However, temperature did not differ significantly between the stations (One Way ANOVA, $F_{(2, 24)} = 3.09$, $p = 0.064$). The lowest temperature of 26.13±1.01^{o}C was recorded during the month of January, 2015 while the warmest month was July 2015 with a mean temperature of 28.66±0.67^{o}C. Wet months were significantly warmer than the dry months (T-test, n =27, p =0.000)

The pH in the lake ranged between 8.24 and 8.99 at the south, 8.29 and 9.00 at the center and 8.59 to 9.08 towards the north. The month of July 2015 recorded the lowest pH of 8.44 while the month of December 2014 recorded the highest pH of 9.01.

The average conductivity of the lake during the entire study period was 463.26±4.95µS/cm. The mean conductivity of the lake during the dry period was 464.20±3.59 µS/cm while that during the wet months was 462.08±6.23µS/cm. Conductivity did not show any significant variation both on spatial scale (One Way ANOVA, $F(2, 24) = 0.96$, $p = 0.397$) as well as temporal scale (One Way ANOVA, $F_{(8,18)} = 2.20$, $p = 0.078$). There was also no significant difference between the two seasons (T-test, $n = 27$, $p = 0.311$).

The average dissolved oxygen concentration of the lake during the entire study period was 7.13±0.19 mgl^{-1}. During the dry months, the mean concentration of DO was 7.10±0.21 mgl^{-1}while that during the wet months was 7.18±0.15 mgl^{-1}. There was no spatial difference in the level of dissolve oxygen during the study period (One Way ANOVA, $F_{(2, 24)} = 1.27$, p =

0.299). The level of DO during the dry and wet seasons did not show any significant difference (T-test, n =27, p = 0.274).

Transparency during the study period was highly variable with a mean of 84.25±20.07cm. The average transparency during the dry month was 100.54±9.95cm while that during the wet month was 63.88±3.40cm. The lake transparency did not differ significantly along the south-north transect of the lake (One Way ANOVA, $F_{(2, 24)} = 0.12$, $p = 0.889$). However, significant variation was detected between the seasons where dry season was found to be significantly clearer than the wet season (T-test, n =27, $p < 0.05$).

4.6 Spatial and Temporal variation in nutrients and chlorophyll a

The mean concentration of nitrite nitrogen (NO_2-N) during the whole study period was 8.79±5.32 μgl^{-1}. Mean nitrite concentration during the dry months was 7.93±3.54 μgl^{-1} while that during the wet months was 9.95±7.11 μgl^{-1}. There was no significant spatial difference in nitrite levels (One Way ANOVA, $F_{(2, 24)} = 0.00$, $p = 1.000$). The two seasons did not show any significant variation in nitrite concentration (T-test, n =27, p = 0.842, Fig. 9a).

The mean concentration of nitrate nitrogen (NO_3-N) during the study period was 0.87±0.02 mgl^{-1}. The mean concentration during the dry months was 0.87±0.01 mgl^{-1}while that during the wet months was 0.88±0.03 mgl^{-1}. There was no significant spatial difference in nitrate levels (One Way ANOVA, $F_{(2, 24)} = 0.05$, $p = 0.948$). However, there was significant variation among the months (One Way ANOVA, $F_{(8, 18)} = 27.93$, $p = 0.000$, Fig. 9b). Further, the two seasons also showed significant variation in nitrate concentrations (T-test, n =27, p = 0.002, Fig. 9c) where the mean nitrate levels during the dry months was significantly lower than the mean concentration during the wet months.

The mean concentration of ammonium nitrogen (NH_4-N) during the whole study period was 29.95±11.02 μgl^{-1}. The mean ammonium concentration during the dry months was 28.65±5.66 μgl^{-1}while that during the wet months was 31.59±15.63 μgl^{-1}. There was no significant spatial difference in ammonium concentration (One Way ANOVA, $F_{(2, 24)} = 0.08$, $p = 0.926$). However, there was significant variation among the months (One Way ANOVA, $F_{(8, 18)} = 3.11$, $p = 0.022$, Fig. 9d).

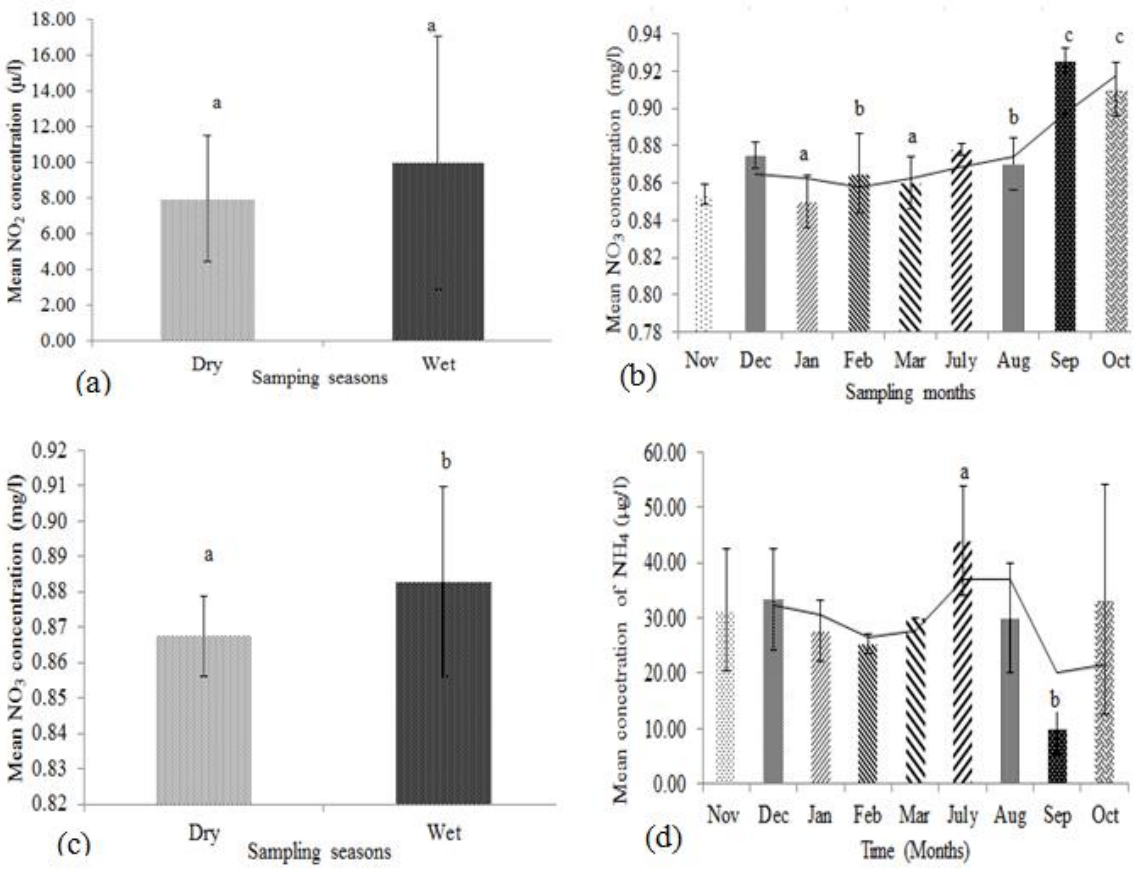

Figure 9. Temporal variation in Nitrite, Nitrate and Ammonium in Lake Baringo *(NB: Means followed by the same letter are not significantly different)*

The mean concentration of total phosphorus (TP) during the study period was 38.63±16.82 µgl^{-1}. The mean TP concentration during the dry months was 31.31±6.57 µgl^{-1}while that during the wet months was 55.33±9.98 µgl^{-1}. There was no significant spatial difference in TP levels (One Way ANOVA, $F_{(2, 24)} = 0.72$, $p = 0.495$). The mean TP concentration in the lake during the wet season was significantly higher than the mean concentration during the dry season (T-test, n =27, $p = 0.000$, Fig. 10a).

Mean concentration of chlorophyll *a* during the study period was 30.15±7.31 µgl^{-1}. The mean chlorophyll *a* concentration during the dry months was 25.79±6.92 µgl^{-1} while that during the wet months was 34.81±4.28 µgl^{-1}. There was no significant spatial difference in ammonium levels (One Way ANOVA, $F_{(2, 24)} = 0.92$, $p = 0.412$). However, the two seasons showed significant variation (T-test, n =27, $p < 0.05$) with the concentration during the wet season being significantly higher than that during the dry season (Fig. 10b).

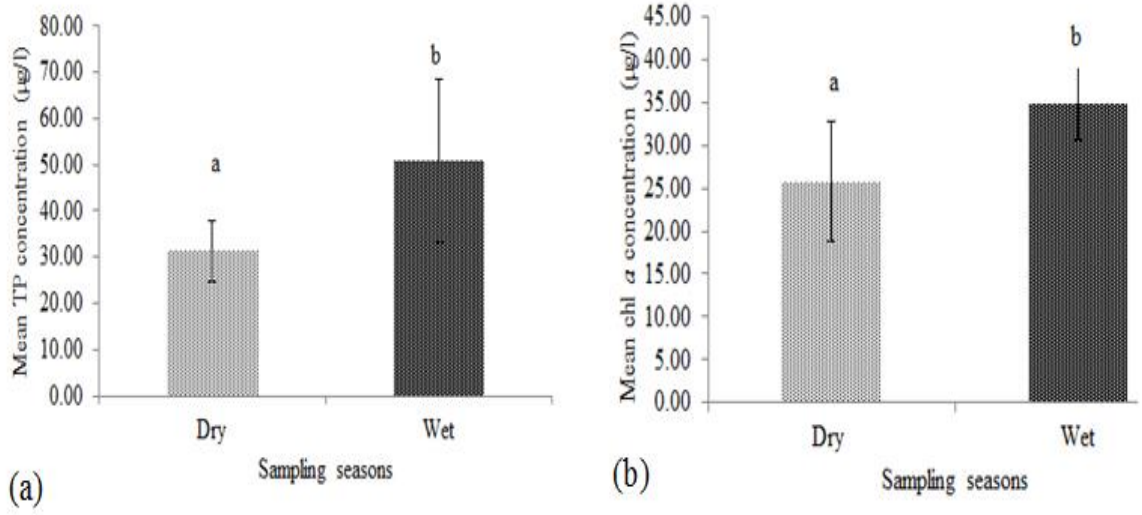

Figure 10. Temporal variation in Total phosphorus and Chlorophyll *a* in Lake Baringo *(NB: Means followed by the same letter are not significantly different)*

The mean DIN/TP ratio during the whole study period was 44.49±34.67. During the dry season, mean DIN/TP ratio was 43.33±22.30 while that during the wet season was 41.46±40.73.

4.7 Trophic state index

The trophic state index calculated for the dry months of the study period were TSI_{CHL} 61.35, TSI_{TP} 53.67 and TSI_{SD} 60.35 while that during the wet months were TSI_{CHL}63.66, TSI_{TP}56.35 and TSI_{SD} 67.03. The combined TSI during the entire study period were TSI_{CHL}61.41, TSI_{TP}53.75 and TSI_{SD}61.33. The trophic status of Lake Baringo was calculated based on the average of TSI_{CHL}, TSI_{TP} and TSI_{SD}. The average TSI based on the above parameters during the dry month was 58.23 while that during the wet months was 62.34. Carlson TSI of the lake during the entire study period was 58.53 (Table 5)

Table 5. Trophic State Indices based on Chlorophyll *a*, TP and SD of Lake Baringo

	Dry season	Wet season	Mean TSI
TSI_{CHL}	61.35	63.66	61.41
TSI_{TP}	53.67	56.35	53.75
TSI_{SD}	60.35	67.03	61.33
CTSI	58.23	62.34	58.53

CHAPTER FIVE

DISCUSSION

5.1 Introduction

The evidence gained from the stratigraphic analysis of core BAR 14-2P provides consistent evidence for lake-wide changes in the ecology of Lake Baringo over the last 200 years. The sediment records reveal differences in the prevalence of benthic and planktonic diatom taxa, varying levels of sediment Magnetic Susceptibility and Biogenic silica. This provides evidence to differentiate the allochthonous components to that produced within the lake at different times during the 200 year history. The variations in proxy records reveals temporal variations in the way the lake responded to shifts in climate of this area.

5.2 Changes in trophic state of Lake Baringo in the last 200 years

5.2.1 Eutrophic phase of AD 1790s-AD 1820s

The bottom most section of the core dated around AD 1790 represents the initial refilling of the lake after the prolonged drought that led to its complete drying towards the end of the 18^{th} century (Bessems *at al.* 2008; Kiage and Liu, 2009b). This transgression began with a shallow eutrophic lake environment as evidenced by the presence of indicator diatom taxa such as *Synedra ulna* which prefers elevated nutrient conditions and *Fragilaria capucina* which is an indicator of eutrophic conditions (Gasse, 1986). The ratio of Centric to Pennate (C/P) diatoms showed that the lake had elevated nutrient levels typical for a eutrophic system. The source of these nutrients could be the decomposition of organic materials that were deposited in the basin during the dry period. This is because when the lake was completely dry, the basin most likely was open to terrestrial animals and plants. These produced organic materials which decomposed under flooding hence releasing nutrients. Nutrient availability in the water column was enhanced by turbulence and re-suspension of sediments from the bottom. The existence of turbulent conditions is indicated by the presence of *Aulacoseira granulata* which has been reported to prefer turbulence and can tolerate some level of turbidity (Haberyan and Heckey, 1987).

The high nutrient levels that prevailed can be taken to be responsible for the gradual increase in the level of Biogenic silica as well as diatom production hence their abundance from the base of the core towards 276 cm dated AD 1810. Ideally, it would be expected that the bottom section of the core dated around AD 1790, representing the desiccation layer would have no diatom frustules since the diatom flora would need some time to establish in

the new aquatic environment. However, the diatom frustules that were counted at this point also include remains derived from the reworked sediments of the previous lake regime.

Although the relative importance of the different rivers in transporting materials into the lake cannot be determined by the scope of the current study, and that it is difficult to tell whether all the rivers currently flowing into Lake Baringo has been in existence since 200 years ago, there is evidence to show that indeed surface runoff played significant role in refilling the lake basin after the prolonged drought. The first line of evidence is seen in continuous rapid rise in the level of magnetic susceptibility from the bottom of the core around AD 1790 to around AD 1795. As more water was brought in by the rivers, allochthonous materials of inorganic nature and therefore higher magnetic content was brought in from the catchment. The second line of evidence to support the role of the rivers in refilling the lake is the presence of diatom taxa known to inhabit both lotic and lentic systems such as *Gomphonema clevei* and *Navicula cuspidata* which were brought into the lake by the inflowing rivers. Further, the presence of aerophilous or 'air loving' diatoms such as *Navicula mutica*, *N. hassiaca* and *Hantzschia amphioxys* (Van Kerckvoorde *et al.* 2000) can be interpreted to mean increased catchment erosion leading to accelerated in-wash of species living in the soils around the lake.

From the base of the core (284 cm) dated around AD 1790 it was observed that the level of magnetic susceptibility increased towards 280 cm then declined towards 270cm. The rising arm of the MS curve represents the decomposition phase of the organic matter before sufficient nutrient accumulation to warrant significant autochthonous production during the transgression process. This can also be taken to be the period of re-colonization of the new environment by other groups of primary producers. The falling arm of the curve represents the phase of increased autochthonous production and the deposition of organic matter with low magnetic content.

The high abundance of *Aulacoseira* during this period of elevated nutrient concentration can be explained by the fact that members of this genus are heavily silicified hence have an accelerated sinking rates. As such, they require turbulence to remain suspended within the trophogenic zone (Bradbury *et al.* 2002), furthermore, they are often found in shallow eutrophic lakes (Rioual *et al.* 2007). Therefore increased turbulence and corresponding nutrient increase during the low water stage favored this genus over other planktonic species.

5.2.2 Oligotrophic –Mesotrophic phase of AD 1830s to AD 1860s

A decline in the nutrient level of the lake which reduced the trophic status occurred between AD 1830 to AD 1861 and lasted for about 4 decades. Biogenic silica as well as diatom stratigraphy provides sufficient evidence for the decline in the nutrient level of the lake. The ratio of centric to pennate (C/P) diatoms was below 1 which according to Nygaard, (1949), shows that the lake was oligotrophic.

The poor diatom community structure and the low abundance of diatom frustules that was observed around AD 1833 and AD 1848 could also be due to decline in the level of nutrients hence limiting the level of the lake productivity and that of the diatoms. The dominance of benthic diatom communities over the planktonic forms as shown by P/B ratio less than 0.5 confirms the existence of clear nutrient poor conditions with light penetration down to the lake bottom. The observed increase in the sedimentation rate from 0.4cm/year between AD 1790s and AD 1820s to 0.6cm/year after AD 1825 can be attributed to increase in surface runoff and hence flooding. This is shown by the presence of flood indicator taxa such as *Gomphonema parvulum* (Johan *et al.* 2009).The increasing trend in the level of magnetic susceptibility around this time indicates the presence of floods, it also means that autochthonous production was low hence deposition of materials with high magnetic content from the catchment.

5.2.3 Mesotrophic-Eutrophic phase of AD 1870s to AD 1920s

A positive shift in the trophic status of the lake occurred between 240 and 216 cm of the core dated between AD 1870 to AD 1920s. The presence of indicator species such as *Fragilaria capucina* confirms the existence of this state. The ratio of centric to pennate diatoms was between 3 and 5 meaning that the lake was eutrophic. The increase in nutrients level which led to shift in the lake productivity is also shown by the high abundance of diatom frustules observed during this time as well as increasing trend in the level of biogenic silica. Further, this period shows a declining trend in the level of Magnetic Susceptibility implying that the materials of low magnetic content derived from autochthonous production dominated the sediment.

5.2.4 Oligotrophic – Mesotrophic phase of AD 1930 to AD 2000

Diatom stratigraphy confirms the presence of low nutrient levels as shown by the presence of *Fragilaria capucina*. This species has been described by Gasse, (1986) as a eutrophic indicator but also develops optimally under oligotrophic systems. The high diatom

abundance around AD 1950 cannot be interpreted to mean increase in lake nutrient level. Since this coincides with periods of high MS values, it signifies a period of high erosion which possibly transported lotic diatom taxa into the lake (Holmgren *et al.* 2011). The increased water input through surface run off possibly increased the lake water level hence expanding the habitat available for littoral species such as *Navicula gawaniensis* and *Nitzschia umblicuta*. Therefore, the high diatom abundance was as a result of different species from the littoral, lotic and planktonic habitats. While determining the trophic state of the lake using the ratio of Centric to Pennate diatoms, during this period, the poor lake productivity and low nutrient levels is confirmed by the fact that the ratio was below 3 therefore meaning that oligotrophic-mesotrophic conditions prevailed.

The poor diatom community structure around AD 1955 and AD 1963 is a clear indication of low lake productivity. Secondly, MS values show high peaks around this time meaning that the sediment is made up of allochthonous materials with high magnetic content as compared to autochthonous component of low magnetic properties. During this interval, the lowest abundance in diatom community structure was observed around AD 1975. This time coincides with a peak in MS values representing allochthonous dominance in the deposited materials hence low productivity under low nutrient levels. The highest diatom productivity as shown by diatom abundance was found around AD 1979. Although this indicates increase in the general lake productivity, no diatom taxa specialized for high nutrient levels were recorded. Additionally, the C/P ratio shows the existence of oligotrophic conditions.

Another low abundance of diatoms was observed around AD 1983 which also coincided with another peak in the level of magnetic susceptibility. This was another period of low lake productivity since allochthonous materials with high magnetic content dominated the sediment. This low productivity is confirmed by the poor diatom community structure observed during this time where only two diatom genera i.e. *Navicula* spp and *Cymbella* spp. dominated the community structure. This time was interrupted by a short mesotrophic phase sometimes around AD 1993 as shown by the C/P ratio. A minor peak in MS values was observed around AD 1998 reflecting increased erosion and reduced autochthonous production.

5.2.5 Eutrophic-Hypertrophic phase of AD 2001 to AD 2009

The low levels of MS values observed during this time suggests the deposition of autochthonous materials with low magnetic content, mainly organic matter, thus suggesting increased lake productivity. Further, the C/P ratio shows that the lake had elevated nutrient levels typical of eutrophic to hypertrophic conditions. These results are in good agreement with the work of Ballot *et al* (2002) who recorded TP concentrations of 1.0 mg l^{-1} and TN levels of 2.8 mg l^{-1} typical for hypertrophic lakes, in Lake Baringo. Oduor *et al* (2003) measured mean TP concentration of 365µg l^{-1} and mean Chl - *a* of 55.2µg l^{-1} typical for hypertrophic lakes according to OECD, (1982) trophic classification system.

The high diatom productivity and abundance as reflected by elevated levels of biogenic silica around AD 2003 and AD 2006 represent the time with the highest concentration of nutrients. This was also probably the period when the lake was most turbid as shown by the 90% dominance of the planktonic forms during the entire 200 year history. The main source of this nutrient could have been nutrient re-suspension from the bottom of the lake under wind turbulence which also causes some level of turbidity. The reason for the absence of diatom frustules around 16 cm (dated AD 2009) is not clear.

5.2.6 Mesotrophic phase of AD 2010 to AD 2014

Towards the sediment surface, the dominance of benthic *Synedra cunningtonii* agrees with the fact that benthic productivity increases under low nutrient, and clear water conditions. This is also shown by the C/P ratio which was <3 implying existence of a nutrient poor lake hence low primary production.

5.3 Limnological characteristics of Lake Baringo as reflected in water samples

5.3.1 Physico-chemical parameters and Nutrients

Small tropical lakes have been shown to exhibit slight spatial variations in their environmental variables (Sarma *et al.* 2005). As such, the slight variations in the physicochemical parameters between the sampling stations can be partly attributed to daily wind induced mixing coupled with its small size. A difference in temperature variations was observed along the south-north transect where the waters of the northern end were found to be warmer than the waters of the southern end. This could be attributed to the differences in the time of sampling. The southern end was sampled at around 0900 hours while the northern end was sampled around 1200 hours when the sun is directly overhead. This was also observed by Omondi *et al* (2014). The variation in lake water temperature with time comes

due to mixing pattern where the lake mixes completely at dawn due to regular wind on the water surface but stratifies at daytime thus creating a stable thermocline with a warmer epilimnion (Oduor *et al.* 2003). The wet months were also found to be warmer than dry months. This could be attributed to increase in the amount of suspended materials which enhance absorption of solar energy (Wetzel, 2001) as reflected in the significant reduction in Secchi depth during the wet season. Previously, Patterson and Kiplagat, (1995) attributed the high temperatures of Lake Baringo to suspended materials.

The level of nutrients during the wet season was found to be higher than during the dry season. This could also be attributed to inflow of materials from the catchment into the lake. This resulted into increase in the phytoplankton productivity as reflected by higher chlorophyll *a* concentration during the wet season.

5.3.2 Trophic state

Lakes are dynamic systems and can shift the degree of their trophic status on a temporal scale. Water bodies are often classified either as, oligotrophic (low nutrient content), mesotrophic (moderate nutrient content), eutrophic (high nutrient content) and hypertrophic (very high nutrient content) (Carlson, 1977). The trophic state classification of water bodies is an important management tool which allows comparison between ecosystems within and among different ecoregions as well as offering an idea of the extent of cultural eutrophication suffered by the system. Environmental data, such as the concentration of total phosphorus (TP), total nitrogen (TN), chlorophyll *a* (Chl *a*) as well as Secchi depth are basic trophic state indices (Vollenweider, 1989).

The mean values of TP, Secchi disk transparency and chlorophyll *a* measured during dry months were 30.96µg/l, 0.98m and 24.5µg/l while the mean values measured during the wet months were 42.02µg/l, 0.64m and 36.51 µg/l respectively. The overall mean values of the above parameters during the entire study period were 32.17µg/l, 0.94m and 25.82µg/l for TP, SD and Chl *a* respectively. Based on the OECD, (1982) 'open limit' as well as Carlson, (1977) trophic state classification, and considering chlorophyll *a* and Secchi depth values, The mean value of 0.5 m which was measured for Secchi disk towards the end of the study period in October 2015 is characteristic of a Hypereutrophic system. However, this is doubtful since the low transparency of the lake has been associated with suspended inorganic matter, not algal density (Oduor *et al.* 2003). Additionally, the use of Secchi disk transparency to estimate Chlorophyll *a*, and hence trophic state, has been criticized because of the light diminution effect of abiosestons (Lorenzen, 1980). Taking into consideration the

seasonal fluctuations along with the mean and maximum values of the co-examined nutrient (i.e. Phosphorus), it is suggested that the lake exhibits eutrophic characteristics. While determining the trophic state using Carlson trophic state index (CTSI) using the mean of the above parameters, it is evident that the waters of lake Baringo fall in the eutrophic category during both seasons (Table 6).

Although the trophic state of Lake Baringo shows no sensitivity to season, reflected by change in the amount of rainfall, other lakes within the Kenyan rift have been shown to shift their trophic status with the change in the amount of rainfall (Kitaka *et al.* 2002).

Table 6. Variations in the trophic state of Lake Baringo during the dry and wet season

	Dry season	Wet season
TSI_{CHL}	61.35	63.66
	Eutrophic	Eutrophic
TSI_{TP}	53.67	56.35
	Eutrophic	Eutrophic
TSI_{SD}	60.35	67.03
	Eutrophic	Eutrophic
CTSI	58.23	62.34
	Eutrophic	Eutrophic

5.3.3 Factor limiting phytoplankton growth in Lake Baringo

Deviations in Trophic state indices based on TP, Chl *a* and SD have been used to draw inferences regarding factors that may be limiting autochthonous production in lake systems. Based on Havens, (2000), when TSI_{CHL} is lower than $TSI_{TP,}$ it indicates that there is less algal material present than expected based on phosphorus concentration and that some other factors other than phosphorus may be limiting phytoplankton production. If TSI_{CHL} is less than TSI_{SD} it suggests that seston is dominated by very small (abiotic) particles which encourage high light diminution and that light may be limiting algal production. Based on this, it was evident that light limitation in Lake Baringo occurs during the wet season as a result of turbidity caused by suspended non-algal particles (Table 7). When TSI_{CHL} is equal to or greater than TSI_{TP} then phosphorus is likely to be limiting the algal growth. The deviations between TSI_{CHL} and TSI_{TP} in Lake Baringo provide evidence for existence of phosphorus limitation (Table 7). The deviations in TSI to infer nutrient limitation in lakes have also been used by An and Park, (2003) and Lee *et al* (2010).

Using the nutrient ratios based on Axler *et al* (1994), phosphorus is not limiting when DIN/TP fall below 4. Nitrogen co-limitation with phosphorus is indicated when DIN/TP

ratios are between 1.3 and 4. These ratios also support the discussion that phytoplankton development in Lake Baringo is limited by phosphorus supply and that there is no evidence for co-limitation with nitrogen (Table 7). Phosphorus limitation in Kenyan Rift Valley lakes has also been shown by Kalff, (1983), who supported the hypothesis of primary phosphorus limitation for lakes Oloidien, Naivasha and Sonachi and therefore contradicting a wide range of literature suggestions that nitrogen is the primary limiting nutrient in tropical lakes.

Table 7. Phosphorus and light limitation in Lake Baringo as shown by TSI deviation concept

	TSI_{CHL}- TSI_{TP}	DIN/TP ratio	TSI_{CHL}- TSI_{SD}
Dry season	6.36	23	0.67
	P Limited	P limited	Light not limited
Wet season	12.09	14.83	-3.37
	P Limited	P limited	Light limited
Mean	6.93	18.91	-1.35
	P Limited	P limited	Light limited

5.4 Water level Fluctuations.

Reconstructions of past lake level changes have been used increasingly to provide *paleo*-climatic perspectives (e.g, Magny *et al.* 2007) especially changes in the amount of precipitation. In Lake Baringo, it has been established that the lake is sensitive to variations in the amount of precipitation where, high water levels coincide with periods of above average rainfall while low water level coincides with episodes of below average rainfall (Omondi *et al*. 2014).

5.4.1 Interpretation of P: B ratio

Planktonic diatoms often dominate the open water environments while benthic diatoms and tychoplanktons (accidental plankton) dominates littoral habitats. In freshwater lakes, variation in the ratio of planktonic to benthic diatom taxa has been used to infer water level fluctuations (Barker *et al.* 1994; Hyvarinen and Alhonen, 1994; Wolin, 1996; Tapia *et al.* 2003; Stone and Fritz, 2004; Bergner and Trauth, 2004; Wilson *et al.* 2008). In large and deeper lakes such as Lake Victoria, a high P:B ratio is interpreted to mean dominance of planktonic diatoms and low abundance of shallow water diatoms under increase in water level while a low P:B ratio means dominance of shallow water diatoms under low water level accompanied by light availability (Stager *et al.* 2005). However, in shallow eutrophic lakes the productivity of planktonic diatoms exceeds that of benthic forms (Wolin, 1996;

Vadeboncoeur *et al.* 2008). Further, water level decline in these shallow systems results in reduced benthic habitat due to turbidity-driven light limitation (Jeppesen *et al.* 2000; Gattuso *et al.* 2006). According to Noges *et al* (2003), an overall decline in diatom productivity can occur during low-water phases in shallow lakes due to light limitation in benthic communities. As a result, the poor light climate becomes available only for few planktonic forms within the top thin layer of the water column (Oduor *et al.* 2003). Turner *et al* (2005) studied the effect of lake level decline on algal communities, and reported no significant change in the planktonic taxa while the benthic algae declined due to disruption of habitat and loss of colonizable area. If water level falls, sediments become more exposed to wave-induced re-suspension (Noges and Noges, 1999) leading to high turbidity in the water column and light limitation in the benthos. Moreover, stronger re-suspension at low water levels leads to release of phosphorus from the sediment which has a positive effect on plankton community (Noges and Noges, 1999).This increases the P:B ration due to dominance by planktonic diatom taxa.

A low P:B ratio means dominance of benthic taxa under increased water level and high light penetration due to low turbidity as a result of reduced sediment re-suspension. Since these small shallow lakes depend on nutrient recycling from the bottom, increase in water level also causes nutrient dilution and this further reduces the production of planktonic taxa. Omondi *et al* (2014) found a negative correlation between conductivity and water depth in Lake Baringo and attributed this partly to increased evaporation during drawdown and dilution effect of high water levels. Increase in ionic concentration in lakes during low water levels has also been shown by Swaine *et al* (2006).The high lake level also increases the benthic habitat due to flooding hence increased productivity and abundance of benthic taxa (Wilson *et al.* 2008).

5.4.2 Early 19th Century (AD 1790s - AD 1820s)

The bottom of the core, dated between AD 1790 and AD 1800, was characterized by a high P:B ratio of between 0.8 and 0.9 implying the dominance of planktonic diatoms mostly represented by *Aulacoseira* spp. This means the existence of a shallow lake environment. This is because *Aulacoseira* species are heavily silicified diatoms with high sinking rates. Their ecology requires turbulence to remain in the photic zone (Bradbury *et al.* 2002) and they are often found in shallow eutrophic lakes (Rioual *et al.* 2007). Increased turbulence and corresponding nutrient increases during low water stages in a lake can favor this genus over other planktonic species. The presence of *Thalassiosira faurii* also indicates periods of low

lake level and increase in salinity due to evaporation since this species has been shown to be tolerant to high salinity (Gasse, 1986). During the same period, Lake Victoria experienced the lowest water level (Stager *et al.* 2005), Lake Rukwa totally dried up (Owen *et al.* 1990), Lake Turkana sunk to very low level and Lake Naivasha was reduced to a puddle (Verschuren, 1999). During the same time, the Nile floods were extremely low and Lake Chad was desiccated (Nicholson, 1995). According to Nicholson (2001), swamps, rivers and wet plains across Africa were left dry with farmers and communities complaining of low rainfall. These observations are attributed to the wide spread drought of the late 18th Century which was probably most extreme during the early parts of the 19th century (Nicholson, 1999; Nicholson and Yin, 2001). Anderson, (2016) describes this event as the most severe drought experienced in the Eastern Africa region in 750 years and defines it as "the catastrophic drought of the early 19th century". Although the effects of this drought were severely felt in Eastern Africa, no instrumental rainfall data exists for this period (Fig. 11a).

5.4.3 Mid -19th Century (AD 1830s – AD 1860s)

After AD 1820s, there was a rapid increase in the lake level up to AD 1861, during which the P:B ratio remained below 0.5 due to dominance by benthic diatom taxa over planktonic forms. Similar transgression episodes were also observed in other lake of East Africa. Around AD 1858, Lake Rukwa covered a reasonably large surface area compared to the low stand of the early 19th century (Hobley, 1914). Nicholson and Yin, (2001) reconstructed levels of 10 lakes spanning latitude 15^{0}N and 22^0 S. They suggested that climatic episode of the mid-19th century was marked by extremely high stands of East African lakes. Lake Malawi, Chad, Tanganyika, Victoria and Naivasha rose between 3 to 10m above their early 19th century stands (Nicholson and Yin, 2001). Nicholson, (2001) reported that during the mid-19th century, most African lakes recovered from the low levels of the early 19th century with some achieving very high stands. Although rainfall data during this period is sporadic, available data provides that wet conditions prevailed in East Africa at the time (Fig. 11b).

5.4.4 Late 19th Century – Early 20th Century (AD 1870s to AD 1920s)

The transgression of the mid-19th century was followed by a late 19th century lake level decline. During this time the P:B ratio was above 0.6 implying that planktonic diatom taxa contributed most to the total diatom assemblage. The low stand observed during this time was a direct response to a series of climate related drought that affected Baringo area

during the late 19th century and the early 20th century (Anderson, 2002). The existence of drought-induced shallow lake environment during this period is also confirmed by a number of evidence.

The first line of evidence lies in oral tradition pre-colonial histories. According to Thomson (1887), before AD 1850, Lake Baringo area was used by Arab traders and early European explorers as an important source of food for caravans moving from the East African coast towards the North and West of the African continent to trade ivory. However, in AD 1880s, European missionaries and explorers found Baringo in the middle of a serious drought and traders could not find food for their caravans. Another expedition led by Gregory in AD 1893, encountered drought in the area characterized by dry river beds (Gregory, 1896). Ambler (1988) recounted a series of droughts that occurred in the area towards the end of the 19th century leading to frequent wars between pastoralists and agriculturalists. The second line of evidence is provided by paleolimnological surveys of East African lakes. For example, Cort *et al.* (2013) described the late 19th to early 20th century drought as more severe than any other in recorded history in this region. This drought coincided with the worst known drought in Ethiopian history, which severely reduced the level of Lake Abiyata (Legesse *et al.* 2002).

According to other lake level reconstructions made in the region, this was also the period when Lake Tanganyika shifted from open to closed basin when surface outflow was cut due to negative shift in rainfall (Bootsma and Hecky, 1993). Similarly, outflow from Lake Malawi through the river Shire ceased around AD 1915 (Owen *et al.* 1990). Nicholson, (1999) attributed the abrupt drop of lake levels during this time to drastic climatic dislocation. The 20th century started with bellow average rainfall (Fig. 11c) signifying another period of aridity somewhat similar to the beginning of the 19th century. This caused severe and widespread droughts during the 1910s leading to a general concern over the desiccation of Africa (Nicholson, 2001).

5.4.5 Mid - Late 20th Century (AD 1930s - AD 2000)

Mid-20th century was characterized by wet conditions with a consequent increase in water level. Beadle, (1932) recorded that Lake Baringo depth was approximately 7.5m in AD 1932. Lakes throughout East Africa experienced spectacular rise in water level during the mid-20th century. According to Stager *et al* (2005), this is the period when Lake Victoria experienced its highest level of the century and Lake Tanganyika rose over two meters above the zero scale of the level gauge (Nicholson, 1999). Outflow from Lake Malawi resumed when water level rose by 6m (Beadle, 1981). Lake Baringo water level dropped briefly

during mid-AD 1950s following the relatively dry conditions which reoccurred after the extreme drought of the early 20th century (Nicholson, 1996), but increased towards AD 1980 as a consequence of abnormally wet conditions in the early 1960s and late 1970s (Nicholson, 1996) (Fig. 11d). According to Nicholson, (2001), a shift in climate occurred over equatorial Africa during the early1960s when there was an increase in rainfall which was about 20-40% above monthly means in magnitude (Nicholson, 2000) followed by a consequent increase in the levels of East African lakes (Nicholson and Yin, 2001) including lake Baringo. The stations of Wajir, Eldama and Lokitaung recorded abnormally high rainfall of 612, 402 and 302 mm, respectively, in November 1961, compared with monthly means of 58, 48 and 39 mm (Nicholson, 1996). Similar conditions but of a lesser magnitude reoccurred in 1963. Based on Ssentongo, (1995), the mean depth of Lake Baringo during the 1960s was 5.6m. This trend continued towards AD 1970s. Instrumental records show that in 1970s, the lake was over 8 m (Kallqvist, 1987) and 8.6 m deep in 1975 (Johansson and Svension, 2002). However, this transgression was interrupted by a short regression episode during the late 1960s towards early 1970s following a period of a brief dry spell (Nicholson, 1996).

The period between AD 1990 and AD 1994 witnessed a shallow lake environment as a response to below average rainfall over East Africa, (Fig. 11e). Wilson, (1989) recorded a mean value of 4m in March 1989. According to Hickley *et al* (2004), the depth of the lake in AD 1993 was below 3m. Between 1992 and 1994 there was severe drought in the region around Lake Baringo which caused drastic reduction in the water level. Subsequently the lake was closed down and no gillnet fishing was allowed except hook and line fishing permitted for a few fishermen (Aloo, 2002). From AD 1995 the water level increased towards AD 1998 through to AD 2000. Hickley *et al* (2004) reported that in 1998, the mean lake level was 4.5m. This transgression reflects the effects of El Niño rains of AD 1997-98 (Fig. 10e) which caused flooding (Birkett *et al.* 1999) and also affected other lakes in East Africa, including Lake Naivasha, whose water level rose by 2 m (Kitaka *et al.* 2002). These floods were accompanied by devastating economic, ecological, hydrological and agricultural impacts in East Africa (Conway, 2002). Further, these heavy rains were widespread and saw the levels of Lake Victoria, Tanganyika and Malawi rise by 1.7 m, 2.1 m and 1.8 m respectively (Birkett *et al.* 1999).

5.4.6 Early 21st Century (AD 2001 - AD 2014)

From AD 2001 to AD 2009, evidence for a shallow lake environment was observed during which the P:B ratio was ≥0.9 signifying the dominance of planktonic diatoms. In AD

2001 the lake was 2.1m deep (Johansson and Svension, 2002). Hickley *et al* (2008) as well as Bessems *et al* (2008) measured mean water depth of 2.65m in 2003 and Kiage and Liu, (2009a) measured the depth of Lake Baringo to be 2.5m in 2005. Between AD 2006 and AD 2009 the water level stayed low and was <4m in 2006 (Corrine *et al.* 2006) and 2.95m in 2009 (Omondi *et al.* 2014). These low levels were a direct response to a series of droughts that affected most parts of Kenya in AD 2005 and 2008/2009 when rainfall was in the magnitude of 25-80% below monthly mean (Nicholson, 2016) (Fig. 11f). Lake Baringo levels rose towards AD 2011. Low P:B ratio provides evidence to support a rising lake level towards AD 2014. Omondi *et al* (2014) who recorded a depth of 9.55m in 2012 as a consequence of heavy rainfall around AD 2010 towards AD 2012 which was 50-150% above the 1998 - 2014 mean (Nicholson, 2016) (Fig. 11f). By AD 2014 the water level had risen to 11.6m (Authors' field observation). However, the lake was already receding by 2015 in direct response to below average rainfall observed in AD 2013-14 (Fig. 11f).

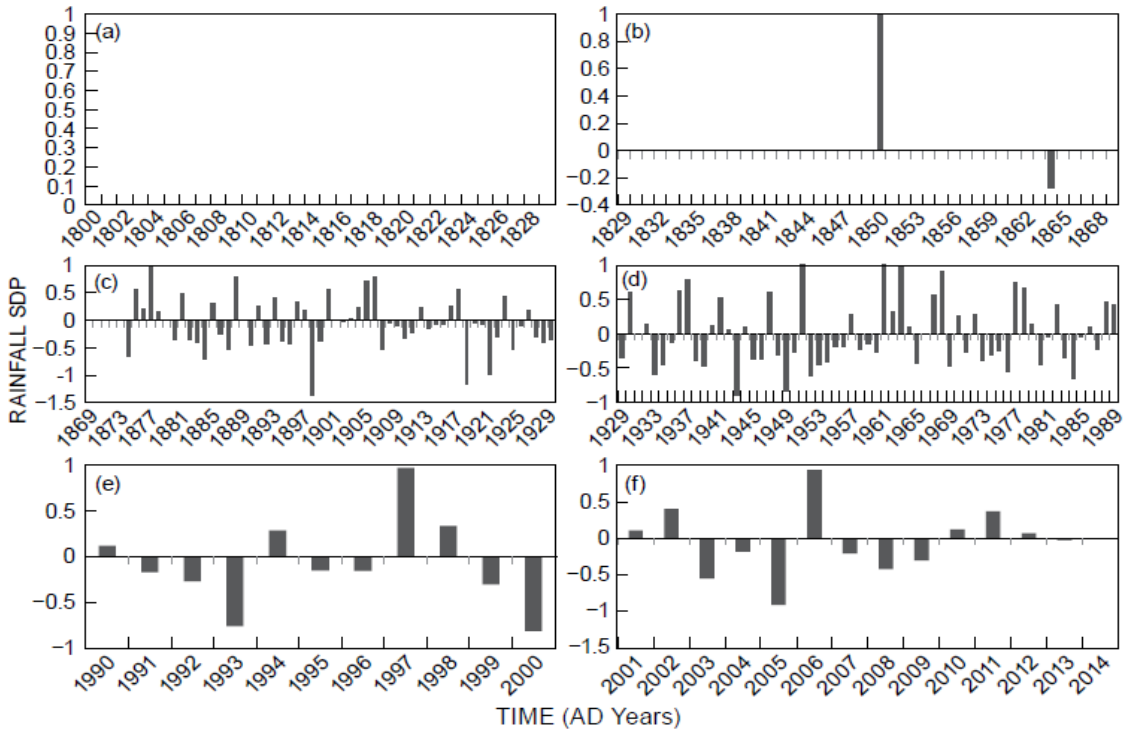

Figure 11. Rainfall fluctuations in east Africa (1800-2014), expressed as standardized departures ($X_{ij} = (r_{ij} - \bar{r}_i)/\sigma_i$). Where, X_{ij} is the annual rainfall departure, r_{ij} is the annual totals for station *i* in the year *j*, $\bar{r}_i$ is the long term mean for the station *i* and σ_i is the standard deviation of annual totals at station *i* (Nicholson, 1986). In the resultant time series, a value of +1/-1 indicates an average positive/negative anomaly of one standard deviation from the mean (Data used with permission from Sharon E Nicholson).

CHAPTER SIX
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

i. Abundance and species composition of fossil diatoms varied significantly during the 200 years. This implies that the sediments archive show distinct zones dominated by different life forms of diatoms species composition (P:B ratio) and their abundances thus providing evidence that Lake Baringo has had fluctuations in its water level over the years. The results show that climate plays major role in controlling water level. The lake level reconstructions show a pleasing correspondence between the inferred lake levels from the P:B ratio and historical accounts.

ii. Biogenic Silica concentrations in Lake Baringo did not vary significantly since AD 1800. However, minor differences are observed which corresponds and are interpreted together with other variables to show the alternating patterns in the trophic state of the lake during the 200 year history. Furthermore, trophic status of the lake increases under low water level and reduces as water level rises due to dilution effect.

iii. Nutrient concentrations, chlorophyll *a* and temperature levels were significantly higher during the wet season. Noteworthy is increase in non-algal turbidity leading to light limitation during the wet season. However, Lake Baringo trophic state shows no sensitivity to seasons associated with changes in precipitation. None of the physico-chemical and nutrient parameters showed significant variation on a special scale.

6.2 Recommendations

i. The correspondence between the inferred lake levels from the P:B ratio and historical accounts provides a level of confidence that P:B ratio can be used to infer lake levels and appears to be a useful tool in describing history of shallow lakes.

ii. Lack of significant difference in the levels of biogenic silica since AD 1800 in Lake Baringo sediments emphasizes the importance of a multi-proxy approach in this kind of study to compensate for information loss.

iii. There is need for proper catchment as well as riparian zone management strategy through reduction of anthropogenic activities and re-afforestation programmes to stabilize sediment and reduce the influx of sediments into the lake through point and diffuse sources.

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APPENDICES

Appendix 1

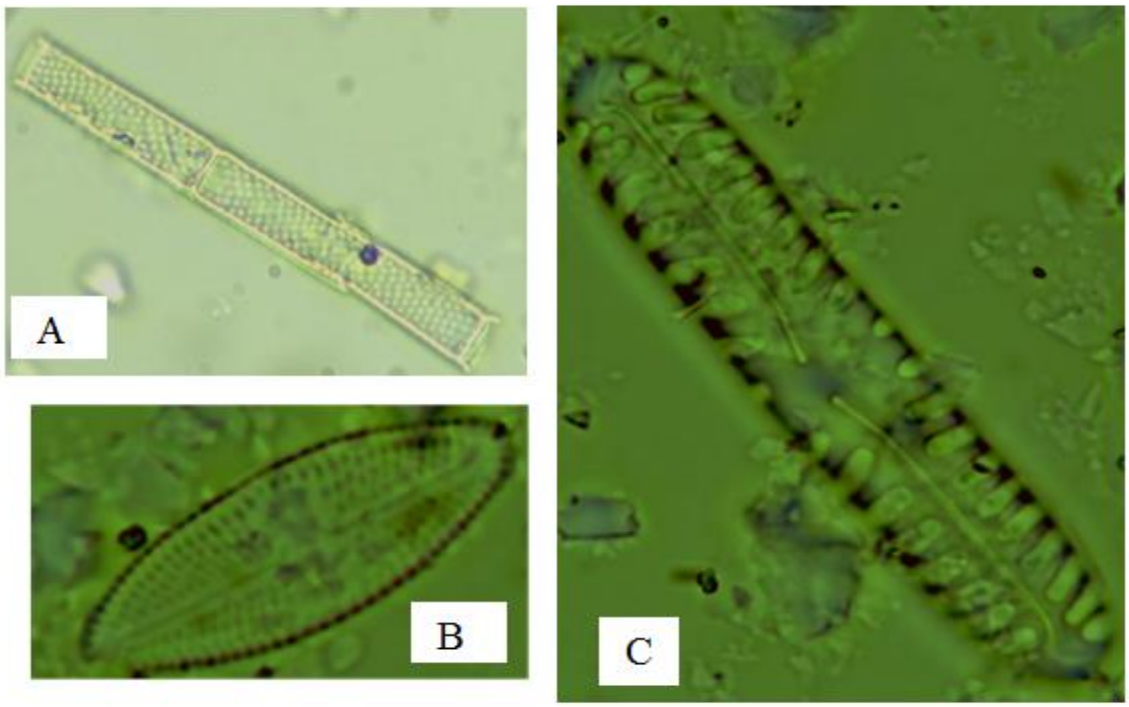
Some diatom species observed in core BAR14-2P (+ present, - absent)

Diatom species	ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5	ZONE 6
Achnanthes inflata	-	-	+	-	-	-
A. lanceolata	-	-	-	+	-	-
Aulacoseira granulata	+	-	-	-	+	-
Amphora strigosa	-	-	-	+	-	-
A. veneta	-	+	-	-	-	-
Cocconeis pediculus	+	-	-	+	+	-
C. placentula	-	-	-	+	-	-
Cymbella muelleri	-	+	-	-	-	-
C. obscura	-	+	-	-	-	-
C. naviculiformis	-	-	-	+	-	-
Diatoma vulgaris	-	+	-	-	-	-
Eunotia serpantina	+	-	-	-	+	-
E. tchirchiana	+	-	-	-	-	-
Eunotia vumbae	+	-	-	+	+	-
E. flexiosa	+	-	+	-	-	-
Epithemia zebra	+	+	-	+	-	-
Fragilaria construens	-	+	-	+	-	-
F. ulna	+	-	-	-	-	-
F. capucina	+	+	+	+		+
F. leptostauron	-	+	-	-	-	-
F. fasciculata	-	-	-	+	-	-
Gomphonema clevei	+	+	+	-	+	-
G. lanceolatum	+	-	-	-	+	-
G. clavatum	-	-	-	+	-	-
G. parvalum	+	-	-	+	-	-
G. clevei	+	+	+	+	+	-
G. acutiusculum	+	-	+	-	-	-
Hantzschia amphioxys	-	+	+	+		-
Luticola cohnii	-	-	-	+	-	-
Aulacoseira granulata	+	-	-	+	+	+
Navicula gawaniensis	-	-	-	+	+	+
Navicula cuspidata	+	-	-	-	-	-
N. hassiaca	+	-	-	-	-	-
N. saxiphila	-	-	+	+		

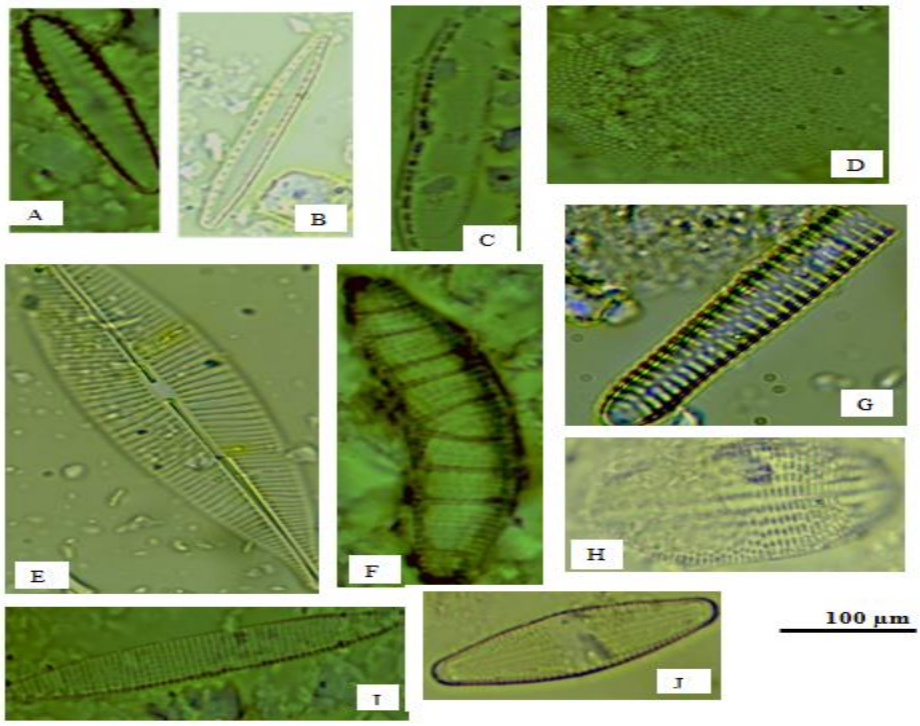
N. mutica	+	+	-	-	-	-
Nitzschia linearis	-	+	-	-	-	-
N. amphibia	+	+	+	+	+	-
N. obtuse	-	+	-	-	-	-
N. subrostrata	-	-	+	-	-	-
N. umblicuta	-	-	-	+	+	-
Pinnularia borealis	-	-	-	+	-	-
P. acrosphaeria	+	-	-	-	-	-
P. gibba	+	-	+	-	-	-
S. borolinensis	-	-	-	+	-	-
S. ulna	+	+	-	-	-	-
S. cunningtonii	-	+	-	-	+	+
S. rumpens	-	-	-	+		
S. tabulata	-	-	-	+	-	+
Thalassiosira faurii	+	-	-	-	-	-

Appendix 2

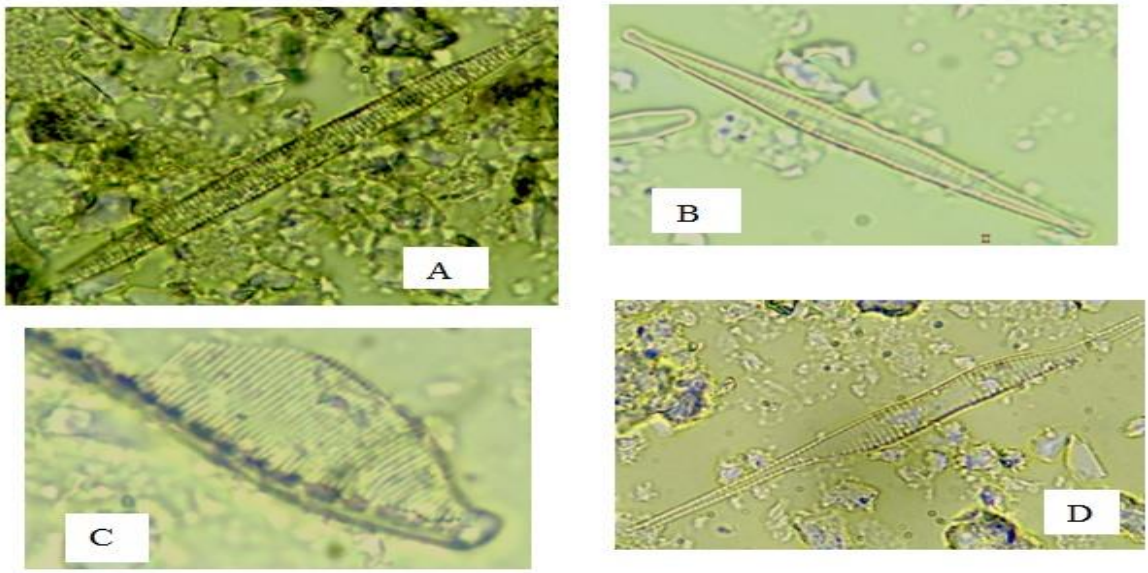
Light microscope micrographs of some selected diatoms



A), *Aulacoseira granulata*, B), *Luticola cohnii*, C), *Pinnularia borealis*



(A) *Gomphonema clevei,* (B) *Fragilaria capucina,* (C) *Nitzschia umblicuta,* (D) *Thalassiosira faurii,* (E) *Navicula cuspidate,* (F) *Epithemia zebra,* (G) *Fragillaria sp,* (H) *Cocconeis pediculus,* (I) *Nitzschia amphibia* and (J) *Navicula mutica.*



(A) *Nitzschia subrostrata,* (B) *Synedra rumpens,*

(C) *Hantzschia amphioxys* and (D) *Synedra cunningtonii*