ASSESSMENT OF PLANKTONIC ALGAE COMMUNITY STRUCTURE, PHYSICO AND CHEMICAL CHARACTERISTICS, AND MICROCYSTIN CONCENTRATIONS IN KISUMU BAY, LAKE VICTORIA, KENYA

BY

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BSC (UNIVERSITY OF ELDORET)

A THESIS SUBMITTED TO THE SCHOOL OF POST-GRADUATE STUDIES IN PARTIAL FULFILMENT OF THE REQUIREMENTS OF THE DEGREE OF MASTER OF SCIENCE IN LIMNOLOGY OF THE SCHOOL OF AGRICULTURE AND NATURAL RESOURCES MANAGEMENT, DEPARTMENT OF ENVIRONMENTAL, NATURAL RESOURCES AND AQUATIC SCIENCES, KISII UNIVERSITY

NOVEMBER, 2021

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DEDICATION

I dedicate this work to my beloved mother Yunes Mocheche, father Mishael Miruka (deceased), my dear wife Beatrice Makini and, my sons Brian, Alex and Miruka, my daughter Emma, my brothers Robert, Joshua, Machuki, Job and Mauti. I love you and may God Bless you.

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ABSTRACT

Studies on algal community structure and diversity in relation to their impact on water quality and ecosystem function are important in informing policy on water quality management. Consequently, studies were conducted in Kisumu Bay of Lake Victoria to establish factors that determine phytoplankton community structure, in relation to their toxins and impact on water quality and ecosystem health from September 2017 to May 2018. Triplicate samples of physico-chemical Parameters, Nutrients, Phytoplankton, Chlorophyll-a and algal toxins were collected at eleven sampling stations georeferenced by Geographical Positioning Systems (GPS) model number 35 C to help show their spatial and temporal variability. Enumeration and identification of phytoplankton was carried out using Axioinvert 35 inverted microscope at 400x magnification. Nutrients concentrations were analyzed using standard procedures described in APHA 2017. Physico-chemical parameters: Dissolved Oxygen (DO), Temperature, Conductivity and pH were measured using YSI multiparameter probe model No. 650). Other physical chemical parameters: Turbidity, Total Suspended Solids, Total hardness, alkalinity and Secchi depth were measured as described in APHA (2014). Chlorophyll a concentration was determined by filtration of water samples followed by cold extraction in ethanol then by determination of their optical densities at 665nm and 750 nm. Microcystin algal toxins were analyzed using Elisa Kit Model No. 357 C. Algal biodiversity was assessed using Shannon Wiener, Simpson and species richness evenness diversity indices. Spatial and temporal differences of all the parameters were tested using analysis of variance followed by F-test at $p < 0.05$. Other Statistical analysis were performed using the Minitab version 17 Inc. software for windows to determine significant differences followed by post-hoc test to identify pairs of samples which had significant differences. The main algal taxa identified were: Cyanophyceae, Bacillariophyce, Chlorophyceae, Euglenophyceae, Zygnematophycea and Dinophceae. The most dominant algal species were Microcystis aeruginosa (25.44 %), Merismopedia spp (23.49 %) and Anabaena flos-aquae (16.06 %). Five Microcystin toxins were identified namely MC-LR, MC-YR, MC-LA, MCRR and MC-dmLR. Concentrations of two of the toxins namely MCLR and MCRY exceeded WHO acceptable standards at two sampling stations of which they were significantly correlated. Cocacola had a mean of $2.360 \pm 4.41A$ MgL^{-1} MCLR and pier $1.100 \pm 1.88A$ MgL^{-1} respectively. There were significant difference in chlorophyll a, temperature, dissolved oxygen, conductivity, pH and Secchi depth among different sampling stations (ANOVA; $p < 0.05$). However, no significant differences were observed in nutrients concentrations measured in Mid Bay. The total phosphate concentration to total nitrogen concentration ratios (TP : TN) for all the eleven sampling stations differed from the expected TP : TN Ratio of 1:16 and did depict a highly eutrophic environment. Showing situation where effluents with high, nutrient concentrations especially phosphates are discharged into bay. The disproportionate ratio of total phosphate and total nitrogen into the Bay may be responsible for the enhanced cyanobacterial blooms. This result will be useful to scientists, managers and authorities of the water sector in formulating regulations for management of water quality.

Key words: Physico-chemical, Nutrients, Phytoplankton, Microcystis, and Lake Victoria

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LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA:	Analysis of Variance
APHA:	American Public Health Association
Chl-*a*:	Chlorophyll-*a*
DO:	Dissolved Oxygen
E.H:	Ecosystem Health
EDTA:	Ethylene Diamine Tetra Acetic Acid
ELISA:	Enzyme Linked Immunosorbent Assay
KMFRI:	Kenya Marine and Fisheries Research Institute
LVEMP:	Lake Victoria Environmental Management Project
MC-LR:	Microcystin - LR
NEMA:	National Environment Management Authority
NH_3:	Unionized Ammonia
NH_4-N:	Ionized Ammonia
NTU:	Nephelometric Turbidity Units
SRP:	Soluble Reactive Phosphorous
TDS:	Total Dissolved Solids
TP:	Total Phosphates
TSS:	Total Suspended Solids
UNEP:	United Nations Environmental Program
USEPA:	United States Environmental Protection Agency
WHO:	World Health Organization

CHAPTER ONE

INTRODUCTION

1.0 Background to the Study

Phytoplankton constitute of a large diversity of photosynthetic organisms which are eukaryotic and are not necessarily closely related, they are therefore polyphyletic. Organisms in this group include unicellular microalgae, for example Chlorella and the diatoms such as Nitzschia or Ampora spp to multicellullar groups, for example the giant kelp, a large brown algae that can grow to a size of approximately 50 m (Lee & Bong, 2008). The body morphology of unicellular forms includes Chlorella, colonial forms, Microcystis and Merismopedia spp, filamentous forms Aulacoseira and Planktolyngbya spp, flagellated forms such as Euglena and Trachelomonous spp to the multicellular forms already mentioned. Although cyanobacteria can also be referred to as "blue-green algae", most authorities exclude all prokaryotes in the definition of algae. However due to the fact that Cyanobacteria do have in their cells chlorophyll a as the primary photosynthetic pigment, some authors include it as one of the major algae groups (Reynolds *et al.*, 2006). The broader grouping of algae therefore includes Cyanophytes, Glaucophytes, Rhodophytes Chlorophytes, Euglenophytes, Crytophytes and Heterokonts. Algae reproduce both sexually and asexually, they lack complex body organs such as roots, leaves, stomata and stems found in higher plants.

They further constitute phoautotrophs, micoauthotrophs and heteroautotropes and chemoautotrophs. Algae have a global distribution inhabiting both aquatic and terrestrial habitats. In the aquatic habitats they inhabit cold, temperate and warm tropical marine environments, alkaline, saline and freshwater lakes, small water bodies (dams), wetland and rivers (Hossain *et.al.*, 2007). In terrestrial habitats they can be found in damp places as well as rocks, soils and on buildings. Algae are of great

significance to mankind as they have both useful and harmful properties to life. They constitute the primary source of energy in aquatic habitats that support life in water and in particular the world fisheries on which mankind depends on for food (Schwoerbel, 1994; Chalinda *et al.*, 2004). Phytoplanktons are very sensitive to the environment in which they live in and alteration in the environment leads to change in phytoplankton communities in terms of biomass and diversity (Bhatnagar *et al.*, 2013).

They form harmful blooms which produce toxins that can cause serious illness or death to humans and other life forms (Sivonen *et al.*, 1999; Merel *et al.*, 2013). The blooms negatively impacts on water quality causing odour problems and deoxygenation of the water column when they decompose (WHO, 1998). Occurrence and persistence of massive algal blooms in Kisumu Bay of Nyanza Gulf in 2004 resulted in foul smells in the air within Kisumu city and in piped drinking water forcing the closure of the water treatment works for several days (LVEMP, 2002a).

They further clogged filtration apparatus and cause breakdown of domestic water intakes. Algae are indicators of water quality, whereas presence of certain algae can indicate different categories of water quality. In Kisumu bay, algal problems are due to occurrence of harmful Cyanobacteria blooms and have been a frequent event in the last two decades. This include unsightly algal scums on surface waters, clogging of gill nets, deoxygenation of the water column and itching of the body skin when one gets in contacts with the water (Codd *et al.*, 2005). There have been few studies aimed at investigating changes in the algal community structure, their biodiversity and toxin producing characteristics in Kisumu Bay of Lake Victoria, Kenya. Further, there have been few biomonitoring programmes of harmful cyanobacteria as well as presence of algal toxins in both raw and portable domestic water. The abundance and diversity of the populations of phytoplankton

are majorly regulated by inorganic nutrients which include but are not limited to nitrogen, phosphorous and silica all of which enhance growth of phytoplankton. Nutrient enrichment resulting from sediment erodiment from agricultural runoff and low lying deforested riparian zones which contribute to eutrophication of the lake (Hecky *et al.*, 2010). Similarly, the release of untreated or poorly treated domestic sewage into the lake contributes to the Lake's eutrophication (Ndaruga *et al.*, 2004). Recent studies in the Lake Victoria basin show that human activities are major source of Nitrogen and phosphorous which encourages excessive phytoplankton growth into the Lake. This study assessed the algal community structure and its microcystin producing characteristics in Kisumu Bay of Lake Victoria. Information obtained from this study will be useful in mitigating effects of harmful algal blooms and their toxins.

1.1 Statement of the Problem

Recent studies on harmful cyanobacterial blooms have concentrated on algal toxins and their effects on humans and other forms of life. Occurrences of harmful cyanobacteria blooms in many parts of the world are due to nutrient enrichment of water bodies. If the latter is left unchecked, the frequency and severity of such occurrences is likely to increase. Lake Victoria is a major source of fresh water that is used for domestic, agricultural and industrial purposes. Like in many other developing countries where clean water is scarce, the lake represents the only source of fresh water for the riparian communities. Occurrence and persistence of massive algal blooms in Kisumu Bay of Nyanza Gulf in 2004 resulted in foul smells in the air within Kisumu city and in piped drinking water forcing the closure of the water treatment works for several days.

Exposure to cyanobacterial toxins via drinking water is a major concern for human health since they may induce both acute and chronic illnesses. A recent case in Embu, Kenya where hundreds of

children died after drinking insufficiently treated water from a river blooming with Cyanobacteria serves to highlight the seriousness of the problem (Codd *et al.*, 2005). Pollution in Lake Victoria is increasing, thus resulting to deteriorate of water quality. This can bring about worsening health conditions as well as reduce benefits to riparian communities that largely depend on the lake for livelihood. The purpose of this study was to assess algal community structure and microcystin occurring in Kisumu Bay. Therefore, there is need to obtain information on occurrence of algal blooms and their toxins for use in formulating regulations that can be used for managing water quality.

1.2 Justification of the problem

Algae and their toxins are some of the major causes of poor water quality. The poor water quality results from decomposition of dense algal blooms and the release of their toxins into the water column. Decomposition further causes deoxgenation of the water column thus endangering aquatic life. The toxins produced by the algae are potent and are known to cause fish kills and serious illiness or death to humans and other forms of life. Some of this algae types such as cyanobacteria are carriers of pathogens that cause cholera. Studies have indicated that cyanobacteria causes colon, liver and tumours. There is need to characterise algal communities which produce algal blooms and toxins in Kisumu Bay, Lake Victoria. There is also need to undertake studies on structure of algal communities that produce harmful blooms and toxins, while identifying the types of algal toxins produced by this algal communities. Information obtained in this study will be useful in informing policy on water quality management and conservation.

1.3 Objectives of the Study

1.3.1 General Objective

To assess the algal community structure, Microcystin production and their relationship with Phyico and Chemical parameters, in Kisumu Bay, Lake Victoria, Kenya.

1.3.2 Specific Objectives

(i) To determine the spatial and temporal composition of phytoplankton community structure in Kisumu Bay;

(ii) To determine relationship between physical-chemical parameters, phytoplankton community structure and microcystin concentrations in Kisumu Bay;

(iii) To identify and quantify microcystin toxins produced by phytoplankton in Kisumu Bay.

1.4 Null Hypotheses

HO1: There are no significant differences in the relationship between the physical-chemical parameters, phytoplankton community, and microcystin toxin in Kisumu Bay.

HO2: There is no significant relationship between physico and chemical parameters and algal abundance.

HO3: There is no significant difference in spatial distribution of phytoplankton at different sites in Kisumu Bay.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter provides the literature review on phytoplanktons, physico-chemical parameters and the mycrosystin toxins.

2.2 Planktonic Algae Community

Phytoplankton are microscopic aquatic organisms that occur in unicellular, colonial or filamentous forms; are free-floating or suspended in open waters (Zakariya *et al.,* 2013). They are the main sources of food for most fauna, both in lotic and lentic waters as they are the chief primary producers. Phytoplankton are important water quality indicators because of their short life cycles, diverse spatial and temporal distributions and their ability to respond to environmental changes. Their standing crop and species composition indicate the nature of water quality (Reynolds 2001; Walsh *et al.,* 2001). According to Reynolds *et al*., (2002) and Brettum and Andersen (2005), phytoplankton biomass and composition can be used to monitor water quality since they give more accurate information on ecological changes than nutrient or chlorophyll-a concentrations.

When reservoirs and lakes become more eutrophic, phytoplankton diversity decreases eventually resulting in cyanobacteria dominance further leading to toxin production (Chellappa, 1990; Azevedo & Carnouze, 1994; Kotut *et al.,* 2001). Cyanobacteria such as Anabaena sp. and Microcystis sp. are usually dominant in eutrophic freshwaters. Their blooms are prevalent in waters affected by cultural nutrient enrichment (Medupin, 2011; Reynolds, 2001). According to Sitoki et al. (2012), phytoplankton species composition, abundance and spatial distribution in Lake Victoria are directly related to environmental factors such as temperature, light intensity, dissolved oxygen concentration

and nutrients. Studies by Kling *et al.* (2001), on changes in the phytoplankton community of Lake Victoria demonstrated that nutrient enrichment has brought about a profound shift in the phytoplankton community from diatoms and chlorophytes dominance throughout much of the year to near continuous dominance by filamentous and colonial cyanobacteria. A major consequence of algal blooms is reduced transparency of a water body (Silsbe, 2006); Hecky & Bugenyi, 1992).

According to Kling *et al.* (2001), the relationship between chlorophyll a concentration and light extinction in Lake Victoria exhibits an inverse exponential relationship. Phytoplankton are an integral component of aquatic communities and form the basis of primary production on which all organisms in higher aquatic trophic levels depend. They also serve as food for humans. For example, the algae *Spirulina* species is harvested from certain lakes ecosystem such as Lake Chad for human consumption. However, certain types of phytoplankton including certain species of Cyanophyceae, Bacillariophyce, Chlorophyceae, Euglenophyceae, Zygnematophycea and Dinophceae form algal blooms that produce toxins which have been found to cause serious illnesses and death to humans and other forms of life (Zingone *et al.*, 2002: Zingone *et. al.*, 2015).

The harmful algal species are distributed in both marine and fresh water habitats. They form dense scams of different colours on water surfaces known as algal blooms. Further they produce toxins which can persist in water for several days to months. Thus during such extended periods, there toxins continue to affect organisms in aquatic ecosystems. It has also been observed that bacteria causing cholera in humans thrive in sheaths of cyanobacteria blooms thereby making them even more dangerous to live. The algal blooms often cover the entire Nyanza Gulf of which Kisumu Bay is part of (Sitoki *et al.,* 2012). It has also been observed that frequent outbreaks of cholera occur in different urban centers and fish landing beaches along the shores of the Kenyan sector of Lake

Victoria. However, it is not documented whether the *Vibrio cholerae* which causes cholera is harbored by cyanobacteria blooms (Islam *et al.*, 2004).

Some organisms such as mussels that feed on algae are known to bio-concentrate algal toxins and on consumption by humans and other forms of life such as birds cause illness or even death. This is particularly of great concern because the aquatic organisms that graze on phytoplankton are not able to differentiate between the toxic and non-toxic forms. Algal toxins are released when algal blooms undergo decomposition thereby releasing them into the water column where they persist for extended periods posing danger to aquatic life and users (WHO, 2005).

Blue green algae or cyanobacteria have a vacuole in them which helps them to regulate their buoyancy in water, and with its help they are able to position themselves in the water column where conditions of their survival are optimal. They also have chlorophyll a in their cells which they use to capture light energy for their photosynthesis. The cyanobacteria use the vacuole to position themselves at localities in the water column where they can capture light more efficiently and in this way they can effectively photosynthesize and develop high biomass levels leading to the formation of blooms. This is an advantage they have over other phytoplankton which are not able to regulate their buoyancy in the water column (Paerl, 2009). Algae are the main primary producers in the aquatic food chain and also act as indicators of water quality and ecosystem health (Blahova *et al.*, 2008).

The mushrooming of urban centers and industries along the shores of Lake Victoria has resulted in rapid population increase. These has led to increased pressure on the lake's resources and a progressive decline in water quality. The resultant large inputs of nutrients and pollutants have also lead to deterioration of water quality and eutrophication (Kairu, 2001; Kasangaki *et al*,. 2008).

Majority of the riparian populations live directly off the shoreline and riverine areas, leading to severe deforestation to create land for agriculture and wood for fuel. Removal of the vegetation cover results in soil erosion and nutrient loading into Lake Victoria that ultimately lead to development of algal blooms and poor water quality (Verschuren *et al.,* 2002). Studies by UNEP (2005) on the nutrients load established that deforestation and poor agricultural practices have contributed to increased sediment and nutrient transport by Kenyan rivers and more so river Yala into Lake Victoria. The pollutants contribute to siltation, chemical contamination and nutrient enrichment (Bootsma & Hecky, 1993; Gikuma-Njuru & Hecky, 2005). Lake eutrophication has helped to sustain the invasive water hyacinth and algal blooms covering the littoral zones (Opande *et al.*, 2004; Okely *et al.*, 2010).

2.2 The Status and Interactions of Phytoplanktons, Physico-chemical Variables and Nutrients Concentration in the Lake Victoria

Lake Victoria water is greatly polluted by discharges from untreated sewage and chemical effluents from the urban centers such as Kisumu, Homa Bay, Kendu Bay, and Port Victoria (UNEP, 2006). The lake is the final destination of factory effluents, oil, grease and sewage. Its waters also receive 2.3 mm per year of sediment loads that contains -silt, phosphorus, nitrogen, and other pollutants (Odada *et al.*, 2004; Veschuren *et al*., 2002).Therefore, deteriorating of water quality is due to point and nonpoint pollution fuelled by anthropogenic activities in catchment areas (Charles & Alexander, 1993). Eutrophication may be identified in surface waters through the proliferation of algal blooms and aquatic macrophytes. This is due to disturbed balance of trophic levels that destabilize species dominance and distribution at higher trophic levels. This may also result in explosive growth of a few species which disturb nutrient cycles therefore affecting water quality (Awange *et al.*, 2006).

Over the last several decades, multiple stressors (including population growth, land cultivation, nutrient pollution, meteorological variability, resource extraction, intensive fishing, the introduction of non-native fish and plant species, and climate change) have dramatically altered lake water quality and fisheries ecology (Hecky, 2010). The proliferations of Cyanobacteria has a negative impact on the livelihood and health of the local communities. Therefore phytoplankton community structure and their toxicity impacts negatively on human health and contribute to fishery decline. Worldwide excessive inputs of sewage and fertilizers runoff impact lakes and drinking water reservoirs through eutrophication and increased algal and cyanobacterial growth (Paerl, 2001; Russell & Connell, 2009). The blooms can produce a variety of potent toxins and allergenic compounds (Paerl *et al.,* 2006; Paerl *et al.,* 2009) that can increase risk of waterborne infectious diseases in dependent and vulnerable populations (Ahmed, 2007; Smith & Schindler, 2009). The blooms also have a profound impact on lake ecology and fisheries dynamics, promoting anoxic conditions and fish kills (Davies *et al.,* 2009). Communities inhabiting tropical areas are vulnerable to the impacts resulting from eutrophication. Anthropogenic pressures and climate change increasingly amplify nutrient fluxes on aquatic systems. Expanding global population exerts increased demand on ecosystem services provided by aquatic systems. Bioavailabity of goods and services is generally lower whenever organic materials, sediment or mineral particles are present.

Drinking water is a major source of microbial pathogens in developing countries, although poor sanitation and food sources are integral to enteric pathogen exposure (Ashbolt, 2004). According to WHO (2006) human health can be compromised when harmful bacteria contaminate drinking water either at the source or within the distribution system. Surface water is often more vulnerable to the immediate influence of many contamination sources which include

leaking sewerages, defecation in the bushes, and pit latrines (Nwachukwu & Ume, 2013). Contamination of surface water is more frequent where these sources of pollution are not prevented. This may occur through leakage of sewer lines or animals defecating into water bodies while being taken to drink water (WHO, 2003; WHO, 2008). Biological monitoring metrics have been developed and used widely to measure phytoplankton analyses that include determining presence or absence of various algae species, species composition and their abundance (Reynolds *et al.*, 2001).

Nutrient enrichment in our water bodies has been exacerbated by lack of/or scarcity of proper treatment of domestic wastes before being released into the rivers or lake (Iwata *et al.,* 2003). Studies by Scheren *et al.* (2000) and Ntiba *et al.* (2001) indicate that direct discharge of untreated municipal effluents into rivers and lakes contribute to nutrient enrichment and decline in water quality. Treatment works in municipalities are either inadequate, use old and obsolete technology, have ageing components, or have simply been grounded. They have also not been able to expand to keep pace with the increasing populations. The conventional treatment system at Kisumu, which was originally constructed to cater for a population of 50,000, now caters for a population of over 500,000 producing an excess of over 7,000 cubic meters of sewage, that is passed as semi treatment sewage effluent into Kisat river that drains into Kisumu Bay of Lake Victoria., approximately 0.5 km downstream (Gichuki *et al.,* 2006).

More recent studies (Mugidde, 2003; Lung'ayia *et al.*, 2001) have shown a shift in phytoplankton species composition from a moderate mix of diatoms, greens and blue-greens to the predominantly bloom forming and nitrogen fixing cyanobacteria. The blooms have become an increasingly common phenomenon near the shores of Lake Victora (Ochumba & Kibaara, 1989; Gichuki *et al.,* 2006; Sitoki *et al.,* 2012, Babu *et al.,* 2015). Their effects are diverse and include

frequent anoxia due to algal respiration and decomposition. Some of these changes have been studied and reported (Ochumba & Kibaara, 1989; Hecky, 1993; Lung'ayia *et al.,* 2001 and Sitoki *et al.* 2012). Cyanotoxins are a health hazard and have serious ecological impacts on aquatic food webs. The toxins cause skin irritations; stomach upsets and makes water unsuitable for domestic, agricultural and industrial use. The blooms clog fishing nets making them heavy and inefficient. Past and present studies have shown that fish kills in Lake Victoria are attributed to the occurrence of dense cyanobacterial blooms (Ochumba & Kibaara, 1989; Hecky, 1993; Lung'aiya *et al.,* 2001 and Sitoki *et al.,* 2012). Effects of the toxins on fish, aquatic ecosystems, public health and livestock have not received much attention in Lake Victoria.

Temperature is a key indicator of water quality and exerts an enormous influence on aquatic organisms. In general, alteration in the overall temperature of an aquatic system can lead to a shift in phytoplankton community composition (Mugidde, 2001). Most biochemical reactions within a cell of an organism are temperature dependent (Harper, 1992). Increased water temperatures have resulted in acceleration of temperature dependent chemical reactions as well as microbial processes such as denitrification hence affecting nutrient cycling as well as algal composition and biomass development (Mugidde, 2001). Higher temperatures in lakes and closed river mouths reduce the oxygen-carrying capacity of the water leading to low dissolved oxygen concentrations hence reducing the number of organisms that can survive in the water (Hecky *et al.,* 2003). High temperatures also leads to thermal stratification which has direct physical impact on the depth of the mixed layer that in turn affects the vertical distribution of nutrients, oxygen and biota (Talling, 1965; Hecky *et al.,* 1996; Mugidde, 2003). Dissolved oxygen is critical for survival of aquatic organisms as they use it for respiration. Nutrient enrichment leads to increased algal growth resulting in a

bloom whose death and decomposition results in anoxic conditions (Michaud, 1991). Studies on the chemical environment of Lake Victoria, Kenya, have established that the deoxygenation of deep waters caused by the decomposition of algal biomass has precluded a stable demersal fishery in the lake (Gichuki, 2000). The periodic bottom oxygen deficiency caused by decomposition of algal biomass and aggravated by a stronger thermal stability directly affects the distribution of nutrients and organisms including invertebrates and fish (LVEMP, 2002b; 2003). The low oxygen concentration has led to loss of approximately 50 % of aerated fish habitat since the 1960s and has been greatly associated with fish kills in Lake Victoria. When dissolved oxygen decreases to below the critical concentration of 3 mg L^{-1} (Golterman, 1975), it ignites a series of chemical reactions which results in the release of nitrites, ammonia and hydrogen sulfide which are toxic and results in fish kills. Studies have shown that the invertebrate *Caridina nilotica* has become a keystone species in the lake, as it is resilient to low oxygen conditions. These low oxygen conditions favours the release of phosphorus from bottom to surface waters but not nitrogen (Kling *et al,* 2001), hence the continuous loss of nitrogen to denitrification has led to nitrogen deficiency, which favours the growth of nitrogen fixers such as the cyanobacteria which produce toxins. The blooms cause deoxygenation at night during respiration and decomposition (Ochumba *et. al.,* 1990) and supersaturation during the day. Such large fluctuations in oxygen concentrations and pH are not tolerated well by many organisms.

Turbidity is a measure of the amount of suspended material in water and is usually determined by the relative light transmission of the water body (USEPA, 1999). High turbidity levels interfere with light penetration, thus hindering photosynthesis by aquatic plants, which in turn interferes with oxygen production. High turbidity levels also increase light absorbance by water leading to

increased or decreased primary productivity and phytoplankton community change as turbid waters are heated more rapidly by the sun reducing its ability to hold dissolved oxygen. This is because turbid water is heated more rapidly by the sun and as it warms, water loses its ability to hold dissolved oxygen. Inflows containing turbid water leads to eutrophication since the suspended tiny soil particles contain nutrients that increase the nutrient concentration of the receiving water body. Studies have shown that Nephelometric Turbidity Units (NTU) of less than 25 is acceptable for aquatic life (Hecky & Bugenyi, 1992). Turbidity of the waters is influenced mainly by algal productivity and also through mineral composition. Various lakes exhibit a spatial and temporal variations in the abundance diversity of phytoplankton, but with turbidity, light and autogenic factors with regard to biological components such as parasitism, competition in Lake Victoria has been studied hence turbidity is a temporary phenomenon, as individual cells have a short life span. Phytoplankton does cause turbidity and cells have the ability to garner more of the light if it is getting minimal. If the waters are charged with P, then the bloom may be prolonged hence harnessing algal toxins and lengthening turbidity time and space. The Turbidity mostly causes a shift in the zooplankton communities as well (Sitoki *et al.,* 2012). Such changes at the base of the food chain results in the reorganization of trophic levels ultimately impacting fish stocks.

Nitrogen and phosphorus are essential constituents of all organisms and are therefore regarded as macronutrients that ultimately limit organic productivity. The fundamental role of the nutrients phosphorous and nitrogen implies that fundamental change in their sources, loading and remobilization has far reaching effect on the lakes productivity (Talbot, 2001). Changes in Land- use activities within basins have raised loaded nutrient concentrations into aquatic ecosystems way above natural background limits; indicating pollution. Increased loading of nutrients above the

natural background concentrations transform the trophic status of an aquatic ecosystem from less trophic to hypertrophic. Evaluation of Lake Victoria's historical data to recent measurements have indicated rapid eutrophication (from oligotrophic to eutrophic) in a span of about 6 decades (Adams & Ochola, 2002; Sitoki *et al.,* 2010). However, nitrogen influx can independently increase algal biomass, altering proportion of Cyanobacteria and increasing toxicity of some of phytoplankton, particularly in the bay where total phosphorous concentrations (TP) are over 100 μg L^{-1} and N: P mass ratios 20:1. Nitrate favors initial growth of centric diatoms, before giving way to colonial Microcystis sp which can replace diatoms and some of phytoplankton that are N-enriched in eutrophic environments (Bernman *et al.,* 1999).

Studies on toxins and nutrients in aquatic ecosystems are considered to be important for prudent management of water resources. They can be used to predict any ecological changes that can occur. (Mugidde, 2001; Reynolds *et al.,* 2001, Brettum & Andersen, 2011). Microcystin concentrations measured in Kisumu bay between November and March 2008 (Sitoki *et.al.,* 2012 and Kolding *et.al.,* 2008) were consistently above the World Health Organization (WHO) guideline of 1 gL^{-1} with the highest measurement of 80 μgL^{-1} in November 2012 Sitoki *et.al.,* 2012. Fishing communities living around Kisumu Bay utilize lake water directly for drinking, cooking, and bathing with little treatment. The subsistence communities often face disproportionate risks in removing environmentally-stable toxins, which are also difficult to remove by boiling of water. Researchers should engage the communities to obtain sustainable solutions that address health issues caused by cyanobacteria. This study therefore focused on the assessment of algal community structure, microcystin production and their relationship with environmental factors.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This chapter focuses on the materials and methods that were employed in carrying out this research. It provides an account of the study area, research design, the sampling procedures, data collection and analysis.

3.2 Study Area

The study was conducted in Kisumu Bay, Lake Victoria (adjacent to Kisumu city) situated at about 1134 m above sea level. The Bay covers an area of 25 km^2 and has a depth range of 0 to4 m (Odada *et al.,* 2004). Lake Victoria experiences complete annual mixing from June to August (Nyamweya *et al.,* 2016) however the bay has continuous mixing due to its shallow depth. Besides the annual mixing, wind induces strong shear forces at the bottom of the lake and vigorous vertical mixing occurs within the water column (Nyamweya *et al.*, 2016).

The catchment area of Kisumu Bay is one of the most agriculturally productive and densely populated regions in Kenya (Awange, 2006). By 1986, about 35-45 % of the land was used for agriculture; the area supported 0.75million units of livestock and had a mean population density of 170 people km-2 (Awange, 2006). There are two waste water treatment facilities; the conventional municipal sewage treatment work adjacent to Kasat River and Nyalenda waste stabilization ponds which discharge their semi treated sewage effluents into the Kisumu Bay through Kisaft and Nyalenda rivers respectively. Along the shores of the Bay are papyrus wetland at the Kisumu Golf Club, off the Kenya pipeline fuel storage tanks, Hippo Point, Kisian and Dunga. The bay is surrounded by Kisumu city, an industrialized town and provides ideal environment for

conducting studies on Cyanobacteria and their toxins, due to its highly eutrophic status. The city has dysfunctional wastewater treatment systems and several surrounding factories, breweries, tanneries, Molasses plant, soap processing company, swan industries and slaughter houses whose effluent find their way into the bay either directly or indirectly. The agro-based industries; namely Kibos and Mollases plant at Otonglo also discharge their effluents into the rivers draining into the bay. Kisumu Bay in particular, is reported to be stressed since most of the aforementioned rivers discharge their effluents into the lake, LVEMP II (2002b). These anthropogenic activities degrade water quality in the rivers draining into the Bay. Degradation is manifested through reduced fish stocks; decline in biodiversity; dense algal blooms, increased sedimentation, nutrient loading, and anoxia in the water column (Sitoki *et, al.*, 2012). The population density around the Kisumu Bay is one of the highest in the world and almost each and every person relies on the lake as the only water source for domestic use (Obiero, 2006). As a result of this pollution there have been cascading effects on the lake ecosystem including the occurrence and persistence of cyanobacterial blooms reported from every part of the bay.

Other anthropogenic activities in the immediate regions surrounding the bay which cause environmental pollution include wetland degradation and the discharge of nutrient rich agricultural effluents resulting from the use of fertilizers from agricultural farms. (Babu *et al.*, 2015).

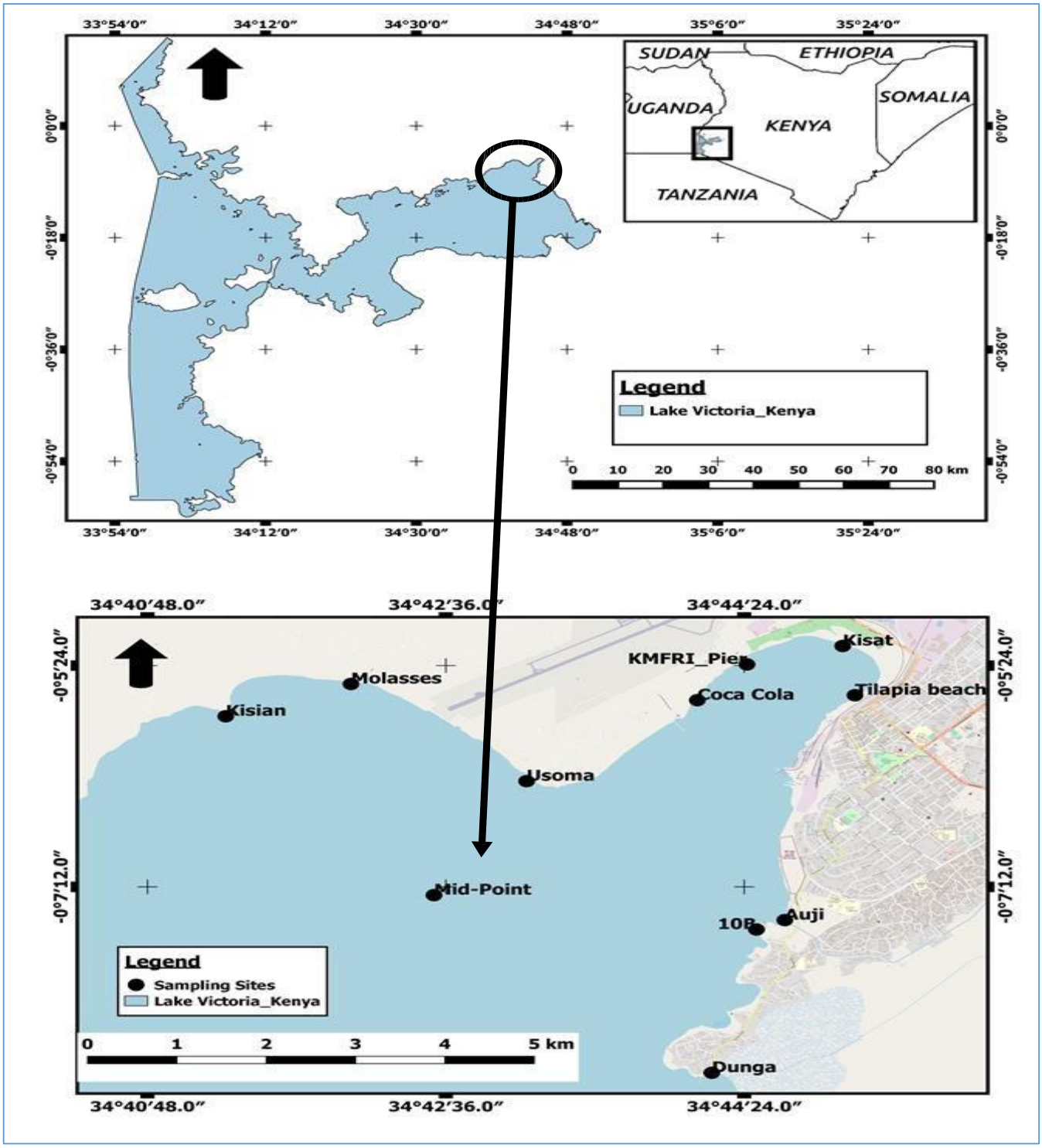

Figure 1: Map of Kisumu Bay, Lake Victoria, Kenya showing location of sampling stations

Investigations were carried in eleven sampling stations from September 2017 to May 2018. The stations were selected based on proximity to points of pollution discharges, inshore and offshore. All stations were located in Kisumu Bay and one in the mid lake.

Table 1: Location and characteristics of eleven station sampled in Kisumu Bay, Lake Victoria, Kenya

Station	Longitude	Latitude	Description and mean depth
St 10	-0.1257927	34.744088	Inshore shallow with river Influence, 1m
Auji	- 0.12551223	34.744088	Inshore shallow with river Influence, 1m
Coca-cola	-0.09469228	34.7352891	Inshore with influence from Industries, 1m
Dunga	-0.41521	34.73674	Shallow with river influence, cage farming, 2m
Kisat	-0.08734648	34.7498382	Local breweries, Industrial area, sewage treatment, 2m
Kisian	-0.0968651	34.6878665	Shallow river influences, sand Harvesting, 1.8m
Midpoint	-0.00618	34.4464	Off-shores, fairly deep, 4.5 m
Molasses	-0.09249135	34.700458	Industrial areas, urban runoff and sand extraction, 2m
KMFRI Pier	-0.08917259	34. 7391178	Domestic sewage from airport and urban settlement , 2m
Tilapia	-0.09542184	34.7486501	Urban influence, open fish frying Activities, 1m
Usoma	-0.1056698	34.7181213	Agricultural activities and sand Extraction, 1m

3.3 Research Design

The study employed purposive sampling at points where different types of effluents are discharged. This included river mouths where agro-based industrial effluents were discharged, the domestic water intake point at Dunga, sewage effluent discharge points, the port where ships and boat vessels dock and towards the mid lake, off Maboko Island. Sampling points are represented in Fig: 1. These points were sampled once every month from September 2017 to May 2018. The design also involved laboratory analyses for detection and quantification of algal toxins and microscopic examination of algae for identification, enumeration and spectrophotometric measurements to determine nutrient concentration using a standard UV-IR spectrophotometer (IR). Further the design involved the measurement of Physico and chemical parameters namely: Temperature (oC), Dissolved Oxygen (mg L-1), Conductivity (µScm-1), pH and Total Dissolved Solids (TDS), Secchi depth, Total alkalinity, and Total hardness.

3.4 Sampling Procedure

At each station, triplicate measurements were recorded for physico and chemical parameters. Water samples for analyses of nutrients were collected directly from the lake using 1 litre polyethylene sample bottles pre-washed with double distilled water. The bottles were labeled, filled and stored in cooler boxes at temperatures of 4 °C, for further laboratory analysis using methods adopted from APHA (2005). Both phytoplankton and toxin samples were collected from the sub-surface. Water was put in a 25 ml borosilicate bottles and preserved in acidic Lugol's solution. 250 mls of water samples for toxin analysis were collected in sterilised bolosilicate plastic bottles and stored in cooler boxes at 4 °C for further laboratory analysis.

3.5 Measurements of Physico-chemical parameters

The physico and chemical parameters: Temperature (oC), Turbidity. Dissolved oxygen (mg L^{-1}), Conductivity (μScm^{-1}), pH and Total Dissolved Solids (TDS) were measured *in situ* using YSI multiparametre metre models 35C. Measurement of the parameters in the water column started at approximately 0.2 m from the surface (Surface) and ended just 0.2 m above the lake bottom. Water samples for the determination of Total Suspended Solids (TSS), Nutrients and chlorophyll-*a*, were collected directly from the lake using pre- washed with (double distilled water) 1 litre polyethylene sample bottles. The bottles were labeled, filled, with water sample and stored in cooler boxes at temperatures of 4 °C for further laboratory analysis (APHA, 2005). Secchi depth was measured with a standard Secchi disk of 20 cm diameter, with four quadrants of which two are painted black and another two are painted white. It was estimated at the shadowed part of the boat and derived as the average of the depth at disappearance and that of reappearance of the disk in water. General environmental observations about the stations like the maximum depth of the sampling site, time of sampling, weather conditions and station features such presence of floating aquatic weeds were noted. Total alkalinity was determined by measuring the amount of acid needed to bring the sample to a pH of 4.5. Measurement of total hardness followed the same method using 0.02 N (EDTA) Ethylene Diamine Tetra Acetic Acid as tilter. TSS was determined by filtration of a known volume of the water through pre-weighed GF/C glass-fibre filters which were then oven dried and final weights taken to determine the difference as the TSS weight per unit volume of water sample.

3.6 Determination of chlorophyll-*a* Concentrations

Chlorophyll-*a* concentration was determined from the water samples according to the method described in Bartram and Balance (1996) and APHA (1998). 500 ml of the water samples were collected from each station for the determination of chlorophyll- *a* concentration. The samples were filtered through Whatman GFC GF/C glass-fibre filter paper of pore size into an Erlenmeyer flask connected to 0.47µm using a hand vacuum filter pump with plastic tube. The filter paper was then inserted in a 25 ml test tube containing 15 ml of ethanol. The test tube was further wrapped in aluminum foil and put in an ice cooler box over night to allow the extraction of chlorophyll-a into the ethanol solution. After this, the filter paper was squeezed using tweezers to remove the remaining chlorophyll-*a* into the test tube. Eleven milliliters of the chlorophyll-a extract were decanted into the test tube and then poured centrifuge tube and centrifuged at 2500 rpm for 10 minutes. After this, the supernatant chlorophyll-a solution was decanted into 1cm pathway spectrophotometer cuvettes and absorbance measurements obtained at wavelengths of 665 nm and 750 nm using distilled water as a blank. The actual absorbances of chlorophyll-a concentration were obtained by subtracting the two absorbencies respectively. The chlorophyll-a concentration were calculated using the formulae by Talling and Driver (1961).

Formulae: Chl-a, $\mu g\ l^{-1} = (11.40\ (E665 - E750) * V_1) / (V_2 * L)$

Where:

11.40 is the absorption coefficient for chlorophyll-a;

V_1 = volume of extract in ml;

V_2 = volume of the filtered water sample in litres;

L = light path length of cuvette in cm;

E665, E750 = optical densities of the sample.

3.7 Determination of Nutrient concentration

The nutrient compounds that were analyzed were Nitrates-N, Ammonia-N, Nitrites-N, Soluble Reactive Phosphorous (SRP), Silicates. Total Nitrogen (TN) and Total Phosphorus (TP). There were no prior preservation of the samples, this were analyzed following the standard methods detailed in APHA (1998). Chemical analyses of nutrients were carried out in the laboratory using spectrophotometric methods.

3.7.1 Determination of Ammonium

Ammonium nitrogen determination was carried out using the phenol hypochlorite method. Except under very alkaline conditions (pH >9), most of the am monia (NH_3) in fresh water exists in the ionic form (NH_4^+). Ammonia reacts with phenol and hypochlorite under alkaline conditions to form indophenols blue. The colour intensity was proportional to concentration of ammonium within an ammonium nitrogen concentration range of between 0-1000µg. Colour intensity (absorbance) was measured with a spectrophotometer at 630 nm using highly double distilled water as a blank (APHA, 1998).

3.7.2 Determination of Nitrite Nitrogen (NO_2-N)

Nitrite –Nitrogen (NO_2-N) concentration was determined by the diazotization method. An amount of 50 mL of a filtered water sample was treated with sulphanilamide followed by N-1-Napthyl ethylene diaminedi hydrochloride catalyst to form a coloured compound whose colour intensity was determined using a UV-IR spectrophotometer after 2 – 8 minutes at a wavelength of 543 nm APHA (1998).

3.7.3 Determination of Nitrates

The nitrates in water are quantitatively converted to nitrites when a sample is run through cadmium reduction column. The nitrites produced were then be quantified by the diazotization method. A buffer solution was added to 50mL of a filtered water sample and run through the cadmium reduction column. The final 25 ml of the water sample was analyzed by adding 0.5 ml of each of sulphanilamide and N-1-Napthylethylene hydrochloride solution, allowed to stand for 2-8 minutes and absorbance read at a wavelength of 543 nm.

3.7.4 Determination of Total Nitrogen (TN)

Samples for total nitrogen (TN) were analyzed using the hydrazine reduction technique, (APHA, 1998). Persulphate method was used to determine Total Nitrogen from the unfiltered samples. Buffers 1 solution was prepared by weighing 10 grams of ammonium chloride and dissolving in 1000ml volumetric flask then topped up to the mark by distilled water. 5 drops of sodium hydroxide pellets was then added. Buffer 2 solution was prepared by measuring 50g of ammonium chloride 10g of sodium tetraborate and 0.5g of disodium EDTA. All the measured grams were placed in closed borosilicate bottles and autoclaved for 30 minutes at a temperature of 121°C. The digestion process converts all forms of nitrogen to nitrate nitrogen, whose concentration were determined using the cadmium reduction method and a UV-IR spectrophotometer after 2 – 8 minutes at a wavelength of 543 nm APHA (1998).

3.7.5 Determination of Soluble reactive phosphorous

Sample for (SRP) were then filtered using GFC filter papers upon reaching the laboratory. Mixing 15 ml of Ammonium Molybdate, 50 ml of sulphuric acid, 30 ml of Ascorbic acid and

5ml of potassium antimony tartrate prepared mixed reagent. All measured volumes were placed in a conical flask then covered. A phenolphthalein indicator was also prepared by dissolving 0.5g of Phenolphthalein in 50 ml of ethyl alcohol and adding 50 ml of distilled water. Twenty five millitres of each of the samples were taken and put in a bottle. Two drops of Phenolphthalein indicator was added to each of the sample to including the blank. Four millitres of the mixed reagent was then added to each of the samples using a micro pipette then swirled. Twenty minutes timing was given to the sample to allow for colour change. Light extinction (absorbance) of the solution was measured with a UV-IR spectrophotometer at a wavelength of 880nm (APHA 1998).

3.7.6 Determination of Total phosphorus

Determination of Total phosphorus (TP) did not involve sample filtration. 50 ml of the sample from each station was measured and put in bottles. To each of the samples, 2 drops of phenolphthalein indicator was added and swirled. 1 ml of aqueous sulphuric acid was then added and swirled. To each of the samples, 10 ml of potassium per sulphate was added and swirled. The sample was autoclaved for digestion for 30 minutes until the green colour was attained. After the 30 minutes, the samples were removed and let to cool to room temperature. 2 drops of phenolphthalein indicator was then added to each of the samples and swirled. If the colour turned to pink due to the addition of sulphuric acid, sodium hydroxide was added until the colour faded away each of the samples topped to 100ml mark using

distilled water. From 100ml of the each sample, 25ml was then measured and put in another bottle to each of the sample; 4 ml of the mixed reagent was then added, swirled and left for 20 minutes for colour. Absorbance was then read at 880nm was determined using the atomic absorbance spectrophotometer (APHA 1998).

3.7.7 Determination of silicates

Silicon solution (H_4SiO_2) or silicate (SiO_2^{-2}) was reacted with acidic ammonium molybdate to form yellow silicomolydate complex. The complex was then reduced by sodium sulphate to form the yellow colour. The extinction was measured at 700nm. The reagents that were used were prepared as follows.

1) Hydrochloric acid (0.25M). Mix 22 ml of concentrated hydrochloric acid (sp. gr. 1.18) with water and dilute to 1litre.

2) Ammonium molybdate 5 %, 52 g Dissolve of Ammonium molybdate was dissolved in water then diluted in 1 litre.$(NH_4)Mo_7O_{24}$ $4H_20$) in water and dilute to 1litre.

3) Disodium EDTA 1 %, Dissolve 10 g of Disodium EDTA in water and dilute to 1 litre.

4) Sodium sulphite 17 %, Dissolve 170 g of $NaSO_3$ in water and dilute to 1 litre. Colour intensity was measured by spectrophotometer at wavelength of 700 nm (APHA, 1998; Wetzel and Likens, 2000).

3.8 Collection and Identification of Phytoplankton

Water samples for phytoplankton identification were collected from sub-surface; monthly sampling was carried out from January 2017 to May 2018. All samples were collected from the sub-surface at 0.5m. Water samples was put in a 25 ml borosilicate bottle and preserved in acidic Lugol's solution. In the laboratory, a 2 ml water sub-sample was placed in an Utermöhl sedimentation chamber and left to settle for at least three hours. Phytoplankton species identification and enumeration were done using a Zeiss Axioinvert 35 Inverted Microscope at 400x magnification. At least, ten fields of view were counted for the very abundant coccoid cyanobacteria and a 12.42 mm^2 transect was counted for the abundant and large algae. The whole bottom area of the chamber was examined for the big and rare taxa under low (100x) magnification. Phytoplankton taxa were identified using the methods of Huber –Pestalozzi (1968) from publications on Komarek and Anagnostidis (2014) as well as some publications on East African lakes (Cocquyt *et al*., 1993). Phytoplankton was estimated by counting all the individuals whether these organisms were single cells, colonies or filaments.

3.9 Phytoplankton diversity

Phytoplankton diversity was studied using Shannon-Winner diversity index (Shannon and Weaver, 1963) and Simpson species richness index:

I. Shannon and Winner Index

Shannon Winner Index of diversity was calculated using the formula:

$H' = -\Sigma PiLn(Pi)$ ……Eq.

Where,

H' = the Shannon-Weaver Diversity Index

Pi= the relative abundance of each group of organisms

H = Shannon-Weaver index

II. Simpson Index of diversity

$D = \Sigma(n/N)2$……...…Eq2.

n = the total number of organisms of a particular species

N = the total number of organisms of all species

Simpson's index of diversity = 1-D

III. Species evenness "J" or equitability index pielou, 1975 was determined by the equation

J'=H''/H' Max

Where H' = the Shannon and Weaver Diversity (1963) Index

H'' Max= theoretical maximum diversity in population: H:max=log2 S

J = Shows the evenness with which individual are distributed among the species

3.10 Collection of water samples for analysis of toxins

Samples for algal toxins were collected by the same equipment from the same depth as above. Appropriate plastic bottles of 250 ml were used to store the samples in a cool box ready for transportation. In the laboratory, they were immediately refrigerated at -18 ^{o}C and analyzed within one week of collection. Using a 25 cc syringe, a total of 100 ml of each sample were filtered through the syringe filter (re-usable) with disposable 0.22 micron filter paper. During analysis, the samples were removed from the freezer and placed on the table at room temperature to thaw. Thereafter, 96 well plates were filled out for sample processing, labelling and dilution. The number of wells needed in 96 well plate readers were determined and unneeded ones removed from the plate holder. Fifty ml of relevant standard (0, 0.1, 0.3, 0.8 and 2.0 μgL^{-1} or ppb) and positive control (1.0 μgL^{-1}) were added to appropriate micro wells. Samples were added to labelled wells with appropriate dilutions made as necessary. Standard curves and control were repeated at least twice. The contents were covered by parafilm and shaken before incubation for 90 minutes at room temperature. After incubation, the parafilm covers were removed and contents vigorously shaken and washed in a sink. The strips were washed three times with a buffer solution, thereafter, a specific enzyme conjugate, microcystin-LR solution was added to the wells, covered and mixed once again

and incubated for 30 minutes at room temperature (Fawell et al., 1993). After incubation, the coving was removed and contents shaken and poured into a sink. A substrate solution was added and incubated for 30 minutes at room temperature. Finally, a stop solution was added to the wells before reading the absorbance at 450 nm using the Elisa photometer. The cyanotoxin concentration was inversely proportional to the intensity of the colour and cyanotoxins were determined from a standard competitive curve of the particular toxin e.g. microcystin-LR.

3.11 Data analysis

Microsoft Excel spreadsheets program was used to analyze the data. Descriptive statistics were used to calculate measures of central tendency: ranges, standard deviation and standard error of means. Spatial and temporal trends of Physico-chemical parameters were plotted; bar graphs were obtained for some of the physical and chemical parameters, algal densities and nutrients for describing changes occurring over time. Data were subjected to a two-way ANOVA to test spatial and temporal differences of algal densities using Minitab software package and Principal Component Analysis was used to determine the relationship between environmental parameters and algae abundance indices, biological parameters and algal toxins. Temporal and spatial variations of algal densities and physical and chemical parameters were correlated using Spearman's Rank Correlation. Simpsons Species Richness Index, Shannon Wieners Index of biodiversity and species evenness indices were explained above in (3.10) as using the appropriate formulae as estimated.

CHAPTER FOUR

RESULTS

4.1 Introduction

This chapter presents results on algal community structure and toxins in Kisumu bay. On algal community structure biodiversity indices namely: Shannon Wiener Index and Species richness. Simpson indices and species richness index together with percentage composition of major algal species are presented. Results of the Physico and chemical parameters and nutrient concentrations and their relationship with algal community structure also presented. The physico and chemical parameters and nutrients studied were; temperature, dissolved oxygen, conductivity, pH, turbidity, hardness, alkalinity, Secchi depth, total suspended solids (TSS), total dissolved solids (TDS), total nitrogen (TN), total phosphorous (TP), ammonia, nitrites, phosphorous and chlorophyll- *a*.

4.2 Physico and chemical parameters in Kisumu Bay, Lake Victoria

A summary of the physico and chemical characteristics of Kisumu Bay are presented in Table 2. The depth in Kisumu Bay ranged from 1.2m at Kisat river mouth to 4.38 m off Maboko island (Midpoint) and varied significantly between different sampling stations ANOVA, ($F_{10,65}$, 8.96) df = 9, $p < 0.0001$. Secchi depth varied only narrowly ranging between 0.25 at Kisat to 0.38m off Maboko Island (Mid-point) but did not show any significant variations ANOVA, ($F_{10,65}$, 0.75) df=9 , $p < 0.67$. The recorded levels of Secchi disk transparency are too low and could be due to existence of algal blooms, high turbidity resulting from presence of suspended materials originating from decomposing of water hyacinth and silt from river discharges and surface runoff. Dissolved oxygen ranged from 3.7

mgl-1 at Tilapia beach to 5.69 mgL^{-1} at St 10 B near (Kisumu port), but varied significantly across all the sampling locations. ANOVA, (F10,65, 2.67) df = 9, $p < 0.0098$. It was therefore observed that the oxygen concentrations in the bay ranged from stressful levels of approximately 5 mg/L^{-1} o lethal levels of 3 mgL^{-1} to most organisms that live in water. Conductivity ranged from 140.5 µS/cm^{-1} at Kisat to 184.2 µS/cm^{-1} at the fisheries pier, which varied significantly across sampling points ANOVA, ($F_{10,65,}$ 6.62) df = 9, $p < 0.0001$.

Table 2: Data on Physico and chemical parameters at various sampling locations in Kisumu Bay, Lake Victoria

Location	N	Parameters						
		Secchi depth (m)	Depth (m)	pH	DO (mg/l-^{1})	Cond (µS/cm)	Turbidity (NTU)	Temperature (°C)
10 B	7	0.37±0.11^{A}	3.6±0.35^{A}	7.84±0.78^{A}	5.69±0.64^{A}	152.0±8.70^{DC}	70.2±11.2^{A}	26.7±1.17^{A}
Auji	6	0.38±0.21^{A}	1.9±1.30^{B}	7.89±0.86^{A}	5.29±0.91^{AB}	162.8±14.6^{BC}	71.2±9.49^{A}	25.7±1.40^{A}
Coca cola	6	0.38±0.27^{A}	1.13±0.24^{B}	8.02±0.85^{A}	5.17±1.96^{AB}	164.0±10.9^{BC}	77.1±28.12^{A}	24.9±1.83^{A}
Dunga	7	0.37±0.06^{A}	1.87±0.60^{B}	7.51±0.71^{A}	4.26±1.00^{ABC}	151.3±8.22^{DC}	71.9±8.46^{A}	26.5±1.45^{A}
Kisat	5	0.26±0.08^{A}	1.12±0.18^{B}	7.80±1.05^{A}	5.69±2.21^{A}	168.6±4.72^{B}	92.72±14.14^{A}	26.6±2.09^{A}
Kisian	6	0.32±0.09^{A}	2.0±1.96^{B}	7.74±0.81^{A}	3.64±0.85^{BC}	140.5±10.2^{D}	72.63±42.49^{A}	24.6±0.78^{A}
Midpoint	5	0.37±0.08^{A}	4.38±0.29^{A}	7.44±0.64^{A}	5.59±0.64^{A}	159.0±13.7^{BC}	82.0±3.81^{A}	25.4±0.88^{A}
Molasses	6	0.31±0.07^{A}	1.35±0.29^{B}	7.69±0.49^{A}	4.14±0.71^{ABC}	153.8±12.1^{DC}	107.8±51.7^{A}	24.8±1.04^{A}
Fisheries Pier	5	0.25±0.10^{A}	1.36±0.96^{B}	7.97±1.25^{A}	3.47±2.19^{C}	184.2±14.3^{A}	115.86±73.6^{A}	25.9±4.03^{A}
Tilapia Beach	6	0.35±0.08^{A}	1.98±0.04^{B}	7.91±0.88^{A}	3.77±1.04^{BC}	172.5±7.23^{AB}	94.92±43.31^{A}	25.1±2.25^{A}
Usoma	7	0.33±0.04^{A}	1.56±0.57^{B}	7.94±0.77^{A}	4.47±0.68^{ABC}	158.3±11.9^{BC}	78.97±7.09^{A}	25.3±2.08^{A}

Means with the same letter along the columns are not significantly different µgL^{-1}

Results of nutrient concentration at different sampling sites in Kisumu Bay are presented in Table 3. Total phosphorus concentrations ranged from 135.7 μgL^{-1} at St 10 B to 303.0 μgL^{-1} at Kisat and varied significantly across sampling points ANOVA, ($F_{(10,86)}$, 2.03) df = 9, p <0.0415. Total nitrogen concentration ranged from 988.1 gL^{-1} at St 10 B near Kisumu Port to 998.1 gL^{-1} at Fisheries pier and varied significantly across sampling points ,ANOVA,($F_{10,86}$, 0.98) df = 9, $p < 0.0001$). Nitrate concentrations ranged from 38.7 gL^{-1} at Auji to 189.9 gL^{-1} at Kisat river Mouth and varied significantly across all sampling stations ANOVA, ($F_{10,86}$, 1.39) df = 9, $p < 0.00012$. Nitrite concentrations ranged from 652 ugL^{-1} at Dunga to 238.9 ugL^{-1} at the Fisheries pier and varied significantly across all sampling points ANOVA, ($F_{10,86}$, 1.08) df=9, $p < 0.3847$. Silicate levels ranged from 24.8 gL^{-1} to 52.8 gL^{-1} at molasses and did not vary significantly across all sampling Stations ANOVA, ($F_{10,86}$, 1.47) df=9, $p < 0.1679$.

Table 3: Data on nutrient concentrations at different sampling stations in within Kisumu Bay, Lake Victoria

		DISSOLVED NUTRIENT LEVELS IN THE LAKE						
Location	**N**	TP (μgL^{-1})	SRP (μgL^{-1})	TN (μgL^{-1})	Nitrates (μgL^{-1})	Nitrites (μgL^{-1})	Ammonium (μgL^{-1})	Silicates (mgL-1)
10 B	8	135.7±34.1C	77.36±18.03A	988.18±914.5A	40.39±24.30A	45.12±45.93A	65.8±36.6A	36.58±19.7A
Auji	8	247.23 ± 131.5^{ABC}	97.66 ± 57.3^{A}	1218.9 ± 926.0^{A}	38.77 ± 12.6^{A}	32.36 ± 13.5^{A}	128.09 ± 158.9^{AB}	36.42 ± 20.3^{A}
Dunga	8	190.61 ± 137.9^{ABC}	74.66 ± 19.6^{A}	1210.0 ± 976.6^{A}	52.02 ± 44.9^{A}	37.553 ± 33.3^{A}	65.28 ± 22.6^{A}	34.5 ± 13.5^{A}
Kisat	8	303.03 ± 146.9^{AB}	82.62 ± 25.9^{A}	1533.2 ± 835.6^{A}	187.9 ± 347.6^{A}	54.54 ± 77.1^{A}	174.3 ± 162.9^{AB}	36.8 ± 17.8^{A}
Kisian	8	151.8 ± 42.7^{BC}	69.7 ± 22.2^{A}	984.1 ± 794.7^{A}	57.3 ± 43.6^{A}	46.8 ± 44.9^{A}	96.53 ± 65.8^{B}	26.9 ± 6.96^{A}
Midpoint	7	146.7 ± 39.9^{BC}	65.3 ± 12.7^{A}	1009.7 ± 971.7^{A}	63.42 ± 50.91^{A}	375.7 ± 881.5^{A}	70.02 ± 34.3^{B}	52.33 ± 25.24^{A}
Molasses	8	331.3 ± 302.3^{A}	169.3 ± 196.8^{A}	1712.5 ± 1451.9^{A}	45.39 ± 26.5^{A}	34.82 ± 20.56^{A}	73.5 ± 53.5^{B}	24.8 ± 1.04^{A}
Fisheries	8	273.2 ± 175.5^{ABC}	109.6 ± 46.3^{A}	1685.7 ± 969.9^{A}	221.8 ± 336.3^{A}	71.1 ± 81.2^{A}	238.9 ± 128.7^{A}	38.6 ± 20.61^{A}
Tilapia	8	183.9 ± 40.6^{ABC}	85.9 ± 19.69^{A}	1103.4 ± 852.5^{A}	66.0 ± 42.3^{A}	40.7 ± 29.4^{A}	137.4 ± 161.02^{AB}	32.12 ± 15.6^{A}
Usoma	8	171.87 ± 66.2^{BC}	84.1 ± 18.7^{A}	1042.5 ± 896.2^{A}	80.24 ± 71.1^{A}	60.81 ± 69.3^{A}	126.61 ± 61.76^{AB}	27.94 ± 7.08^{A}
Auji	8	247.23 ± 131.5^{ABC}	97.66 ± 57.3^{A}	1218.9 ± 926.0^{A}	38.77 ± 12.6^{A}	32.36 ± 13.5^{A}	128.09 ± 158.9^{AB}	36.42 ± 20.3^{A}

Ammonium -nitrogen concentrations ranged from 65.28 µgL-1 at Dunga to 238.9 µgL-1 at Kisian river mouth ANOVA, ($F_{10,86}$, 2.65) df=9, p <0.0079).

The total phosphate concentration to total nitrogen concentration ratios (TP: TN for all the eleven sampling points is presented in Table 4. It can be noted that all the Ratios differ from expected TP: TN Ratio of 1:16 thereby depicting a highly eutrophic environment. This portrays a situation where effluents with high phosphates are discharged into bay. The disproportionate ratio of Total phosphate and Total nitrogen into the Bay could responsible for the variance of TP: TN ratio from the normal.

Table 4: Total Phosphates to Total Nitrogen concentrations ratios at different sampling points in Kisumu Bay

Sampling Stations	TP/TN
ST 10	1:72
Auji	1:49
Dunga	1:63
Kisat	1:66
Kisian	1:66
Mid Point	1:69
Mollases	1:51
Pier	1:61
Tilapia	1:6
Usoma	1:6
Coca-Cola	1:71

Auji River was the most stressed with TP: TN ratio of 1:49 probably due to the river carrying sugar processing effluents from Kibos Sugar Factory and semi treated sewage effluents from the Nyalenda waste stabilization ponds. Generally, all the values of nutrient concentration were high and this, agricultural and domestic effluents from Kisumu City and the immediate catchment of the bay. The high nitrogen in the TN is therefore mainly organic nitrogen derived from algae. The algal group also utilizes NO_2^- in the water, hence the significant correlation of NO_2^- with Chlorophyll-a (R^2 = 0.71) and with secchi depth (R^2 = 0.59). Because a greater portion of nitrogen in the TN is organic, TN/TP ratios also had significant correlations with chlorophyll-*a* (Table 4.2).

4.3 Hardness and Alkalinity Levels at Different stations in the Kisumu Bay, Lake Victoria, Kenya

A summary of the value for alkalinity and hardness are presented in Table 5. Hardness ranged from 38.33 mgL^{-1} at Mid point off Maboko to 49.43 mgL^{-1} at Auji with and varied significantly across the sampling stations within the bay ANOVA, ($F_{10,75}$, 2.25) = df = 9 , $p < 0.025$. However, alkalinity ranged from 77.71 mgL^{-1} at Kisian to 112.2 mgL^{-1} at Molasses and did not show any significant differences between sampling stations ANOVA, $F_{(10,75)} = 0.99$= df, $p < 0.4652$)

Table 5: Mean concentrations of Hardness and Alkalinity levels at Different stations in the Kisumu Bay, Lake Victoria, Kenya

Location	N	**Hardness ± SD (mgL^{-1})**	Alkalinity ± SD (mgL^{-1}**)**
10 B	7	41.71±2.93^{BCD}	78.29±6.97^{A}
Auji	7	49.43±16.32^{A}	86.28±5.59^{A}
Coca-Cola	7	42.86±1.07^{ABCD}	83.42±6.29^{A}
Dunga	7	40.29±1.38^{B}	77.43±5.74^{A}
Kisat	7	48.0±5.42^{AB}	90.29±12.88^{A}
Kisian	7	42.0±4.76^{BCD}	77.71±7.25^{A}
Midpoint	6	38.33±4.08^{D}	80.67±7.34^{A}
Molasses	7	42.86±1.95^{ABCD}	112.29±83.02^{A}
Pier	7	47.14±4.59^{ABC}	91.14±15.61^{A}
Tilapia	7	44.29±3.55^{ABCD}	82.86±9.65^{A}
Usoma	7	41.14±1.95^{BCD}	80.86±8.86^{A}

Note: Means with the same superscript letter along the columns are not significantly different Duncan's Multiple Range Test (DMRT)

4.3 Chlorophylla (MgL1) concentrations

Results of chlorophyll-a are presented in Table 6. Chlorophyll-a varied significantly across the sampling locations within the bay ANOVA, (F(10,54, 3.06,)df=9, P<0.005) with the highest chlorophyll a levels (513.09 mgL-1) recorded at the Coca cola sampling location and lowest (20.57 mgL-1) at Usoma sampling stations. A post hoc test (DMRT) established that chlorophyll a levels at the coca cola sampling stations were significantly higher than the levels recorded in the other 10 sampling locations within Kisumu Bay, Lake Victoria.

Table 6: Mean concentration of chlorophyll a levels within the Kisumu Bay, Lake Victoria, Kenya

Station	N	Chlorophyll *a.* ±SD (mg/l)
10 B	5	35.79 ± 33.55^{B}
Auji	5	140.28 ± 154.59^{B}
Coca- cola	5	513.09 ± 518.33^{A}
Dunga	5	47.08 ± 45.26^{B}
Kisat	5	244.26 ± 223.02^{B}
Kisian	5	29.11 ± 29.62^{B}
Midpoint	5	153.58 ± 171.14^{B}
Molasses	5	33.83 ± 16.14^{B}
Pier	5	127.47 ± 112.53^{B}
Tilapia	5	35.98 ± 12.53^{B}
Usoma	5	20.57 ± 9.21^{B}

Means with the same superscript letter along the columns are not significantly different (DMRT) Chlorophyll a showed a significant strong positive correlations with turbidity ($r = 0.6959$, $p = 0.03$), conductivity ($r = 0.8071$, $p = 0.009$), total nitrogen ($r=0.7389$,

p=0.023), Ammonia (r=0.8864, p=0.002), temperature (r = 0.8129, p=0.008), total phosphorus (0.7619, p = 0.017), SRP (r = 0.8438, p = 0.004), Alkalinity (0.7499, p = 0.02) and hardness (r = 0.7416, p=0.022). It as well depicted strong negative correlation with dissolved oxygen (r = -0.6999, p = 0.036). There was a strong negative correlation between Cyanophyceae and Bacillariophyceae (r = -0.7983, p = 0.0099). All other phytoplankton families did not show any significant correlations between themselves. Among the phytoplankton families, only Euglenophyceae showed a strong positive correlation with nitrites (r = 0.7436, p = 0.022).

4.5 Correlation between Physico and chemical parameters and nutrients

The pH showed a positive significant correlation with Total Phosphorus and Dissolved Oxygen ($p < 0.05$), but a negative significant correlation with Total Nitrogen and Secchi depth. Total Nitrogen also showed a significant positive correlation with Total Phosphorus and Soluble Reactive Phosphorus, Total Nitrogen, Nitrites, Ammonium and Silicates but a negative correlation with pH. Depth exhibited a negative significant correlation with turbidity, ammonium-nitrogen, hardness and total phosphorus but a positive correlation with dissolved oxygen and silicates (Table 7).

Table 7: Correlation (Spearman rank correlation coefficient) between physico-chemical parameters. Means with the same letter along the columns are not significantly different

Variables	TP	SRP	TN	Nitrates	Nitrites	Ammonium	Silicates	Hardness	Alkalinity	Secchi depth	Depth	pH	DO	Cond	Turb	Temp
TP	1.000															
SRP	0.574*	1.000														
TN	0.355*	0.216*	1.000													
Nitrates	-0.006	0.008	0.455*	1.000												
Nitrites	-0.105	-0.038	-0.012	0.187	1.000											
Ammo	0.125	0.1471	0.223*	0.384*	0.063	1.000										
Silicates	0.046	0.221*	-0.199	-0.011	0.341*	-0.002	1.000									
Hardness	0.001	0.020	0.146	0.128	0.053	0.035	-0.121	1.000								
Alk	-0.049	-0.023	-0.080	0.039	-0.063	0.089	0.006	0.083	1.000							
Secchi	-0.259*	-0.074	0.211	0.386*	0.217	0.002	0.178	0.258*	-0.003	1.000						
Depth	-0.256*	-0.111	-0.073	-0.090	0.211	-0.240*	0.296*	-0.381*	-0.141	0.129	1.000					
pH	0.371*	0.068	-0.288*	-0.347	-0.158	0.106	-0.054	-0.199	0.036	-0.249*	-0.097	1.000				
DO	0.129	-0.089	-0.149	-0.111	0.038	-0.059	0.037	-0.228	-0.094	0.287*	0.320*	1.000				
Cond	0.125	-0.046	0.113	0.228	0.101	0.179	-0.064	0.364*	0.010	-0.123	-0.305	-0.138	0.287	1.000		
Turb	0.448	0.061	0.138	-.0.174	-0.030	-0.140	-0.072	-0.079	-0.043	-0.315	-0.266*	0.351	0.011	0.181	1.000	
Temp	-0.116	-0.109	-0.127	-0.084	-0.035	-0.101	-0.188	-0.066	-0.106	-0.105	-0.091	0.070	-	-0.39	-0.181	1.000

4.6 Phytoplankton community structure within Kisumu Bay, Lake Victoria.

The abundance and percentage composition of the major phytoplankton groups in Kisumu Bay are presented in Table 8. A total of six phytoplankton families namely, Chlorophyceae, Cyanophyceae, Bacillariophyceae (Diatoms), Dinophaceae, Euglenophyceae and Zygnematophyceae were identified in Kisumu bay. Cyanophyceae commonly referred to as the blue-green algae was the most dominant family across the sampling stations.

Table 8: Spatial distribution and mean abundance of major phytoplankton family in Kisumu Bay, Lake Victoria

Algal Taxa	Chlo	Cyn	Diat	Dino	Eug	Zyg
St. 10B	152.9±538.9	1989.3±6551.6	23.3±30.9	53.2±69.1	25.9±50.9	24.2±38.5
Auji	94.4±367.9	706.2±2087.5	45.5±164.6	33.8±54.1	17.5±24.8	10.2±11.7
Dunga	74.6±218.9	1154.9±3228.7	63.3±342.3	27.9±51.0	25.1±42.2	57.4±184.4
Kisat	223.6±736.2	2649.9±7168.9	58.5±341.1	31.1±61.1	40.1±109.9	12.5±16.5
Kisian	18.8±27.4	908.8±2301.4	12.5±16.4	92.4±237.5	11.7±11.6	17.1±51.9
Molasses	61.7±315.3	1053.4±2758.2	25.4±39.6	52.6±78.1	20.6±24.9	31.5±61.5
Pier	132.3±569.8	4263.5±9863.4	19.9±35.6	69.3±99.5	41.6±102.7	17.7±25.1
Tilapia	39.7±119.5	2243.4±7126.8	20.3±29.5	127.4±307.7	22.6±29.4	79.6±204.5
Usoma	111.5±437.4	1154.2±3359.6	24.0±31.5	103.0±191.4	29.3±38.1	12.5±19.9
Cocacola	232.4±815.5	4057.1±11319.2	60.5±270.7	79.2±145.2	26.8±61.3	179.3±515.1

Midpoint	136.4±576.3	2450.5±7043.7	71.8±279.8	34.4±44.8	35.3±46.7	16.3±22.7

Legend-Key

Chlo = Chlorophyceae

Cyn = Cyanophyceae

Diat= Bacillariophyceae (Diatoms) Dino=Dinophaceae

Eug =Euglenophyceae

Zyg= Zygnematophyceae

The spatial distribution and percentage composition of major algal taxa in Kisumu Bay is presented in Table 9. The algal composition was dominated by Cyanophytes constituting up to 35 % of all algal groups followed by diatoms with 30 % in all the months of sampling. The latter formed an important component of the algal flora constituting 98% in December and 13 % in May. Chlorophytes were most important in most stations constituting about 12 % in November 2017 and 15 % in February. The contribution of Cyanophytes to the overall phytoplankton community remains largely significant in most stations. Occurrence of Euglenophytes were lowest in almost all stations but in November and March were 32 % and 13 % respectively. This family was mainly dominated by *Phacus and Strombomonous* genera. Two species of dinoflagellates were encountered *Glenodinium pernardii* and *Ceratinium* spp. Diatoms appeared in all the months and were mainly represented by *Surillella* sp, *Nitzschia*, *Synedra*, *Diatoma* spp and *Cyclotella* genera. From September to April *Microcystis* spp remained the most dominant more detailed temporal distribution of major algal families in Kisumu Bay is presented in Fig 2.

The most abundant phytoplankton genera were *Microcystis aeruginosa* (25.44 %), *Merismopedia* spp (23.49 %) and *Anabaena flos-aquae* (16.06 %) Table 9.

Table 9: Percentage composition of major phytoplankton Taxa in Kisumu Bay, Lake Victoria

Genus/ Taxa	Numbers per ml	Percentage Composition
Microcystis aeruginosa	11780	25.44
Merismopedia spp	10876	23.49
Anabaena flos-aquae	7435	16.06
Anabaena circinalis	6234	13.46
Pediastrum tetras	2019	4.36
Chroococcus limnetica	1500	3.24
Scenedesmus acuminatus	1200	2.59
Plankolyngbya tallingii	1143	2.47
Chroococcus disperses	1092	2.36
Microcystis wasenbergii	850	1.84
Fragillaria gracilis	476	1.03
Amphora ovaries	398	0.86
Chroococcus disperses	321	0.69
Coelastum microporum	321	0.69
Phacus pleuronectes	265	0.57
Synedra cunningtonii	188	0.41
Cyclotella kutzinghiana	76	0.16
Fragillaria sp	58	0.13
Others	50	0.11
Strombonous sp	27	0.06
Total Percentage Composition	46309	100.00

4.7 Spatial and temporal variation of phytoplankton families in Kisumu Bay

The temporal distribution of major algal groups in Kisumu Bay during the period September 2017 to May 2018 is presented in Table 10. The cyanophytes dominated the algal community throughout the sampling period. Chlorophytes were the second dominant group to cyanophytes except only in November 2018 when Zygnematophyceae become the second most dominant group.

Table 10: Temporal distributions of phytoplankton families in Kisumu Bay Lake Victoria

	Chlo	Cyn	Diat	Dino	Eug	Zyg
September	189.7±622.7	2889.0±8332.3	33.3±120.5	66.4±135.3	36.5±52.8	16.2±19.7
October	36.7±121.9	1494.5±4037.2	39.5±285.1	12.1±11.0	12.7±17.9	7.4±9.8
November	208.6±678.7	3083.5±9698.7	57.5±137.7	122.3±308.7	36.4±53.5	240.0±457.4
December	226.4±765.2	1353.3±2649.6	52.7±111.8	55.3±53.2	29.3±23.8	105.9±235.9
January	179.2±730.6	1555.5±4212.7	33.5±42.3	97.6±230.1	31.2±32.5	26.3±43.7
February	113.5±497.8	3196.0±8744.4	36.1±178.9	110.3±148.6	43.5±110.5	32.8±55.9
March	149.5±510.8	2037.4±6794.1	45.1±212.5	100.9±163.5	27.8±27.1	16.6±22.4
April	68.3±216.2	893.5±3082.6	37.8±256.5	12.7±7.4	19.1±48.1	9.6±15.0
May	28.9±133.1	1044.7±3022.2	13.1±23.3	22.3±33.1	18.5±46.4	15.9±15.9

Dinoflagellates were the third most dominant group in September 2017, October and November 2017 and in January to February 2018, while the diatoms displaced Zygnematophyceae during the rest of the period. Euglenophytes were the least dominant group throughout the sampling period.

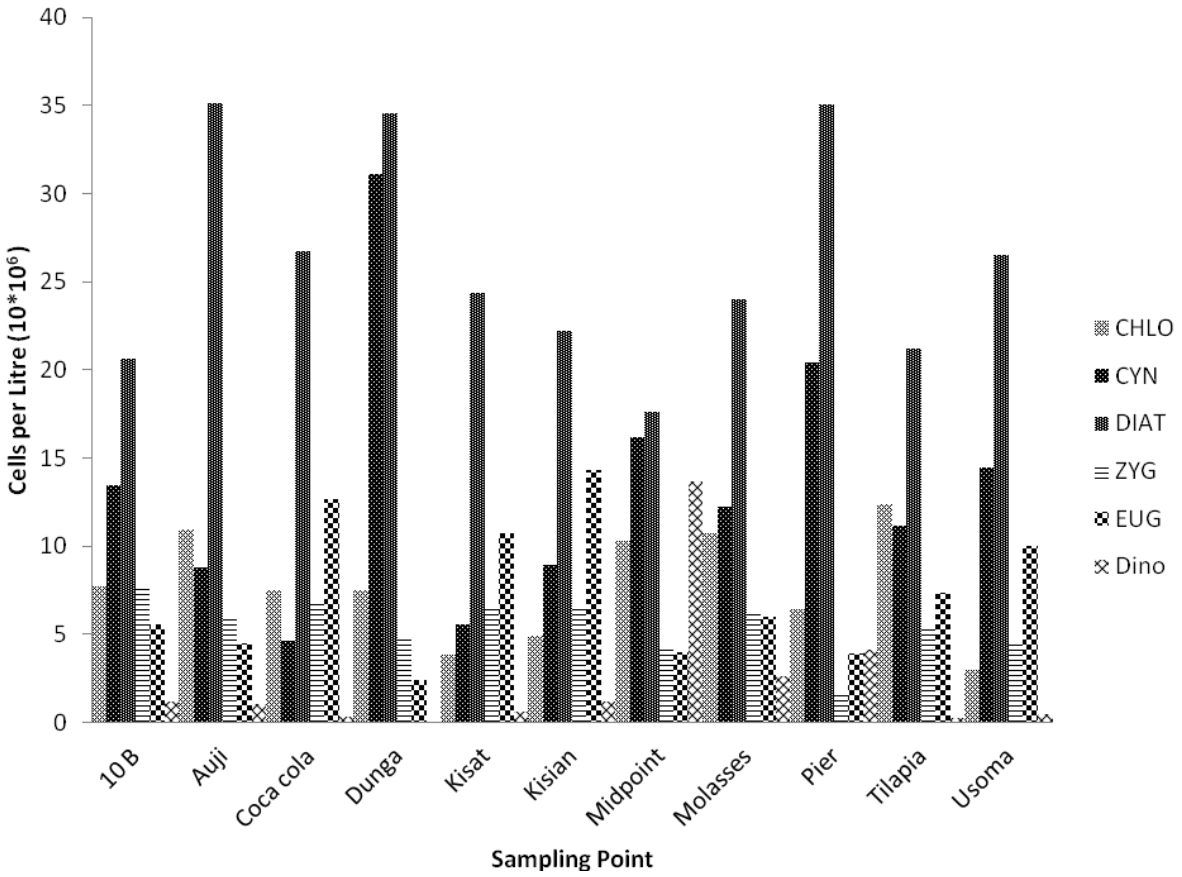

Figure 2: Spatial distribution of phytoplankton in the Kisumu Bay of Lake Victoria

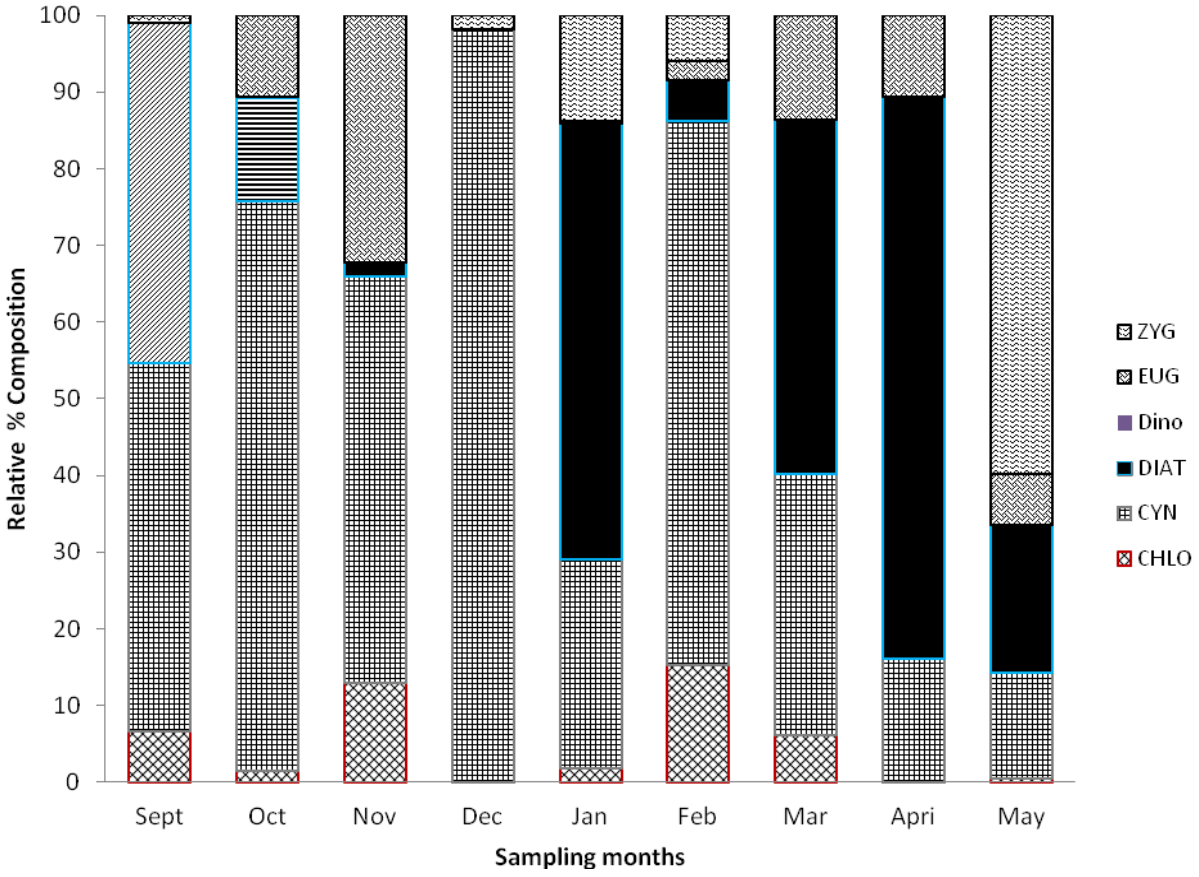

Figure 3: Temporal distribution of major algal taxa in Kisumu Bay, Lake Victoria

The percentage composition of algal community structure in Kisumu Bay indicates that *Microcystis aeruginosa* is the most abundant species .and is major algal species in Lake Victoria. There were 130 different species of phytoplanktons identified throughout the sampled period of which 43 species of chlorophytes were encountered in wet April, July and September 2017, *Scenedesmus* spp, *Botrycoccus* sp, *Ankistrodesmus falcatus* and *Pediastrum* spp were the most common genera in the entire sampling period. On the contrary, there were 15 species of Zygnematophyceae encountered in January, February, November and December of which *Cosmarium* and *Straurastrum paradoxum* were the most frequently encountered genera. Three

species of dinoflagellates were encountered, the common ones being *Ceratium* and *Glenodinium pernardii* in St 10 with 15 % recorded in November and January 2018. There were 38 species of diatoms observed in entire study period, constituting mainly *Surillella* sp, *Nitzschia*, *Synedra*, *Aulacoseira* spp and *Cyclotella* spp. The fifth major algal group encountered was the euglenophytes which were represented by a genera which recorded 11 species in entire period, the most dominant being *Phacus* spp, *Euglena* spp, *Trachelemonous* and *Strombomonous* spp. Cyanobacteria was represented by 20 species with *Microcystis* spp and *Anabaena* spp being the dominant, and are known to be buoyant with ability to fix nitrogen from the atmosphere (Fig: 3).

Table 11: Physico-chemical parameters in relation to eleven (11) most abundant species in the phytoplankton community

Taxa	**D.O** mgL^{-1}	**Conductivity**	**Temperature**	**pH**	**Total Phosphorus**	**Total Nitrogen**
Microystis sp	+0.656*	-0.336	-0.461	+0.244	-0.731*	-0.673*
Scenedesmus sp	+0.331	-0.044	-0.394	+0.159	-0.757*	-0.626*
Kirchnella sp	0.139	-0.366	-0.270	+0.130	-0.317	-0.441
Synedra sp	-0.463	+0.276	+0.519*	-0.347	+0.662*	+0.510*
Nitzschia sp	-0.579*	+0.137	+0.647*	0.517*	+0.758*	+0.574*
Euglena sp	+0.518*	+0.257	-0.119	+0.183	-0.344	-0.244
Strombomonous	+0.217	+0.153	-0.264	-0.063	-0.417	-0.217
Cyclotella sp	+0.241	+0.194	-0.048	+0.037	-0.550*	-0.433
Ceratinium spp	-0.285	+0.326	+0.374	-0.129	+0.228	+0.447
Ampora sp	-0.067	-0.321	+0.043	+0.169	+0.350	+0.261
Crucigenia sp	+0.125	-0.093	-0.382	+0.153	-0.356	-0.310

The correlation between physical chemical parameters and abundance of major algal taxa in Kisumu bay is presented in Table 11. Considering individual Cyanobacteria taxa, *Microystis* sp showed a significant positive correlation with dissolved oxygen and pH while it showed a significant negative correlation with total phosphorus and total nitrogen. Its correlations with other physical chemical parameters were insignificant. *Scenedesmus* species did not show any significant positive correlation with physical chemical parameters; however it showed significant negative correlation with total phosphorus and total nitrogen. The *Kirchnella* sp showed a significant positive correlation with pH while it did not show any significant correlation with other physical chemical parameters. The diatom *Synedra* showed significant positive correlations with the parameters Temperature, total phosphate and total nitrogen. The diatom *Nitzschia* spp exhibited significant correlation with total phosphorous, total nitrogen, temperature and pH while it showed a strong negative concentration with dissolved oxygen. A similar trend was shown by *Ceratinium* spp and *Amphora* spp. which showed significant positive associations with dissolved oxygen. *Euglena* Spp showed a significant positive correlation with dissolved oxygen concentration. Lastly the diatom *Cyclotella* spp only showed a significant negative correlation with total phosphorous.

4.8 Phytoplankton diversity indices of different groups in Kisumu Bay

Results of phytoplankton diversity indices are presented in table 12. The number of families of phytoplankton at different sampling sites ranged from 5-6. The major groups in order of dominance constituted: Chlorophyceae, Cyanophyceae, Bacillariophyceae, Dinophaceae, Euglenophyceae and Zygnematophyceae.

Table 12: Shannon wiener index of biodiversity indices of algae in Kisumu Bay

	Kisian	Molasses	Usoma	Cocacola	Kisat	Pier	Tilapia	Auji	10_B	Dunga	Midpoint
Taxa_S	6	6	5	5	6	6	5	6	6	5	6
Individuals	57	62	58	59	53	71	57	66	57	80	66
Dominance_D	0.253	0.24	0.299	0.2933	0.2844	0.337	0.2435	0.34	0.239	0.3538	0.2084
Simpson_1-D	0.747	0.76	0.701	0.7067	0.7156	0.663	0.7565	0.66	0.762	0.6462	0.7916
Shannon_H	1.525	1.591	1.37	1.406	1.469	1.339	1.508	1.36	1.564	1.208	1.653
Evenness_e^H/S	0.766	0.818	0.787	0.8159	0.7242	0.636	0.9035	0.65	0.796	0.6692	0.87

The Shannon wiener index of biodiversity ranged from 1.2 at Dunga to 1.6 at off Maboko Island. This value depicts a habitat which is moderately polluted and has a low biodiversity. The Simpsons richness ranged from 0.6462 at Dunga to 0.747 at Kisian indicating that algal species were not evenly distributed.

4.9 Algal Toxins in Kisumu Bay, Lake Victoria

Results on algal toxins identified in Kisumu Bay are presented in Table 13. A total of five different microcystin were identified, all of which are produced by Microcystis spp blooms (Fawell et.al., 1993). However their concentration varied from site to site. The World health organization sets the minimum acceptable algal toxin concentration in domestic water supplies at below 1.0 μg/L

Table 13: Spatial distribution of means of algal Toxin in mgL^{-1} ,Kisumu Bay, Lake Victoria

Location	Toxins				
	MCLR	**MCYR**	**MCLA**	**DmLR**	**MCRR**
10 B	0.107 ± 0.20^{A}	0.058 ± 0.12^{A}	0.022 ± 0.04^{A}	0.008 ± 0.01^{A}	0.003 ± 0.004^{B}
Auji	0.201 ± 0.31^{A}	0.062 ± 0.10^{A}	0.024 ± 0.04^{A}	0.020 ± 0.04^{A}	0.009 ± 0.01^{B}
Cocacola	2.360 ± 4.41^{A}	1.840 ± 3.76^{A}	0.333 ± 0.63^{A}	0.173 ± 0.34^{A}	0.033 ± 0.05^{B}
Dunga	0.122 ± 0.25^{A}	0.060 ± 0.10^{A}	0.041 ± 0.07^{A}	0.009 ± 0.02^{A}	0.002 ± 0.01^{B}
Kisat	0.312 ± 0.48^{A}	0.119 ± 0.15^{A}	0.041 ± 0.05^{A}	0.019 ± 0.03^{A}	0.011 ± 0.01^{B}
Kisian	0.270 ± 0.38^{A}	0.144 ± 0.24^{A}	0.076 ± 0.11^{A}	0.017 ± 0.03^{A}	0.008 ± 0.01^{B}
Midpoint	0.962 ± 2.22^{A}	0.803 ± 1.90^{A}	0.146 ± 0.34^{A}	0.049 ± 0.12^{A}	0.012 ± 0.03^{B}
Molasses	0.326 ± 0.38^{A}	0.137 ± 0.20^{A}	0.061 ± 0.09^{A}	0.026 ± 0.03^{A}	0.002 ± 0.004^{B}
Pier	1.272 ± 1.76^{A}	1.100 ± 1.88^{A}	0.199 ± 0.33^{A}	0.090 ± 0.12^{A}	0.087 ± 0.14^{A}
Tilapia	0.232 ± 0.37^{A}	0.118 ± 0.20^{A}	0.044 ± 0.06^{A}	0.016 ± 0.03^{A}	0.013 ± 0.02^{B}
Usoma	0.147 ± 0.21^{A}	0.055 ± 0.10^{A}	0.040 ± 0.06^{A}	0.009 ± 0.01^{A}	0.005 ± 0.01^{B}

Legend-Key

MC-LR- MC desmethyl microcystin-LR

MCYR- MC didemethyl-microcystin-YR

MCLA- MC didemethyl-microcystin-LA

dmLR- - MC didemethyl-microcystin-LR

MCRR –MC didemethyl-microcystin-RR

Concentrations of two of the toxins namely MCLR and MCRY exceeded WHO acceptable standards at Cocacola and Fisheries pier sampling sites. In all the other sampling sites concentration levels of two the two toxins were below the WHO acceptable standards. Levels of the other toxins were insignificant in all sampling sites. The highest mean concentration of 2.360±4.41 of MC-LR was measured at Cocacola depicting levels above the WHO threshold. Also a mean concentration of 1.840 ± 3.76^{A} also a mean concentration of 1.840 ± 3.76^{A} of MCYR was measured at the pier sampling sites. The spatial of the toxins can better be visualized in fig: 4.

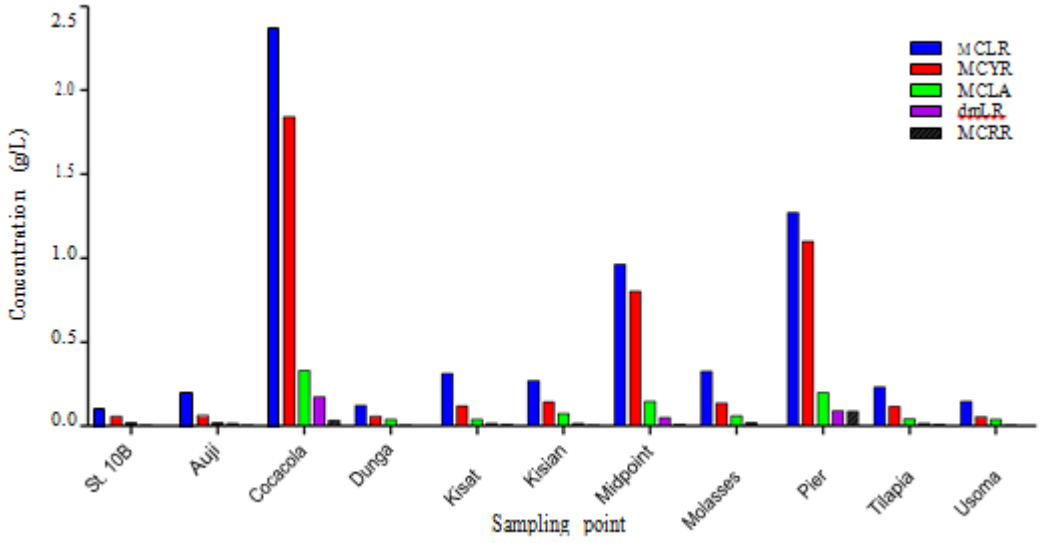

Figure 4: Concentration of the different toxins per sampling station in the Kisumu Bay of Lake Victoria

Coca-cola, Pier and Mid-point sampling stations recorded the highest concentration of toxins in that order, while station 10B recorded the lowest. MC-RL was the most dominant toxin across all the stations, followed by MC-YR and MC-LA in that order. Only two sampling stations (Coca-cola and Pier) had varying amounts of all the 5 toxins, with the rest of the sampling stations having either two or three variants of microcystin toxins.

4.10 Toxins concentrations

Microcystin structural variants microcystin-LR was the most common toxin with the highest concentration while MC-RR was the least. According to the study Microcystin MC-LR and

MC-RR were above detection limit of mgl-^{1}. The relationship between particulate Microcystin-LR equivalents and other MCLA, dmRL and MCRR did not show a similar trend and did not appear in most of the sampling period and were below the detection limit. MC-LR equivalent concentrations were greater than 0.05 µgl-^{1}

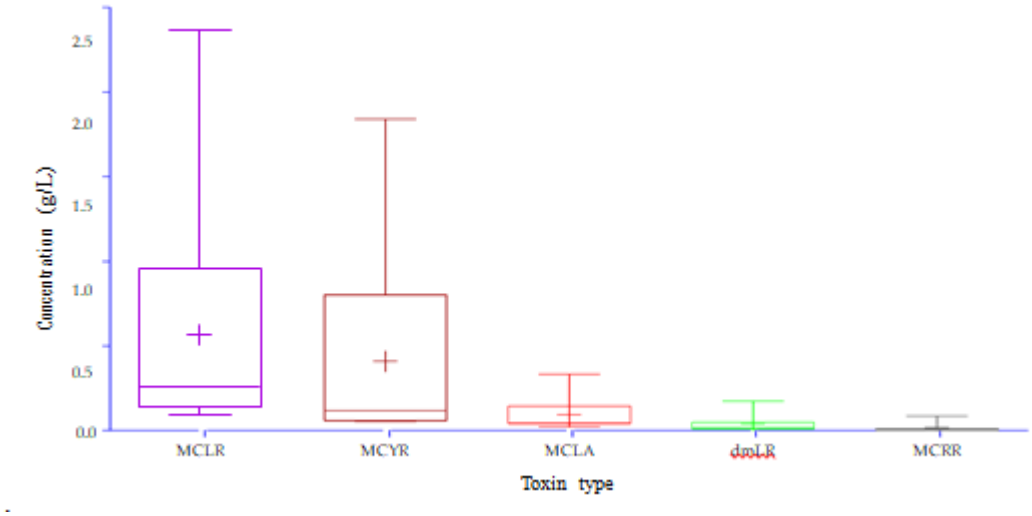

Figure 5: Concentration of different toxins recorded across all stations combined

Coca cola, Fisheries Pier and Mid-point sampling locations recorded the highest concentration of toxins in that order, while station 10B recorded the lowest. MC-RL was the most dominant toxin across all the stations, followed by MC-YR and MC-LA in that order. Only two sampling locations (Coca- cola and Pier) had varying amounts of all the 5 toxins, with the rest of the sampling stations having either two or three variants of microcystin toxins.

4.11 Correlation between algal toxin and Nutrients concentration

The correlations between algal toxins and nutrients are presented in table 14. All the toxins were strongly positively correlated with nutrients at R2 <0.606. Total nitrogen showed a strong positive correlation with all the five algal toxins comparably. TP did not show any significant correlation with algal toxins. However soluble reactive phosphorous had a strong positive concentration with MCRR. Chlorophyll *a* concentration which represent total algal biomass all abundance also showed strong positive correlations with the all algal toxin.

Table 14: Correlation Matrix of Microcyctins, nutrients concentration in Kisumu, Lake Victoria, Kenya

Variables	MC-LR	MC-YR	MCLA	dmLR	MCRR	TP	SRP	TN	Nitrates	Ammo	Chlo. A
MCLR	1.000										
MCYR	0.985*	1.000									
MCLA	0.977*	0.979*	1.000								
DmLR	0.985*	0.965*	0.963*	1.000							
MCRR	0.627*	0.686*	0.694*	0.606*	1.000						
TP	0.209	0.201	0.181	0.208	0.103	1.000					
SRP	0.109	0.083	0.111	0.132	0.252*	0.308*	1.000				
TN	0.183	0.105	0.132	0.209	0.054	0.381*	0.288	1.000			
Nitrates	0.494*	0.404*	0.372*	0.469*	0.146	0.189	0.071	0.441*	1.000		
Ammo	0.215*	0.177	0.172	0.229*	0.254*	0.295*	0.539*	0.348*	0.423*	1.000	
Chlo A	0.603*	0.541*	0.530*	0.604*	0.184	0.791*	0.191	0.342*	0.610*	0.403*	1.000

Ammonia showed a significant positive correlation with MC-LR, dmLR and MC-RR. Both conductivity and soluble reactive phosphorus showed a significant positive correlation with MC-CR. (Table 13). The principal component analysis of algal toxins and nutrients is depicted in Figure 6.

4.12 Correlation between physico-chemical parameters, phytoplankton and algal Toxins

The correlations between physical-chemical parameters, phytoplankton and algal toxins are presented in Fig: 6 to 8. Dinoflagallates, Cyanophyceae and diatoms showed positive significant relationship with Chlorophyll *a* MCLR extracelluar equivalent. Cyanophyceae, Euglenophyceae and Dinophceae showed a strong correlation at Dunga Midpoint and Auji. Chlorophceae showed a strong correlation with turbidity and conductivity indicating that some groups which are not buoyant cannot thrive hence photosynthesis is reduced. Tests of significance using a PCA revealed that of the six groups of phytoplankton and microcystin-LR equivalents and other

environmental variables like Oxygen ($p < 0.05$) were significant in explaining the variance in the species data in the bay. According to the above PCA, that was performed using different algal taxa like Cyanophyceae, Bacillariophyce, Chlorophyceae, Euglenophyceae, Zygnematophycea and Dinophceae to determine the strength of each one of them in the species dispersion and if they are only ones to explain the dispersion. All the six variables were still significant in the PCA ($p < 0.05$). The six groups of phytoplankton with one microcystin-LR equivalents revealed that other environmental variables at Coca-Cola, Dunga and pier including chlorophyll *–a* strongly explains the distribution of algal community structure in space and time. This was also confirmed by soluble reactive phosphorous, total phosphates and Total Ammonia (NH4--N) and Total Nitrogen (TN) which were significantly higher in the Pier ($p<0.01$. However, the remaining part of the variation cannot be explained by our data and may be due to other variables not included in the analysis or measured in the study.

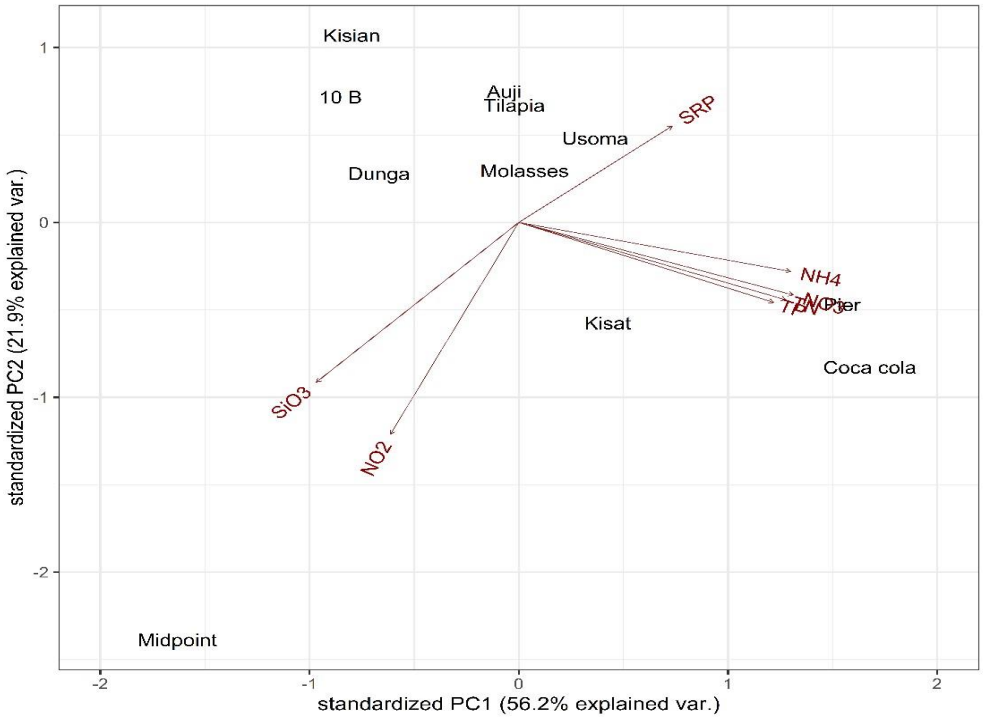

Figure 6: Correlation between nutrients and Toxin extracellular Microcystin variables

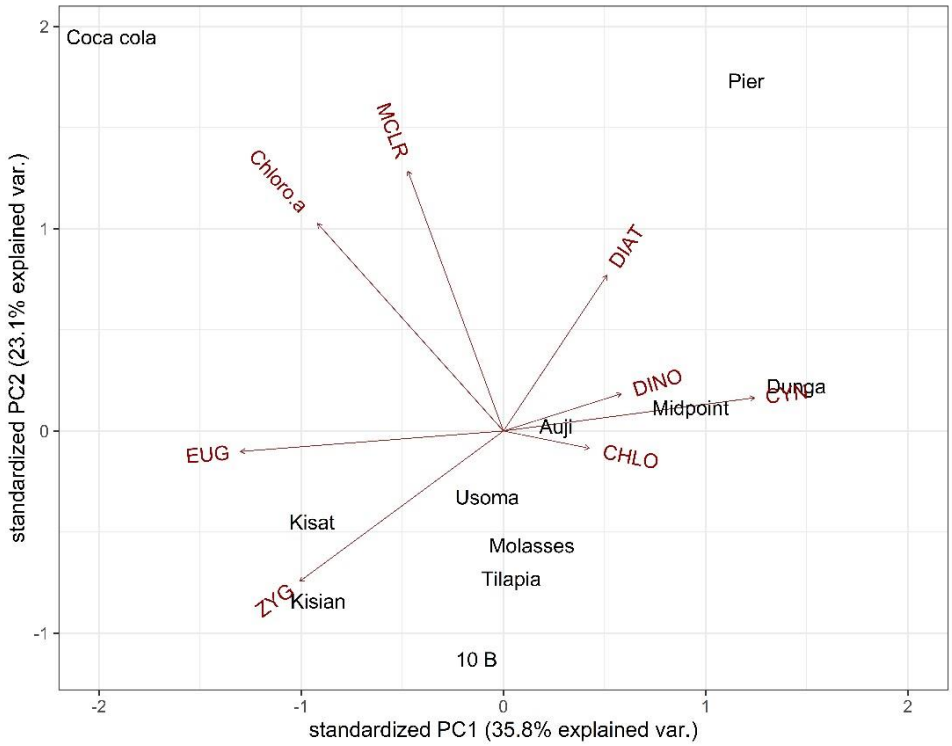

Figure 7: Correlation between algal toxins, Chlorophyll a and Phytoplankton Taxa

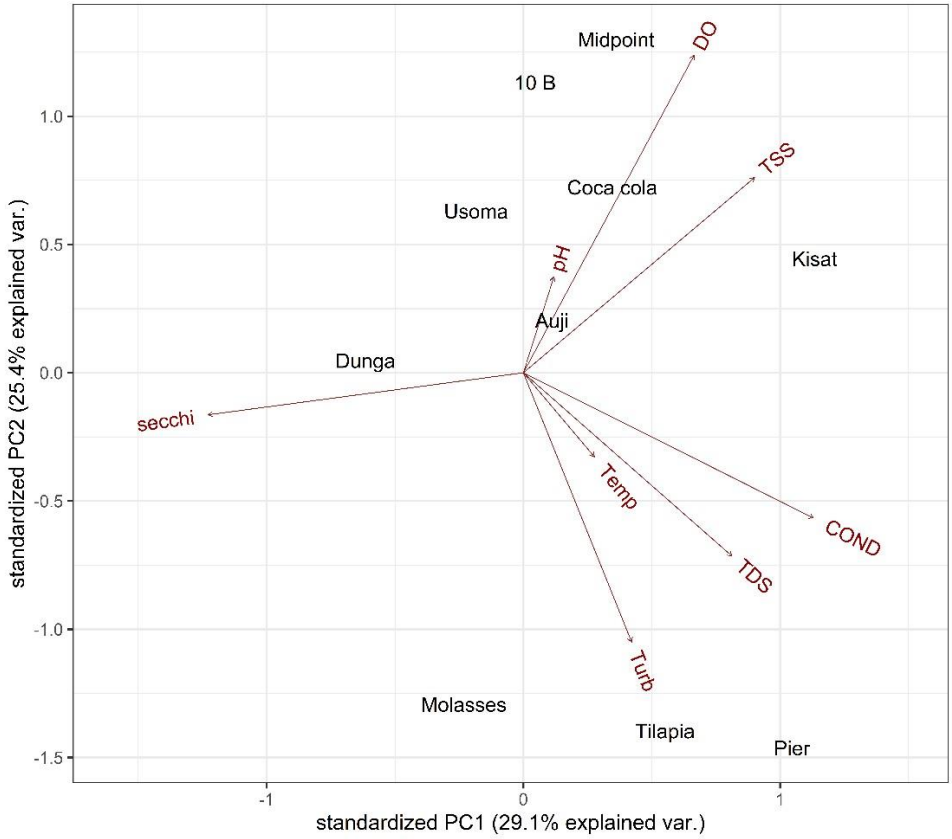

Figure 8: Correlation between Physico-chemical parameters and Toxin extracellular Microcystin variables

CHAPTER FIVE

DISCUSSION

5.1 Introduction

This chapter presents the discussions on the results of the phytoplankton community structure, water quality (physico-chemical) parameters, and mycrocystin toxins concentration in Lake Victoria.

5.2 Physico-chemical parameters

The differences in physico-chemical parameters observed in this study could have influenced the ecological status of the lake including species composition and abundance of the aquatic organisms which in turn, influence aquatic processes and lake productivity. As the data shows, the pattern of change of physical and chemical parameters in Kisumu Bay is extremely variable and unpredictable across sampling stations. This may be attributable to the shallow mean depth and landscape context of the Kenyan part of the lake, which is strongly influenced by extremely variable seasonal/diurnal wind patterns, shear and runoff from Kisumu City and adjacent agricultural farm lands and industrial effluent (Okely et al., 2010). This together with the nature of the bays and river inflows influences the development of algal blooms and production of algal toxins. All these factors are indicators of cultural eutrophication in the lake ecosystem health. Further these factors together with climate change may be responsible for the variable nature of spatial and temporal changes in the algal community structure.

Dissolved oxygen showed significant differences between sampling stations. The significantly low oxygen levels particularly those recorded at the Fisheries pier could have been as a result of increased load of nutrient rich organic matter originating from the city sewage treatment works and runoff. These will encourage the development of algal blooms and eutrophication on the overall. The decomposition of nutrient rich organic matter and aging of algal bloom together with dead organic materials and water hyacinth could trigger microbial activities which lead to reduced oxygen concentration in the water column (Hecky & Bugenyi, 1993).

The high temperature levels in Dunga and Pier could be attributed to the relatively shallow depth compared to other sampling sites. However, lack of significant differences in temperature was ascribed to almost similar water depth levels across the sampling sites within the Bay.

The high conductivity observed at all sampling sites in Kisumu Bay could also be due to discharge of effluent from motor vehicle garages, Metal work workshops, car washes, institutional laboratories and run off from petrol stations. The eutrophication and polluted states of the bay are exacerbated by its sheltered nature, which results in minimal water mixing (Nyamweya *et al*.,2016). The sheltered nature of Auji and Dunga sampling sites could also contribute to the observed gradual increase in temperature gradient from the littoral towards the offshore zones.

The high temperatures observed at Kisat sampling sites could be due to high turbidity of the waters which absorbs and retains solar energy. A recent study by KMFRI, (2005) technical report indicated that in areas with high suspended and dissolved solids, high temperatures are persistent, often associated with a high concentration of total suspended solids. Studies show that high water

temperatures can accelerates oxygen consuming reactions and result in oxygen depletion at particular times of the day (Nyamweya *et al.*, 2016). The near neutral but alkaline pH observed in the bay could be attributed to the discharge of alkaline effluent by equator soft drink bottling plant in Kisumu city. Such pH conditions favor algal communities dominated by Cyanobacteria as observed in the bay. The sampling sites located at the river mouth generally recorded almost the same pH levels that were not significantly different compared to those in the Bay. Untreated sewage waste and livestock activities along the Kisat and Kisian river mouths could result in the low pH levels recorded there. The high pH recorded at Dunga, Coca-cola and Pier sampling sites indicates a dramatic increase in alkalinity of the water over the sampling period. This can be attributed to the cumulative effect biochemical processes associated with fish cage aquaculture and discharge of raw sewage into the Bay. Fluctuations in temperature and pH highly influence the dissociation of ionized ammonia (NH_4—N) into unionized ammonia (NH^3). For example, Ammonium (NH_4^+) and nitrate (NO_3^-) assimilation by algae are through two principle processes by which nitrogen is obtained during primary production (Hossain *et al.*, 2007). Nitrite provides an additional, but subsidiary, dissolved N source Nutrient made available through such processes encourage the growth of algae and in the case of nitrogen since it is one of the limiting primary productivity high biomass of blue green algae develop. These further support the observed dominance of cyanophceae in the bay. At highly elevated concentrations, NH_4^+ becomes toxic depending on water quality factors mainly temperature and pH (Carey & Migliaccio, 2009). The unionized ammonia (NH_3) at concentration levels > 20 μgL-1 are toxic to aquatic organisms and affects the phytoplankton community structure. Therefore, the toxicity levels of total ammonia are expressed as a function of temperature and pH. The NH_4^+ concentration level at Dunga site and the observed temperature as well as pH, gave NH_3- level above the acceptable limit consequently

toxic. High residence time coupled with intense vertical mixing within the gulf encourages enhanced Physico-chemical values of the water due to particle associated nutrient remobilization. Conductivity, TA, TH, SRP, TP, NH_4^+, NO_2^-, NO_3^- and TN levels were significantly higher within the gulf compared to the Midpoint sampling site. It was clear that Kisat, Auji and Dunga had relatively high conductivity levels, which could be attributed to the presence of dissolved ions resulting from the surrounding areas. A study by (Sitoki *et al*., 2010) indicated conductivity levels of between 157.72-195.1 μScm^{-1} within Kisumu Bay, which were slightly lower than those recorded at the Kisan, Molasses and Midbay sampling stations in the current study. This could have been as a result of the difference in sampling design since in the current study, both river mouths and the open waters were sampled, while (Sitoki *et al*., 2012) study showed only deeper parts of open lake were sampled. Nevertheless, the relatively high levels of conductivity at certain sampling points like Kisat river for instance ware higher since they serve as a conduit of urban effluents; fertilizers, sewage and other wastes (Lung'aiya et al., 2000; Gikuma-Njuru & Hecky, 2005). The hardness recorded across all the sampling sites was relatively low implying that the water was considered to be having low calcium Ions concentrations and was hence corrosive and soft. High alkalinity could result into the growth of cyanophytes as reported by Touloupakis et al. (2016).

The higher turbidity observed at sampling sites in the bay was due to presence of high concentration of total suspended solids in water that was associated with poor light penetration, and re-suspension of Lake bottom sediments. However, the high turbidity levels at Pier s sampling site was attributed to presence of high algal productivity and concentration of mineral ions. These could also lead to proliferation of Cyanobacteria especially *Microystis* and *anabaena*

spp which are known for their efficiency in nitrogen fixing from the atmosphere because they have specialized cells known as heterocyst which enable them to fix nitrogen for their photosynthetic requirements. This type of algae have vacuoles in their cells which enable them to maintain buoyancy in the water column and are therefore capable of positioning themselves at depth levels which have optimal photic conditions for their photosynthesis. According to Wetzel (1991), eutrophic waters provide a conducive environment for algal proliferation. Such eutrophic waters are characterized by high nutrient levels particularly those of nitrogen and phosphates. Under such conditions blue green algae dominate. Similar observation were made in the gulf whereby total nitrogen and total nitrites were high and a rich community of cyanophytes algae constituting of *Microcystis spp, anabaena spp, Merismopedia spp* and *Planktolyngbya spp* was prominent. TN showed highly significant correlation with chlorophyll-a and secchi depth reading during the entire sampling period. Algal communities are highly enriched in nitrogen compound, due to their high protein (which accounts for much of the N) and lipid content. The high nitrogen content in the water column is therefore mainly organic nitrogen derived from algae. The Cyanobacteria actively extracts nitrogen from the water column, hence the significant correlation between NO_2^- with Chlorophyll-a obtained in this study. Due to the altered TN /TP ratio from the normal 16:1 observed in this study both chlorophyll a concentration and abundance of Cyanobacteria were higher. The higher TN/TP concentrations observed at Dunga and Auji could be attributed to nutrient rich effluent emanating from agricultural farms in the neighborhood in which phosphate and nitrate fertilizers are applied to improve productivity. Studies by Wetzel *et.al*., 1983, Sitoki *et al.,* 2012, Babu *et al*., 2015, indicatee that rich algal community develop in water bodies containing high nutrient concentrations particularly phosphates and nitrates under such situation in which the water body is eutrophic. Cyanobacteria

do develop cells that are lysed and during certain periods some species of Cyanobacteria can produce toxins (Schatz *et al.,* 2007). Similar observations were made in this study in which dense algal bloom constituting of *Microcystis spp* and *Anabaena spp* produce toxins. Thus the nature and health of aquatic communities is an expression of the limnological status of water body. High light intensity areas can attain high photosynthetic activity to increase primary production. This is in agreement with earlier studies by Gichuki (2001, 1995); Hecky, (1993); Mugidde, (1993); and Lungaiya *et al.* (2000). Silica levels were however recorded to be the highest at the Mid-Point sampling station. However no significant differences were recorded during sampling and this could probably be associated with the presence of Bacillariophyceae and Cyanophytes in most of the sampling stations.

Studies by Sitoki *et al* (2012) in Kisumu Bay showed that nutrient concentrations have escalated compared to the previous periods. The Total Nitrogen (TN) concentrations have risen to nearly six-fold due to particulate nitrogen and nitrogen embedded in the algal biomass. Chlorophyll-a concentration within the gulf were above 10 MgL^{-1}. Other studies in other parts of the world for example studies by Wetzel *et.al.,* 1983 showed that the health of aquatic communities is an expression of the limnological status of water body. High light intensity areas can attain high photosynthetic activity to increase primary production, (Gichuki, 2000, 1995; Hecky, 1993; Mugidde, 1993; Lungaiya *et al.,* 2000). The waters within the gulf are turbid and less in Chlorophyll-a. The peripheral areas in the Kisat and Mollases are more enriched in chlorophyll a than the mid gulf. High Chlorophyll-a concentrations observed at the peripheral stations resulted from the diffusion of the remobilized nutrients within the turbulent areas.

5.3 Phytoplankton species diversity and abundance

The dominance of cyanophytes and diatoms in Kisumu Bay was due to a direct result of supply of nutrients from agricultural land, the city's waste water treatment works and runoff that encourage their growth. The significance and presence of Euglenophytes in the sampling stations can be attributed to organic pollution since these organisms are known to stay in polluted waters. The differences in the algal community structure at the river mouths and at the bay can be attributed the dilution effect of slightly cleaner water from the river mouths flowing from the catchment into the bay for these reason there were pockets of other algal groups such as Chlorophytes, Diatoms and Zygnematophyceae at the river mouths. This situation was different in the bay where cyanophytes were dominant a condition attributed to sewage discharge and semi treated sewage effluent and organic matter input brought down by runoff from Kisumu city. For the diatoms, their observed abundance at the river mouth sampling sites could be due the high concentration of soluble reactive silicates (SRSi) which were measured there. Silicates are an important component in the structure of diatom frustules and as such they are critical in the growth of diatoms. The dominance of Cyanobacteria in the algal community structure of the bay is a pointer its eutrophication status. This is because Cyanobacteria are well known indicators of cultural eutrophication Wetzel (1991). Therefore this study supports the observation that the nature and health of an aquatic community is an expression of the limnological status of the respective water body.

The low Secchi depth measured at the river mouth sampling sites was largely attributed to presence of particulate organic and inorganic matter (Total suspended solids) brought down from the catchment by the river. The high total suspended solids of water samples from the river mouths

sites could have attenuation sunlight thus leading low Secchi disk measurements.. The Low levels of Chlorophyceae abundance observed in the bay concurs with observation by (Lung'aiya *et al.*, 2000).

5.4 Phytoplankton diversity indices

The Simpsons index is normally used to calculate the biodiversity of various habitats ranging from terrestrial to aquatic organisms. It takes into consideration the abundance of those species present. The higher the diversity index values the higher the samples diversity. The observation that the evenness index was not uniform throughout the sampling sites indicated that algae were not evenly disturbed in the bay. The high Shannon-Weiner index (H') index of biodiversity could be explained presence of a high density and variety of species belonging to cyanophytes, chlorophytes,, diatoms, Zygnematophtes, Euglenophtes and dinoflagellates. The Shannon-Weiner index (H') can also be used to determine the pollution status of a water body. Since it was high in this study it implies that the water in Kisumu Bay is highly polluted. The changed in all indices calculated in this study were due to differential nutrient and pollutant input into the bay as well as changing environmental conditions over time. This is because alteration between rainy and dry seasons might influence the life cycle of phytoplankton community structure and colonization.

5.5 Algal Toxins

In our study, *Microcystis spp* and *Anabaena spp* were the dominating phytoplankton in Kisumu Bay. This two species are known to produce powerful neurotoxins -microcystin and anacystins respectively. These toxins can cause serious illnesses all death to human's domestic animals wildlife and other aquatic organisms. (Falconer *et al.*, 1994). However in this study only one of the

algal toxin type: Microcystins were observed and this was because of the limitation of the reagents that could be used to detect other toxins. There is thus a gap in the information on other type of toxins which could be present in Kisumu but have not been identified due to this. The observed changing of algal composition in the bay from time to time means that there also changes in algal toxin production from time to time however this needs to be established. Recent studies (Muggide, 1993; Lung'ayia *et al*., 2001; Sitoki *et al.*, 2005) have shown a shift in phytoplankton species composition from a moderate mix of diatoms, greens and blue-greens to the predominantly bloom forming and nitrogen fixing Cyanobacteria. Frequent massive fish kills in the Nyanza Gulf of L. Victoria have been associated with algal blooms (Ochumba, 1990) and could partly be due to excretion of toxic substances by the Cyanobacteria. This is thought to be as a result of eutrophication, causing excessive growth of the noxious algae to predominate the other groups. High nutrient enrichments especially in the inshore areas has been reported by Lung'aiya *et al*. (2001) and Ochumba (1989) as the principal cause of the persistent high algal densities which are referred to as blooms. Similar occurrence and persistence of massive algal blooms in Kisumu Bay, in 2004 resulted in foul smells in the air within the city and in piped drinking water forcing the closure of the water treatment works for several days. Exposure to cyanobacterial toxins via drinking water is a major concern for human health since they may induce both acute and chronic effects. A recent case in Embu, Kenya where hundreds of children died after drinking insufficiently treated water from a river blooming with Cyanobacteria serves to highlight the seriousness of the problem (Codd *et al.*, 2005).

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusions

According to the study Phytoplankton community structure in Kisumu Bay is dominated by Cyanophyceae constituting 45% in abundance. The other less abundant but common algal groups were Cyanophyceae, Chlorophyceae, Bacillariophyce and Dinophceae. The least taxa in terms of abundant constituted Euglenophyceae, Zygnematophycea. Cyanophycea appeared to be dominant with species like *Microystis spp, Anabaena spp, Planktolyngya spp* and *Aphanocapsa spp* appearing in entire sampling period. A total of 125 species were identified with Cyanophyceae having 20, Chlorophyceae 41, Bacillariophyce 38, Zygnematophycea 15, Dinophceae 3 and Euglenophytes 11 species respectively.

Species biodiversity in Kisumu Bay was found to be moderate and are known to prevail nutrient rich lake (Wetzel and Liken, 1991), with presence of Cyanophyceae and high nutrients load depicted the bay to be eutrophic. The high eutrophication in the Bay is attributed to frequent formation of algal blooms in the bay. More so, the bay ecosystem indicated poor quality and may be attributed to intrinsic sources of nutrients, especially phosphorus and TP demonstrated clearly the intrinsic existence of varying amounts of various fractions of particulate hence lead to a stressful status with oxygen concentration changing from lethal to stressful levels.

Further the presence of *Microystis spp, Anabaena spp* are known for nitrogen fixing hence affects buoyant species which are known to produce algal toxins, of which the common type is

Microcystin-LR. . There were five different types of Microcystin identified namely: MCLR, MCYR, MCLA, dmLR, MCRR. The significant correlations between groups of phytoplankton community structure and environmental variables confirm that Microcystin can be employed successfully in assessing the water quality of the Bay in this study.

The pattern of change in physical chemical variables in Kisumu bay (of Lake Victoria) is highly unpredictable, due to the shallow mean depth, high nutrient inputs, pollutants and regular mixing by wind. This encourages development of algal biomass which leads to the formation of algal blooms and production of lethal toxins. The total phosphate to total nitrogen ratio (TP: TN) in Kisumu is perturbed, differing from the normal 1:16. This is due to nutrient enrichment mainly from Kisumu city sewage and runoff effluents and from anthropogenic activities mainly agricultural and industrial from the surrounding catchments. The aforementioned factors leads Kisumu bay to suffer from cultural eutrophication. There could be other toxins produced by algae apart from microcystin. This is because in this study we did not have full capacity of assessing the presence of a wide range of other algal toxins due to high expenses need in purchasing equipments. The total number of species in Kisumu bay could not be easily determined due to limitations in clearly identifying the species. In this study, identification was based on morphological characterization and not on molecular or genetic techniques or evident.

6.2 Recommendations

i. Further research or detailed studies need to be conducted on algal species identification based on molecular and genetic techniques. These findings should be further confirmed by algal identification based on morphological characteristics that are accurate.

ii. There is need to carry out further research on identification and characterization of algal toxins and the species that produce them.

iii. There is need to consider regular monitoring of algal blooms and toxins at intervals over an extended period and to include an element of diurnal sampling of 24 hours.

iv. Riparian communities should be advised not to abstract and use water from the lake when algae are blooming as there is a potential for microcystin or other algae toxins intoxication.

v. There is also need to establish standards on permissible levels of algal toxins for Lake Victoria. There is need to conduct studies to enable the prediction of the occurrence and effects of different algal toxins in Kisumu Bay and also on the environmental condition under which they are produced. Further mechanism involved in production in algal cells need to be elucidated.

vi. All the information on the above recommendations will be useful in formulation regulations for management for water quality management.

vii. Study should be conducted on the effect of climate change on algal community structure and production of algal toxins.

viii. Research should be conducted to develop water treatment plants that are efficient in removing Microcystin that are efficient in remo vini have the capacity to remove algal toxins Consider recommendations for water purification plants with efficiency to counteract microcystins and other algal toxins.

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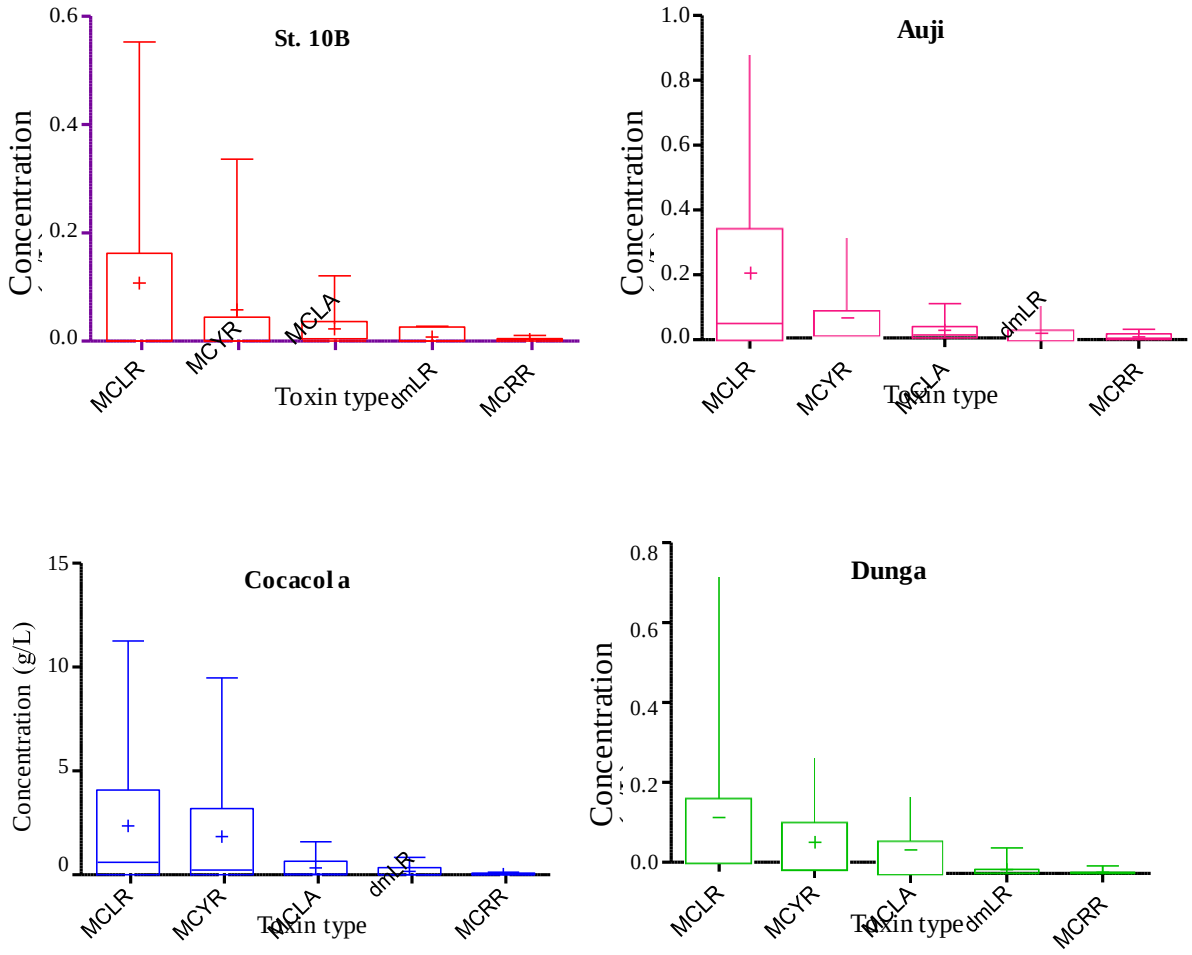
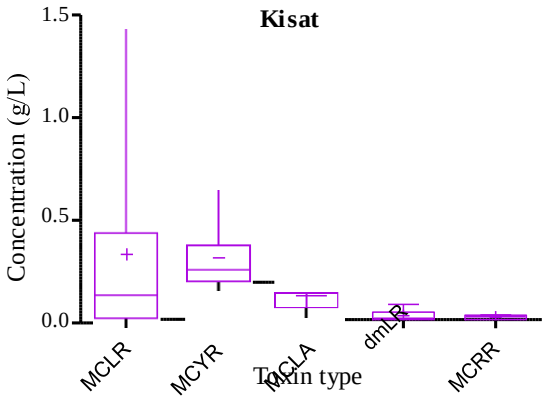
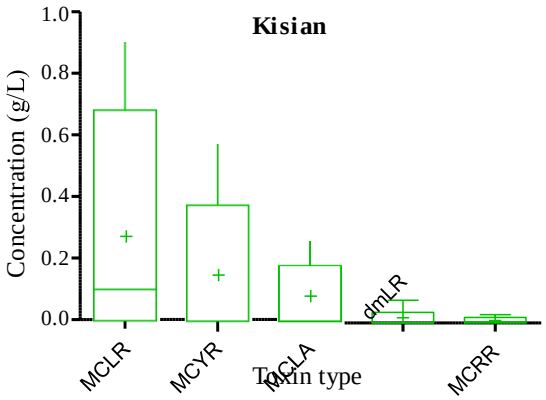
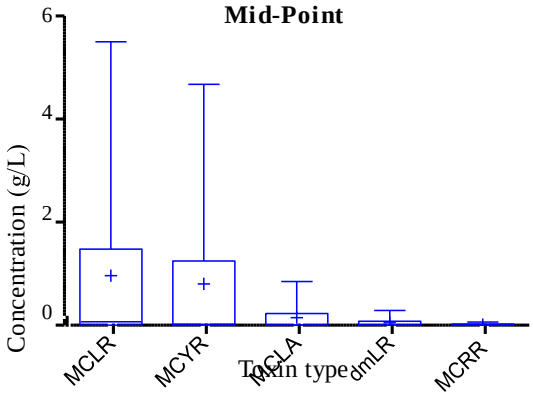
APPENDICES

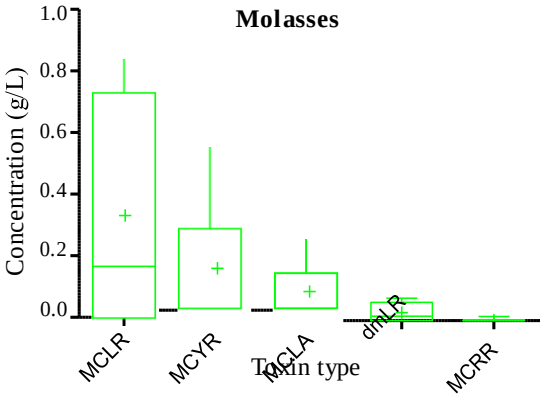
Appendix I: Spatial Concentration of toxins in different sampling locations within Kisumu Bay, Lake Victoria

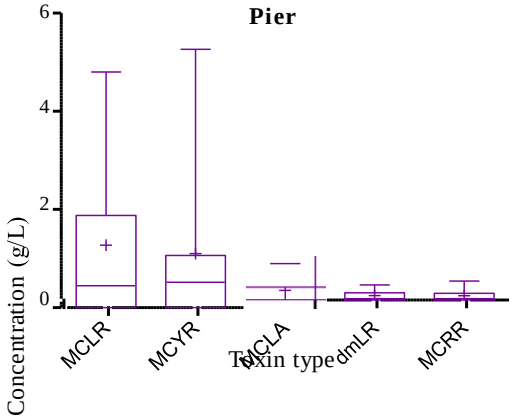


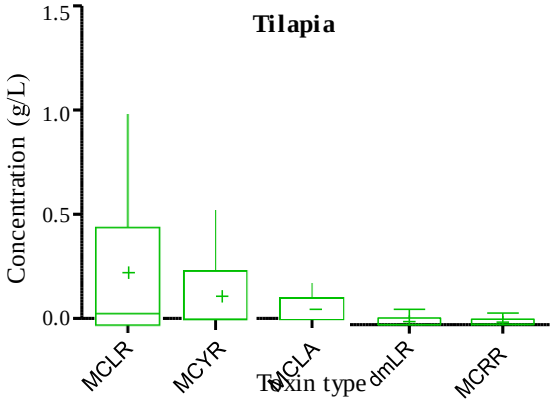

Kisat
Concentration (g/L)
1.5
1.0
0.5
0.0
MCLR
MCYR
MCLA
dmLR
MCRR
Toxin type

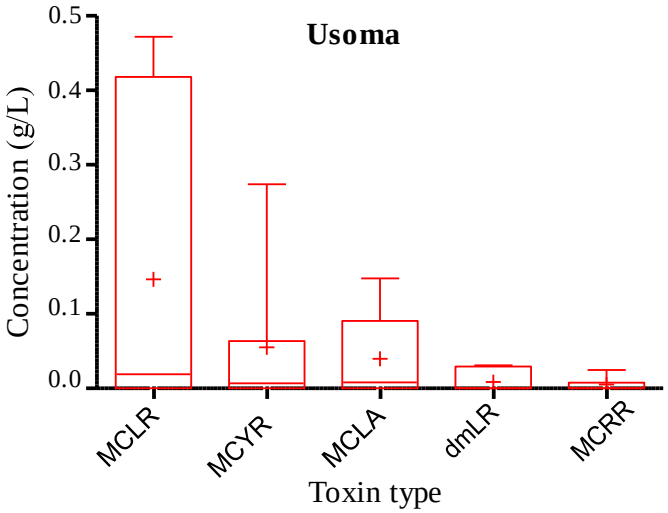

Kisian
Concentration (g/L)
1.0
0.8
0.6
0.4
0.2
0.0
MCLR
MCYR
MCLA
dmLR
MCRR
Toxin type


Mid-Point
Concentration (g/L)
6
4
2
0
MCLR
MCYR
MCLA
dmLR
MCRR
Toxin type


Molasses
Concentration (g/L)
1.0
0.8
0.6
0.4
0.2
0.0
MCLR
MCYR
MCLA
dmLR
MCRR
Toxin type

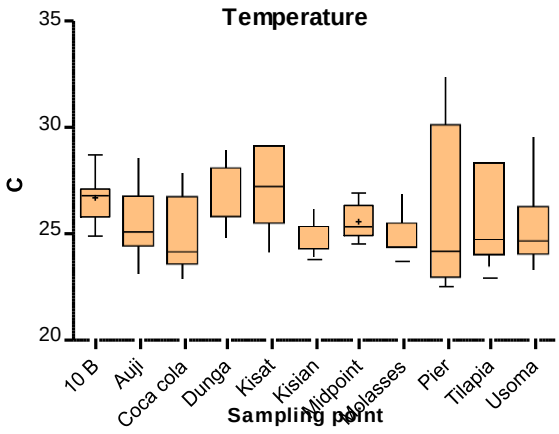

Pier
Concentration (g/L)
6
4
2
0
MCLR
MCYR
MCLA
dmLR
MCRR
Toxin type


Tilapia
Concentration (g/L)
1.5
1.0
0.5
0.0
MCLR
MCYR
MCLA
dmLR
MCRR
Toxin type

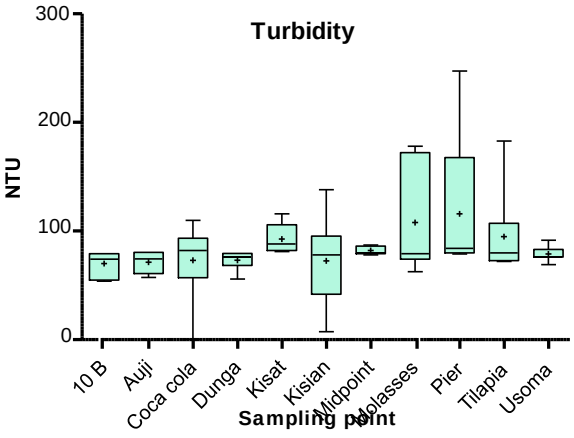


Appendix II: Physico-chemical parameters at various sampling locations in Kisumu Bay, Lake Victoria, Kenya

(i)

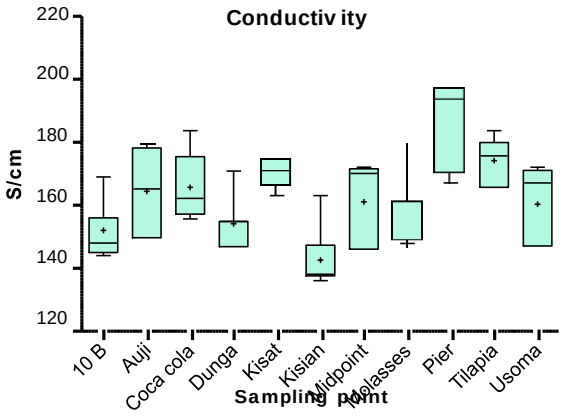


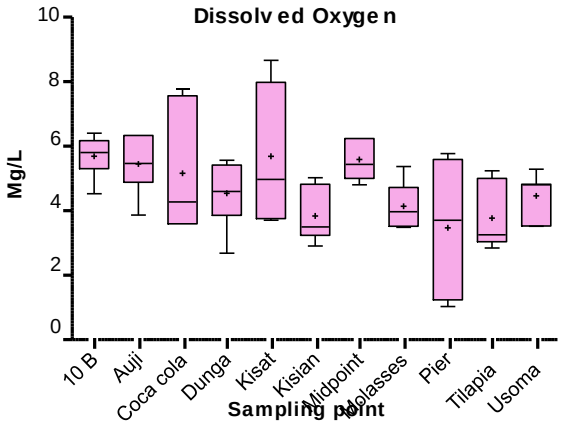
(ii)

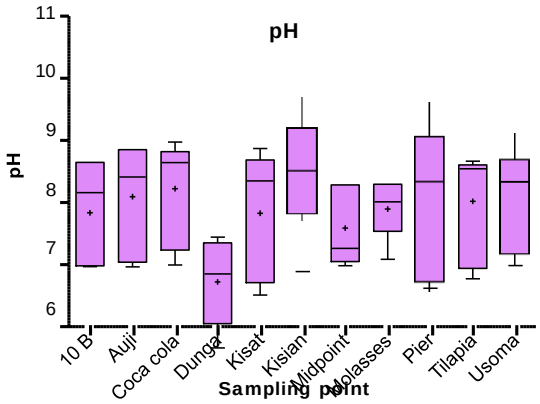


(iii)

(iv)


Conductivity
S/cm
220
200
180
160
140
120
10 B
Auji
Coca cola
Dunga
Kisat
Kisian
Midpoint
Molasses
Pier
Tilapia
Usoma
Sampling point


Dissolved Oxygen
Mg/L
10
8
6
4
2
0
10 B
Auji
Coca cola
Dunga
Kisat
Kisian
Midpoint
Molasses
Pier
Tilapia
Usoma
Sampling point


pH
pH
11
10
9
8
7
6
10 B
Auji
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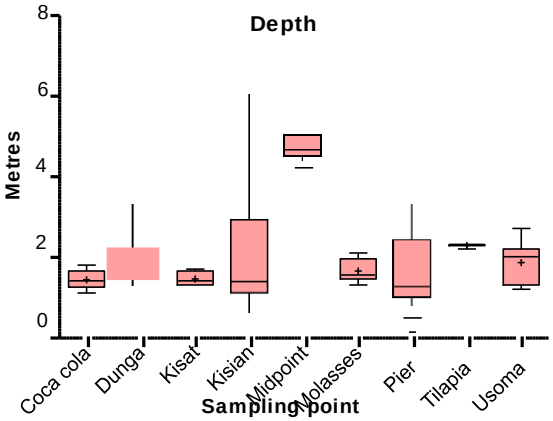
Midpoint
Molasses
Pier
Tilapia
Usoma
Sampling point

(V)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Dunga
Kisat
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Molasses
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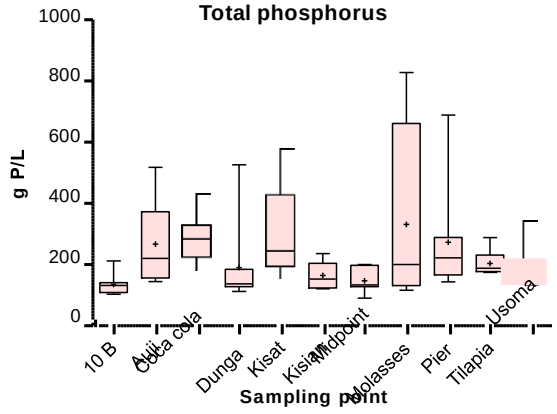
Usoma
Sampling point

(Vi)

Appendix III: Spatial Dissolved nutrients in Kisumu Bay, Lake Victoria, Kenya

(I)



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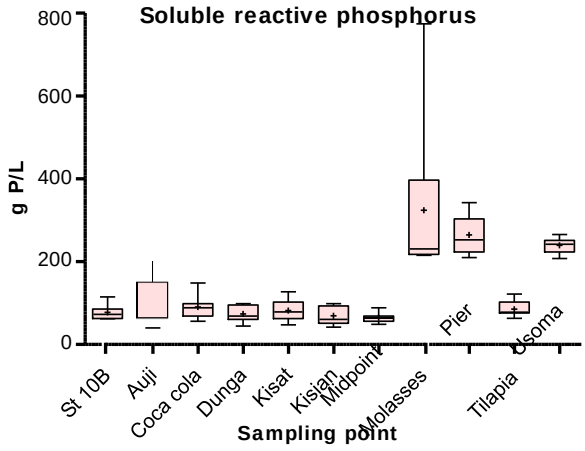

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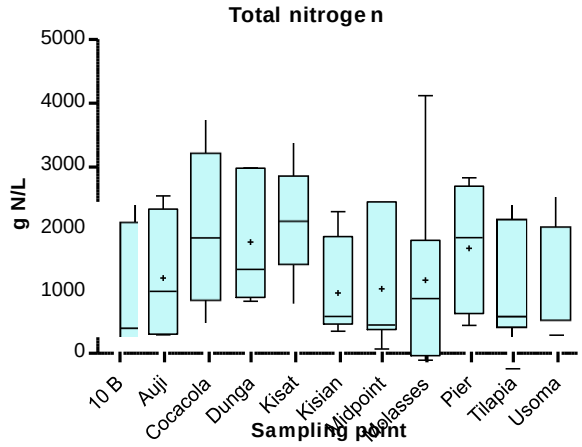

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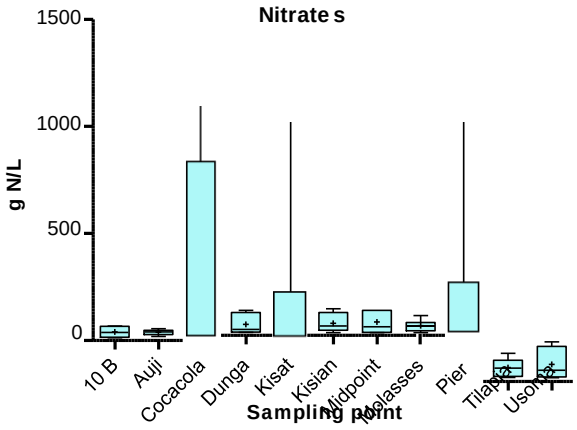

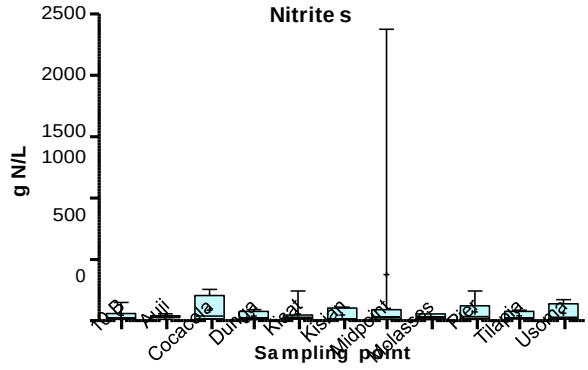
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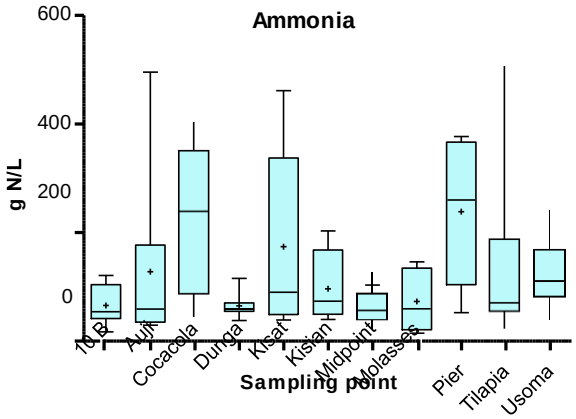
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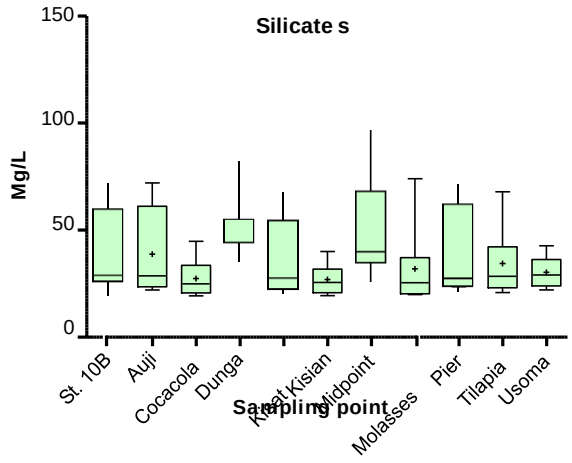
Usoma
Sampling point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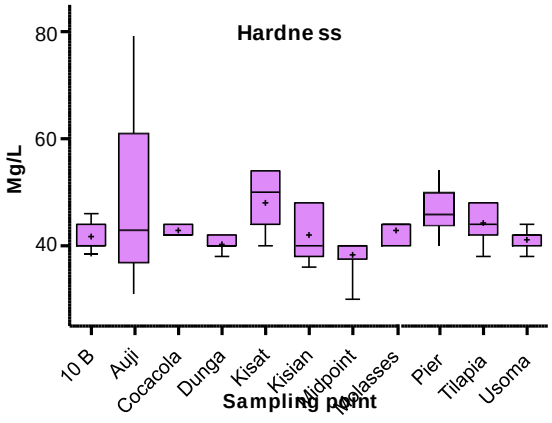
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Usoma
Sampling point

(V) (VII)

Appendix IV: Phytoplankton composition

Phytoplankton Species of Kisumu Bay, Lake Victoria Kenya

Chlorophyceae

Ankistrodesmus falcatus
Ankistrodemus convolutes
Ankistrodesmus gracilis
Bottyococcus braunii
Chrollella vulgaris
Coelastrum microphorum
Crucigenia excarata
Eunotia lunaris
Kirchnella contrata
Kirchnella falcatus
Kirchnella lunaris
Kirchnella obese
Monoraphidium carbeum
Monoraphidium griffitnii
Monoraphidium sp
Oocystis nageli
Oocystis burgei
Oocystis lucastris
Oocystis parva
Oocystis regularis
Oocystis risilla
Oocystis solitaria
Ooystis lacustris
Ooystis pusilla
Pediastrum tetras
Pediastum boryanum
Pediastum duplex
Scenedesmus acuminatus
Scenedesmus curvatus
Scenedesmus longus
Scenedesmus maximus
Scenedesmus obliquus
Scenedesmus perforates
Scenedesmus quadricuada
Scenedesmus rusboskii
Schroederiella Africana
Schroidera setigera
Selenastrum gracile
Tetraedron arthromistforme
Tetraedron trigonum
Tetraedron triangulare
Tetredon inflatum

Cyanophyceae

Oscillatoria gemirata
Anabaena circinalis
Anabaena flos-aquae
Anabaenopsis tanganyikae
Aphanocapsa pulchra
Aphanocapsa rivularis
Aphanothece sp
Choococcus turgidus
Chroococcus disperses
Chroococcus limnetica
Cylindrospermopsis Africana
Merismopedia tenuissima
Microcystis aeruginosa
Microcystis wasenbergi
Plankolyngbya circumcreta
Plankolyngbya limnetica
Plankolyngbya tallingii
Planktolyngbya contrata
Pseudo- anabaena tanganyikae
Romeria ankensis

Dinophceae

Ceratinium branchyceros
Glenodinium penardii
Glenordinium pulvastitus

Euglenophyceae

Euglena acus
Euglena spirogyra
Euglena sporoides
Euglena viridis
Phacus lenticularis
Phacus longicauda
Phacus pleuronectes
Phacus sp
Strombomonas sp
Trachelomonas armata
Trachelomonas volvocina

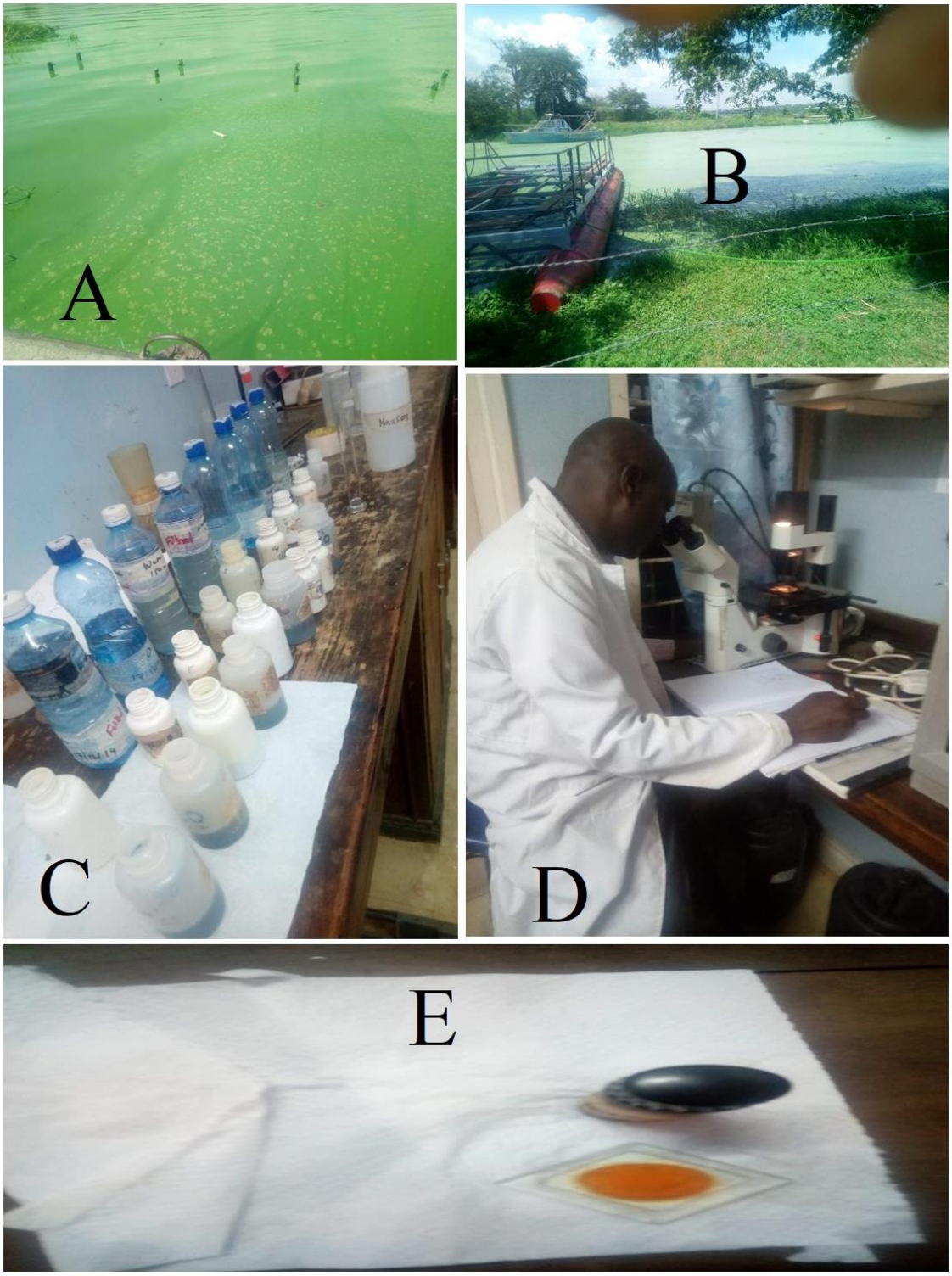
Bacillariophyceae

Amphora ovaries
Amphora sp
Aulacoseira ambigua
Aulacoseira dickiel
Aulacoseira nyansenssis
Aulacoseira schroidera
Chodatella subsalsa
Chodatella armata
Chodatella longiseta
Cyclotella kutzingiana
Cyclotella ocellata
Cymbela cistula
Cymbela parva
Cymbella solea
Diatoma elongatum
Diatoma hiemiale
Diatoma vulgare
Flagilaria athiopica
Fragillaria construens
Fragillaria intermedia
Navicula exigulformis
Navicula granatum
Navicula merostoides
Navicula muticum
Navicula simplex
Navicula sp
Nitzchia lucastris
Nitzchia palea
Nitzchia recta
Nitzschia dessippata
Nitzschia stagnorum
Nitzschia sub-acicularis
Stephanodiscus astrea
Surillella biffins
Surirella ovalis
Synedra cunningtonii
Synedra ulna
Tabellaria sp

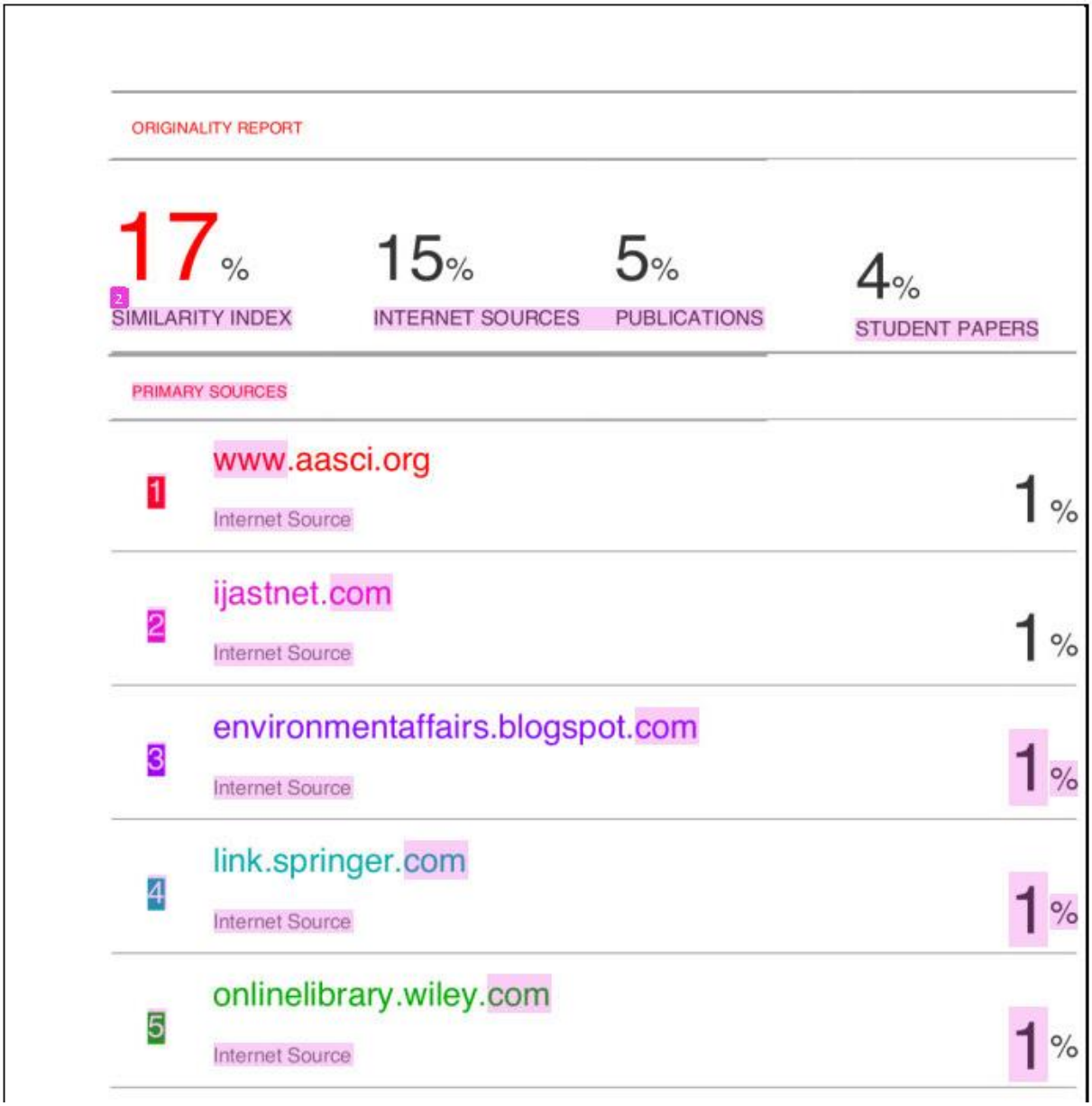
Zygnematophyceae

Closterium abruptum
Closterium gracile
Closterium navicula
Cosmarium contractum
Cosmarium cunningtonii
Cosmarium minimum
Cosmarium moniliforme
Cosmarium regnelium
Cosmarium retusiforme
Cosmarium succisum
Crucigenia tetrapedia
Staurastrum gracile
Straurastrum muticum
Straurastrum paradoxum
Straurastum limnetica

Appendix V: Pictorial Representation of the Laboratory Analysis of Phytoplanktons and Microcystins



Appendix VI: Turnit In Plagiarism Report



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Appendix VIII: Publication Paper

Received: 8 July 2020 | Revised: 28 July 2021 | Accepted: 11 September 2021

DOI: 10.1111/lre.12380

ORIGINAL ARTICLE

Lakes & Reservoirs Science, Policy and Management for Sustainable Use | WILEY

Water quality, phytoplankton composition and microcystin concentrations in Kisumu Bay (Kenya) of Lake Victoria after a prolonged water hyacinth infestation period

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Abstract

The production of phytoplankton (algal) toxins and their control is of concern because of the need to reduce their negative impacts on water quality and facilitate effective management of algal blooms. The present study was conducted between September 2017 to May 2018, focusing on Kisumu Bay in the Kenyan portion of Lake Victoria, in order to establish the magnitude of potential impacts on phytoplankton composition and microcystin following a prolonged presence of water hyacinth coverage between 2013 and 2018 within the gulf, with an estimated coverage range varying between 644 and 1224 ha. Triplicate samples of physico-chemical parameters, nutrients, phytoplankton, chlorophyll-*a* and algal toxins ($N = 88$) were collected at eleven sampling sites to determine their spatio-temporal variability. The main identified algal taxa comprised Cyanophyceae, Bacillariophyceae, Chlorophyceae, Euglenophyceae, Zygnematophyceae and Dinophyceae. The most dominant algal species were *Microcystis aeruginosa* (25%), *Merismopedia* spp. (23%) and *Anabaena flos-aquae* (16%). Enzyme-linked immunosorbent assay (ELISA) technique was used to determine microcystin (MC) toxins in the water. Mean MC-LR and MC-YR concentrations were significantly correlated ($R^2 = 0.972$), exceeding WHO standards at three sampling sites (Coca Cola, 2.84 ± 4.76; Kisumu pier, 1.78 ± 1.87; Midpoint, 1.44 ± 2.71 µg/L MC–LR). There were significant temporal variations ($p < .05$) in the SRP, TN, NO_3-N, NO_2-N, NH_4-N, SiO_2-Si, MC-LR, MC-YR, dissolved oxygen (DO), total dissolved and suspended solids (TDS; TSS), turbidity, electrical conductivity, Secchi depth, temperature and pH levels. The water depth, TP and DO also vary spatially. The nitrogen to phosphorus concentration ratios differed from the expected N:P ratio of 16:1, indicating a highly eutrophic status. The disproportionate ratio of total phosphorus and total nitrogen in the bay may be responsible for the enhanced cyanobacterial blooms it exhibits. The results of the present study provide useful information and data for formulating regulations for water quality management.

KEYWORDS
chlorophyll a, Lake Victoria, microcystin, nutrients, phytoplankton

1 | INTRODUCTION

Phytoplankton constitute a large diversity of eukaryotic, polyphyletic photosynthetic organisms that include unicellular microalgae (e.g. *Chlorella*) and diatoms (e.g. *Nitzschia* and *Amphora* species) and multicellular macroalgae (e.g. giant kelp; Lee and Bong, 2008). Algae are grouped broadly into Cyanophytes, Glaucophytes, Rhodophytes Chlorophytes, Euglenophytes, Crytophytes and Heterokonts. Cyanobacteria, also referred to as 'blue-green algae', have chlorophyll-*a* as their primary photosynthetic pigment. (Reynolds et al., 2006). They constitute the primary source of energy in aquatic habitats that support life in water, and particularly the world fisheries on which mankind depends for food (Chalinda et al., 2004; FAO, 2020). Farming of such microalgae as *Spirulina* spp. and other marine species is common in many countries, ranging from backyard to large-scale production for human nutrition and supplements for other uses (FAO, 2020).

Phytoplankton are very sensitive to their environment, with any alteration leading to changes in phytoplankton communities in terms of biomass and diversity (Bhatnagar et al., 2013). They can form harmful blooms that produce toxins, which can cause serious illness or even death to humans and other life forms (Carmichael, 1992; Merel et al., 2013; Sivonen & Jones, 1999). The Microcystis genera is well known to produce microcystins (hepatotoxins) with studies indicating the toxin production is encoded by microcystin genes (*mcy*). MCs are synthesized via non-ribosomal peptide synthetases and polyketide synthases assembled into large multifunctional proteins encoded by the *mcy* gene cluster (Tillett et al., 2000). The extent of the impacts of the toxins throughout different trophic levels, especially zooplankton and fish species, is not well established because of limited studies. The frequent presence of harmful algal blooms can exert large treatment costs to water sources for public water supplies. The occurrence and persistence of massive algal blooms in 2004 in Kisumu Bay, Nyanza Gulf, for example, resulted in foul smells in the air within the city of Kisumu and in piped drinking water, forcing closure of the water treatment works for several days (LVEMP, 2002). They further clogged filtration apparatus, causing the breakdown of domestic water intakes. The algal blooms have also resulted in the formation of massive scums on surface waters, clogging of gill nets, deoxygenation of the water column and human skin allergies and reactions when a person comes in contact with the water (Codd et al., 2005).

Past and more recent studies in the Lake Victoria basin indicate human activities are a major source of nitrogen and phosphorus (Lung'ayia et al., 2000, 2001; Orina et al., 2020) that encourage excessive phytoplankton growths in the lake (Sitoki et al., 2012). Phytoplankton are an integral component of the aquatic community, forming the basis of primary production upon which all organisms in higher aquatic trophic levels depend. They also serve as a food source for humans. The algae *Spirulina* species, for example, is harvested from certain lake ecosystems (e.g. Lake Chad) for food (Abdulqader et al., 2000). However, certain types of phytoplankton, including Cyanophyceae, Bacillariophyceae and Dinophyceae species, can form algal blooms that produce toxins that have been found to cause serious illnesses and even death to humans and other forms of life (Zingone and Enevoldsen, 2002; Zingone et al., 2015). These toxins can persist in water for several days to months, continuing to affect organisms in the aquatic ecosystem. It has also been observed that cholera-causing bacteria can thrive in sheaths of cyanobacteria, thereby making their blooms even more dangerous (Islam et al., 2004).

Studies elsewhere in the African Great Lakes region have demonstrated the potential for satellite detection and near real-time monitoring of harmful cyanobacterial algal blooms (HABs), using satellite-derived chlorophyll-a (Binding et al., 2018; Sawtell et al., 2019). These algal blooms can affect the entire Nyanza Gulf, and the extreme eastern end formed by Kisumu Bay, in the Kenyan portion of Lake Victoria during certain periods of the year (Sitoki et al., 2012). Frequent outbreaks of cholera also occur in different urban centres and fish landing beaches along the shores of the Kenyan sector of Lake Victoria. It is not clear, however, if the *Vibrio cholerae* that causes cholera is harboured by cyanobacteria blooms, as suggested by Islam et al. (2004). Some organisms, such as mussels that feed on algae, are known to bioconcentrate algal toxins and, when consumed by humans and other forms of life such as birds, cause illness or even death. This is of particular concern because the aquatic organisms that graze on phytoplankton are not able to differentiate between the toxic and non-toxic algal forms. Algal toxins are released when algal blooms undergo decomposition in the water column, thereby releasing toxins into the water where they can persist for extended periods, posing danger to other aquatic life and users (WHO, 2017). Accordingly, studies on toxins and nutrients in aquatic systems are important for fostering prudent management of water resources and prediction of potential changes in aquatic ecosystems (Brettum & Andersen, 2005; Haande et al., 2011; Mbonde et al., 2015; Miles et al., 2013; Mugidde, 2001; Okello et al., 2010; Reynolds et al., 2002; Triantis et al., 2010). Microcystin concentrations measured monthly in samples taken at a 3.5 m depth at one sampling site between March and November 2008 were consistently above the World Health Organization guideline of 1 μg/L MC-LR (WHO, 2017), with the highest measurement at 81 μg/L occurring in November (Sitoki et al., 2012). Simiyu et al. (2018) compared the MCs concentrations in water and a small cyprinid (*Rastrineobola argentea*; Pellegrin 1904), collected at one site in Kisumu bay (October 2011 to January 2012 at Dunga Point on the outer edges of Kisumu Bay) and an open sampling site near the Rusinga Channel (in January 2012). The overall MC content in fish was found to be related to seston MC contents (Simiyu et al., 2018). Communities living around Kisumu Bay utilize the lake water directly for drinking, cooking and bathing, with little to no treatment. As communities face disproportionate risks of the environmentally stable and difficult to remove toxins (which are concentrated, not eliminated, by boiling), which are often accompanied by equally difficult to remove pathogens (Muyodi et al., 2009), researchers must begin to engage with these communities for sustainable solutions to address health issues in a culturally appropriate and sensitive manner.

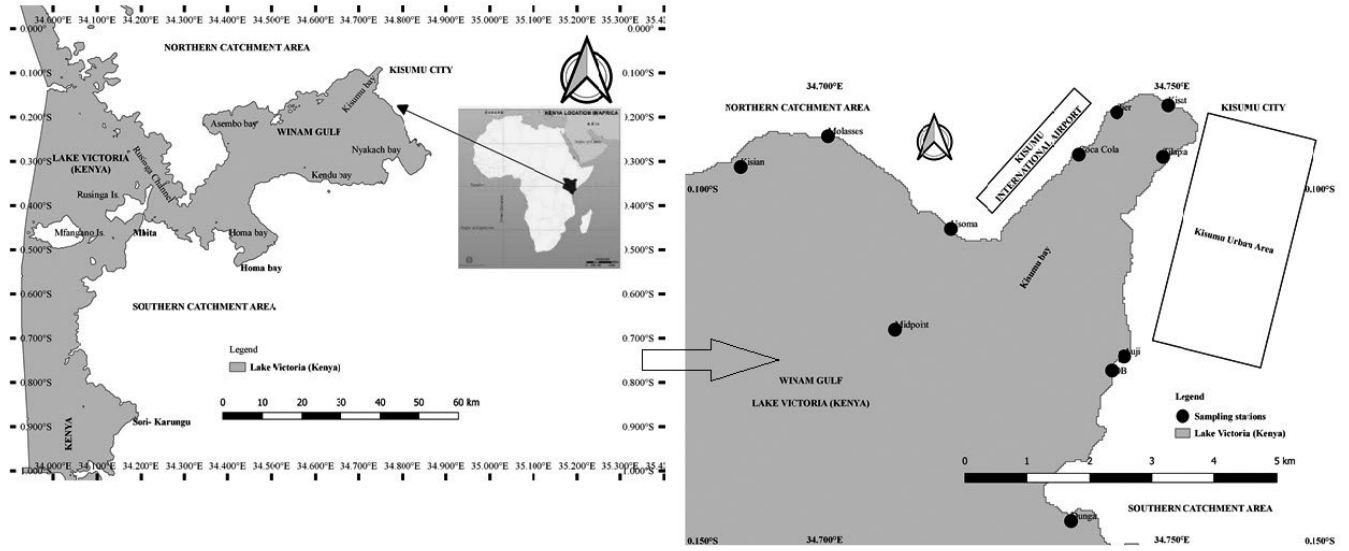

FIGURE 1 Map of Kisumu Bay, Kenya, Lake Victoria showing location of sampling sites

In spite of the above-noted challenges, caused primarily by algal blooms, there have been limited studies focused on investigating changes in the algal community structure, biodiversity and toxin-producing characteristics in Kisumu Bay. This situation is further compounded by the fact that water hyacinth exert considerable impacts on water quality and phytoplankton density. There also are inadequate biomonitoring programmes of harmful cyanobacteria, as well as the presence of algal toxins in both raw and portable water. Water hyacinth was first reported in the Ugandan sector of Lake Victoria during 1988 to the 1990s, with large coverages beginning to appear in Nyanza Gulf from 1995 to mid-1998 and onwards. Before any control methods were introduced within the gulf, this situation was associated with the obstruction of boat transport, the blockage of access to fishing grounds and lake water supply abstraction points, port operations and as a contribution to the degradation of domestic water supplies and decreased lake water quality. The ecological impacts included provision of habitat for fish species tolerant to low dissolved oxygen concentrations and refugia to prey fish species, resulting in overall changes in aquatic biodiversity, and an increased incidence of waterborne diseases. An increased lake water coverage by water hyacinth may be expected to lead to reduced fisheries production. Ongore et al. (2018), however, reported that the association of water hyacinth with the catch of *O. niloticus* was not significant. The abundance and diversity of the phytoplankton are mainly regulated by inorganic nutrients that include, but are not limited to, nitrogen, phosphorus and silica. Nutrient enrichment from agricultural runoff and low-lying deforested riparian zones contribute to eutrophication of the lake (Lungayia et al., 2001; Orina et al., 2020; Triest et al., 2012). Similarly, the release of untreated or poorly treated domestic sewage directly into the lake contributes further to the lake's eutrophication (Ndaruga et al., 2004), thereby enhancing the proliferation of algal blooms. There are few studies on specific bays in Winam Gulf since most previous studies focused on better understanding of the influences and exchanges between the open lake and Nyanza Gulf. Misiko et al. (2014), Sitoki et al. (2012), Triest et al. (2012) and Kobingi et al. (2009) reported on the water quality status of Kisumu Bay and the associated, but urbanized, river basins. Accordingly, the present study focused on determining the impacts of a prolonged invasion of water hyacinth on phytoplankton composition, abundance and diversity, as well as the microcystin concentrations resulting from algal blooms. Because the present study does not present a measure of water hyacinth coverage during sampling times, it cannot directly quantify the impacts of water hyacinth on phytoplankton species. The present study of Ongore et al. (2018) documented the presence of cyanobacteria in the mapped gulf areas. The present study analyses and provides inferences on possible significant influences from prolonged water hyacinth coverage in the major water hyacinth hotspot bays, but cannot provide direct relationships because of differing water sampling periods and coverage analyses. Temporal variations were also studied, as well as determining the impacts on the lake water quality and ecosystem health. Thus, the information obtained in the present study will be useful in informing policy on water quality management and conservation.

2 | MATERIALS AND METHODS

2.1 | Study area

The present study was conducted in Kisumu Bay (Figure 1) in the Kenyan sector of the Lake Victoria basin, situated about 1134-m above sea level. Although Lake Victoria experiences complete annual mixing of its water column from June to August (Cózar et al., 2012; Nyamweya et al., 2016), the bay has continuous mixing throughout the annual cycle due to its shallow depth. In addition, prevailing winds induce strong shear forces that cause vigorous vertical mixing in the water column (Nyamweya, Desjardins, et al., 2016; MacIntyre et al., 2014). The Kisumu Bay area adjacent to the

city of Kisumu covers an area of 25 km^2 and has a depth range of 0–4 m (Odada et al., 2004). Its catchment area lies within Kisumu County, among the agriculturally productive areas in Kenya, and other densely populated regions (554 persons/km^2) (KNBS, 2019) within the Kenyan sector of the Lake Victoria basin. There are two wastewater treatment facilities, including the conventional municipal sewage treatment work adjacent to the Kasat River and the Nyalenda waste stabilization ponds, which discharge their semi-treated sewage effluents into Kisumu Bay through the Kisat and Nyalenda rivers, respectively. In addition to the city's wastewater treatment systems being dysfunctional, several surrounding factories, industries, breweries, tanneries, molasses plant, soap processing company and slaughter houses also discharge their effluents either directly or indirectly into the bay. Kisumu Bay in particular is reported to be stressed since most of the aforementioned rivers discharge their effluents into the lake via this route (LVEMP II, 2002). Situated along the shores of the bay area are papyrus wetlands at the Kisumu Golf Club and Kenyan pipeline fuel storage tanks at Hippo Point, Kisian and Dunga. These anthropogenic activities degrade water quality in the rivers draining into the bay. Water quality degradation is manifested in the form of reduced fish stocks, decreased biodiversity, dense algal blooms, increased sedimentation and nutrient loadings and anoxia in the water column (Hecky, 1993; Hecky et al., 1996, 2010; Ochumba & Kibaara, 1989; Sitoki et al., 2012). Cascading effects on the lake ecosystem have occurred as a result of these polluting activities, including the occurrence and persistence of cyanobacterial blooms reported within every part of the bay. Based on the most recent monitoring data, water hyacinth within the gulf peaked around September and November 2016 (Ongore et al., 2018), although the cyclic invasion pattern continued until 2019. According to Ongore et al. (2018), higher coverages were observed in the gulf areas (5000-ha) than in the open lake (<200 ha). Significant water hyacinth coverage was also observed in other bays of the Winam Gulf before and during the present study, especially in July 2015, January to June 2016, January to April 2017 and September 2017 to May 2018.

2.2 | Sampling

Sampling and measurements of the water quality variables were made between 0800 and 1600 hours. during sampling trips made between the short and long rain periods (October to November 2017; March–May 2018) and the dry season months (December 2017–February 2018). Sub-surface water samples were taken at each sampling site using a van Dorn sampler for nutrients, quantification of phytoplankton abundance, biovolume and microcystin extracellular quantification. A vial bottle containing 25 ml of the sample was fixed with Lugol's solution for quantitative phytoplankton analysis. A phytoplankton net (30 mm mesh size) was used to collect samples for qualitative analysis of phytoplankton, and MC samples were taken at the 0.5-m depth, according to the procedure of Sitoki et al. (2012). The physico-chemical parameters, including water temperature and turbidity, dissolved oxygen (DO) concentration, electrical conductivity, pH and total dissolved solids concentration, were measured in situ with a YSI multi-parameter (Model 35C). Measurement of water column parameters was begun ~0.2-m below the water surface, ending about 0.2-m above the lake bottom. Water samples for determination of total suspended solids (TSS) were collected separately and filtered (0.45-μm pore size filter paper) before drying at 103°C to 105°C to a constant weight in the laboratory (APHA, 2000). The Secchi depth was measured *in situ* with a standard Secchi disk (20-cm diameter) comprised of two black and two white quadrants. It was measured in the shadowed part of the boat and derived as the average of the depth at disappearance and reappearance of the Secchi disk in the water column. Water samples for nutrient fractions were collected using pre-cleated 1-litre polyethylene sample bottles. The bottles were preserved with sulfuric acid and stored in cooler boxes at ~4°C, for further laboratory analysis of dissolved nutrients according to Standard Methods (APHA (2000). Silicates and ammonium concentrations were analysed using the hetropolyblue technique and phenol hypochlorite methods, respectively (APHA, 2000). Nitrates and nitrites were analysed using the cadmium-reduction method. Soluble reactive phosphorous (SRP) was determined using the ascorbic acid method, whereas total nitrogen (TN) and total phosphorus (TP) were determined for unfiltered water samples using the potassium persulphate digestion method. Water samples for chlorophyll-*a* concentrations were filtered using Whatman® GF/F filters and subsequently wrapped in aluminium foil and stored in a desiccator for subsequent seston solvent extraction and spectrophotometric analyses using Standard Methods (APHA, 2000).

Phytoplankton samples were collected from the water surface. A 25-ml portion of the sample was preserved with acidic Lugol's solution. A 2-ml phytoplankton sub-sample was placed in an Utermöhl sedimentation chamber and allowed to settle for at least three hours. Phytoplankton species identification and enumeration were done with a Zeiss Axioinvert 35 Inverted Microscope (400× magnification). A minimum of ten fields of view were counted for the very abundant coccoid cyanobacteria, and a 12.42 mm^2 transect was counted for the abundant and large algae. The whole bottom area of the chamber was examined for the big and rare taxa under low (100×) magnification. Phytoplankton taxa were identified using the method of Huber-Pestalozzi (1968), as well as some publications on East African lakes (Cocquyt et al., 1993). Phytoplankton were estimated by counting all the individuals, whether these organisms were single cells, colonies or filaments. For determining the chlorophyll-*a* concentrations, 50-ml of the water sample was filtered through GF/F filters (0.45-μm nominal pore size; 47-mm Ø, Sigma-Aldrich, St. Louis, MO) with a hand pump, and the filters subsequently frozen at −20°C.

Samples for algal toxins were collected with 250-ml borosilicate glass bottles for further analyses. Upon collection, they were immediately stored in a chilled cool box for transportation to the laboratory. They were subsequently refrigerated at 100°C in the laboratory and analysed within one week of collection. A total of 100-ml of

sample were filtered with a 25-cc syringe through the syringe filter (re-usable) with disposable 0.22-μm filter paper. This treatment was performed for all samples analysed prior to analysis. The analysed samples were mixed with antibody solution and added to a 96-well microtiter plate. The contents were covered with parafilm and shaken before incubation for 90 min at room temperature. The parafilm cover was removed, and the contents vigorously shaken into a sink. The strips were washed three times with a buffer solution, after which a particular enzyme conjugate (microcystin - LR conjugate solution) was added to the wells, covered and mixed once again and incubated for 30 minutes at room temperature (Fawell et al., 1994). The covering was removed after the incubation, and the contents shaken and poured into a sink. The strips were then washed three times with a buffer solution, and a substrate solution was added and incubated for 30 min at room temperature. A stop solution was then added to the wells before reading the absorbance at 450-nm with a ELISA photometer (Model NO 35CC). The microcystin concentration was inversely proportional to the intensity of the colour, with microcystins determined from a standard competitive curve of the particular toxin (e.g. microcystin-LR). The structure of MC variants was determined with a high-performance liquid chromatography (HPLC-DAD) analysis method according to equipment conditions (Fastner et al., 1999; Kurmayer et al., 2003).

2.3 | Data analysis

The Microsoft Excel 2013 package was used to provide descriptive statistics and plots of the derived data. The SPSS software version 20 (IBM-SPSS Inc. version 20.0, IBM Corp. Released 2011, IBM SPSS Statistics for Windows, Armonk, NY: USA) and R Software version 3.5.0 (R Core Team, 2014) statistical packages were used to determine the normality of the data before analysis of variance (ANOVA), and multiple comparison tests were used to identify significant values (level of significance $\alpha = 0.05$) of the tested parameters. Significant correlations were determined to better understand associations between water quality variables. Non-metric multidimensional scaling (NMDS) analysis of the relationships between phytoplankton taxa and environmental variables was also determined.

3 | RESULTS

3.1 | Physico-chemical parameters in Kisumu Bay

Most of the physico-chemical characteristics (TDS, TSS, DO, electrical conductivity, Secchi depth, pH, turbidity and temperature) of Kisumu Bay water exhibited significant variations among the sampling months. Significant spatial variations were only observed for the total depth, DO and TP concentration. The total depth of the sampling sites (wet season) in Kisumu Bay (Tables 1, 2)) ranged from 0.5-m at Kisian and Pier to 4.8-m off Maboko Island (Midpoint sampling site), and varied significantly between different sampling sites (Kruskal–Wallis test, $p < .05$). The Secchi depth during the wet season varied narrowly, ranging from 0.1-m at the Pier to 0.9-m at the Coca Cola site. The dissolved oxygen concentration ranged from a minimum of 1.0 mg/L at Pier to 8.7 mg/L at Kisat (wet season), varying significantly across all the sampling sites and months ($p < .05$). The water pH ranged from 6.5 (Dunga) to 9.6 (Pier). The total suspended and dissolved solids concentrations (TSS, 6.38–327.95 mg/L; TDS, 2–120 mg/L), turbidity (53.4 – 182.9 NTU) and electrical conductivity (122.0–197.0 μS/cm) of water from the bay ranged from low to very high values normally associated with lakeshore zones. The surface water temperature ranged from 22.0°C (December at Kisian, Molasses and Usoma) to 35.40°C (Usoma, dry season). The temporal mean values (minimum and maximum) of the TDS, TSS, DO, electrical conductivity, Secchi depth, pH, turbidity and temperature were 10.45; 49.09; 3.19 mg/L; 124.64 μS/cm; 0.2 m; 6.9; 62.45 NTU; 22.6 °C and 79.09; 135.18; 5.70 mg/L; 171.4 μS/cm; 0.4 m; 8.4; 92.63 NTU; and 27.31°C, respectively. Most physico-chemical variables exhibited low, but significant, negative and positive correlations (Tables 3, 4).

The nutrients exhibited significant temporal variations (Kruskal–Wallis test, $p < .05$) among sampling months, except for the TP levels, which varied spatially. Total phosphorus concentrations ranged from 38.11 μg/L at Auji (March 2017) to 803.43 μg/L at Molasses (November 2017). The total nitrogen concentrations ranged from 240.55 μg/L (Kisian, January 2018) to 4327.82 μg/L (Molasses, November 2017), whereas the nitrate concentrations ranged from 11.30 μg/L; (10B, March 2018) to 993.09 μg/L (Pier, February 2018), while the nitrite concentrations ranged from 4.6 μg/L at 10B (March 2018) to 309.27 μg/L at the Pier (February 2018). The soluble reactive silicon levels ranged from 3.12 to 141.89 mg/L at Molasses in December and November 2017, respectively.

The chlorophyll-a concentrations ranged from very low levels (1.40 μg/L; Molasses) to a maximum value at Coca Cola (2673.74 μg/L) during the wet season, but did not exhibit any significant variations ($p > .05$) between sampling sites and seasons. The month of January exhibited the lowest monthly mean chlorophyll-a content (33.23 μg/L), while the highest monthly mean (± S.D) chlorophyll-a concentrations (277.88 ± 465.71 to 342.98 ± 779.64 μg/L) were observed in the months of February, March and April 2018 (Figure 2a, b). The TN:TP ratio maxima was observed during February 2018 at the Midpoint site (Figures 2c,d). The mean TN:TP ratio in the bay was significantly different (Kruskal–Wallis test, $p < .05$) between sampling months, suggesting a possible nitrogen deficiency. The values among the sampling sites ranged from 11 to 26.

Oxidized nitrogen forms were correlated with SRP, TN, MCs and chlorophyll-a (Figure 2b). Chlorophyll-a exhibited significant, but weak, positive correlations (Table 4; Figures 3a–d) with electrical conductivity ($r = 0.229$, $p < .05$), MC-YR ($r = 0.272$, $p < .05$) and nitrite ($r = 0.292$, $p < .01$). Among the inter-element correlations, low, but significant, positive associations were observed between TP, TN, NO_3-N, SiO_2-Si and SRP levels. Silica-Si was negatively correlated

TABLE 1 Overall mean (±SD), median and range values of physico-chemical parameters, microcystins and nutrient concentrations in Kisumu Bay and comparison with some permissible drinking water guideline values

						Spatial	Temporal	Drinking water		
						Sig.	*p*-value	Gv		
	Mean[1] (±SD)	Min.	Med[2]	90th p	Max			NEMA	WHO	EPA
Total depth (m)	2.0 (1.1)	0.5	1.6	3.9	4.8	Sg**	Ns	–	–	–
Secchi depth (m)	0.3 (0.1)	0.1	0.4	0.4	0.9	Ns	Sg**	–	–	–
pH	7.8 (0.7)	6.5	8.0	8.7	9.6	Ns	Sg**	6.5–8.5	–	–
DO (mg/L)	4.8 (1.3)	1.0	5.5	6.2	8.7	Sg*	Sg**	–	–	–
Temperature (°C)	25.28 (2.39)	22.00	24.80	24.77	35.40	Ns	Sg**	–	–	–
Cond (µS/cm)	81.05 (24.68)	122.0	152.0	177.10	197.0	Ns	Sg**	–	–	–
TDS (mg/L)	37.14 (29.12)	2.0	30.5	82.2	120.0	Ns	Sg**	1200	–	–
TSS (mg/L)	83.42 (55.1)	6.38	75.0	146.0	327.95	Ns	Sg**	30	–	–
Turbidity (NTU)	81.05 (24.68)	53.40	78.0	100.1	182.9	Ns	Sg**	–	5	–
Chlorophyll-a (µg/L)	164.58 (428.39)	1.46	52.97	267.3	2673.7	Ns	Ns	–	–	–
MC-LR (µg/L)	0.794 (1.772)	0.0	0.232	1.730	11.26	Ns	Sg**	–	1.0	1.6(*0.3*)
MC-YR (µg/L)	0.549 (1.558)	0.0	0.082	0.950	9.480	Ns	Sg*	–	–	–
TP (µg/L)	203.29 (121.07)	38.11	166.28	382.57	803.43	Sg*	Ns	–	–	–
SRP (µg/L)	77.13 (29.71)	12.98	72.72	115.15	167.71	Ns	Sg**	–	–	–
TN (µg/L)	1080.61 (918.88)	240.55	576.91	2,446.07	4,327.82	Ns	Sg**	–	–	–
NO_3-N (µg/L)	72.30 (154.80)	11.30	32.37	87.45	993.09	Ns	Sg**	10^4	$11x10^3$	10^4
NO_2-N (µg/L)	38.41 (49.49)	4.60	23.17	67.32	309.27	Ns	Sg**	10^3	–	10^3
NH_4-N (µg/L)	103.93 (89.87)	5.81	78.05	219.14	440.0	Ns	Sg**	–	–	
SiO_2-Si (mg/L)	31.95 (20.36)	3.12	26.28	65.41	141.89	Ns	Sg**	–	–	–

Notes: Sample size (*n*) = 88; DO, dissolved oxygen concentration; Cond., electrical conductivity; TDS, total dissolved solids; TSS, total suspended solids; TP, total phosphorus; SRP, dissolved reactive phosphate; TN, total nitrogen; NO_3-N, nitrate nitrogen; NO_2-N, nitrite nitrogen; ammonia nitrogen; NH_4-N, ammonia nitrogen; SiO_2-Si, silicon dioxide silica; Med, median values; Min and Max, minimum and maximum values; 90th p, 90th percentile values; Gv, guideline values; USEPA *0.3* µg/L value in italics established as child drinking water advisory value; USEPA MCL, maximum contaminant level; WHO 2003, NEMA = EMCA 2006; Ns, variation not significant; Sg, significant variation at * (0.05) and ** (0.01) level of significance; one-way analysis of variance for DO, Cond, TDS, TSS and SRP only[1]; Kruskal–Wallis test of median values[2].

TABLE 2 Mean (±SD) and median values of physico-chemical variables at various sampling locations in Kisumu Bay (means with a different or superscript letter[a] along the columns are significantly different at $p < .05$; chlorophyll-a, microcystins and nutrient elements reported as μg/L, except for Si, mg/L)

		Parameters						
Sample site	N	Secchi (m)	Depth[a] (m)	pH	DO[a] (mg/L)	Cond (μS/cm)	Turb (NTU)	Temp (°C)
Kisian	9	0.4 (0.1)	1.5 (2.0)	7.74 (0.64)	3.98 (1.26)	141.9 (12.5)	79.71 (23.70)	25.7 (3.73)
Molasses	8	0.3 (0.1)	1.7 (1.1)	7.69 (0.53)	4.18 (1.32)	148.8 (21.1)	96.96 (48.23)	24.2 (1.52)
Usoma	8	0.3 (0.0)	1.5 (0.5)	8.20 (0.34)	4.70 (0.64)	147.5 (13.6)	75.10 (8.43)	26.1 (4.29)
Coca Cola	8	0.4 (0.3)	1.5 (0.9)	8.01 (0.72)	5.21 (1.66)	154.3 (20.3)	78.48 (16.03)	24.5 (1.89)
Pier	8	0.3 (0.1)	1.6 (1.2)	7.83 (1.02)	4.13 (1.91)	168.4 (26.2)	87.29 (25.34)	24.2 (1.74)
Kisat	8	0.3 (0.1)	1.2 (0.4)	7.84 (0.79)	5.46 (1.71)	153.9 (20.9)	91.70 (27.65)	25.6 (2.19)
Tilapia	8	0.3 (0.1)	1.9 (0.1)	7.64 (0.90)	3.96 (1.07)	166.9 (19.2)	88.56 (38.72)	24.5 (2.19)
Auji	8	0.3 (0.2)	1.9 (1.2)	7.77 (0.83)	5.08 (0.99)	158.8 (19.2)	73.90 (13.79)	25.1 (1.93)
10B	8	0.4 (0.1)	3.3 (1.0)	7.84 (0.73)	5.66 (0.61)	148.4 (13.0)	69.20 (10.79)	26.5 (1.30)
Dunga	8	0.4 (0.1)	1.9 (0.6)	7.57 (0.68)	4.40 (1.01)	147.8 (12.6)	70.73 (8.59)	26.2 (1.60)
Midpoint	7	0.4 (0.1)	3.7 (1.2)	7.56 (0.57)	5.67 (0.62)	154.9 (17.8)	79.93 (8.74)	25.1 (1.48)

		Parameters						
Sample site	N	TP[a]	SRP	TN	NO_3-N	NO_2-N	NH_4-N	SiO_2-Si
Kisian	9	132.11 (39.10)	66.07 (17.86)	615 (635.39)	46.54 (34.37)	30.20 (26.94)	76.54 (49.15)	26.09 (8.87)
Molasses	8	229.39 (234.36)	70.99 (25.30)	1,242.59 (1407.69)	35.53 (24.17)	25.70 (17.04)	79.80 (39.26)	29.0 (21.61)
Usoma	8	231.19 (161.79)	83.71 (15.04)	967.74 (777.39)	68.60 (84.11)	52.97 (82.14)	120.51 (63.63)	24.36 (10.79)
Coca Cola	8	273.0 (145.23)	76.95 (37.3)	1648.89 (1189.47)	164.0 (314.24)	55.90 (82.90)	174.62 (130.19)	24.44 (11.32)
Pier	8	248.72 (72.61)	89.83 (36.2)	1396.3 (1030.27)	166.89 (334.54)	69.72 (99.44)	182.90 (141.34)	26.28 (8.87)
Kisat	8	264.86 (126.23)	73.04 (26.7)	1219.48 (873.86)	106.67 (213.6)	29.49 (18.48)	100.08 (62.61)	36.40 (21.04)
Tilapia	8	184.83 (50.0)	84.56 (39.46)	859.71 (778.83)	50.09 (38.33)	40.20 (38.87)	128.21 (139.15)	28.99 (17.96)
Auji	8	178.24 (99.66)	96.52 (35.21)	1,082.09 (888.89)	46.89 (17.24)	32.51 (11.92)	86.65 (62.92)	34.43 (21.15)
10B	8	140.52 (30.55)	80.21 (28.41)	810.22 (742.68)	38.84 (26.86)	29.78 (24.11)	59.42 (54.99)	36.84 (21.25)
Dunga	8	192.30 (110.63)	63.96 (26.35)	904.94 (736.07)	39.04 (22.42)	26.46 (19.22)	59.96 (37.27)	32.69 (14.56)
Midpoint	7	165.15 (66.52)	62.16 (27.46)	1216.27 (900.54)	30.19 (19.59)	29.52 (22.25)	74.24 (51.66)	57.92 (40.61)

		Parameters				
				Chlorophyll-a		
Sample site	N	TDS (mg/L)	TSS (mg/L)	Mean (±SD)	min	max
Kisian	9	35.22 (36.89)	63.74 (36.30)	34.24 ± 32.76	4.70	109.34
Molasses	8	42.56 (40.56)	67.54 (46.64)	61.79 ± 80.56	1.46	238.36
Usoma	8	32.66 (24.95)	82.88 (49.75)	61.71 ± 73.04	4.00	227.09
Coca C ola	8	42.29 (30.38)	86.30 (51.15)	866.83 ± 1224.66	3.50	2673.74
Pier	8	41.48 (27.17)	86.22 (35.34)	144.51 ± 186.80	40.04	589.62
Kisat	8	41.88 (37.39)	112.80 (71.16)	196.48 ± 210.37	22.33	664.20

(Continues)

TABLE 2 (Continued)

		Parameters				
				Chlorophyll-a		
Sample site	N	TDS (mg/L)	TSS (mg/L)	Mean (±SD)	min	max
Tilapia	8	42.43 (31.23)	80.55 (54.13)	61.91 ± 32.57	15.49	121.80
Auji	8	39.03 (33.87)	76.05 (43.03)	175.91 ± 168.19	19.64	403.38
10B	8	35.08 (18.10)	87.81 (52.01)	61.76 ± 45.22	14.94	154.01
Dunga	8	31.99 (23.95)	74.67 (49.12)	79.41 ± 50.69	13.63	141.89
Midpoint	7	22.33 (15.42)	103.99 (109.91)	70.41 ± 50.63	13.66	141.89

Note: Abbreviations as listed in Table 1.

with TSS ($p < .01$). The trophic classification based on the Carlson's lake trophic state (CTSI) and mathematical equations (Carlson, 1977), based on chlorophyll-a (mean $TSI_{chl\ a} = 78$), TP (mean $TSI_{TP} = 80$) and Secchi depth (mean $TSI_{secchi\ depth} = 76$), suggested the bay was hypereutrophic (mean CTSI of 78) (Figure 2c,d).

3.2 | Phytoplankton abundance and diversity within Kisumu Bay

A total of six phytoplankton families (Chlorophyceae; Cyanophyceae; Bacillariophyceae (diatoms); Dinophyceae; Euglenophyceae; and Zygnematophyceae) were identified in Kisumu Bay (Figure 4a, b). Cyanophyceae, commonly referred to as blue-green algae, was the most dominant family across the sampling sites. Cyanophytes constituted up to 35% of all algal groups, followed by diatoms with 30% during all months of sampling (Table 5). The latter comprised an important component of the algal flora, constituting 98% in December and 13% in May. Chlorophytes were the most important at most sites, constituting about 12% in November 2017 and 15% in February. The contribution of cyanophytes to the overall phytoplankton community remained largely significant for most sites. The occurrence of euglenophytes was lowest at almost all sampling sites, but did constitute 32% and 13% in November and March, respectively. This family was mainly dominated by *Phacus* and *Strombomonous* genera. Two species of dinoflagellates (*Glenodinium pernardii*; *Ceratium* spp.) were observed. Diatoms appeared in all the sampling months, being mainly represented by *Surillella* sp, *Nitzschia*, *Synedra*, *Diatoma* spp. and *Cyclotella* genera. *Microcystis* spp. remained the most dominant algal families in Kisumu Bay from September to April (Figure 5a,b). The most abundant phytoplankton genera were *Microcystis aeruginosa* (30%), *Merismopedia* spp. (28%) and *Anabaena flos-aquae* (16%).

3.3 | Spatial and temporal variation of phytoplankton families in Kisumu Bay

The cyanophytes dominated the algal community throughout the sampling period (Figure 5a,b). Chlorophytes were the second dominant group, except in November 2018 when Zygnematophyceae become the second most dominant group. Dinoflagellates were the third most dominant group in September 2017, October and November 2017 and in January to February 2018, while the diatoms displaced Zygnematophyceae during the rest of the sampling period. Euglenophytes were the least dominant group throughout the sampling period.

3.4 | Spatial distribution of phytoplankton within Kisumu Bay

The percentage composition of the algal community structure in Kisumu Bay indicated *Microcystis aeruginosa* is the most abundant species of the major algal species in Lake Victoria. There were 130 different phytoplankton species identified throughout the sampled period, with 43 species of chlorophytes observed during the wet season. *Scenedesmus* spp., *Botrycoccus* sp, *Ankistrodesmus falcatus* and *Pediastrum* spp. were the most common genera during the entire sampling period. The calculated Shannon–Weiner Diversity Index increased from 1.229 (Dunga) to 1.693 (Midpoint), with a spatial mean value of 1.435 ± 0.132 (Figure 6). Dinophytes exhibited the lowest diversity value ($H' = 1.387$), compared to the remaining species.

There were no significant ($p < .05$) correlations among the phytoplankton families. However, the diatom composition and abundance was significant, being positively correlated with TSS and negatively with TP ($p < .05$), respectively, whereas the Cyanobacteria were significantly correlated ($p < .05$) with Secchi depth and nitrites. The Chlorophyte composition and abundance was negatively correlated with silica-Si ($r = -0.320$ and -0.334, respectively; $p < .01$). The composition of Zygnematophyceae and Dinophyceae was moderately correlated with SRP ($r = 0.339$; $p < .05$) and nitrates ($r = -0.448$; $p < .05$), respectively. The Euglenophytes abundance was also negatively correlated with TSS ($r = -0.279$; $p < .05$) and electrical conductivity ($r = -0.291$; $p < .05$).

There were significant differences in the chlorophyll-*a*, temperature, dissolved oxygen concentrations, electrical conductivity, pH and Secchi depth between the sampling sites ($p < .05$). The pattern of change in the physical–chemical variables in Kisumu Bay was highly unpredictable, because of the shallow depth, high nutrient inputs, pollutant loadings and regular mixing by wind (Figures

TABLE 3 Spearman correlation coefficients (*r*) between physico-chemical parameters (** and *, significant at $p < .01$ and $p < .05$ level, respectively)

	TP	SRP	TN	NO_3-N	NO_2-N	NH_4-N	SiO_2Si	Secchi	depth	pH	DO	Cond	Turb	Temp	TDS	TSS
SRP	0.322**	1.000														
TN	0.351**	0.245**	1.000													
NO_3-N	−0.122	0.274**	0.245*	1.000												
NO_2-N	−0.002	0.251*	0.414**	0.628**	1.000											
NH4-N	0.235*	0.424**	0.315**	0.055	0.049	1.000										
SiO_2-Si	0.180	0.225*	0.062	−0.105	−0.193	0.101	1.000									
Secchi	−0.187	0.073	−0.139	0.166	−0.122	−0.174	0.310**	1.000								
Depth	−0.126	−0.060	−0.086	−0.116	−0.099	−0.284**	0.180	0.373**	1.000							
pH	−0.112	−0.365**	0.083	0.076	0.350**	−0.144	−0.566**	−0.431**	−0.028	1.000						
DO	0.003	*−0.097*	0.123	−0.107	0.087	−0.000	0.080	−0.353**	0.207	0.250*	1.000					
Cond	0.259*	*0.179*	0.039	0.027	0.105	−0.073	−0.102	−0.342**	−0.238*	−0.014	*−0.250**	1.000				
Turb	0.192	−0.051	0.141	0.170	0.240*	−0.190	−0.112	−0.227	−0.196	0.198	−0.169	0.442**	1.000			
Temp	0.029	−0.195	−0.075	−0.195	0.058	−0.393**	−0.069	−0.360**	0.135	0.254*	0.378*	0.280**	−0.097	1.000		
TDS	0.240*	*0.024*	−0.139	−0.030	0.047	−0.207	0.041	−0.127	0.105	0.119	*0.230**	*0.105*	0.242*	0.370**	1.000	
TSS	0.055	*−0.144*	−0.039	−0.139	−0.145	0.034	−0.294**	0.118	−0.168	0.134	*−0.097*	*0.157*	0.057	0.001	*−0.065*	1.000

Abbreviations: Cond, electrical conductivity; DO, dissolved oxygen concentration; NH_4-N, ammonia nitrogen; NO_2-N, nitrate nitrogen; NO_3-N, nitrate nitrogen; ammonia nitrogen; SiO_2-Si, silicon dioxide silica; SRP, dissolved reactive phosphate; TDS, total dissolved solids; temp, temperature; TN, total nitrogen; TP, total phosphorus; TSS, total suspended solids; turb, turbidity; values in italics, Pearson correlation coefficients.

TABLE 4 Spearman correlation coefficients between phytoplankton abundance, chlorophyll a, microcystins levels and physico-chemical parameters (** and *significantly at $p < .01$ and $p < .05$ level, respectively)

	CHLO	CYN	DIAT	ZYG	EUG	DINO	MC-LR	MC-YR	Chl a
TP	−0.177	−0.214	−0.210	−0.037	−0.226	0.083	−0.045	−0.169	−0.088
SRP	−0.088	0.110	−0.071	0.127	−0.129	−0.053	0.180	0.399	−0.056
TN	0.026	0.082	0.019	−0.114	0.033	0.094	0.041	0.123	0.020
NO_3-N	0.049	0.118	0.026	0.159	0.235	−0.223	0.378**	0.244	0.137
NO_2-	−0.119	0.221*	−0.125	0.228	0.085	−0.181	0.309*	0.192	0.292**
NH_4-N	−0.076	0.036	−0.116	−0.065	−0.90	0.017	0.029	0.040	0.031
SiO_2-Si	−0.119	−0.089	0.167	−0.029	0.124	−0.114	−0.334**	−0.128	0.036
Secchi	0.136	0.311**	0.158	0.231	0.010	−0.108	0.198	0.016	−0.172
Depth	−0.006	0.103	0.064	0.120	0.155	0.343	0.162	0.219	−0.154
pH	0.179	0.010	−0.044	=0.038	0.178	−0.080	0.107	0.060	0.163
DO	0.080	−0.167	0.066	0.043	0.182	0.305	−0.037	0.098	0.042
Cond	−0.149	−0.176	−0.170	−0.015	−0.291*	−0.147	−0.033	−0.008	0.229*
Turb	−0.089	−0.176	−0.153	−0.258	−0.117	−0.110	−0.037	0.000	0.161
Temp	0.016	−0.111	−0.123	−0.009	0.013	0.205	−0.101	−0.031	−0.002
TDS	−0.074	−0.041	−0.198	0.117	−0.104	0.217	0.150	0.060	−0.080
TSS	−0.021	−0.176	0.054	−0.030	−0.279*	−0.099	−0.088	−0.233	0.108
CYN	0.473**	1.000							
DIAT	0.394**	0.265**	1.000						
ZYG	0.177	0.414**	0.212	1.000					
EUG	0.250*	0.177	0.093	0.061	1.000				
DINO	0.181	0.127	−0.051	0.090	−0.277	1.000			
MC-LR	−0.045	0.336	0.098	0.399	1.000	−0.045	0.048		
MC-YR -	0.095	0.106	0.180	0.909**	1.000	0.169 -	0.073	0.008	
Chl a	−0.088	0.002	−0.189	0.119	−0.077	−0.056	0.203	0.272*	1.000

Abbreviations: Chl a, chlorophyll a; CHLO, Chlorophyceae; Cond, electrical conductivity; CYN, Cyanophyceae; DIAT, Bacillariophyceae (diatoms);DINO, Dinophaceae; DO, dissolved oxygen concentration; EUG, Euglenophyceae; NH_4-N, ammonia nitrogen; NO_2-N, nitrite nitrogen; ammonia nitrogen; ammonia nitrogen; NO_3-N, nitrate nitrogen; SiO_2-Si, silicon dioxide silica; SRP, dissolved reactive phosphate; TDS, total dissolved solids; temp, temperature; TN, total nitrogen; TP, total phosphorus; TSS, total suspended solids; turb, turbidity; ZYG, Zygnematophyceae.

7a,b, 8). This observation was depicted in the ordination (stress of 0.08834 for the first two dimensions; r^2 for axis 1 = 0.9175 and axis 2 = 0.1385) and plots (except for the relatively deep Midpoint site located outside the bay conditions), where water hyacinth can cover the surface for extended times during infestation periods, affecting the light climate and underwater environment.

In contrast, there were 15 species of Zygnematophyceae encountered in January, February, November and December, with *Cosmarium* and *Straurastrum paradoxum* being the most frequently encountered genera. Three species of dinoflagellates were encountered, the common ones being *Ceratium* and *Glenodinium pernardii* at sampling site 10, with 15% recorded in November and January 2018. There were 38 species of diatoms observed over the entire study period, comprised mainly of *Surillella* sp., *Nitzschia*, *Synedra*, *Aulacoseira* spp. and *Cyclotella* species. The fifth major algal group encountered was the euglenophytes, being represented by a genera comprising 11 species over the entire study period, with the most dominant being *Phacus* spp., *Euglena* spp., *Trachelemonous and Strombomonous* spp. Cyanobacteria were represented by 20 species, with *Microcystis* spp and *Anabaena* spp being dominant and which are known to be buoyant and possess the ability to fix nitrogen from the atmosphere.

The frequency of the MCs variants detection was about 61%, increasing towards the long rains period, with a relatively higher rate of MC-LR and MC-YR being detected at the Kisat and Tilapia sampling sites, respectively. The MC toxin concentrations (MC-LR and MC-YR) in the lake water ranged from not detected to a maxima of 11.26 μg/L MC-LR (Coca cola) and 9.48 g/L (Coca cola) in February 2018 (Table 6). The mean concentrations of the two toxins were below the WHO (2017) acceptable standards of 1.0 μg/L, ranging between 0.25 ± 0.27 μg/L to 0.52 ± 0.35 μg/L (MC-LR) and 0.08 ± 0.11 μg/L to 0.23 ± 0.25 μg/L (MC-YR) for all the other sampling sites. The MC-LR and MC-YR concentrations exhibited insignificant ($p > .05$) spatial and temporal variations. Spatially, the three highest mean concentration of MC-LR was 2.84 ± 4.41 μg/L (Coca Cola), 1.78 ± 1.87 μg/L (Pier) and 1.44 ± 2.71 μg/L (Mid-point), exceeding the WHO threshold for drinking water of 1.0 μg/L (WHO, 2017). Similarly, the MC-YR concentrations were highest at the same sites, being 2.21 ± 4.08 μg/L, 1.54 ± 2.12 μg/L and 1.61 ± 2.66 μg/L,

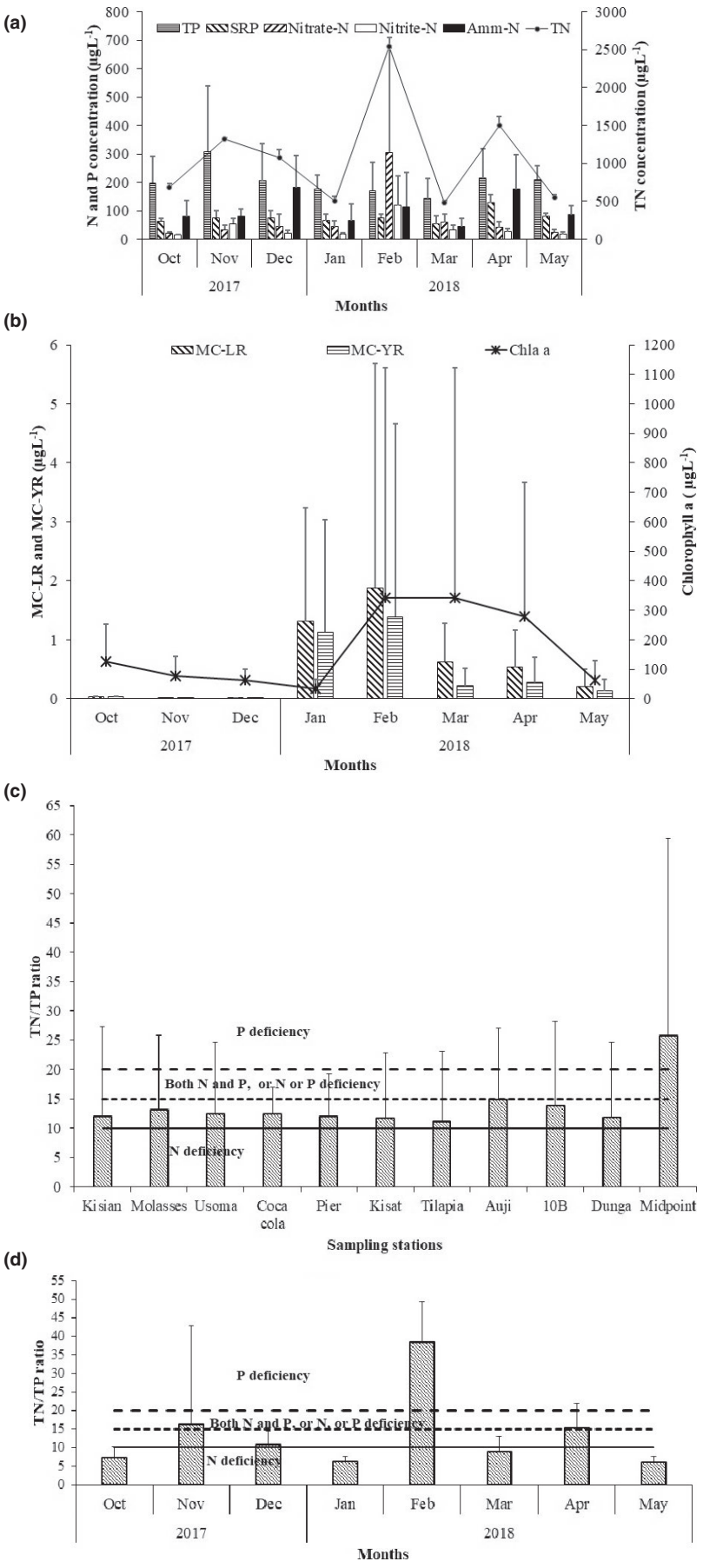

FIGURE 2 (a, b) Temporal mean (±SD) variations in nutrient elements, chlorophyll-a and microcystins in Kisumu Bay. (c, d) Spatial and temporal changes in mean (±SD) TN:TP ratio in Kisumu Bay

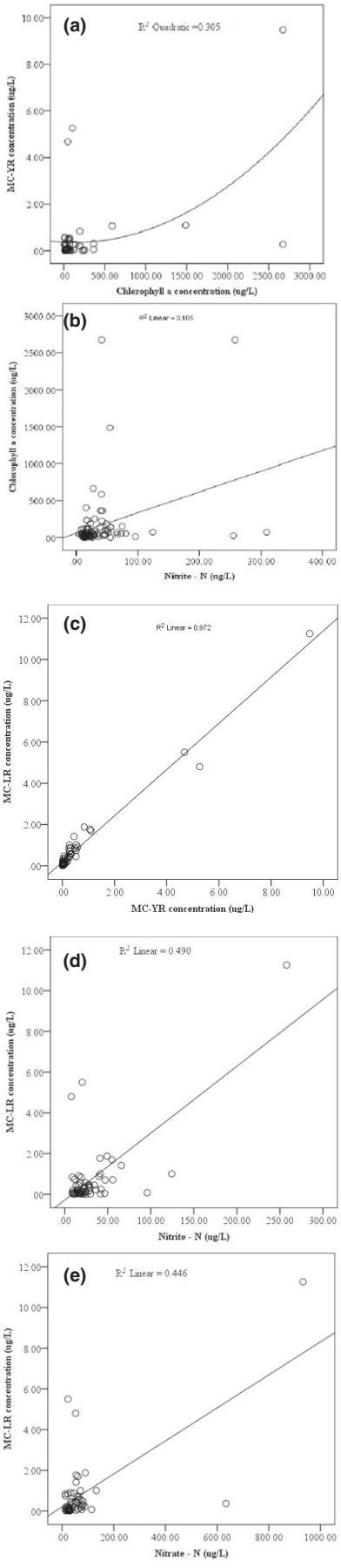

FIGURE 3 (a–d) Scatter plots of relationships between microcystins ($n = 54$), nutrients and chlorophyll-a ($n = 88$) in Kisumu Bay

at the Coca Cola, Pier and Mid-point sites, respectively. Mirocystin levels increased significantly from January 2018, reaching a maximum mean concentration in February and March (Figure 2a,b), with the two variants being highly correlated (Figure 3a,b). Significant positive correlations ($p < .05$) were observed between MC-LR, nitrate and nitrite concentrations, whereas MC-YR was only correlated with chlorophyll-a concentrations.

4 | DISCUSSION

4.1 | Water quality, phytoplankton composition and distribution

Lake Victoria in East Africa is a large transboundary lake ecosystem with a shoreline dotted with several small and large relatively shallow embayments (open and semi-closed) that are considered critical aquatic habitats but, which, and depending on their settings, can experience varying hydrological influences and different scales of anthropogenic pressures. Water hyacinth and frequent algal blooms were observed during the present study within the sheltered bays of the Winam Gulf (which act as water hyacinth hotspot) exhibiting varying coverage levels. The presence of cloud cover, however, hampered satellite data analysis within the gulf, resulting in discontinuous trends in coverage data to relate to collected phytoplankton and water quality data. Available Landsat-8 satellite data that were analysed, indicated an estimated 644, 597a and 1224 ha coverage in Nyakach and Osodo bays during September 2017, October 2017 and February 2018, respectively (Ouko J. personal comm.). Since the floating weed shifted its location within the bays, it was hypothesized that its presence indicated some significant influences on water circulation and underwater conditions during the present study period. This was especially the case for the present study sites within and near Kisumu Bay, which also occasionally suffered from long periods of water hyacinth coverage. The same areas were frequently covered by algal blooms, especially around Midgulf, Asembo, Osodo, Kisumu and Nyakach bays. Water hyacinth mats thereafter spread into Kisumu Bay around June 2018 onwards. The present study was conducted in the most extreme eastern bay of Nyanza Gulf (Winam Gulf) during a time when the connection to the main lake (Mbita Channel, which was previously a causeway) was opened around 2017. Therefore, and coupled with the differences in physico-chemical parameters observed in the present study, such conditions may influence the ecological status of the lake, including species composition and abundance of aquatic organisms which, in turn, influence aquatic processes and lake productivity.

The results of the present study indicated the patterns of change of physical and chemical parameters in Kisumu Bay were extremely variable and unpredictable across the sampling sites.

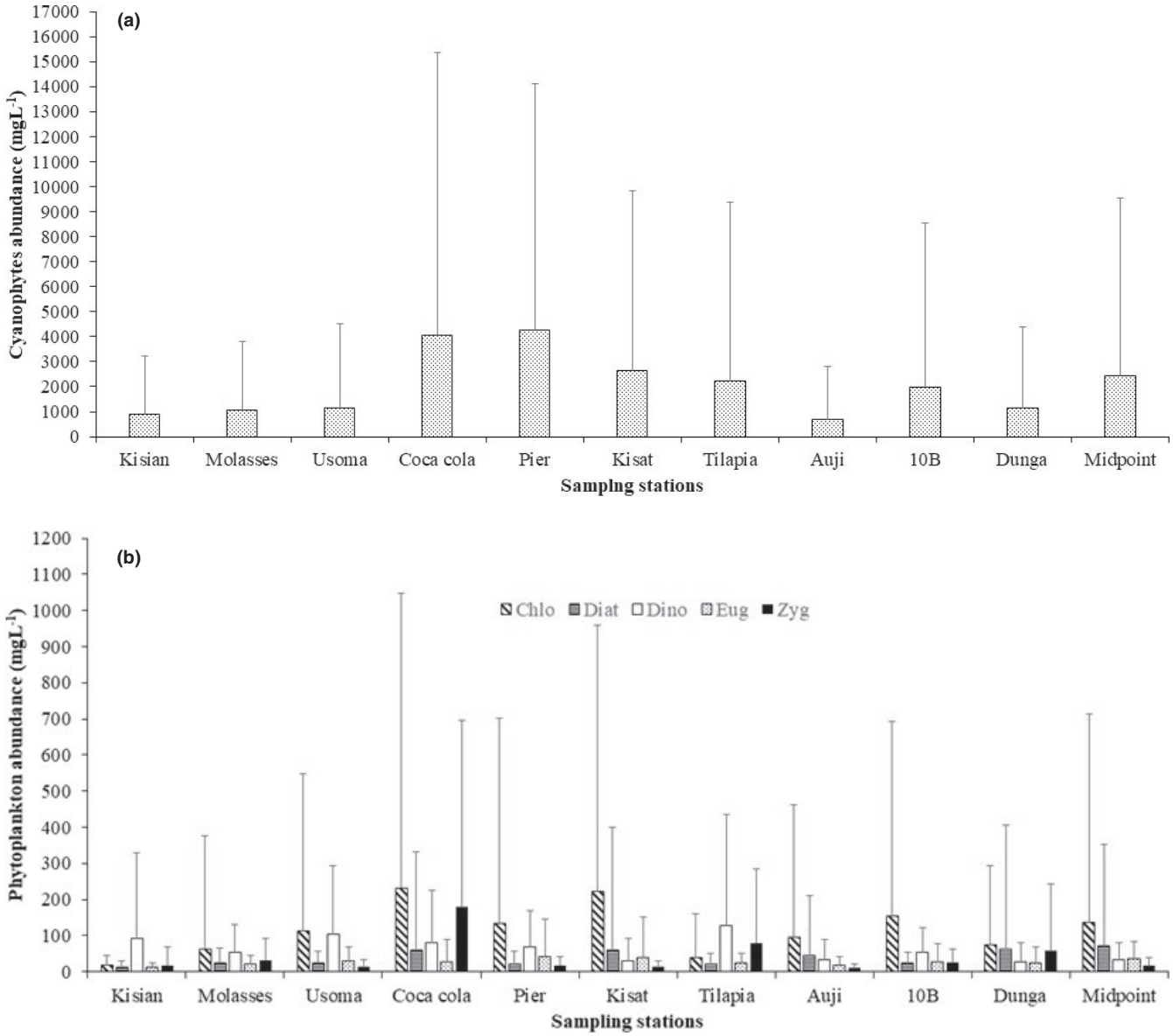

FIGURE 4 (a, b) Spatial distribution and mean abundance of major phytoplankton group (mg/L; Kisumu Bay, Lake Victoria. (Chlo, Chlorophyceae; Cyn, Cyanophyceae; Diat, Bacillariophyceae (diatoms); Dino, Dinophyceae; Eug, Euglenophyceae; Zyg, Zygnematophyceae)

Measured Secchi depth values are low possibly attributable to the existence of algal blooms and high turbidity resulting from the presence of suspended materials originating from decomposition of water hyacinth, as well as silt river discharges, stormwater and surface runoff into the lake. This may be attributed to the shallow mean depth and landscape of the Kenyan sector of Lake Victoria, which is strongly influenced by extremely variable seasonal/diurnal wind patterns, shear and runoff from the city of Kisumu and adjacent agricultural farm lands and industrial effluents (Okely et al., 2010). These factors together with the shallow nature of the bays and the river inflows influence the development of algal blooms and the production of algal toxins. Gulf-wide variations indicate a gradient in the physico-chemical conditions towards the open lake (Gikuma-Njuru et al., 2018). These factors are indicators of cultural eutrophication of the lake ecosystem which, together with climate change impacts, may be responsible for the variable nature of the spatial and temporal changes in the algal community structure in the bay.

The dissolved oxygen (DO) concentrations exhibited significant differences between sampling sites. DO concentrations in the bay ranged from stressful levels of ~5 mg/L to levels of 3 mg/L, which are lethal to most organisms that live in water. The significantly low DO levels, particularly those observed at the Pier site, may be a result of an increased load of nutrient-rich organic matter originating from the city treatment works and runoff, which can facilitate the development of algal blooms and the overall eutrophication. The decomposition of nutrient-rich organic matter and the ageing of algal blooms, together with dead water hyacinth and macrophyte material, could trigger microbial activities that lead to further reduced DO concentrations in the water column (Hecky and Bugenyi, 1992).

TABLE 5 Percentage composition of major phytoplankton taxa in Kisumu Bay, Lake Victoria

Genus/Taxa	Number/ml	Composition (%)
Microcystis aeruginosa	11,780	30.3 (30%)
Merismopedia spp.	10,876	27.98 (28%)
Anabaena circinalis	6,234	16.04 (16%)
Pediastrum tetras	2,019	5.19 (5%)
Chroococcus limnetica	1,500	3.86 (4%)
Scenedesmus acuminatus	1,200	3.09 (3%)
Plankolyngbya tallingii	1,143	2. 94 (3%)
Chroococcus disperses	1,092	2.81 (3%)
Microcystis wesenbergii	850	2.19 (2%)
Fragillaria gracilis	476	1.22 (1%)
Amphora ovaries	398	1.02 (1%)
Chroococcus sp.	321	0.83 (1%)
Coelastum microporum	321	0.83 (1%)
Phacus pleuronectes	265	0.68 (1%)
Synedra cunningtonii	188	0.5 (1%)
Cyclotella kutzinghiana	76	0.20 (0%)
Fragillaria sp.	58	0.15 (0%)
Others	50	0.13 (0%)
Strombonous sp.	27	0.07 (0%)
Total % composition	46,309	100%

High-water temperature was observed around Dunga and the Pier, possibly attributable to the relatively shallow water depth characterizing most of the sampling sites, except for Midpoint site. In addition, the presence of high TSS concentrations and solar radiation along with effluent discharges can have a significant influence on the water temperature. The high electrical conductivity observed at all the Kisumu Bay sampling sites could also be due to effluent discharges from motor vehicle garages, metal work workshops, car washes, institutional laboratories and petrol station runoff. Eutrophication and pollution of the bay are further exacerbated by its sheltered nature that results in minimal water mixing (Nyamweya, Desjardins, et al., 2016). The sheltered nature of the Auji and Dunga sampling sites could also contribute to the observed gradual increase in the temperature gradient from the littoral towards the offshore zones. The high temperatures observed at the Kisat sampling site could be due to a high turbidity level of the waters that can absorb and retain solar energy. Other studies have indicated that high-water temperatures can accelerate oxygen-consuming reactions, resulting in oxygen depletion at particular times of the day (Nyamweya, Desjardins, et al., 2016). At shallow water depths and with relatively high solar radiation, along with frequent water mixing during the day can also lead to increased surface water temperatures, decreasing the solubility of gases such as oxygen, thereby affecting underwater productivity. The near neutral, but still alkaline, pH observed in the bay could be attributed to the discharge of alkaline effluents by the Equator soft drink bottling plant in the city of Kisumu. Such pH conditions favour algal communities dominated by cyanobacteria, a condition observed in the bay. The sampling sites located at the river mouth generally exhibited almost the same pH levels, not being significantly different compared to those observed in the bay. Untreated sewage waste and livestock activities along the Kisat and Kisian river mouths could result in the low pH levels observed there. The high pH observed at the Dunga, Coca-Cola and Pier sampling sites indicates a dramatic increase in the water alkalinity over the sampling period, which could be attributed to the cumulative effect of biochemical processes associated with fish cage aquaculture and the discharge of raw sewage into the bay. Prior to the present study, Orina et al. (2020) reported lakeshore fish landing beaches exhibited maximum NH_4-N and PO_4-P concentration of 1278.3 ± 6.7 µg/L and 310.7 ± 1.7 µg/L, respectively, at the Dunga sampling site in November 2015. Temperature and pH fluctuations can highly influence the dissociation of ionized ammonia (NH_4-N) into unionized ammonia (NH_3). The assimilation of ammonium (NH_4^+) and nitrate (NO_3^-) by algae, for example, occurs because of two principal processes by which nitrogen is obtained during primary production (Hossain et al., 2007). Nitrite provides an additional, but subsidiary, source of dissolved nitrogen. Nutrients that become available through such processes encourage the growth of algae and, because N is one of the nutrients that can limit primary productivity, a high biomass of blue-green algae can develop. These observations further support the dominance of Cyanophyceae in the bay. At highly elevated concentrations, NH_4^+ can become toxic depending on various water quality factors, mainly temperature and pH. The unionized ammonia (NH_3) at concentration levels >20 µg/L are toxic to aquatic organisms and therefore can affect the phytoplankton community structure. A high-water residence time coupled, with intense vertical mixing within the gulf, encourages enhanced water physico-chemical levels because of particle-associated nutrient remobilization. Electrical conductivity, total alkalinity, water hardness, and SRP, TP, NH_4-N, NO_2-N, NO_3-N and TN concentrations were significantly higher within the gulf, compared to the midpoint sampling site. It was clear that Kisat, Auji and Dunga exhibited relatively high conductivity levels, possibly attributable to the presence of dissolved ions from the surrounding areas, which may explain the positive associations between electrical conductivity and turbidity, temperature and TP. A previous study by (Sitoki, 2010) indicated an electrical conductivity of between 157.72 and 195.1 µS/cm within Kisumu Bay, being slightly lower than those observed in the current study at the Kisian, Molasses and Mid-point sampling sites. This could have resulted from differences in sampling design since both river mouths and the open waters were sampled in the present study, while Sitoki et al. (2012) also sampled deeper parts of the open lake. Orina et al. (2020) used two sampling sites in Kisumu Bay (Dunga and Kijinjio) in their study in November 2015, reporting increasing values of temperature, electrical conductivity, TDS, TSS, BOD_5 and DO levels with increasing distance (0 to 100-m) from the fish landing beaches around the shores of Nyanza Gulf. Nevertheless, the relatively high conductivity levels at certain sampling points (e.g. Kisat River) were higher since they serve as a conduit for urban effluents, fertilizers, sewage and other wastes (Gikuma-Njuru and Hecky, 2005; Lung'ayia et al., 2000; Triest et al., 2012).

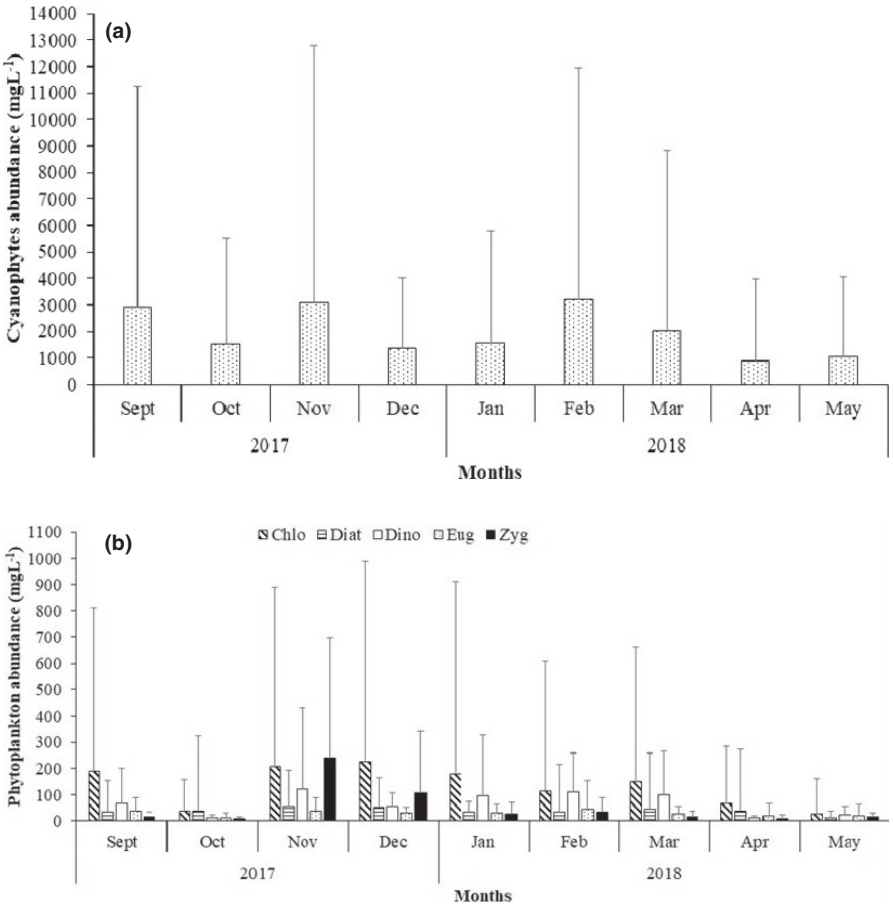

FIGURE 5 (a, b) Temporal distributions and means (± SD) of phytoplankton families in Kisumu Bay, Lake Victoria (Chlo, Chlorophyceae; Cyn, Cyanophyceae; Diat, Bacillariophyceae (diatoms); Dino, Dinophyceae; Eug, Euglenophyceae; Zyg, Zygnematophyceae)

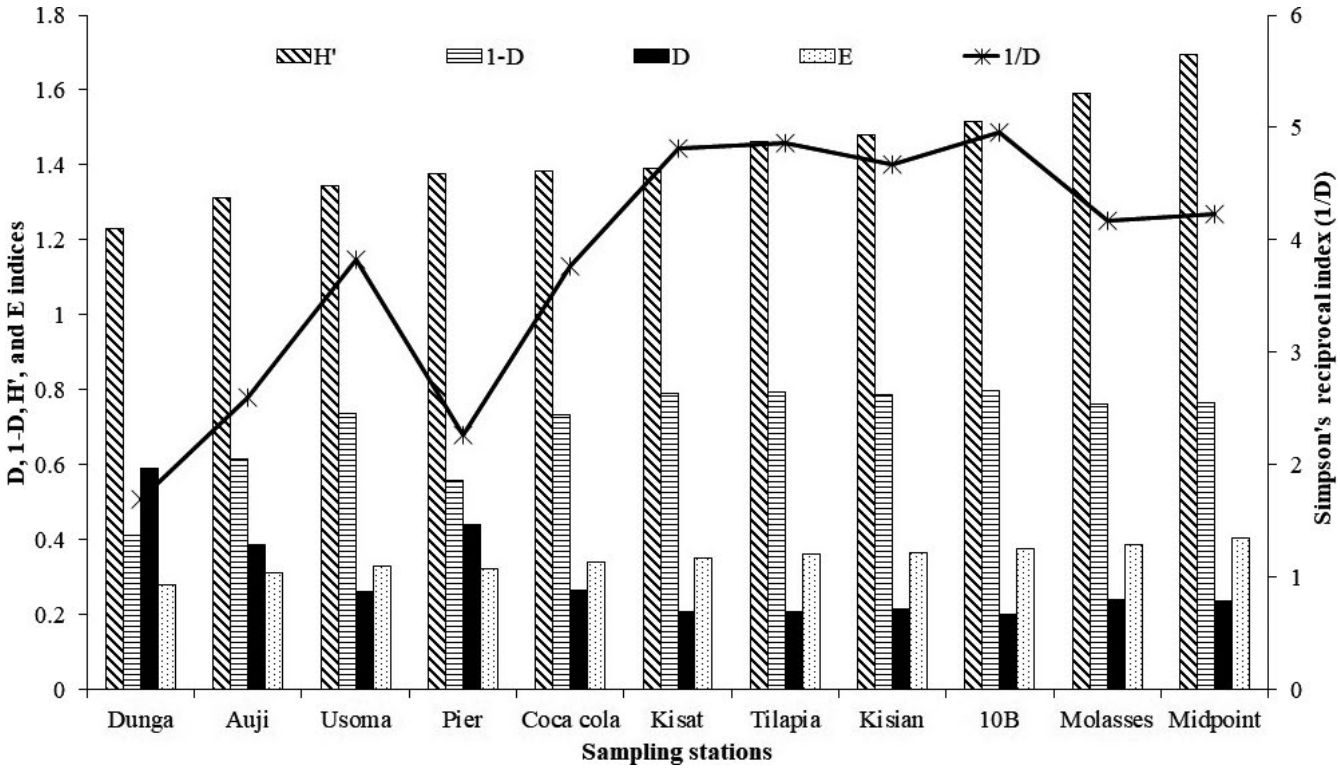

FIGURE 6 Phytoplankton Shannon-Wiener diversity (H′), Simpson's index (D), Simpson's reciprocal index (1/D), Simpson's diversity index (1-D) and Pielou's index of evenness (E) for Kisumu Bay

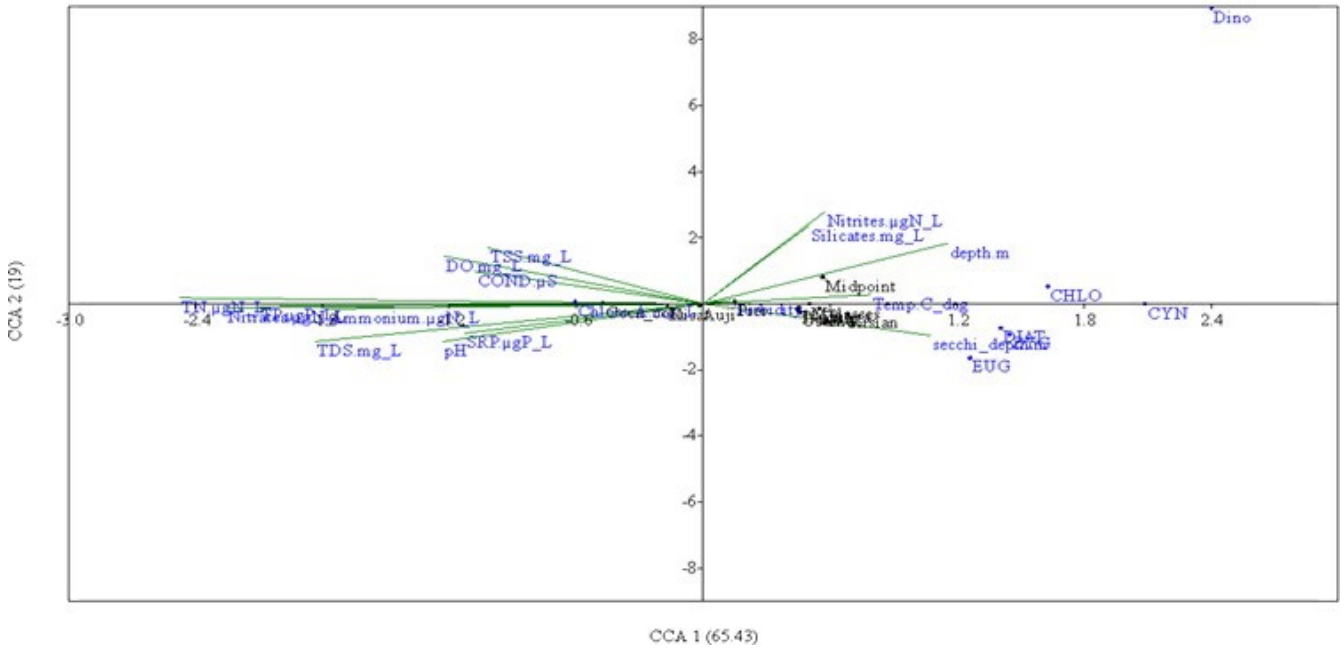

FIGURE 7 (a) Non-metric multidimensional scaling (NMDS) ordination plots showing spatial ordination of sampling (small circles) plots (stress value of 1st and 2nd dimension = 0.0834; NMDS plot based on abundance of major phytoplankton taxa (+ sign) with fitted environmental variables; arrow indicates direction and strength of key environmental variables; Chlo, Chlorophyceae; Cyn, Cyanophyceae; Diat, Bacillariophyceae (diatoms); Dino, Dinophyceae; Eug, Euglenophyceae; Zyg, Zygnematophyceae); (b) NMDS plot showing hull and 95% ellipse of sampling sites based on same variable)

The high turbidity levels at the Pier sampling site can be attributed to high algal productivity and the concentration of mineral ions. This could also lead to proliferation of cyanobacteria, especially *Microcystis* and *Anabaena* spp., which are known for their efficiency in fixing nitrogen from the atmosphere for photosynthesis via their specialized heterocyst cells. This type of algae has vacuoles in their cells that enable them to maintain buoyancy in the water column, therefore being capable of positioning themselves at depths exhibiting optimal photic conditions for photosynthesis. Eutrophic waterbodies are characterized by high nutrient levels, particularly nitrogen and phosphates, under favour the domination by blue-green algae. Similar observations were made in the Gulf, whereby total nitrogen and total nitrite concentrations were high, and a rich community of cyanophytes algae (*Microcystis* spp.; *anabaena* spp.; *Merismopedia* spp.; and *Planktolyngbya* spp.) was prominent. The TN concentration exhibited a highly significant correlation with the chlorophyll-*a* concentration and the Secchi depth over the entire sampling period. Algal communities are highly enriched in nitrogen compounds because of their high protein (which accounts for much of the N) and lipid contents. Thus, the high nitrogen content in the water column is mainly organic nitrogen derived from algae. The cyanobacteria actively extract nitrogen from the water column, leading to the significant correlation between NO_2-N and chlorophyll-*a* concentration observed in the present study. Due to the altered TN:TP ratio from the normal 16:1 observed in the present study (spatial mean range of 11–26), both the chlorophyll-*a* concentrations and cyanobacteria abundance were higher. The higher TN:TP concentrations observed at the Midpoint and Auji sites could be attributed to nutrient-rich effluents emanating from phosphate and nitrate fertilizers used in agricultural farms in the neighbourhood. Horizontal transects towards the open lake from the entire Nyanza Gulf exhibited found similar trends in TN:TP and total dissolved N and P ratios, respectively. High values existed in the gulf (20.6), while levels around the Rusinga Channel and open lake ranged from 13.3 to 19.9 (Gikuma-Njuru et al., 2013). Studies by Wetzel (1983), Sitoki et al. (2012) and Babu et al. (2015) have indicated that rich algal communities develop in waterbodies containing high nutrient concentrations particularly phosphates and nitrates. According to Reynolds (2006) functional classification, *Microcystis* tolerates low total light availability and high temperatures, and also inhabits shallow, daily mixed layers of eutrophic lakes, forming surface algal blooms. Cyanobacteria do develop cells that are lysed and some cyanobacteria species can produce toxins during certain periods (Schatz and McCauley, 2007). Similar observations occurred in the present study, in which dense algal blooms, constituting *Microcystis* spp. and *Anabaena spp*., were capable of producing toxins. Thus, the nature and health of aquatic communities is an expression of the limnological status of a waterbody. High light intensity areas can result in high photosynthetic activity that increase primary production, in agreement with the findings of earlier studies (Gichuki, 2000; Hecky, 1993; Lung'ayia et al., 2000; Mugidde, 1993). High silica levels were observed in the bay, the maxima being reports for the offshore Midpoint sampling site, also being significantly and negatively correlated with total water depth and positively associated with the Secchi depth. This finding was

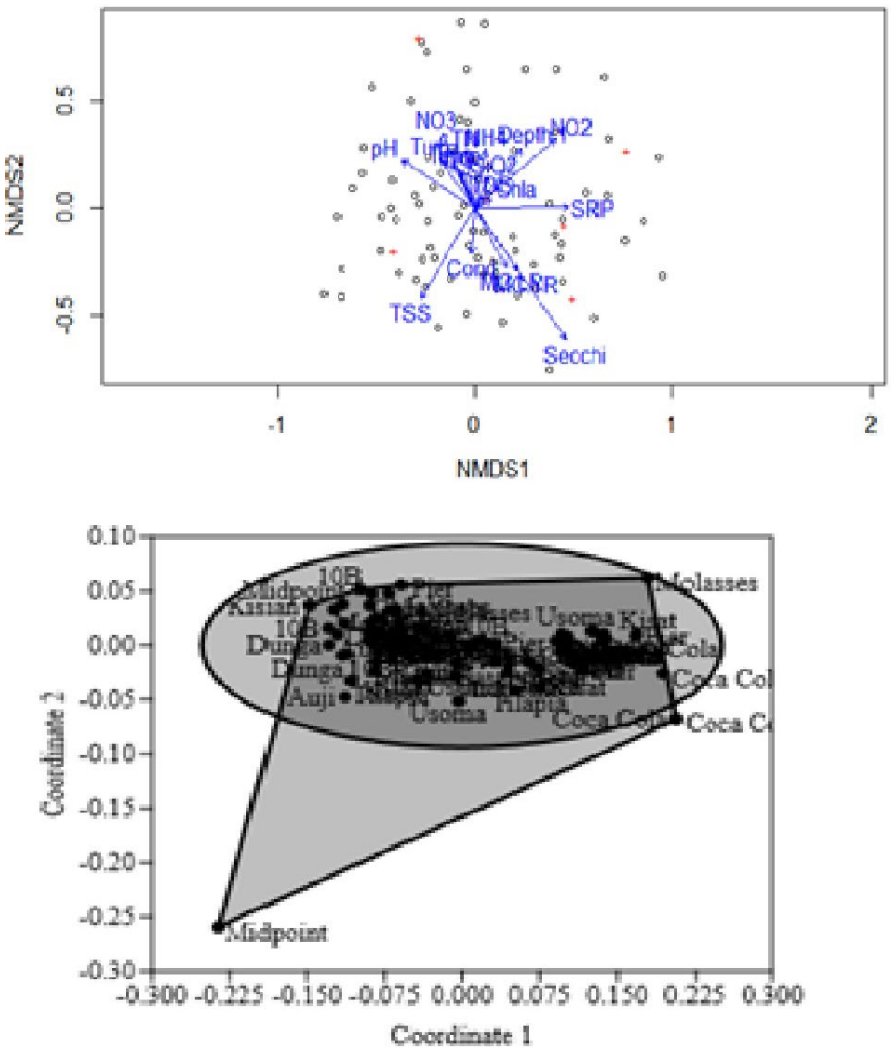

FIGURE 8 Relationships between phytoplankton taxa and environmental variables based on canonical correspondence analysis (CCA) (arrow indicates direction (correlation) and strength (length) of key environmental variables to phytoplankton taxa among sampling sites; Chlo, Chlorophyceae; Cyn, Cyanophyceae; Diat, Bacillariophyceae (diatoms); Dino, Dinophyceae; Eug, Euglenophyceae; Zyg, Zygnematophyceae)

TABLE 6 Spatial distribution of means of algal toxins (μg/L) in Kisumu Bay, Lake Victoria

	Toxins				
Sample site	**MC-LR**	**MC-YR**	**MC-LA**	**DmLR**	**MC-RR**
Kisian	0.437 ± 0.36	0.233 ± 0.25	0.076 ± 0.11	0.017 ± 0.03	0.008 ± 0.01
Molasses	0.521 ± 0.35	0.220 ± 0.21	0.061 ± 0.09	0.026 ± 0.03	0.002 ± 0.004
Usoma	0.256 ± 0.22	0.077 ± 0.11	0.040 ± 0.06	0.009 ± 0.01	0.005 ± 0.01
Coca Cola	2.836 ± 4.76	2.214 ± 4.08	0.333 ± 0.63	0.173 ± 0.34	0.033 ± 0.05
Pier	1.780 ± 1.87	1.541 ± 2.12	0.199 ± 0.33	0.090 ± 0.12	0.087 ± 0.14
Kisat	0.357 ± 0.50	0.135 ± 0.17	0.041 ± 0.05	0.019 ± 0.03	0.011 ± 0.01
Tilapia	0.309 ± 0.40	0.158 ± 0.22	0.044 ± 0.06	0.016 ± 0.03	0.013 ± 0.02
Auji	0.321 ± 0.34	0.100 ± 0.12	0.024 ± 0.04	0.020 ± 0.04	0.009 ± 0.01
10B	0.250 ± 0.27	0.102 ± 0.16	0.022 ± 0.04	0.008 ± 0.01	0.003 ± 0.004
Dunga	0.262 ± 0.30	0.125 ± 0.11	0.041 ± 0.07	0.009 ± 0.02	0.002 ± 0.01
Midpoint	1.44 ± 2.71	1.61 ± 2.66	0.146 ± 0.34	0.049 ± 0.12	0.012 ± 0.03

attributed to the external influx and presence of high suspended solids levels, as reflected in high turbidity levels that limit light penetration and algal production. Offshore areas experience more settling out, and less frequent resuspension, of bottom sediments compared to the shallower inshore bay areas. Chlorophytes revealed a low, but significant, negative association with the dissolved Si concentration. There were no significant differences, however, observed between the sampling sites, which could probably be associated

with the presence of diatoms, which exhibit increased Si uptake and utilization, and cyanophytes at most of the sampling sites. Seasonal succession of diatoms and their higher abundances in the dry season also was reported by Sitoki et al. (2012), with a significantly higher species diversity observed in the dry than in the wet season (2009), and a gradual increased abundance and diversity of Chrococcales and Zygnematophyceae from January to September 2009.

Studies by Sitoki et al. (2012) in Kisumu Bay highlighted nutrient concentrations have escalated, compared to previous periods. The total nitrogen (TN) concentrations have risen nearly sixfold due to particulate N and nitrogen embedded in the algal biomass. TN has increased from 983 to 1356 μg/L from 2000 to 2009), compared to a current lower level of 1081 μg/L (overall mean in the bay), although the available inorganic N pool may be relatively small (representing only about 4%–9% of total N) and imply a significant unavailability of N as organic N, which possibly explains the observed N-limited conditions, and marked nitrate losses through denitrification. Chlorophyll-*a* concentrations within the gulf were previously above 10 mg/L, although a higher mean concentration was observed in the bay. Wetzel (1983) highlighted that the health of aquatic communities is an expression of the limnological status of the waterbody in which they are located. High light intensity areas can facilitate high photosynthetic activity and increase primary production, (Gichuki, 2000; Hecky, 1993; Lung'ayia et al., 2000; Mugidde, 1993). The waters within the gulf are turbid and contain lower chlorophyll-*a* concentrations. The peripheral areas at the Kisat and Molasses sites are more enriched in chlorophyll-*a* than the mid-gulf. High chlorophyll-*a* concentrations observed at the peripheral sampling sites resulted from the diffusion of the remobilized nutrients within the turbulent areas.

The dominance of cyanophytes and diatoms in Kisumu Bay was attributable to a direct supply of nutrients from agricultural lands, the city's wastewater treatment works, and runoff, all encouraging their growth. The significance of the presence of euglenophytes in the samples can be attributed to organic pollution since these organisms are known to remain in polluted waters. The differences in the algal community structure at the river mouths and in the bay can be attributed to the dilution effect of the slightly cleaner water from the rivers. Thus, there were pockets of other algal groups (chlorophytes; diatoms; and Zygnematophyceae) at the river mouths. The situation was different in the bay, in which cyanophytes were dominant. Sewage discharges and semi-treated sewage effluents and organic matter input in runoff from the city of Kisumu are likely factors. The observed abundance of diatoms at the river mouth sampling sites could be due the high concentration of soluble reactive silicates (SRSi) measured there. Silicates are an important component in the structure of diatom frustules, therefore being critical for the growth of diatoms. The dominance of cyanobacteria in the algal community structure of the bay is an indication of its eutrophication status (Wetzel & Likens, 1991, 2000). Thus, the present study supports the observation that the nature and health of an aquatic community is an expression of the limnological status of its respective waterbody.

The low Secchi depth measured at the river mouth sampling sites was largely attributed to the presence of particulate organic and inorganic matter (TSS) from the catchment via the river. The high TSS concentration in water samples from the river mouth sites could have attenuated the sunlight in the water column, thereby resulting in low Secchi depth measurements. The low Chlorophyceae abundance observed in the bay concurs with observation of Lung'ayia et al. (2000). The environmental variables explained about 65% of the phytoplankton taxa composition between sampling sites, with significant correlations between dominant taxa and the surface water variables. Silicates and nitrites were correlated with dinophytes, whereas the surface water temperature was associated with chlorophytes at the deeper sampling site (Midpoint). Diatoms (zygnematophyceae; cyanobacteria; and euglenophytes) were associated with higher Secchi depths (Figure 7). The shallow sampling sites are in close proximity, and exposed to similar influences, especially stormwater and surface runoff and effluent discharges from the expanding urban areas around Kisumu. The midpoint site is located further offshore and is deeper, as clearly indicated by a non-metric multidimensional scaling (NMDS) ordination plot showing the hull and 95% ellipse of the sampling site based on the same variables (Figure 8a,b).

With development of new methods and analytical protocols for monitoring cyanotoxins in water (Triantis et al., 2010), lower detection limits for MCs are possible. *Microcystis* spp. and *Anabaena* spp. were the dominating phytoplankton in Kisumu Bay in the present study, known to produce the powerful neurotoxins microcystin and anacystins, respectively. These toxins can cause serious illness or death in domestic animals, wildlife and other aquatic organisms (Falconer et al., 1999). In the present study, however, only Microcystins were observed, believed to be due to the limitation of the reagents that can be used to detect other toxins. Thus, there is an information gap regarding the other toxins, indicating they may also be present in Kisumu Bay, but have not yet been identified. The observed changing of algal composition in the bay from time to time also suggests changes in algal toxin production from time to time, although this possibility still needs to be established. Other studies have demonstrated that a variable abundance of MC-producing genotypes versus non-MC-producing genotypes in natural populations is a key factor influencing overall MC net production in algal blooms (Kurmayer et al., 2003). Recent studies (Lungayia et al., 2001; Muggide, 1993) have reported a shift in phytoplankton species composition from a moderate mix of diatoms, greens and blue-greens to the predominantly bloom-forming and nitrogen-fixing cyanobacteria. Massive fish kills in the Nyanza Gulf of Lake Victoria have been associated with algal blooms (Ochumba, 1990) and might partly be attributable to the excretion of toxic substances by cyanobacteria. This phenomenon is thought to be a consequence of eutrophication, causing excessive growth of the noxious algae and its predominance over other groups. High nutrient enrichment, especially in inshore areas, has been reported by Lungayia et al. (2001) and Ochumba and Kibaara (1989) as the principal cause of the persistent high algal blooms. Similar occurrences and persistence of massive algal blooms

in Kisumu Bay in 2004 resulted in foul smells in the air within the city and in piped drinking water that forced the closure of the water treatment works for several days. Exposure to cyanobacterial toxins via drinking water is a major concern for human health since they may induce both acute and chronic effects. A recent case in Embu, Kenya, wherein hundreds of children died after drinking insufficiently treated water from a river containing cyanobacteria blooms highlights the seriousness of the problem (Codd et al., 2005). The ample evidence of toxic effects from recreational exposure to cyanotoxins attests to a need to establish recreational water guidance/action levels based upon the relative probability of acute health effects, noting cyanobacteria cell density and abundance, being less than 10 μg/L and <20,000 cyanobacteria cells/ml, respectively, represent a low acute health effect (WHO, 2017). Several unmonitored surface water sources should be prioritized for cyanotoxin monitoring juxtaposition with the development of suitable and simple methods for removal of algal toxins in drinking water sources.

4.2 | Water hyacinth impacts on phytoplankton and water quality

Initial water hyacinth infestations in the Winam Gulf between 1990 and 1994 were estimated to cover between 50 and 100 ha (Ochiel et al., 2000), although the most recent estimated coverage is about 5000 ha (Ongore et al., 2018). Previous and ongoing studies on their distribution and quantification (Ouma et al., 2005, Ongore et al., 2018) confirm their cyclic patterns of appearance and horizontal shifting around the bays of the Winam Gulf, with the weed exhibiting a prolonged coverage of Kisumu Bay at different infestation periods. During the present study, however, continuous Landsat-8 satellite coverage data were not available because of cloud cover over the present study area. The estimated mat coverage was between 644 and 1224 ha around bays in the Winam Gulf (mainly Nyakach and Osodo bays) in September 2017 to November 2017. In addition to the socio-economic effects of the water hyacinth (Albright et al., 2004; Ochiel et al., 2000; Villamagna and Murphy, 2010), varied and significant ecological effects also have been reported in diverse aquatic habitats as a result of the changes in surface and underwater environmental conditions (Bicudo et al., 2007; Brendonck et al., 2003; Masifwa et al., 2001; Ofulla et al., 2010; Rommens et al., 2003; Wang & Yan, 2017). Water hyacinth typically forms dense, interlocking mats because of its rapid reproductive rate and complex root structure (Mitchell, 1985). Biological control of water hyacinth by *Neochetina spp.* weevils reduces its buoyancy, causing the plants to sink to the bottom of the waterbody and decomposing (Wilson et al., 2007). Accordingly, surface water areas devoid of the floating water hyacinth and other associated macrophytes cover can experience improved DO concentrations. Additional effects could be attributable to horizontal shifts in interlocked mats and scattered plants, changes in available light and/or nutrients, and ongoing decay of plant material sinking to the bottom of the waterbody. Fish generally die when exposed to DO concentrations lower than 1.5 mg/L (Miranda et al., 2000) and can, therefore, result in limited habitat use (Chapman et al., 1995; Kramer, 1987). Factors affecting vertical water mixing (e.g. wind; temperature) can lower DO concentrations in bottom waters to anoxic levels (Njiru et al., 2012), which is stressful for sensitive fish species such as Nile perch and which has been attributed to some previous (Ochumba, 1990) and more recent fish kills observed in Lake Victoria. Although water hyacinth mats were dislodged out of the bay during the sampling procedure, residual patches and shoreline strands were still evident, an example being thick water hyacinth mats being observed heading to Kisumu Bay around June 2018 after termination of the present study field sampling activities. Although there were no clear relationships between the presence of water hyacinth mats and phytoplankton communities in Kisumu Bay due to frequent horizontal shifting and sinking of decaying plant matter, its persistence in the bay and other shallow lake hotspot zones within Winam Gulf are of concern since this situation could potentially result in changes in the phytoplankton, invertebrate and fish communities and the diversity of aquatic birds precipitated by prevailing environmental conditions and/or nutrient availability. This complex combination of interacting factors may seriously hinder prediction of specific location effects on phytoplankton species. Brendonck et al. (2003), however, reported that water hyacinth can trap phytoplankton and detritus, thereby increasing, at least temporarily, phytoplankton densities beneath the water hyacinth mats. Substantial increases in total phytoplankton and cyanobacteria biomass contributed to lost water clarity in a shallow Brazilian reservoir (Bicudo et al., 2007). The phytoplankton species in Kisumu Bay were characterized by spatial and temporal variations in composition and abundance. Cyanophyceae dominated the phytoplankton in both seasons and at sampling sites depicting the eutrophic status. There also were significant ($p < .05$) changes in the cyanobacterial biovolume between sampling months. The remaining phytoplankton taxa exhibited no significant ($p > .05$) variations between the sampling sites and months. Water hyacinth moderates surface water conditions via shading that reduces penetration, thereby also affecting photosynthesis. The high-water temperatures in the bay, which also receives nutrients from industrial and municipal effluents, may selectively and to unknown extents promote Cyanophyceae growth and dominance, which have a competitive edge over other species known to fix atmospheric nitrogen. Cyanophyceae have been frequently observed in the blooms formed in the bay. Additional studies in the future focusing on the timing of the weed infestation in the various bays will facilitate a better understanding of the specific effects of water hyacinth on phytoplankton communities (in water and epiphytes) during the reappearance of the floating macrophyte. This will both enrich taxonomic records data and provide base information on their diversity and habitat changes.

5 | CONCLUSIONS

The phytoplankton community comprising 125 species in the shallow sheltered Kisumu Bay water was found to be

dominated by Cyanophyceae (20 species), accounting for about 45% of the total abundance, followed by Chlorophyceae (41 species), Bacillariophyceae (38 species) and Dinophyceae (3 species). The least abundant taxa were Euglenophyceae (11 species) and Zygnematophyceae (15 species). The Cyanophyceae was dominated by *Microcystis* spp, *Anabaena* spp, *Planktolyngbya* spp. and *Aphanocapsa* spp. during the present study period.

Species biodiversity in Kisumu Bay was found to be moderate and are known to prevail in nutrient-rich lakes. The presence of Cyanophyceae and the high nutrient loads to the bay contribute to its eutrophication, which is further aggravated by frequent algal blooms. Further, the presence of *Microystis* spp. and *Anabaena* spp., known for fixing nitrogen from the atmosphere, adds to the TN burden and facilitates production of algal toxins. There were five different types of identified microcystin, including MC-LR, MC-YR, MC-LA, dmLR and MC – RR. The WHO drinking water guideline value of 1 μg/L for MC-LR was exceeded at only three sites, reaching up to 2.84 μg/L. The probability of acute health effects from recreational exposure, however, is established at levels exceeding 20 μg/L, with over 100,000 cyanobacterial cells/ml. The significant correlations between the phytoplankton community structure and environmental variables observed in the present study confirm that microcystins can be effectively utilized to assess the water quality of the bay.

It is clear that the pattern of changes in the physical–chemical variables in Kisumu Bay is highly unpredictable because of its shallow mean depth, high nutrient and pollutant loads, and regular wind-induced water mixing. This situation encourages the development of algal biomass, leading to the formation of algal blooms and the production of lethal toxins. The N:P ratio in Kisumu Bay differs from the normal 16:1 value. This is attributable to nutrient enrichment mainly from Kisumu sewage and runoff effluents, and from anthropogenic activities mainly comprising agricultural and industrial activities in the surrounding catchments. The aforementioned factors enhance the cultural eutrophication of Kisumu Bay, although other toxins might also be produced in addition to microcystin.

The results of the present study enhance the need for further detailed research studies directed to algal species identification on the basis of molecular and genetic techniques. Such findings also should be confirmed by careful algal identification based on their morphological characteristics. There also is a need to model algal blooms based on the results of previous studies as needed input for future scenario predictions. Further research also is needed on temporal and spatial variations in phytoplankton diversity, algal toxin concentrations and harmful algal blooms (HABs) and their impacts on aquatic and terrestrial organisms. It is important to assess human exposure risks as well that are attributable to algal toxins, as well as the associated social economic impacts, and available remediation measures. Studies on specific interactions between phytoplankton and water hyacinth mats also can enhance information and taxonomic base data regarding the gulf. Finally, riparian communities should be advised not to use lake water during algal blooms in order to reduce the risks of intoxication with microcystin and/or other algal toxins.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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