SPATIAL VARIATION IN WATER QUALITY, NUTRIENTS AND HEAVY METAL BIOACCUMULATION IN NILE TILAPIA, *Oreochromis Niloticus* (L.) IN FISH CAGE SITES AND OPEN WATERS OF USENGE, LAKE VICTORIA, KENYA

BY

ADINO EDWARD ODWORI

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN ENVIRONMENTAL SCIENCE

SCHOOL OF AGRICULTURE, FOOD SECURITY & ENVIRONMENTAL SCIENCES

MASENO UNIVERSITY

DECLARATION

Declaration by the Candidate

I certify that this thesis is my original work and has not been submitted for any academic award in any other institution; and shall not be reproduced in part or in full, or in any format without prior written permission from the author and/or Maseno University.

Sign ……………………………..……………Date……………………………….…………….

Edward Odwori Adino

MSC/NS/00142/2015.

Declaration by Supervisors

This thesis has been submitted for examination with our approval as university supervisors.

Sign ……………………………..……………Date……………………………….…………….

Dr. Paul O. Abuom (Ph.D.)

Department of Environmental Science

Maseno University.

Sign ……………………………..……………Date……………………………….…………….

Dr. Emmanuel Shikanga (Ph.D.)

Department of Chemistry

Maseno University

ACKNOWLEDGEMENT

I first thank God for giving me strength to pursue my Master's degree and Maseno University which gave me an opportunity to study. I express my sincere thanks to my supervisors, Dr. Paul Abuom and Dr. Emmanuel Shikanga for their guidance and supervision in making this study complete. Thanks also go to the respondents from the selected fish cages and fish cage farmers in Usenge, Siaya County. My special thanks to Lake Victoria Environmental Management (LVEMP) and Safe Water and Aids Project (SWAP) as well as laboratory technicians in Maseno University for their assistance during data collection and analysis respectively. Lastly, I thank my wife Maureen, my children, Sessly, Ryan, Myral and Hudson for their understanding and patience and my parents for their day-to-day encouragement.

DEDICATION

I dedicate this thesis to God for granting me the strength and resilience to conduct this research. I equally dedicate this work to all those who have in one way or the other contributed to my success in this project especially my dear wife, Mrs. Maureen Achieng Odwori and my children. In a particular way, I dedicate this thesis to the honor of my mother whose academic path has impacted much on me especially through her dedication to academic excellence.

ABSTRACT

Fish cage farming is an aquaculture production system involving the holding of fish in floating net pens and was introduced in Lake Victoria to improve fish production due to diminishing stocks and subsequent increase in demand. The lake has experienced a decrease in water quality recently resulting from increased anthropogenic activities. Emerging fish cage farming in the lake may be contributing to alteration of water physico-chemical parameters, nutrient levels and high concentration of heavy metals in water and bioaccumulation in fish. The information on spatial variations of water quality, nutrients and bioaccumulation of heavy metals in fish cage sites and open waters in Lake Victoria and particularly in Usenge area is a critical environmental issue. This study's main objective was to determine the spatial variation in water quality, nutrients and heavy metal bioaccumulation in Nile Tilapia (*Oreochromis niloticus* L.) in fish cage sites and open waters of Lake Victoria in Usenge area. The specific objectives were; to assess the spatial variations in water physico-chemical parameters (temp, turbidity, conductivity, dissolved oxygen and biological oxygen demand) within the fish cages and open waters, investigate the spatial variations of levels of nutrients (nitrates and phosphates) and selected heavy metals (Pb, Fe, Cd, Zn and Cu) within the fish cages and open waters and investigate the level of bioaccumulation of selected heavy metals in gills of *O. niloticus* fish obtained from the fish cages and open waters in the waters. A quasi experimental design was adopted in which water and fish samples were collected from selected sites within fish cages and open waters and analyzed. Physico-chemical parameters were analysed *in situ* while the heavy metals were analysed using atomic absorption spectroscopy. One-way analysis of variance (ANOVA) was performed to check the variations and associations within and between variables. Only DO, pH, Fe and Cu ($p<0.05$) varied significantly between fish cage sites and open waters sites. The levels of pH, DO, conductivity, phosphates, Fe and Cu showed variations in the different directions from the cages where water samples were collected. Both Cu and Fe were higher in fish obtained from the open waters than the fish cage sites and also varied in the different directions from the center of the cage. Turbidity, total nitrates, total phosphate and Cd were beyond acceptable limit for portable water in accordance to WHO and USEPA. The findings revealed that tilapia cage farming studied did not have any significant impact on the lake water quality and nutrients nor did it contribute to heavy metal bioaccumulation in water and in fish in the cages and open waters except turbidity and phosphate levels. The findings of this study are important for policymakers in setting guidelines for effective cage culture system management to protect lake waters and for safe fish human consumption. It is therefore, recommended that regular water quality monitoring be done for appropriate management interventions.

TABLE OF CONTENTS

LIST OF ACRONYMS

AAS	Atomic Absorption Spectroscopy
ANOVA	Analysis of Variance
AR	Analytical reagent
BMUs	Beach Management Unit
BOD	Biological Oxygen Demand
DO	Dissolved Oxygen
EC	Electrical Conductivity
EMCA	Environmental Management and Coordination Act
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
GoK	Government of Kenya
GPS	Global Positioning System
KEBS	Kenya Bureau of Standards
KMFRI	Kenya Marine and Fisheries Research Institute
LVEMP	Lake Victoria Environmental Management Project
MCL	Maximum Contaminant Level
NGO	Non-Governmental Organization
NAS	National Academy of Sciences
NTU	Nephelometric Turbidity Unit
SPSS	Statistical Package for Social Science
SWAP	Safe Water & Aids Project
TDS	Total Dissolved Solids

TSS	Total Suspended Solids
UNDP	United Nations Development Programme
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme
USEPA	United States Environmental Protection Agency
UV/Vis	Ultra Violet/visible
WHO	World Health Organization
WRA	Water Resources Authority
WRC	Water Research Centre

WORKING DEFINITIONS

Aquaculture: refers to the rearing of aquatic animals or the cultivation of aquatic plants for food.

Bioaccumulation: refers to the process through which certain toxic substances (such as heavy metals and polychlorinated biphenyls) accumulate and keep on accumulating in living organisms such as fish, posing a threat to health, life, and to the environment.

Cage Fish farming: refers to an aquaculture production system in which fish are held in floating net pens and utilizes existing water resources. In this system, the fish is enclosed in a cage or basket thus allowing water to pass freely between the fish and the lake (natural water body) permitting water exchange and waste removal into the surrounding water.

Cage: is a system that confines the fish or shellfish in a mesh enclosure. It is also called net pen.

Control point: refers to the open water in the lake where the fish cages is not installed.

Tilapia: An African freshwater cichlid fish that has been widely introduced to many areas for food.

Treatment point: refers to the section of the lake where fish cages containing Tilapia has been installed.

Water quality: refers to the chemical, physical, biological, and radiological characteristics of water. It is a measure of the condition of water relative to the requirements of one or more biotic species and or to any human need or purpose.

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

1.1 Background to the study

Water is one of the most crucial natural resources for sustaining life and the wellbeing of ecosystems. Despite the fact that water covers nearly 70% of the earth's surface, two-thirds of the world's population, or 4.0 billion people, endure catastrophic water events every year (Mekonnen and Hoekstra, 2016). According to earlier studies (Hoekstra *et al*., 2012; Wada *et al*., 2011), the number was between 1.7 and 3.1 billion. This shows that the situation is worse than past studies revealed. Only 0.5% of the earth's surface water is considered fresh and potable, and it primarily originates from streams, rivers, and freshwater lakes, which is the cause of this water scarcity. The availability of this fresh water is further limited by increased pollutant load into water sources from the catchment areas thus rendering most of that available fresh water unsuitable for users (Mishra *et.al*. 2023). An exponential increasing in population growth rates has triggered a rise in anthropogenic activities such as agriculture and urbanization subsequently exerting immense pressure on natural water resources like rivers and lakes with significant negative effects on water quality (Nassali *et al*., 2020). Most water pollutants emanate from agricultural, domestic and resource exploitation activities like logging (Ogidi and Akpan, 2022).

The fastest-growing industry for producing animals worldwide is aquaculture, which is commonly regarded as having a significant impact on closing the expanding gap between fish demand and supply (FAO, 2014, 2016). Fish cage farming has also been linked to severe water quality problems in the recent past (Memet, 2019). The fastest-growing industry for producing animals worldwide is aquaculture, which is commonly regarded as having a significant impact on closing the expanding gap between fish production and supply (FAO, 2014, 2016). An important method of aquaculture production that dates back many centuries to China is fish cage farming (Yu, *et al*., 2023). The first fish to be domesticated was a species of fish called the common carp (*Cyprinus carpio*), which is indigenous to China (Xu, *et al*., 2020). Later, cage culture spread around the globe, with significant producers including China, Japan, Chile, Indonesia, Vietnam, Canada, Turkey, Greece, and the Philippines (Njiru, *et al*., 2019). The common carp (*Cyprinus carpio*), which was first cultivated, is a species of fish that is native to China (Wang *et al*., 2022). While this technology is on an upward trajectory and is being taken up rapidly in recent times, especially in developing countries, the direct impact of the fish cage culture activities on the spatial water quality variations remains unknown and the little information available is scanty and to a large extent fragmented.

After the 1930s, when Africa's cage culture first emerged, large levels of production were produced in Ghana, Cote d'Ivoire, Malawi, Uganda, and Zimbabwe (Curnow, 2021). The principal focus of sub-Saharan Africa's contribution to fish output through aquaculture is the culture of the tilapia *Oreochromis niloticus (L.)* (Lubembe *et al*., 2022). Tilapia is the preferred culture species because to its quick growth, disease resistance, and tolerance of low dissolved oxygen (DO) levels (Fitzsimmons, 2016). In order to provide rural poor households with food security, money, and work, aquaculture was originally developed in Sub-Saharan Africa in the 1950s (Akegbejo-Samsons, 2022).In Ghana for instance, fish farming started in 1953 by the former Department of Fisheries (Agyei, B. P. (2022). In order to help the colonial administration's program for developing reservoir fisheries during the time, they served as hatcheries. In order to cultivate fish for the country's irrigation systems, the Ghanaian government developed a plan in 1957 (Miescher, 2021). The early 1980s saw an increase after the government launched a nationwide campaign. In the 1970s, tilapia cultivation in rice fields was used as a test bed for aquaculture in the Gambia (Romana-Eguia et al.,2020). By 1988, Scan Gambia Limited was operating two fish farms in the western region in a manner similar to this (Jallow, 2009). Between 1982 and 1985, the number of fish ponds increased from 578 to 1,390 (Anand *et al.*, 2020). Amisah and Quagrainie (2007) report that with an average surface area of 685 m^2, the number gradually climbed to 1,400 in 1986.

Scholarly interest has been greatly sparked by the advantage cage culture has over other aquaculture methods. Udayanga *et al*.,(2019) observed that cage culture allowed for better predation control, while Mwamburi, *et al*.,(2021) opines that cage culture is a viable alternative to traditional fish rearing techniques. After reviewing earlier research on cage farming, EL Sayed (2006) reported extremely high production per water volume, high profitability potential, relatively low investment per production unit, ease of movement and relocation, reduced effects of drought on production relative to water availability, and overall management flexibility. Additionally, Orina (2018) reaffirmed the idea of high potential for profit, which he linked to the growing acceptance of cage culture. According to EL Sayed's (2006) review of earlier research on cage farming, there is a very high production per water volume, high profitability potential, relatively low investment per production unit, ease of movement and relocation, reduced effects of drought on production relative to water availability, and overall management flexibility. Tidwe (2017) also mentioned a very high production per water volume, a significant potential for profitability, and a very low investment per production unit.

According to Asmah *et al*. (2014), boosting the yearly fish supply from 6.2 to 9.3 million tonnes will help reduce demand. Based simply on the Sub-Saharan African region's 2010 annual average production, Ahmad *et al*., (2021) said, aquaculture will be needed for more than 8.3% of the total tonnage. The FAO, UNDP, World Bank, and France all provided funding for projects in countries including Cameroon, Cote d'Ivoire, Kenya, Madagascar, and Zambia to help with this (Lazard *et al.* 1991). Additionally, numerous initiatives combining fish/shrimp and rice have been implemented in some West African nations as the Gambia, Senegal, and Guinea Bissau (Vasconcellos *et al*., 2018). Women in Senegal's Basse Cassamance region also participated in the customary fusion of rice and fish culture. Another instance of this practice was discovered in Gabon, where women would collect wild fingerling fish and put them in ponds that belonged to their husbands (Trottier, 1987). Additionally, fish producers in Gabon employ cage cultivation. The Fadamas of Sokoto state in Nigeria also frequently engaged in pond culture (Trottier, 1987).

African nations including Malawi, Côte d'Ivoire, Zimbabwe, Ghana, and Uganda have generated up to 6,000 tonnes of fish per year by building fish cages out of local materials and stocking them with local fish that are fed local feeds. Today, cage aquaculture technology is readily accessible to smallholder farmers in Africa including Kenya (Obiero *et al*., 2019). The technology includes local skills in fish stocking, feeding other than the cage-construction technology. However, there is limited information on spatial variations on water quality and heavy metal bioaccumulation in *O. niloticus* in fish cages and open waters and also in aquatic organisms – more so *O. niloticus* fish in Africa.

Fish cage farms have been built to increase fish output in Kenya, as they have in many other nations of the world due to dwindling fish catches and a rising need for protein. Kenya currently ranks fourth in Africa for aquaculture production, behind South Africa, Nigeria, and Egypt (Walakira *et al*., 2023). Around 2005, cage culture on the Kenyan side of Lake Victoria started, and in 2007, trials by the Dominion Group of Companies (US) in the Yala Swamp near the mouth of the Yala River started. The European Union's (EU) cage fish cultivation program, which began in bodies of water in the Lake Victoria Basin, provided backing for the project (Munguti *et al*., 2014). By 2008, cage culture trials were being conducted on Lake Victoria beaches (like Dunga) by the Fisheries Cooperative Societies under the Beach Management Units (BMUs) (Munguti *et al*., 2014).

The majority of Kenya's aquaculture fish production is made up of *Oreochromis niloticus,* also known as Nile tilapia (Figure 2.1) (Fisheries Department, 2012). According to Shaalan *et al*., (2018), the species has a long aquaculture history and has been raised in Egypt for almost 2,500 years. Typically, semi-intensive static ponds are used for production. The ideal water temperature for tilapia growth is between 20 and 35 °C. In eight months, a fish of this species can reach a weight of 500 g if it has access to enough food and is not allowed to reproduce uncontrollably. The diets of cultured tilapias include a variety of pellet, flakes, and mashed feeds (Ebeneezar *et al*., 2023), as well as formulated feeds made from fishmeal and cereal bran as well as garden waste and greens.

Figure 2.1. Image of *Oreochromis niloticus* (Nile Tilapia). *(*Adopted from Ngugi *et al.,* 2007*).*

In Lake Victoria, cages are either purchased from nearby businesses or constructed using the 15 mm multifilament stretched mesh netting that is normally employed in beach seine fishing (Brčić *et al*., 2023). Since deeper cages do not boost production due to reduced food provision in deep waters, shallow cages are typically preferred (Geitung *et al*., 2020). The net basket is then fastened to an oil drum- or plastic barrel-supported pipe frame that was initially supplied with paint or alcohol, both of which are easily accessible on the market, using nylon thread (FAO, 2002). Predation by birds is stopped by a cover placed on top of the cage (Otieno and Shidavi ,2022). Cages must be anchored in a depth of 8 to 10 meters. The fish cages in Usenge, Kenya's Lake Victoria span about four acres of the lake (Otieno, 2020).

Although the growth of cage culture has significantly increased the potential for fisheries production, it has also brought forth considerable environmental concerns and the possibility for sustainability (Orinda *et al*., 2021). Numerous researches have documented the detrimental effects of cage cultivation on the ecological front (Kolda et al., 2020; Tičina et al., 2020). Fish cage farming has been linked to an increase in dissolved nutrients brought on by uneaten fish meals, feces, and excretory secretions(White ,2021). Additionally, anoxic conditions in the sediments underneath fish farms have been connected to fish cage farming (Varol, 2019). Despite these effects, little is known about how fish cage farming impacts the spatial variation in physico-chemical parameters, dissolved nutrients, and heavy metals in lake water, as well as bioaccumulation in *O. niloticus* fish in Kenya and other third world countries.

According to Noori *et al*. (2019), Tibebe *et al*. (2019), and Varol (2020), high pollution levels in lake ecosystems may prevent people from using the water for recreational purposes including drinking, fishing, swimming, and taking a bath. The installation of fish cage farming in such water bodies necessitates routine monitoring of the lakes' water chemistry because numerous factors might cause the water quality in given water body to deteriorate (Keyombe and Waithaka, 2019). Studies demonstrate that both natural and anthropogenic causes have a significant impact on the physico-chemical water quality characteristics of every lake (Vasistha and Ganguly, 2020; Jain *et al*., 2022). Natural variables include, for instance, relief, precipitation, weathering, geology, inputs from the catchment and atmosphere, mixing of riverine freshwater from rivers and saline water, and climate fluctuation (Ontumbi, 2020).

Similar to agricultural runoff, fish cage farming is a substantial source of freshwater pollution and may have a considerable influence on aquatic ecosystems (Ioannidou and Stefanakis, 2020). The physical and chemical characteristics of freshwater lakes have changed significantly as a result, frequently demonstrating a perceptible transition from the state of clear water to that of turbidity (Huse *et al*., 2022). Thus, it is crucial to regularly determine how changes in physico-chemical parameters that affect water quality are affected by increased anthropogenic activity. Researchers have employed a range of physico-chemical measures to monitor and evaluate the state of a water body, including suspended particles, pH, electrical conductivity, temperature, dissolved oxygen, biological oxygen demand, and turbidity among others (Butt *et al*., 2021).

It has not been determined how variations in water quality physico-chemical parameters, dissolved nutrients, and heavy metals buildup in waters surrounding the fish cages in the Usenge area of Lake Victoria are affected by fish cage farming and related human activities. Additionally, it is yet unknown how the lake water currents around fish cages within the Lake affect periodic spatial changes in physico-chemical parameters, nutrients, and heavy metals. This is crucial because, as recently occurred in Lake Victoria, a sudden change in the physico-chemical characteristics of lake water, such as temperature and dissolved oxygen, can cause enormous fish kills and create significant financial losses for fish farmers. Few studies have attempted to illustrate the spatial variability in physico-chemical water quality parameters together with other parameters, such as dissolved nutrients and heavy metals in the lake following cage culture, despite the fact that some studies have been conducted to assess the status of Lake Victoria (Mawundu, (2024; Orina *et al*., 2018). In light of the growing cage culture production system, it was required to perform a thorough study to better understand the spatial fluctuations of physico-chemical water quality indicators in Lake Victoria. The findings will help us understand how the lake ecology reacts to expanded cage culture systems and, in the end, guide management plans.

While application of nitrogenous and phosphorous and nutrients through fish food pellets in fish cage farming is deemed necessary for improved fish yields, the unutilized nitrogenous and phosphorous and nutrients in such operations result in water pollution and lake eutrophication (Pailan *et al*., 2022). The contribution of surface water nitrogen contamination has increased since 1960, as widespread and intensive use of nitrogen expand rapidly globally (Bijay-Singh, 2018). Some of the effects of nitrogen pollution include; metheamoglobinanemia ("blue baby syndrome") in infants caused by ingestion of greater than 10mg/l of nitrites and nitrates combined (Fewtrell, 2004) and eutrophication, which leads to excessive algae growth that ultimately reduces dissolved oxygen levels in the water (Murdoch *et al.*, 2001) affecting the balance between physico-chemical parameters in lake waters.

Discharge from fish and fish cage farming activities can lead to increased nutrients load and heavy metal pollutants in aquatic systems (Varol, 2019). Fish excretion, manure and domestic waste contribute to organic pollution of water resources. Additionally, heavy metal residues in fish feed pellets frequently build up in the filament gills of fish over time (Boyd, 2018), providing a risk to even the fish eaters at the top of the food chain. Despite increased interest in fish cage farming in Lake Victoria, the spatial variations in quantities of nutrients load and heavy metals in the water around the fish cages and fish filament gills resulting from fish cage farming activities in Usenge area of Lake Victoria have not been established. In addition, studies on the spatial variations in nutrients and heavy metals caused by mixing of the waters around and within the fish cages with high influx freshwater from the rivers that discharge into that part of Lake Victoria likely contributes to dilution are scarce and largely fragmented in terms of the parameters evaluated. In addition, possible effect of fish feed remnants which sink and settle below the fish cages on the water quality within and around the fish cages at the Usenge area of Lake Victoria remains largely unknown. The buildup of nutrients leads to increased growth of aquatic organisms creating a high biological oxygen demand in aquatic systems. Similarly, an increase in temperature is likely to increase the metabolic activity of aquatic life resulting in high oxygen demand (Xie *et al*., 2020). This calls for studies on the spatial variations in dissolved nutrients around fish cages to ascertain the actual level of contribution of the cage culture to eutrophication of Lake Victoria waters, especially around Usenge area.

According to Masindi and Muedi (2018), heavy metals released into water, even in little amounts, can easily accumulate in the environment over time and are likely to change physico-chemical characteristics, enter the food chain, become harmful to aquatic life, and affect humans. Heavy metals cause limited survival, inhibit growth and cause abnormal movement patterns of aquatic plants and animals all of which alters the water quality parameters in the lake (Cai *et al*., 2018). At Usenge area of Lake Victoria waters, there is large scale fish cage farming and related human activities. Fish cage farming and fishing are the primary agricultural pursuits for roughly

62% of the smallholder farmers in Kenya's Lake Victoria Basin (Orina *et al.*, 2018). These activities involve the use of large quantities of nutrients through pellets used as fish food. However, the application of these nutrients through fish food pellets, to the fish cages on the lake may affect the water quality, nutrient loads and bioaccumulation of heavy metals in the body of fish (*O. niloticus*).

Regarding the potential effects of fish culture activities on the lake's water quality and consequent bioaccumulation of heavy metals in fish, there is little information currently available. The spatial changes in heavy metal contents in water and accumulation in fish samples within and outside of cages haven't been the subject of many investigations. The water and fish in the Usenge area of Lake Victoria may be considerably impacted by these sources in addition to fish cage activities that have been linked to heavy metal pollution of lakes in other places. In light of the little and disjointed information available on the subject, this study set out to determine the impacts of fish cage farming on water quality and heavy metal bioaccumulation in *(O. niloticus)* at Usenge, Lake Victoria Kenya.

1.2. Problem Statement

Numerous studies have reported deterioration of water quality in Lake Victoria due to discharges from numerous anthropogenic activities. Due to decreasing fish catches in the Kenyan Lake Victoria Basin and rising demand for fish protein, fish cage farming operations at Usenge, Lake Victoria, have continued to expand and intensify. Increased fish cage farming activities like use of commercial food pellets in fish cages and poor waste management may result in deterioration of water quality in terms of various water physico-chemical water quality parameters thus subsequently contribute to nutrient buildup and heavy metal problem pollutants' load into the water body and subsequent bioaccumulation in fish. The waters of Lake Victoria, especially the microclimate around the fish cages, are likely to present a significant environmental threat resulting from an expansion in cage farming combined with the lake's pollutant load from terrestrial sources. Additionally, the practice of raising fish in cages is likely to increase the chance that stratification may fail due the cage induced friction within the current velocities decreasing upward, it can also hinder horizontal water exchange leading to the upwelling of deoxygenated hypo limnetic water, which has the potential to kill fish as has been shown elsewhere. The environment may suffer if nitrogen and phosphorus buildup occurs in the sediments beneath the fish cages. Despite these, there is currently no information on how cage culture affects water quality in terms of physico-chemical parameters and heavy metal fluctuations in fish cages and nearby open waters in the Usenge area of Lake Victoria.

Most available artificial fish diets which are made up of insoluble dietary components release heavy metals in the lake which can in turn affect the growth of aquatic life and through bioaccumulation and biomagnifications, has the potential to reach higher order animals in the food chain (Noman *et al*., 2022). Despite this, the spatial variations in levels of toxic heavy metals in fish cages within Usenge area of Lake Victoria have not been established. The physico-chemical properties, nutritional levels, and heavy metal concentration in and surrounding Usenge's fish cages in Lake Victoria, on the other hand are yet unclear. In order to determine the spatial variation in water quality, nutrients, and heavy metal bioaccumulation in Nile Tilapia (Oreochromis niloticus (L) in fish cage sites and open waters of Usenge, Lake Victoria, Kenya, this study intended to establish the spatial variation in these variables.

1.3. Objectives of the Study

The main objective of the study was to determine the spatial variation in physicochemical water quality, nutrients and heavy metal bioaccumulation in Nile Tilapia (O*reochromis niloticus*) in fish cage sites and open waters of Usenge, Lake Victoria, Kenya.

1.3.1. Specific objectives

1. Assess the spatial variations in water physico-chemical parameters (pH, Temperature, Turbidity, Biological Oxygen Demand (BOD), Electro-conductivity (EC), dissolved oxygen (DO) between the comparable study between fish cage sites and open waters within Usenge area, Lake Victoria, Kenya.
2. Investigate the spatial variation levels of nutrients (total nitrates and total phosphates) between the fish cages and open waters in the waters of Usenge, Lake Victoria, Kenya.
3. Determine the spatial variation levels of selected heavy metals (Pb, Fe, Cd, Zn and Cu) in water between the fish cages and open waters in the waters of Usenge, Lake Victoria, Kenya.
4. Investigate the spatial variations in levels of bioaccumulation of selected heavy metals (Pb, Fe, Cd, Zn and Cu) in the fish filament gills from samples collected between the fish cages and open waters in the waters of Usenge, Lake Victoria, Kenya.

1.4 Hypothesis

- **H_o1**: There is no significant spatial variations in the water physicochemical parameters (pH, Temperature, Turbidity, Biological oxygen demand (BOD), Electro-conductivity (EC), Dissolved oxygen (DO) within the comparable study between fish cage sites and open waters within Usenge area, Lake Victoria, Kenya.

- **H$_o$2**: There are no significant spatial variation in the levels of nutrients (total nitrates and total phosphates) between the fish cages and open waters in the waters of Usenge, Lake Victoria, Kenya.

- **H$_o$3**: There are no significant spatial variation in the levels of selected heavy metals (Pb, Fe, Cd, Zn and Cu) in water between the fish cages and open waters in the waters of Usenge, Lake Victoria, Kenya.

- **H$_o$4**: There is no spatial variations in levels of bioaccumulation of selected heavy metals (Pb, Fe, Cd, Zn and Cu) in the fish filament gills from samples collected between the fish cages and open waters in the waters of Usenge, Lake Victoria, Kenya.

1.5 Justification and significance of the study

Water pollution and fluctuation in water quality poses a threat to the lives of people, animals and even plants and urgent solutions are required to curb the menace. Common dangers include chronic diseases like cancer, typhoid, dysentery, cholera, massive fish kills, artificial lack of water among others (Bashir *et al*., 2020). Because of their environmental durability, toxicity, and capacity to enter food chains, heavy metals like lead, iron, cadmium, zinc, and copper are considered to be major contaminants of aquatic ecosystems (Mitra *et al*., 2022). Due to home waste, industrial activity, and agricultural practices, the concentrations of heavy metals in Lake Victoria have risen. (Outa *et al*., 2020). Expensive measures are taken but occur after damage including loss of lives have occurred. Lake Victoria has always been considered to be relatively pristine and studies have shown that the lake is still in good health with respect to chemical parameters, except for some localized sites at the tributaries (McCartney, 2010). In recent times however, concentrations of some heavy metals like copper, zinc cadmium and lead especially in the sediments have been reported to be increasing (Outa *et al*., 2020).

With the projected annual population increase of 7% within the lake basin, and an increase in fishing at the rate of 55% over the last 14 years, the basin is under increasing pressure (Mati *et al.,* 2005). An increase in shallow fish cage farming practices within the lake exert additional pressure on the parameters of water quality physico-chemical, nutrients and heavy metal bioaccumulation that may be gradually causing spatial fluctuations in water quality. It is therefore necessary to determine the impact of fish cage farming practices on fluctuations of selected parameters in water and even fish *(O. niloticus)* obtained from this practice. The *Oreochromis niloticus,* often known as Nile tilapia, is a delicacy to humans and is noted for having a high bioaccumulation factor through the gills, or the degree to which contaminants from the water column are deposited into aquatic creatures (Das *et al*., 2017). The ideal species for these studies is O. niloticus, which is also among the most popular culture fish due to its tolerance to a variety of environmental conditions, ability to survive on a variety of natural foods and formulated feeds, high productivity over a short period of time, resistance to disease, and low input costs.

The results are important in informing the development of sustainable policy to control the possible deterioration and fluctuations of the water quality, which can negatively affect human and aquatic life. The results also add to the available knowledge on impact of aquaculture on spatial variations in water quality and bio accumulation of heavy metals.

1.6 Limitations and Scope of the Study

This study was limited by sample size and selection of samples, insufficient sample size for statistical analysis, lack of previous research studies on fish cage farming in Usenge area. Insufficient instruments for data collection, lack of modern techniques for data collection, time limitation and financial constraints.

CHAPTER TWO

LITERATURE REVIEW

2.1 Water Quality and Fish Cage Farming

Water quality management is a key ingredient in a successful fish cage farming. Most periods of poor growth, disease and parasite outbreaks, and fish kills can be traced to water quality problems. Water quality management is undoubtedly one of the most difficult problems facing cage farming (Araujo *et al*., 2022). Water quality problems are even more difficult to predict and to manage. Water quality in the fish cages should be kept at certain levels for optimal fish growth. Due to uncontrolled water quality fluctuations, cage culture may result in poor growth of fish, frequent disease and parasite outbreaks, resulting in fish deaths ((Araujo *et al*., 2022). Water quality management is therefore viewed as one of the most difficult challenges that most fish farmers face. A fish cage water depth of 1 meter is considered best for fish cage farming of tilapia, carps, and shrimps (FAO, 2012). Water quality physico-chemical fluctuations can be determined by evaluation of a number of water quality parameters, nutrients and heavy metals levels.

2.1.1 Physico-chemical properties

The environmental fate of aquatic organisms can be determined by its physico-chemical parameters (Pinheiro *et al*., 2022). Physico-chemical parameters include pH, temperature, turbidity, electrical conductivity, Biological oxygen demand (BOD) and dissolved oxygen. These parameters are affected differently by fish cage farming and are discussed in greater details in subsequent sub-sections.

2.1.1.1 pH

Water processes can be impacted by pH, which is a scale from 1 to 14 that measures acidity and alkalinity (Ontumbi, 2020). Different species thrive in a variety of pH levels. The usual pH range for fish in fresh water is between 5.0 and 9.0, but there are several exceptions, according to Vasistha and Ganguly (2020. Reproduction of fish may decrease when the pH is out of this range due to stress and physiological effects. When the pH is low, it increases the uptake of elements that may be toxic to aquatic animals and plants (Okereafor *et al*., 2020).It was reported that pH of between 6 to 9 is favorable to fish culture by Dauda, *et al*. (2019). According to studies, the decomposition of fish farm waste may result in a drop in pH in fish cages when dissolved oxygen levels are higher (Famoofo and Adeniyi, 2020). The pH may decrease as a result of waste deposits in fish cage farms, according to several researchers. Mawundu, (2024) noted higher pH values of Halali Lake between 7.8 and 8.8 during the summer and attributed this to an increase in higher levels of nutrients from agricultural wastes, photosynthetic activity, and the decomposition of matter already in the lake. Higher levels of pH were also from sewage and agricultural waste. According to Famoofo and Adeniyi, (2020), the decomposition of fish feeds and fish cage activities from fish breathing and excrement generate carbon dioxide that reacts with the water. According to Yee *et al*. (2012), lower pH levels result in low DO and high BOD because the breakdown of organic waste from fish meals requires a high oxygen intake. The researchers failed to determine the amount of nutrients generated by the fish feeds and compare the same with water quality parameters. This research has done so.

Because of the lower pH levels brought on by fish excretion and the breakdown of organic materials, there is less food available for higher species in the food chain because fewer fish are reproducing and growing. Due to this, fish cage culture experiences a reduced number of growth and invertebrates dwelling in the lake waters. Freshwater fish and invertebrates that live in lake waters depend on the proper pH range of 6 to 9. Extreme pH ranges of 4.0 to 10.0 are tolerated by some resistant fish species, however the eggs may hatch with malformed young (Brian *et al*., 2001). In Lake Victoria, contribution to high levels of carbon in the atmosphere which when combined with water leads to formation of acids that lower the pH of the waters with likely effect on cage culture. Moreover, the food pellets used in cage culture also have an effect on the pH.

2.1.1.2 Temperature.

Aquatic life depends on water temperature (Prakash, 2021). Temperature controls all aquaculture operations since it's a factor of fish production and growth. Fish deaths may occur at higher temperatures or at extremely low temperatures and fish growth is reduced (Islam *et al*., 2022). It was reported by Tandel, (2023) that the temperature of 26.06 ºC to 31.97 ºC was the ideal temperature for fish cage culture. Temperature also determines the amount of DO in the water. The cooler the water temperature, the more soluble oxygen becomes. When the temperature levels are low there is a decline in food consumption by aquatic animals and thus reduced fish growth. Aquatic animals will react to changes in water temperature. Thermal/temperature stress on aquatic organisms induce negative changes in their physiological and biochemical processes. The organism's response to thermal extremes varies among different aquatic organisms at metabolic, hormonal and immunological levels (Kazmi *et al*., 2022). Higher temperature, disrupts the molecular and genetic mechanisms of organisms, which leading toward abnormal individual performances (Kazmi *et al*., 2022). The negative biochemical responses (e.g., accumulation and release) significantly affect the organism's adaptation, fitness, growth and development, survivorship and reproduction activities (Kazmi *et al*., 2022). Furthermore, the thermal extremes can have profound implications on chemical toxicity to the aquatic organisms. Higher temperatures increases the rate of chemical contaminants uptake through increased metabolic and ventilation rate which subsequently boost the bioaccumulation of chemicals in the body tissues, ultimately leading to higher chemical toxicity (Borgå *et al.*, 2022). According to Mawundu, (2024), a fish cage cultivation (*Oreochromis niloticus*) system in a lake in Thailand maintained an average temperature of 21.38 ºC, while according to Zanatta *et al*. (2010), a fish cage farming system involving *Oreochromis niloticus* in a lake in Brazil maintained an average temperature of 21.38 ºC. (2010) Jiwyam (2012) for his part measured a temperature from fish cage cultivation in a lake in Thailand that was greater than the norm of 26.81ºC. Higher temperature causes an increase in their metabolic rate hence increasing the uptake of dissolved oxygen (DO). At the same time, elevated temperatures decrease solubility of gases such as oxygen in water (Garcia-Soto *et al*., 2021). Lakes temperature increases gradually since the sun makes the upper water warm gradually than the deeper waters. Monitoring the spatial fluctuations of dissolved oxygen in water around cage culture systems is thus important in ensuring that productivity remains optimum.

2.1.1.3 Turbidity

The presence of turbity is caused by suspended organic matter (Bright *et al*., 2020). Turbidity in water can cause toxins in water from particulate matter (Matsumura *et al*., 2005). Researchers have reported slightly higher turbidity levels around fish cage farm sites and attributed this to feed, fish faeces as well as fish excretions found in the fish cage farming sites. (Nyanti *et al*., 2012). Light penetration can be affected by high levels of turbidity therefore reducing the rate of phosynthesis of aquatic plants and therefore reducing diversity of aquatic life (WRC, 2003).

Organic compounds can be available in suspended solids and serve as carries especially when water soluble compounds are used on fish cage farming practices. Especially when water soluble compounds found in fish food pellets are used in fish aquaculture. The clarity of water is reduced by turbidity since the clarity of water is reduced through the water thus reducing the aquatic life of submerged plants. Heat is higher in turbid water since it heats up more rapidly increasing the total dissolved solids. Aquatic life will in turn be affected by lower or higher temperatures from fluctuations in turbidity. (Brian *et al*., 2001). In Usenge, fish cage farms turbidity levels may be high due to immense fish cage farming activities that may contribute to eutrophication. This study sought to find out if these fish cage farming activities influence the spatial fluctuations in levels of turbidity in water since the information on the spatial variations of turbidity in water in the fish cage sites and open waters in Usenge, Lake Victoria is limited.

2.1.1.4 Electrical conductivity

Conductivity is a measure of the ability of water to pass an electrical current. Conductivity in water is affected by the presence of inorganic dissolved solids such as chloride, nitrate, sulfate, and phosphate anions (ions that carry a negative charge) or sodium, magnesium, calcium, iron, and aluminum cations (ions that carry a positive charge)(Kumar *et al*., 2022). Organic compounds like oil, phenol, alcohol, and sugar do not conduct electrical current very well and therefore have a low conductivity when in water (Mo *et al*.,2022). Conductivity is also affected by temperature: the warmer the water, the higher the conductivity. For this reason, conductivity is reported as conductivity at 25 degrees Celsius (25 C) (Srivaro *et al*., 2021). Concentration of electrolytes in water can be determined by electrical conductivity (WHO, 1989). For most fresh waters, it ranges from 50 to 500 S/cm. Mineral water has an EC value of 100 S/cm, however industrial water might have an EC value of 10,000 S/cm or more (WHO, 2004). Electrical conductivity is influenced by temperature; the higher the temperature, the greater the electrical conductivity. As a result, it is stated to be 25 ºC. An EC range of 1.5 to 2.5 ds/m is suggested for fish cage farming. Increases in osmotic pressure reduce nutrient absorption the higher the EC measurement. Plant and yield are severely impacted by lower EC (Samarakoon *et al*., 2006). Fish cage farming activities could contribute to the electrical conductivity levels in Lake Victoria from the nutrients especially nitrates and phosphates that get into the waters. The study analyzed the EC levels to determine the spatial variations of the fish cage farming activities on water quality since there is limited information on the spatial variations in EC in the fish cage sites and open waters in Usenge, Lake Victoria

2.1.1.5 Biological Oxygen Demand

The amount of oxygen used in breaking down the wastes in micro-organisms is Biological oxygen demand. Chemical oxidation of inorganic matter is measured by BOD (Safitri *et al*.,2021). Water surface systems can be contributed water runoff from storm water that contributes to BOD. BOD in lake waters has a direct impact on the level of dissolved oxygen in the water. Oxygen is depleted in aquatic life when the BOD is higher (McCabe *et al*., 2021). Aquatic organisms lack oxygen when the BOD is high making them get stressed, suffocate and die. Between 0.0 and 4.0 mg/l BOD values was observed in Hathaikheda lake reservoir in Bhopal (Brian *et al*., 2001). In the reservoir of Halali Lake, BOD values were found to range from 3.2 to 6.8 mg/l by Namdev *et a*l. (2011) and Tamot et al. (2008). According to Yee et al. (2012), increased oxygen demand is typically seen towards the bottom of fish cages where nutrients and organic matter from the fish, extra feed, and waste accumulate.

Fish cage farming as for the case in Lake Victoria especially in Usenge area, generates products and wastes from the fish farming activities being a source of pollution to the aquatic life (Anjejo, 2019). The BOD thus increases from the increase in organic matter. Anoxia is caused by elevated BOD levels which promotes the depletion of dissolved oxygen in water bodies (Nezlin *et al*., 2009). Algal bloom causes eutrophication of surface waters from the high nutrient concentration from the effluents (Matsumura *et al.,* 2005). Fish meal leftovers, dead plants and wood, dead animals, and urban storm water discharge are also sources of BOD. BOD and dissolved oxygen are both influenced by the same variables (Brian et al., 2002) The BOD maximum permissible levels are 30 ppm (EMCA, 2015). This study was motivated by inadequate knowledge on spatial variations in BOD near fish cages and open waters in the Usenge area of Lake Victoria.

2.1.1.6 Dissolved Oxygen

As a quantifiable metric, dissolved oxygen (DO) is oxygen in its dissolved state. Low oxygen levels have an impact on aquatic species, causing them to flee to locations with high oxygen levels (Croijmans *et al*., 2021). The oxygen available should be equally produced. Their quantities fluctuate because to differences in dissolved oxygen levels and seasonal changes in water temperature. Warm water stores less oxygen compared to cold water, which holds more oxygen (Brian *et al*., 2002; Yee *et al*., 2012).Microorganisms' breakdown of organic materials has been shown to reduce DO in various fish cage farming locations. In the production of ammonia, depletion of DO can occur from Massive plankton growth. The ideal DO range for fish in lake water, according to Nsonga (2014), is between 5 mg/l and 6.5 mg/l.The low levels of oxygen in the surrounding water and cages is attributed to the breathing of the fish housed in the cages (Bergsson *et al*., 2023). Dissolved oxygen levels below 3.5 mg/l are not recommended for fish cage farming. The ideal dissolved oxygen content for fish in lake water is between 5 and 15 mg/l, according to Swingle (1969), Neill and Bryan (1991), and Boyd (1998).

Lake Taal, Philippines has reported self-pollution from fish culture activities that have resulted in massive fish kills from low oxygen that resulted from low wind conditions during summer. (Yambot, 2000). Rani *et al*. (2004) High temperature seasons in summer reported dissolved oxygen in low values due to organic matter high rate of decomposition and environmental low water content due to high temperature. Karnatak and Kumar (2014) reported that cage culture may experience problems in water quality due to low DO. When temperatures are high and during hot summer days in the morning, aquatic animals are vulnerable to the lowered DO levels.

If it remains unchanged for several hours, dissolved oxygen concentrations below 1 mg/L can cause a large number of fish kills (Brian *et al*., 2001). There shouldn't be more than 11% of the total gas dissolved. Gas bubble illness, where the bubbles (called emboli) impede blood flow via blood vessels and cause mortality, can cause fish to perish in waters with low level of dissolved gases. Most fish deaths occur at dissolved oxygen levels below 2 mg/l, and aquatic animals' ability to function may be impacted by levels as high as 5 mg/l. Chapman and Kimstach (1992). Fish cage farming at Usenge area in Lake Victoria, Kenya could be promoting high DO levels from the fish cage activities that may interfere with the levels. This study was to determine the levels of dissolved oxygen and their spatial variations of water quality around the fish cage since there is limited information on the spatial variations on the levels of dissolved oxygen in the fish cage sites and open waters in Usenge, Lake Victoria.

2.1.2 Fish cage farming and nutrients (Nitrates and Phosphates)

2.1.2.1 Nitrates

It is possible for nitrogen to exist freely as a gas (N_2), nitrite (NO_{2-}), nitrate (NO_{3-}), or ammonia (NH_3) (Abayechaw and Dikr, 2023).. It was reported by Nyanti *et al.* (2012) that the concentration of the nitrate in fish cages was higher than open waters due to the contribution of fish excretion concentrated at one point and excess fish food pellets. Nitrite toxicity can be increased by the increasing pH, high ammonia and low dissolved oxygen (Devi *et al.,* 2017).Aquatic animals can suffer from high levels of nitrates that causes depletion of oxygen in water and since aquatic animals depend on oxygen for survival in water. (Carpenter, 1998). NO_{2-} is quickly converted to NO_{3-} by bacteria. The development of aquatic plants can be accelerated by high levels of phosphates and nitrates in the water, and this can change the kinds of aquatic animals and plants that live there, hastening eutrophication (Matsumura *et al*., 2005). Fish cage culture farming could be therefore affected by the change in dissolved oxygen, temperature and other physico-chemical parameters of water. Because dissolved oxygen is hazardous to aquatic warm-blooded animals at low quantities (10 mg/L), hypoxia is induced by high amounts of excess nitrates. High nitrite concentrations in lake water are the main cause of the fish ailment known as "brown-blood disease" (Brian *et al.,* 2001).

As organic matter breaks down, there is less dissolved oxygen in the water, which inhibits the oxidation of ammonia to NO_{2-} and NO_{3-} High levels of ammonia and nitrites are also harmful to aquatic life (Brian *et al*., 2001). Nitrates are beneficial to the growth of plants however in excess it may indicate contamination of the lake waters from excessive excretion of the fish in the fish cages and from the fish food pellets. This study was to determine the spatial variations of the nitrate levels in Usenge fish cage farming, Lake Victoria given that there is lack of information on the spatial variations of nitrate levels in the fish cage farms and open waters is limited within Usenge area of Lake Victoria, Kenya.

2.1.2.2 Phosphates

Phosphorus can be deposited into a lake water body through anthropogenic activities and surface run off through contaminated soil and from dumping of wastes from other sources. Phosphorus is more distributed in sediments since their solubility in water is not fast in aquatic environment (Wang *et al*., 2021). Total phosphorus is more substantially contributed from wastes deposited from farming activities and waste disposal sites. (Hooda *et al.*, 2000). The clearing up of forests and rivers around the lake for farming activities and human settlements may contribute to phosphorus uptake into the lake water. (Majiwa *et al*., 2001). In addition, fish cage farming practices have resulted in water pollution (Memet, 2019) this causes eutrophication that is as a result of the high phosphorus nutrient load into the water.

A study by Osei *et al*. (2019) on the effect of fish cage culture in Lake Volta in Ghana established higher concentrations of phosphorus at farmed sites compared to control sites and attributed this to possible contribution from the cage farm. Fish farming impact on phosphorous can be contributed from uneaten fish food pellets and fish excretion found beneath the fish cages (Apostolaki *et al*., 2007). Due to the concentration of fish urine at the fish cage site, the fish cage farming site contributes to high amounts of phosphorus (Kibria *et al*.,2000). Similar to this, Phillips *et al*. (1994) reported that 85% of the phosphorus in the water came from fish cage activities. According to Gavine *et al*. (1995), the main source of phosphorus in the water was the addition of fish food to the cages. In an aquatic environment, fish populations concentrated in one location may surpass the area's capacity, which may cause phosphorous levels to rise

(Mallasen *et al*., 2012). Oxygen shortages is caused by growth of algae and aquatic weeds that is a course of phosphorous in water. This limits the use of water for fish and low oxygen demand for the fish due to decomposition of biomass. (Southern Cooperative Series Bulletin, 2000). Algal bloom indicates the presence of phosphorous and imbalances in nitrogen in an aquatic environment as well as high nutrient level concentrations in water e.g. water hyacinth (LVEMP, 2002). This is the situation likely to take place in Usenge fish cage farming area within Lake Victoria following the immense activities from the fish cages that introduce phosphates from food pellets. However, the information on spatial variations of phosphates in fish cages and open waters of Usenge area of Lake Victoria is lacking, hence the reason for this study.

2.1.3 Bioaccumulation of heavy metals

Contaminants from the environment that pose dangers to humans can add heavy metals to water. Although they can be changed from one state to another, heavy metals cannot be eradicated naturally (Maqsood *et al.*, 2022).Due to their poisonous nature and ability to coexist in food chains, they pose a major threat to the environment and aquatic life. in 1979 (Förstner). The water and sediments at fish cage locations contain more heavy metals as a result of fortified fish meals (Sapkota *et al*., 2008). In Eastern Mediterranean, heavy metal concentration was detected at elevation levels of traces of heavy metals that included Cd, Zn, Pb, Fe, Ni, and Cu in the sediments of the sites of fish cage farming sites (Belias *et al.*, 2003; Basaran *et al*., 2010). Aquaculture activities have shown increased levels of heavy metals underneath fish cage farming sites reported by Sutherland *et al.* (2007) Agricultural activities in Lake Victoria have increased levels of heavy metals (Outa *et al.*, 2020; Muli, 1996). Heavy metals harm the cell organs and stop the activity of enzymes by significantly disturbing the physiological state of the living body. Heavy metals enter food systems via being eaten from fish meal pellets in a dissolved state.

Fish absorb heavy metals from the water and accumulate more of them than the nearby water body does. The aquatic animals consume vegetation and absorb the water's heavy metal concentrations. Sediments beneath the locations of fish cage farming have been discovered to contain high quantities of heavy metals (Cu & Zn) in fish. Kalantzi *et al*. (2013); Dean *et al*. (2007). The elevated levels of heavy metals in fish may be due to bioaccumulation from the concentrated fish excrement and feeds used in fish cages. Heavy metals like manganese, copper, zinc, cobalt iron, and other necessary heavy metals are present in commercial fish feeds (Kalantzi *et al*. (2013); Dean *et al*. (2007). In Usenge, Lake Victoria, Kenya, information is sparse about the spatial changes in the concentration of heavy metals in water quality and heavy metal bioaccumulation in *O. niloticus* fish.

2.1.3.1 Lead

Lead is a hazardous environmental contaminant and a serious ecological issue because of its harmful impacts on human health (Mishra *et al*., 2019). When lead enters the metabolic process, it becomes a poisonous heavy metal that is lethal to all living organisms. Lead (Pb) is a natural component of the Earth’s crust, and is generally found in trace amounts in soils, plants, and water (Rahman and Singh, 2019). Although Pb is ubiquitous in aquatic environments, high levels of Pb exposure can be caused by anthropogenic activities including the manufacture of batteries, paint, and cement, as well as mining and smelting (Kim and Kang, 2016a). Recently, with the development of the marine leisure industry, there is an increase in Pb-based wastes in the sea from littering, leading to increased Pb pollution. In particular, Pb forms a flexible bond with oxygen and sulfur atoms in proteins, and its ability to form a stable complex with these elements increases the affinity of Pb to a given protein (Verstraeten et al., 2008). Additionally, Pb accumulation in fish causes hypocalcemia by inhibiting the basolateral transport mechanisms of inocytes in the gill epithelium because of the high affinity of Pb to Ca2+ ATPase, the Na+/Ca2+ exchanger, and Na+/K+ ATPase; this disrupts of the electrochemical gradient and ion regulation (Rogers et al., 2003). Therefore, Pb exposure can be fatal to aquatic animals even at low concentrations owing to bioaccumulation (Kim and Kang, 2015a). Pb exposure causes a large range of toxic effects on physiological, behavioral, and biochemical functions in animals; it also causes damage to the central nervous system (CNS), peripheral nervous system (PNS), hematopoietic system, cardiovascular system, and organs such as the liver and kidney (Hsu and Guo, 2002). For example, Pb2+ arouses Ca2+ and calmodulin to stimulate the release of neurotransmitters in neurons (Zhong et al., 2017). In addition, Pb exposure disturbs the balance of pro-oxidants and antioxidants, causing oxidative stress and Pb poisoning (Kim and Kang, 2017a). in vivo studies have suggested that Pb exposure might induce increases in antioxidant responses in fish through the production of reactive oxygen species (ROS) (Maiti et al., 2010; Kim and Kang, 2017a; Kim et al., 2017a). Pb exposure in fish also has toxic effects on membrane structure and function owing to its high affinity to red blood cells, which increases susceptibility to oxidative stresses (Gurer and Ercal, 2000).

The fish food pellets used for the fish in the cages could have traces of lead which could lead to deposition of traces of lead concentration into the lake. The study will provide information on the spatial variations of the concentration of lead in water and bioaccumulation of heavy metals in the fish in the fish cage sites and open waters of Usenge, Lake Victoria.

2.1.3.2 Zinc

Metal parts like galvanized metals and other metallic components may include zinc. Commercial fish food pellets are its principal source in the water near fish cage farms (Unaeze, 2023). Due to its importance as a trace element in many biological processes, zinc is added to fish meals

(Yildiz, 2008; Fallah *et al*., 2011). Sapkota *et al*. (2008) and Burridge *et al.* (2010) reported high levels of zinc in fish caged farms compared to open waters which they absorbed from the water volume. Water containing zinc levels above 5ppm has an objectionable taste, causes adverse effects on growth, survival and reproduction in aquatic life (Eisler, 1980). Zinc in excess affects metabolism of copper and iron thus leading to anemia (USEPA, 1986). Continued use of fish food pellets at the fish cage farms in Usenge, Lake Victoria, may lead to bioaccumulation of zinc in the fish which eventually interfere with aquatic systems. It is not known whether the zinc levels in the water and bioaccumulation of heavy metals in the fish cages are associated with fish cage activities or not.

2.1.3.3 Cadmium

Cadmium is a heavy metal that can be found from environmental activities such as coal processing, wastes from house hold and mining activities (Hocaoğlu-Özyiğit and Gen,2020).. It mainly finds its way to the lake water from house hold waste and wastes from industries. Commercial fish feed could have some cadmium concentration levels in them thus find their way to the lake water as for the case of the fish cage farms in Usenge, Lake Victoria. Cadmium changes into different forms in the environment and does not break down making it harmful to aquatic life and human beings in the food chain. The caged fish end up taking the cadmium traces from the water while some settle in the sediments of the lake at the fish cage sites and are taken up by aquatic animals and plants. Kuzovkina *et al*. (2004) reported that Cd is poisonous and can cause death since it is not and essential heavy metal for fish and aquatic life for metabolism. If contaminated fish is consumed, the traces of Cd can have substantial adverse health impacts on both humans and animals. Muzuroglu and Geckil (2002). This study investigated the water quality and bioaccumulation of heavy metals in fish gills in fish cage locations and in open waters of Usenge, Lake Victoria, due to a paucity of information. Additionally, it looked at the fish and water's cumulative levels of Cd and spatial variability.

2.1.3.4 Iron

Iron is an essential heavy metal that is mostly found in food that has high concentrations of animal tissues and plants (Rehman *et al.*, 2021). Iron levels in excess can cause caged fish to die by clogging their gills caused by respiratory problems (Lehtinen and Kingstedt, 1983; Peuranen *et al*., 1994; Dalzell and MacFarlane, 1999). Subsequently, high iron concentrations can cause reduction in species diversity of benthic invertebrates and fish. USA has set a maximum permissible level of Fe in water at 1.0 mg/l despite its harmful effects to the environment. Organic waste discharge into the lake is the main source of iron into the lake. The main source of iron into fish can be mainly through household organic waste discharge. Iron is absorbed to the fish via fill gill filaments and the primary source of absorption is through fish diet. (Bury and Grosell, 2003). In order to keep aquatic creatures healthy and to regulate the amount of iron in the water, it is necessary for fish to consume iron in their diets. Little is known about the quantities of iron in water due to the spatial thermal changes of water and fish bioaccumulation in open waterways and fish cages. While iron is generally not a concern in fish cage farming, it could be a huge issue for fish cages that rely on lake water. Because iron is colorless and dissolves in water, it is advisable to regularly check the levels of iron in the water because high amounts of iron can be harmful to the health of young aquatic species.

2.1.3.5 Copper

Copper is mainly introduced in water systems through agricultural activities (Li *et al*., 2020). The presence of copper in aquaculture activities is used to control blue-green algae that are for treating of certain diseases. It is also responsible for controlling foul smell in fish cages and eliminating mollusks in the fish cage sites. (Horne and Dunson, 1995). Cu in high levels is potentially toxic and has a concern on its use to aquatic fish cage farming. The applications of fish food pellets in fish cage farming are possible sources of copper pollutants at the fish cages, and the copper levels at these fish cages have not been established.

The heavy metals investigations carried out in Lake Victoria by Onyari and Wandiga (1989), Mwamburi and Oloo (1996), and Kishe-Machumu and Machiwa (2003) found that the trace element distribution of a few selected heavy metals in surface sediments of (Mn, Cd, Fe,, Zn, Cr, Hg, Cu, and Pb) was found to be 5 cm. It is unclear how the fish cage farms in Usenge Lake Victoria are distributed on a level and how much copper is being bio accumulated there. Zinc, copper and cadmium, have become a study of interest in aquatic culture practices due to their increased use in cage fish farming through fish feeds, faecal waste and antifoulant products (Dean *et al*., 2007), yet the spatial variability in fish cages and open waters in Usenge area of Lake Victoria is unknown.

2.2. Theoretical Framework

Many theories addressing methods for determining the carrying capacity of aquatic ecosystems have been developed all throughout the world (Ryding and Forsberg, 1980; Welch, 1980). All methods focus on the productivity and nonproductively in the water bodies. These various techniques either assess primary production (Granberg, 1970), fish yield (Melack, 1976, Oglesby, 1977), oxygen deficit (Welch, 1980), algal biomass (Dillon and Rigler, 1974), indicator species (Rawson, 1956), production of aquatic macrophytes (Canfield and Daniel, 1983), nutrient concentration (Vollenweider, 1976), or a combination of these factors (Carlson, 1977) to assess the productivity of the water bodies.

According to Riasi *et al*. (2018), reliability theory has essentially been implemented as a lumped, single component-level reliability analysis to processes in environmental situations that are specified by a single performance function. Furthermore, dependability theory can respond to queries like "what is the resilience of any particular area in the watershed, i.e. how severe was water contamination at a given location and time?" (Sarang *et al*., 2008) when framed in terms of sustainability dependability theory can be used to examine the sustainability of water resources, which is described as a function of dependability, vulnerability, and resilience (Loucks, 1997). Previous research on the application of reliability concepts and reliability-based sustainability metrics to water quality challenges has primarily focused on dissolved oxygen (DO) breaches (Sarang et al., 2008). Recent studies have been published (Hoque *et al*., 2016; Teklitz *et al*., 2020) on the application of the concepts of reliability, resilience, and vulnerability to sediments and chemical pollutants. The lumped technique is thus abandoned in favor of a multi-component, distributed analysis. This makes it possible to comprehend how risk and reliability are distributed geographically. Additionally, it enables one to assess the influence of specific physico-chemical factors, nutrients, and heavy metals on the success or failure of the cage culture system.

2.3 Conceptual Framework

Human life and aquatic life depend on the lakes ecosystem for life sustainability. Fish cage farming activities in Usenge area of Lake Victoria and related anthropogenic activities are major sources of pollutants that are likely to alter the water quality. An example of such pollution source includes fish cages in Usenge where immense fish cage farming is taking place. Pollutants have an impact on fish as well as water quality because they change the physico-chemical characteristics of the water, including turbidity, temperature, EC DO, BOD, and pH. Since they build up over time in the fish gills, they may also result in the entrance of heavy metals including zinc, lead, iron, cadmium, and copper into water bodies and contribute to their bioaccumulation in fish. The fish food pellets in use in fish cage farming also may lead to the presence of nutrients like phosphates and nitrates with long time effects.

Most of these pollutants can be controlled by good fish cage farming practices that is cheap and friendlier environmentally. Fish cage farming for this reason may need to be practiced in an environmentally sound manner and the people advised on the need to be enlightened on the control of the pollutants into the water. In this study, the fish cages serve as the independent variable, while the dependent variables are the water quality and the bioaccumulation of heavy metals in fish gills. The intervening variables that are likely to have an impact on the link between the independent and dependent variables include changes in temperature and weather patterns, pollutant loads into lakes, and the lake's inherent mixing capacity. The impacts of the intervening factors were removed from this study by concentrating on the spatial fluctuations rather than examining the lakes and the area around the cages' water quality.

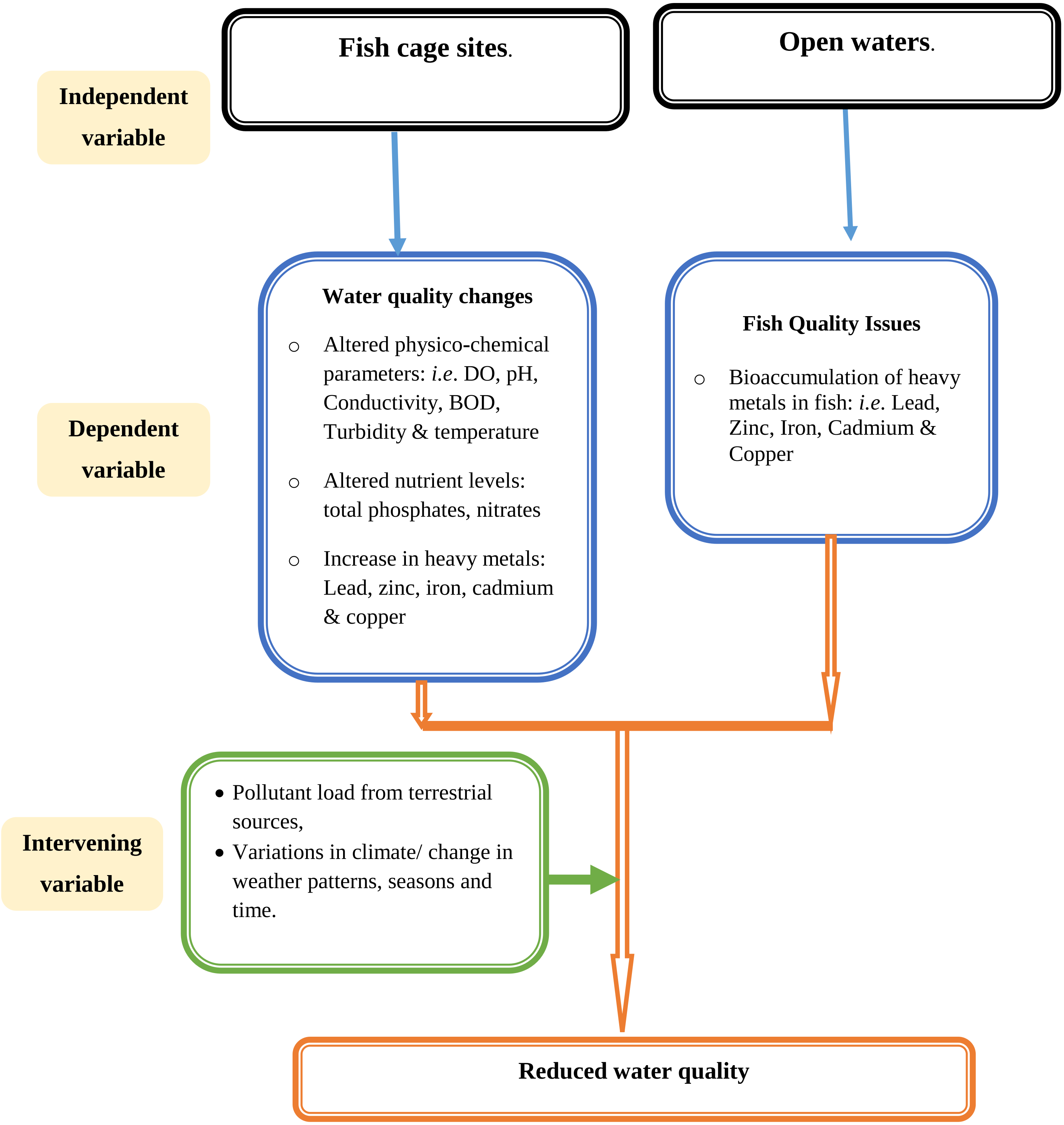


Figure 2.2. Conceptual framework showing the independent, dependent and intervening variables of fish cage farming on water quality

CHAPTER THREE

MATERIALS AND RESEARCH METHODS

3.1 Study Area description

This study was carried out in Usenge area Lake Victoria, Kenya. Usenge area is in Siaya County, located along the great Lake Victoria's shores. The beach mainly attracts fish traders from Kenya, Uganda, and Tanzania. Usenge beach area is a vibrant and bustling fishing village located along the shores of Lake Victoria in Siaya County, Kenya. It is one of the most prominent beaches on the Kenyan side of the lake, known for its lively atmosphere and the important role it plays in the local economy. The beach serves as a key landing site for fishermen who rely on the rich waters of Lake Victoria for their livelihoods. Africa's Lake Victoria has a surface size of about 68,800 km^2. It is the largest freshwater lake in Africa in terms of surface area, the main Nile reservoir, and the largest tropical lake in the world. It has a 3,220 km shoreline and a maximum width of 240 km. Usenge region, Lake Victoria, Kenya served as the site of this investigation. Western Kenya's Usenge region is situated on the beaches of Lake Victoria. Usenge beach is one of the best spots for cage farming on the Kenyan side of Lake Victoria, according to a suitability mapping exercise by KMFRI (www.kmfri.co.ke), making it the perfect location for this study. A total of 5, 242 cages were documented in the waters of Lake Victoria (Musa *et al*., 2022). Siaya county recorded the highest number of cages (n = 3,838; 73.2%) (Aura *et al*., 2024).Based on the survey conducted by Namaemba *et al*. (2022), Usenge beach had a total of 106 cages. The floating cage system is the dominant technology for tilapia production in Lake Victoria with square-metal (n = 95; 79%) and circular-plastic (n = 25; 21%) frames as the major structures reported (ABDP, 2022). At the beach, the main human activities include fishing, small scale agriculture and tourism (GPS Coordinates:-0.081744^0, 34.056689^0).

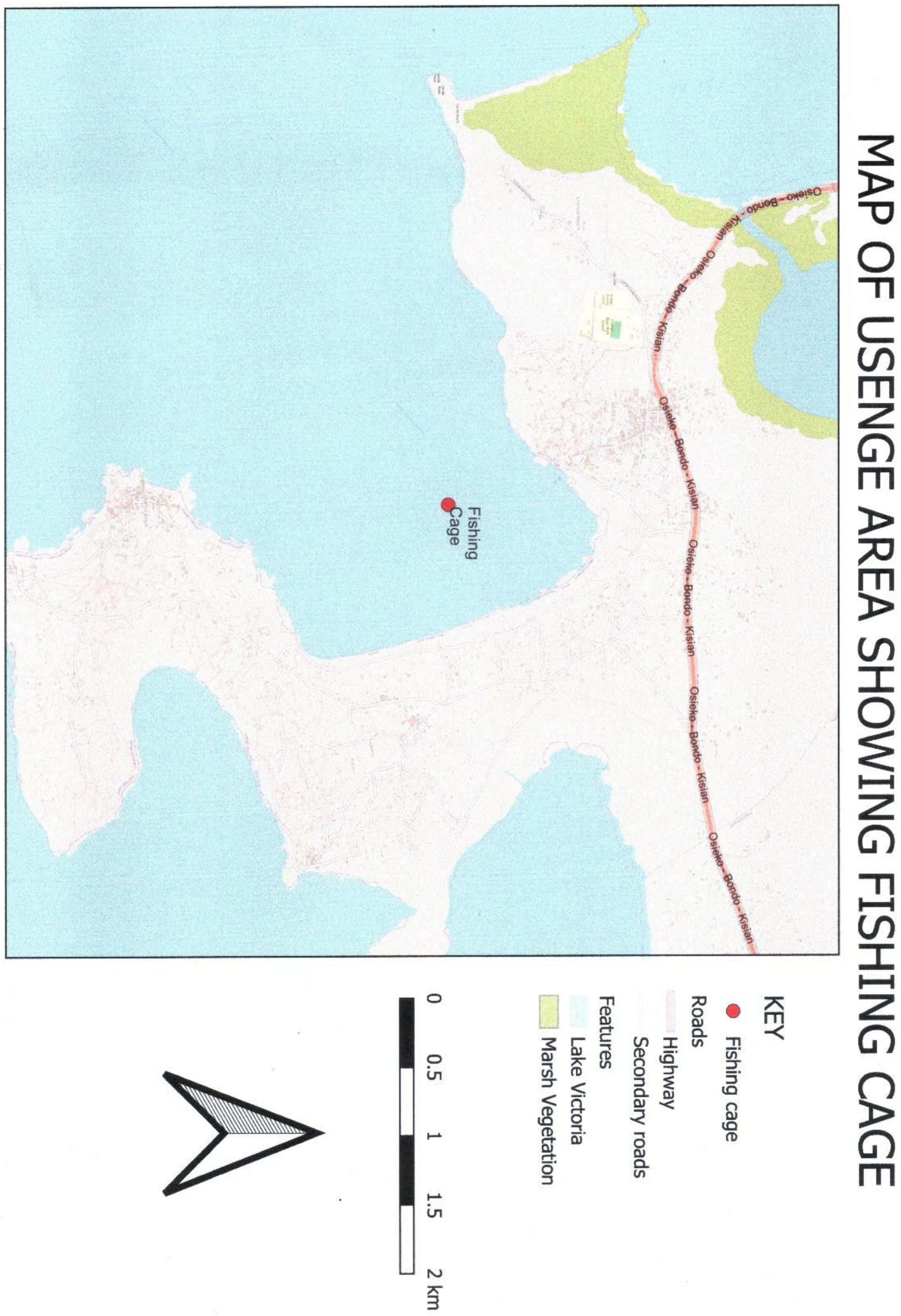


Figure 3.1. Sectional map of Lake Victoria showing the study area of Usenge, Lake Victoria Kenya. (Adopted from www.googglemaps.com)

3.2 Research Design

A quasi-experimental design was adopted to estimate the spatial variation of various water quality parameters, nutrients (phosphates and nitrates) and heavy metals in Lake Victoria fish caged waters and open waters and fish samples. The fish cage sites were purposively selected on assumption that the spatial variations in water quality and heavy metal concentrations were influenced by the activities taking place within and around the fish cages. The study involved analysis of physico-chemical parameters and collection of water and fish samples (for gill analysis) in triplicates from the 20 treatment and 4 control points. A modified procedure of Xie, *et al*., (2020) was used for sampling, five sampling points were marked as treatment points at intervals of 10 m each, starting from the centre of the cage (0 m) in the eastwards, westwards, southwards and northwards directions, within the fish cage area, this ensured equal representation. Control sampling points were located in the open waters, 200 m from the centre of the fish cage in all the four directions. This distance between the control and experimental site was deemed adequate enough to allow for a sufficient buffer between the two sites to avoid contamination. The physico-chemical parameters were measured *in situ* while water samples were collected at a depth of 2 m from each sampling point. Fish samples were taken from the treatment and control stations for gill analysis. The gills were initially the most popular fish organs for investigation because they serve as the primary pathway for gas exchange between fish and water (Oguzie, 2003) and because they have a high surface-to-volume ratio, allowing hazardous heavy metals and nutrients to diffuse quickly (Dhaneesh et al., 2012). In the months of September through November 2021, samples of fish and water were taken and examined every two weeks. This time of year in Kenya is often dry with little or no precipitation. This was the most ideal time to study variations in water quality parameters without much interference from terrestrial surface runoffs.

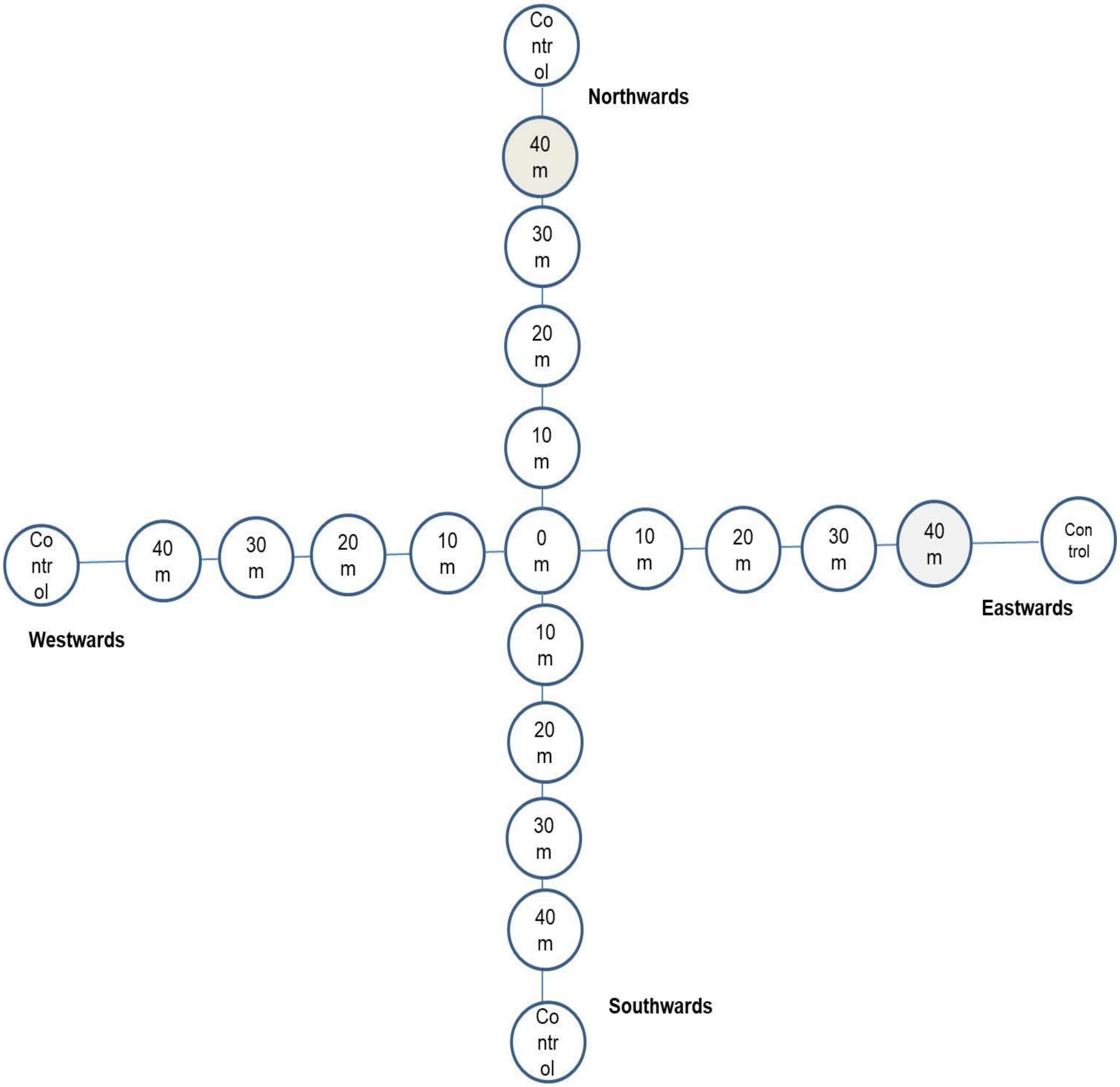


Figure 3.2 Sketch map showing sampling points

Table 3.1 GPS coordinates of sampling points.

DISTANCE	WESTWARDS		SOUTHWARDS		NORTHWARDS		EASTWARDS	
0m	0◦05,01.1 "S	34◦03'38.26E	0◦05,01.12"S	34◦03'38.26E	0◦05,01.12"S	34◦03'38.26E	0◦05,01.12"S	34◦03'38.26E
10m	0◦05,01.20"S	34◦03'39.05E	0◦05,00.73"S	34◦03'38.72E	0◦05,01.20"S	34◦03'38.81E	0◦05,01.36"S	34◦03'37.71E
20m	0◦05,01.20"S	34◦03'39.60E	0◦05,00.53"S	34◦03'38.79E	0◦05,01.75"S	34◦03'38.92E	0◦05,01.31"S	34◦03'36.92E
30m	0◦05,01.20"S	34◦03'40.32E	0◦05,00.28"S	34◦03'38.78E	0◦05,01.98"S	34◦03'38.92E	0◦05,01.26"S	34◦03'36.36E
40m	0◦05,01.20"S	34◦03'40.71E	0◦04,59.94"S	34◦03'38.77E	0◦05,02.91"S	34◦03'39.02E	0◦05,01.20"S	34◦03'35.49E
200m	0◦05,01.29"S	34◦03'45.22E	0◦04,54.67"S	34◦03'38.35E	0◦05,07.81"S	34◦03'39.04E	0◦05,01.29"S	34◦03'31.48E

3.3 Determination of Physico-chemical parameters of water

Physico-chemical parameters of water including pH, temperature, turbidity, electro-conductivity (EC), and dissolved oxygen (DO) from the treatment and control sites were measured *in situ* after every fortnight using a Hydro lab multi-meter. The instrument was calibrated to ensure its validity and the readings recorded. Each measurement was done in triplicate.

3.4 Sampling and Sample Preparation

Fish samples were caught using hooks and baits and deposited in black plastic bags, while water samples were gathered from each sampling site in plastic bottles. Mercuric chloride was used to preserve the bottles used to collect water samples for nutrient analysis, and 1 ml of strong nitric acid was used to acidify the bottles used to collect water samples for heavy metal analysis. Then, fish and water samples were transferred to the lab for analysis while being kept at 4 ^{o}C in a cooler box. Gills were removed from the fish samples and left to dry for three days at room temperature before analysis. The dried gill samples were homogenized by grinding using a pestle and mortar sieved using a 45 µm mesh sieve and kept in clean plastic containers.

Plate 1. Photo showing the set-up of fish cages in Usenge beach area in Lake Victoria (Photo courtesy of Edward Adino)

3.5 Determination of Nutrients in Water

3.5.1 Determination of Nitrates-Nitrogen

All chemicals used in this study were analytical grade (AR).

The amounts of nitrates in the samples were determined using the Franson (1995) method. A 250 ml beaker was filled with 50 ml of each water sample. After that, Whatman No. 40 filter papers were used to remove any potential interference from suspended particulates from the water samples. Each sample's filtrate was acidified with 2 cc of 1 N Cl. By using the acid, up to 100 mg of $CaCO_3$/L of hydroxide or carbonate could not interfere with the experiment. A nitrate standard stock solution was created by dissolving 0.7218 g of potassium nitrate (%purity) in deionized water and diluting it to 1000 ml after it had been dried for 24 hours at 105 ^{o}C in an oven. NO_{3-}N calibration standard dilutions were made using deionized water and ranging from 0 to 7 mg NO_{3-}N/L. A UV/Vis spectrophotometer (Shimadzu UV 1650 PC-U) operating at 260 nm was used to analyze the calibration standards and water samples. The calibration curve created from the analysis of calibration standards was used to calculate the concentration of mg NO_{3-}N in the water samples.

3.5.2 Determination of phosphorus

Digestion of the water sample was carried out in accordance with Anils' (1994) methods. Each water sample's 100 ml was transferred to a 250 ml beaker. Then, 5 ml of HNO_3 and 1 ml of H_2SO_4 concentrations were added to each beaker. The mixtures in the beakers were gently stirred, digested at 150^{o}C in an oven, and then dried out using an evaporator. Each sample's residue was collected, leached with 5 ml of concentrated HNO_3, and then put into a 50 ml volumetric flask. Each sample received 5 ml of 10% ammonium molybdate, followed by 5 ml of 0.25% ammonium vanadate. Deionized water was used to dilute the combinations, and they were then given 10 minutes to stand. Five calibration standards in the range 0.1 to 1.0 mg/ml were prepared from a stock solution of 1000ppm. Both calibration standards and water samples were analysed using UV/Vis spectrophotometer at 480 nm.

3.5 Determination of Heavy Metals in Water Samples

A volume of 100 ml of each water sample was transferred to a 250 ml beaker. Salts of lead, iron, zinc, cadmium and copper, were used to prepare dilution standards used for generation of a calibration curves, which were used to determine the concentrations of the samples.

3.6 Determination of Heavy Metals in Fish Gills' Samples

Using AAS analysis protocol, the bio-accumulation of heavy metals (Pb, Fe, Cd, Zn, and Cu) in fish gills was examined. Each sieved gill sample was divided into a fraction (1g), which was then put into a 100 ml beaker. Then, each sample was given a volume of 10 ml of a 4:1 concentration HNO_3 and HCI combination, which was heated continuously on a hot plate until all the brown fumes had been expelled and only white fumes remained. Using Whatman No. 40 filter paper, the contents of each beaker were filtered into a 50 ml volumetric flask after chilling, and the volume was topped off with deionized water. Prepared with lead, iron, zinc, cadmium, and copper salts. The samples and calibration standards were both analyzed using an atomic absorption spectrophotometer to determine the levels of lead, iron, zinc, cadmium, and copper. The relative amounts of the heavy metals in the samples were calculated using calibration curves of the standards created from examination of standard dilutions.

3.7 Data Analysis

The data obtained from instrumental analysis was examined using descriptive and inferential statistics and visualized with tables and graphs. At 95% confidence levels, the averages and standard deviations of the data were calculated. One-way analysis of variance (ANOVA) were performed to check the variations and associations within and between variables at $\alpha = 0.05$ in clusters of sites that were assumed to have varied pollution levels.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Introduction

The results of this study are presented in this chapter. Which are displayed in text and table formats. Along with the analysis of the results, observations from each of the sampled sites are also included.

4.2. Spatial variations in Water Physico-chemical Parameters

A total of six physico-chemical parameters were monitored between September and November 2021. These parameters were measured in situ in triplicates spatially and presented as Mean ± SD. Results of the spatial variations of the physico-chemical parameters in the experimental and control sites are presented in Table 4.2. Spatially, there were statistically no significant differences in turbidity and temperature between the experimental and their respective control sites (t= -3.8234, *p*=.0002). Mean pH was higher in the control sites relative to experimental sites, while turbidity, conductivity, dissolved oxygen and BOD levels were on average higher in experimental sites relative to control sites (Table 4.2).

4.2.1. Sspatial variability in water pH

Spatially, the average water pH was significantly higher (7.44±0.26-7.47±0.21) towards the Eastward side and the Westward (7.35±0.15-7.52±0.22) direction compared to the Northward (7.28±0.18-7.31±0.14) and Southward direction (7.21±0.26-7.40±0.13) of the fish cage ($p \leq 0.05$). The Scheffe's post hoc test further showed that pH varied significantly between Eastwards/Westwards and Northwards/Southwards (Table 4.2). The pH of the control site in all the four directions were significantly higher than the respective pH of the experimental sites.

Table 4.1. Spatial variations in physico-chemical parameters

	Spatial point (distance from center of cage to the four corners & open lake)						
Parameter	0 M (center of the cage)	10 M	20 M	30 M	40 M	200 M (Control)	ANOVA *(p-value)*
Temperature (ºC)							
Eastwards	21.9±0.64	21.8±1.29	21.9±0.82	22.4±0.57	21.9±0.67	21.7±0.67	.2006
Northwards		20.9±2.01	21.0±2.0	20.6±1.75	20.8±1.56	22.7±1.04	**.0154**
Southwards		22.0±1.57	21.1±1.6	21.4±1.79	20.5±1.92	21.9±0.71	**.0155**
Westwards		21.9±0.94	21.4±1.52	21.4±1.38	21.3±1.77	21.4±1.02	.5303
pH							
Eastwards	7.47±0.20	7.44±0.26	7.46±0.25	7.45±0.27	7.47±0.21	7.62±0.33	.9092
Northwards		7.29±0.09	7.30±0.13	7.31±0.14	7.28±0.18	7.59±0.04	**.0225**
Southwards		7.21±0.26	7.35±0.13	7.40±0.13	7.39±0.16	7.46±0.02	**.0074**
Westwards		7.52±0.22	7.37±0.15	7.35±0.15	7.47±0.22	7.55±0.03	.0956
Turbidity (NTU)							
Eastwards	35.0±3.4	37.4±5.57	33.7±1.18	35.0±3.39	36.5±2.44	35.5±1.71	**.0302**
Northwards		37.2±7.96	33.8±5.28	36.6±6.28	37.5±3.94	35.5±1.71	.2469
Southwards		35.0±3.50	34.3±2.20	35.7±3.51	35.8±2.48	35.5±1.72	.7140
Westwards		34.6±1.39	34.5±3.68	32.8±2.54	35.2±4.26	35.6±1.47	.2616
D.O.							
Eastwards	14.8±2.42	16.8±0.04	16.1±0.72	14.5±0.34	14.9±0.44	11.7±0.91	**.0173**
Northwards		13.8±0.73	13.8±0.23	13.6±0.23	13.8±0.86	11.7±0.68	.6983
Southwards		13.6±0.14	14.2±0.35	14.9±0.95	14.8±0.44	11.8±0.43	.4429
Westwards		16.5±0.68	15.4±0.59	15.2±0.64	14.8±0.19	11.8±0.55	.0678
BOD							
Eastwards	0.26±0.13	0.23±0.01	0.23±0.06	0.22±0.15	0.24±0.03	0.19±0.04	.9853
Northwards		0.24±0.04	0.25±0.02	0.23±0.14	0.25±0.03	0.19±0.08	.9943
Southwards		0.29±0.05	0.29±0.04	0.28±0.13	0.27±0.04	0.19±0.08	.8370
Westwards		0.29±0.06	0.26±0.03	0.25±0.14	0.24±0.04	0.21±0.04	.9044
Conductivity							
Eastwards	85.6±6.99	85.8±3.64	80.5±1.5	81.5±2.19	85.3±7.06	77.3±0.67	.2347
Northwards		81.6±1.4	77.9±7.42	77.1±9.71	73.3±6.59	77.7±0.99	**.0000**
Southwards		85.8±9.95	74.9±1.4	78.1±9.34	80.2±8.83	77.7±0.99	**.0003**
Westwards		64.9±2.9	76.1±2.3	71.2±1.9	74.4±2.3	77.6±0.71	**.0038**

Table 4.2 Physico-chemical parameters at four sampling sites over the three months' period

Parameter	Site	Experimental sites (n=90)				ANOVA
		Eastwards	**Northwards**	**Southwards**	**Westwards**	**F, *p - value***
Temp	Experimental	22.0±0.8	21.0±1.7	21.4±1.6	21.6±1.3	**7.58, *p*= .0001**
	Control	21.8±0.8	22.2±0.89	21.9±0.64	21.6±0.66	1.65, *p*= .1851
Turbidity	Experimental	35.5±3.7	36.0±5.7	35.2±3.05	34.4±3.3	2.54, *p* = .0563
	Control	34.9±3.3	35.2±3.1	35.1±3.52	34.8±3.53	0.05, *p*= .9867
pH	Experimental	7.45±0.23	7.32±0.17	7.36±0.19	7.43±0.19	**8.14, *p*= .0000**
	Control	7.53±0.3	7.42±0.4	7.34±0.26	7.44±0.26	1.34, *p*= .2701
Cond.	Experimental	83.7±8.9	79.1±9.4	80.9±9.9	74.5±20.1	**8.15, *p*= .0000**
	Control	85.5±6.9	85.9±6.76	85.7±6.7	85.8±6.8	0.01, *p*= .9985
BOD	Experimental	0.23±0.14	0.25±0.13	0.27±0.14	0.26±0.14	1.37, *p*= .2529
	Control	0.24±0.13	0.23±0.12	0.23±0.12	0.23±0.12	0.02, *p*= .9969
D. O.	Experimental	15.4±2.4	13.0±2.5	14.5±2.3	15.3±1.9	**8.28, *p*= .0000**
	Control	14.6±2.48	14.5±2.6	14.5±2.42	14.5±2.46	0.01, *p*= .9992

Further analysis of the spatial variation in physico-chemical parameter levels determined from water samples collected from the center of the fish cage (0 m) toward the open lake at 10 m, 20 m, 30 m, 40 m, and 200 m intervals revealed statistically significant (P≤0.05) pH differences (One-Way ANOVA, F(5, 426) = 2.39, p=.0371) at various sampling points. The water pH was significantly (P≤0.05) higher in the control point (200m) as compared to all other sampled points (Table 4.2). These values fell within the range of 6.0 to 8.5, which is typical for most natural waters, as well as the limits established by the European Union (EU) for the environment of fisheries and aquaculture (Chapman, 1992). According to Pitta *et al*. (1999), the decomposition of fish farm waste and the extraction of DO in respiration by the greater number of fish in the cage area may have contributed to the pH drop at the experimental sites found in the current study. The pH levels found in the current study at both the control and experimental sites were remarkably similar to those found in Asase's (2013) and Karikari *et al*.'s (2013) studies, which found pH values ranging from 6.80 to 7.50 at the Volta Lake's Kpong and Yeji sections and 7.70

in Akosombo, respectively. Tepe *et al.* (2005) stated that the pH ranges of the majority of natural waters fall between 6.5 and 8.5, which is consistent with the findings of the current study.

PH typically depends on the equilibrium between photosynthesis and respiration in aquatic habitats. According to Craig and Lois (2008), pollutants can increase the concentrations of carbonates and bicarbonates in water, which explains why all experimental locations had lower pH values as compared to control points, leaning toward acidity. This could be attributed to the pollutant load from the fish feed remnants and increased metabolic activities within the confined fish cages.. Other contributors to pH fluctuations between experimental and control points could have been phosphorous and nitrogen containing compounds in fish feeds. In the present study, pH levels varied significantly ($P \leq 0.05$) at different directions from the centre of the fish cage with water samples from the Eastwards direction having the highest mean pH (7.45±0.23) compared to those collected from the other three sides. The differences observed could be attributed to lake water turbulence which diluted the waters and in the process kept altering the pH levels.

4.1.2. Spatial variability in dissolved oxygen levels

Spatially, the average dissolved oxygen levels were significantly higher ($P \leq 0.05$) towards the Eastwards side (14.5±0.34-16.8±0.04) and the Westwards sides (14.8±0.19-16.5±0.68) of the fish cage compared to the other two directions (Table 4.2). Further analysis showed that DO levels varied significantly ($P \leq 0.05$) across the Eastwards/Westwards directions and, Northwards and Southwards. This was confirmed by the Scheffe's post hoc test. Further analysis of the spatial variation in the levels of dissolved oxygen measured from water samples collected from the middle of the fish cage (0m) towards the open lake at 10m, 20m, 30m, 40m and 200m intervals showed that dissolved oxygen was lowest at the control point compared to the other sampling points in the experimental sites in all the four directions (Table 4.2). In addition, the levels of dissolved oxygen tended to drop as one moves away from the centre of the cage.

Dissolved oxygen is crucial to fish productivity since it directly affects the rate of metabolism, feed consumption, and energy expenditure in farmed fish (Van Dam and Pauly, 1995). Dissolved oxygen (DO) is a need for cage culture. Fishing is required for breathing and other physiological processes. The DO values represent the level of pollution in a water body (Amankwaah *et al.*, 2014). The amount of dissolved oxygen in water is affected by a variety of factors, including diffusion, air pressure, temperature, and metabolic activity rates. In the current study, the mean surface DO concentration at the control location was considerably lower than at the experimental site. This significantly higher DO level in the experimental site may suggest some considerable effect from the cage farming activity within the lake due to mixing of atmospheric oxygen to the water by the cages as they float on water as compared to the control sites. However, the relatively low levels of dissolved oxygen registered in Southwards and Northwards directions may be due to high productivity as a result of more oxygen being used by the chlorophyll of the water hyacinth that has overgrown in Lake Victoria. There should be an attempt to manage the DO required by the fish to aerobically create the necessary energy for growth even if DO changes inversely with water temperature in cage culture systems (Van Dam and Pauly, 1995).

In addition, the amount of oxygen that captive fish require is also influenced by the standing biomass in the cages and the wild fish populations at the farm, which further lower can DO locally in and around the cages. It is suggested that the waters in the experimental and control site in the current study, with a mean DO level above 14.8 mg/l, were suitable for fish growth because tilapias grow at their best rates above 3.0 mg/l (Ross, 2000) and Brown *et al*. (2011) estimate that only 3.38 mg/l of DO is available to fish if the inflowing DO waters are 6.38 mg/l.

Similar to Santhosh and Sing (2007), Yovita (2007) reported that cold water fish require 6 mg/l of dissolved oxygen while tropical freshwater fish require approximately 5 mg/l. Both groups agreed that DO levels of less than 4 mg/l are adequate for fish culture.

The DO values reported in the present study were, however, significantly ($P \leq 0.05$) higher than those reported by Clottey (2014) of between 5.21 and 9.0 mg/l at farmed sites and 4.51 to 8.84 mg/l at control sites on Lake Volta, as well as those reported by Karikari *et al*. (2013) of between 7.3-8.1 mg/L in Lake Volta and Gondwe *et al*. (2011a) of between 4.35-7.68 mg/L in Lake Malawi. Besides fish cage farming activities, external point sources of pollution; most notably contaminants from the dominion farms which farm along the shores of Lake Victoria were also likely to have contributed to the low oxygen levels recorded in parts of the fish cage as some of the waste laden wastewater uses up oxygen in the water in the process of oxidation resulting in low oxygen levels. Similar to the findings of the present study, other studies have shown that significant organic waste loads result in lower DO concentrations and higher BOD levels because the wastes require a lot of dissolved oxygen for decomposition (Busulwa and Bailgy, 2004).

Therefore, if DO concentrations are below the ideal values advised for a specific organism, it may have an impact on fish cage running expenses. Water temperature is a difficult physical parameter to control even though DO and water temperature change inversely in cage culture systems. As a result, farms should work to regulate the DO needed for the fish to produce the energy needed for growth through aerobic metabolism (Van Dam and Pauly, 1995). Avoiding overcrowding of fish in cages, frequent DO sampling, and partial harvesting in the farm to prevent low DO are all active management measures to alleviate oxygen stress, particularly if the issue is assumed to be caused by high stocking biomass.

4.1.3. Spatial variability in Biological Oxygen Demand (BOD) levels

BOD measures the amount of dissolved oxygen that aerobic organisms require to decompose organic matter present in water at a given temperature for a particular period of time. In the present study, Biological Oxygen Demand (BOD) levels ranged between 0.22±0.05 and 0.29±0.05mg/l in experimental sites and between 0.19±0.04 and 0.21± 0.04 mg/l in control sites. Spatially, BOD levels did not show any statistically significant ($p>0.05$) variation between the four sides of the fish cage (Table 4.2). An analysis of the spatial variation in the levels of physico-chemical parameters measured from water samples collected from the middle of the fish cage (0m) towards the open lake at 10m, 20m, 30m, 40m and 200m intervals showed that biological oxygen demand (BOD) was lowest at control sites compared to all the other sampling points in the experimental sites. The mean BOD levels were significantly $p\leq0.05$ higher in experimental sites compared to control sites (Table 4.2).

According to the UNEP (2006), biological oxygen demand (BOD) is a measurement of how much oxygen is taken out of aquatic environments by aerobic microbes for their metabolic needs when breaking down organic waste. In the current investigation, the fish cage's southerly direction yielded significantly higher ($p\leq0.05$) BOD levels. High BOD levels may be brought about by a large inflow of organic material brought in by fish waste from fish cage culture (Adenkunle,2008). According to Allan (2004), nutrient enrichment in water bodies brought on by human activity speeds up the breakdown of litter by bacteria and fungi, which ultimately raises BOD levels. Increased BOD levels signify a fall in DO because bacteria use oxygen for respiration, making it difficult for other aquatic creatures to survive. According to studies, fish cage farms that are built in water bodies can frequently lower the amounts of suspended particles, BOD, nitrogen, phosphorus, and coliform bacteria by 98% (LVEMP 2003). These processes break down organic materials and fish cage contaminants, which use the majority of the oxygen in the water, resulting in high BOD and low DO concentrations. In the present study, sites with high BOD values like the Southwards direction had a considerably low DO value, while those with high DO levels like those in the Eastwards had lowest BOD levels.

Waters that receive wastewaters may have BOD levels as high as 10 mg/l or more, especially in close proximity to the source of wastewater release, compared to unpolluted waters that typically have 2 mg/l or fewer BOD levels (Sekemo *et al*., 2010). The WHO recommended standard for BOD is 1 to 2 mg/l (WHO, 1995), implying that the waters around the fish cage in the present study are relatively pristine with regard to the average BOD levels that were measured in the present study implying that the fish cage farming activity might not have had much impact on the lake waters. In addition, the high lake water turbulence could have led to complete mixing of the waters around the fish cage thus diluting the waters leading to a process akin to natural purification.

4.1.4. Spatial variability in electrical conductivity levels

Electrical conductivity (EC) provides a precise accounting of all the dissolved ions in solution and is a valuable predictor of mineralization in water (Jain et al., 2005). The electrical conductivity levels in the current investigation varied between 77.3± 0.67 and 77.7± 0.99 S/cm in the control locations and between 64.9±2.9 and 85.8±7.06 S/cm in the experimental sites. There were statistically significant variations in conductivity between the control and experimental sites (t= -3.8234, p=.0002). The conductivity levels observed in this study were significantly ($p \leq 0.05$) higher than those reported by Clottey (2014), who measured 56.68 S/cm at the Kpeve section of Lake Volta, and Antwi and Ofori-Danson (1993), who measured 62.0 - 77.5 S/cm at the Kpong section of Lake Volta, fish cage farming sites.

Spatially, conductivity levels were significantly higher towards the Eastwards side of the fish cage compared to the other three sides in the experimental sites. This was confirmed by the post hoc test. Analysis of the spatial variation of conductivity levels measured from water samples collected from the middle of the fish cage (0m) towards the open lake (at 10m, 20m, 30m, 40m and 200m intervals) did not show statistically significant (p>0.05) differences in conductivity (One-Way ANOVA, $F_{(5,\ 426)}$ = 7.81, *p*= 0.0001). Scheffe’s post hoc test further showed that conductivity levels did not differ significantly between the control point (*i.e*. at 200 m) and three other sampling points (20m, 30m and 40m) in the experimental site. Despite the variations, the study's conductivity levels are still regarded as low, which explains Lake Victoria's low ionic content. According to Clottey *et al*. (2016), the Volta Lake had low ionic concentration, which they believed suggested low conductivity, making it favorable for the development of aquatic life. This observation is in line with the findings of the current study. The NEMA recommends an electrical conductivity standard of 400 S/cm. Thus, the average score of 79.6 S/cm observed in the current study was within the range that is considered appropriate for cage fish rearing.

4.1.5. Spatial variability in temperature levels

Temperature levels in the current study ranged from 21.0 to 22.0 ^{0}C at experimental locations and from 21.6 to 22.2 ^{0}C at control sites. Spatially, temperature levels were not significantly different in all the four direction both within the experimental sides and the respective control sides. Scheffe's post hoc test also revealed that there were no substantial temperature differences in all the four directions(Table 4.2). One-Way ANOVA, F(5, 426) = 3.48, p=.0001), a further study of the spatial variation in temperature recorded from water samples collected from the center of the fish cage (0m) toward the open lake, revealed no statistically significant differences between the sampling stations.

Temperature affects every biological and chemical process in an aquaculture operation (Devi *et al*., 2017). Seasonal variations, solar radiation exposure, water depth, local humidity levels, and cloud cover all affect water temperature. The temperature ranges observed in the present study (21.0 ^{0}C and 22.2 ^{0}C) were slightly below the optimum range of 25–32°C reported by Boyd *et al*. (2007) for optimal fish growth. Earlier work by Karikari *et al*., 2013) on Lake Volta in Ghana reported relatively higher temperature ranges of between 27.5 and 30.0°C compared to those reported in the present study. Temperature affects every biological and chemical process in an aquaculture operation (Devi *et al*., 2017).

4.1.6. Spatial variability in turbidity levels

Turbidity, according to Amoako *et al.* (2011), is a measurement of how much dispersed particulates reduce the transparency of water. The turbidity levels rise, making the water murkier. Thus, the presence of dissolved and suspended organic and inorganic elements, as well as plankton and other microorganisms, is indicated by turbidity. At the fish cage sites the turbidity values obtained were in the range of 32.8±2.54 and 37.2± 7.96 for the experimental sites, and between 35.6±1.47 and 35.5±1.71 NTU in the control sites (Table 4.2). The values observed in the present study were far much higher than those observed by Asmah *et al.* (2014) who reported turbidity levels ranging between 1.55 and 6.91 NTU in stratum II of the Volta Lake and even those observed by Clottey (2014) and Ameworwor (2014).

In particular periods of the year, Backwell *et al*. (2012) found that lake water velocities are higher during high tides, which can stir suspend sediments from the lake bed and produce increased turbidities. According to Otieno *et al*. (2017), turbidity in lakes can be impacted by the presence of phytoplankton, sediments from erosion, re-suspended sediments from the bottom, waste discharge, algae growth, material from decaying vegetation, industrial waste, sewage, as well as increased human activities in the lake, like fish cage farming. There were no significant differences (p>0.05) in the present study (Table 4.2) between the turbidity levels in all the four directions (One-Way ANOVA, F (5, 426) = 3.12, p=.0089).This demonstrated how the fish cage farm operated in comparison to the control location. However, there were no significant (p>0.05) variations in turbidity levels between the experimental and control sites in the current investigation. According to Nyanti *et al*. (2012), the similarity in turbidity values could be due to dilution effect caused by waves and currents within the lake.

Fish cages discharge a sizable amount of nutrient-rich wastes (feces, uneaten food, and metabolic products) into the water and underlying sediment, according to Temporetti *et al*. (2001). By decreasing light penetration in the water column, increased turbidity can hinder photosynthesis by phytoplankton and other vegetation (Harrison *et al*., 2005; Cole, 2002), impair fish production, and clog filters. These pollutants may also have significant direct or indirect effects on water quality, some of which show up as changes in physico-chemical parameters as pH, dissolved oxygen, and increased turbidity (Pitta *et al*., 1999). The WHO standard (5.0) is far lower than the average turbidity of the lake water used in this investigation, which was 35.34 NTU on average. Surface water turbidity for optimal growth of fish should be less than 1 NTU or no higher than 5 NTU (Mackay *et al*., 2006). This suggests that none of the study locations had water that was suitable for human consumption without additional treatment.

4.2. Nutrient Levels in the Water Column Around Fish Cages

Total phosphate and total nitrate levels were measured in water samples obtained from both experimental and control sites in the present study.

4.2.1. Spatial variability in total nitrate levels in water

The mean total nitrate levels in the current investigation were higher in control locations (0.69±0.05-0.71±0.07mg/l) than in experimental sites (0.19±0.02-0.62±0.04 mg/l) (Table 4.4). Increased nutrient concentrations may not typically occur close to fish cages, according to Soto and Norambuena (2004). This is because nutrients move quickly up the food chain from phytoplankton to higher levels, as also seen by Mwebaza-Ndawula et al. (2013) at the SON fish farm close to Jinja.

Spatially, total nitrate levels varied significantly across the four sides of the fish cage (One-Way ANOVA, $F_{(3,\ 356)}$ = 9.96, *p*= .0000) with highest total nitrate levels being recorded in the Eastwards side and lowest in the Northwards side of the experimental sites. Further, Scheffe's post hoc test showed that total nitrates were significantly different in all the four directions (Table 4.4).

Table 4.3. Nutrient levels in water samples

Parameter	**Spatial point (distance from centre of the cage towards the four corners & open lake)**						**ANOVA** *p=value*
	0 M	10 M	20 M	30 M	40 M	200 M (Control)	
Total phosphates							
Eastwards	1.24±0.69	1.73±0.02	1.52±0.01	1.38±0.02	1.29±0.08	1.25±0.07	.3369
Northwards		1.31±0.08	1.08±0.09	1.14±0.05	1.30±0.07	1.25±0.02	.8917
Southwards		1.39±0.03	1.39±0.01	1.63±0.02	1.38±0.02	1.26±0.01	.6994
Westwards		1.05±0.06	0.93±0.09	0.92±0.05	0.97±0.06	1.26±0.06	.2583
Total nitrates							
Eastwards	0.69±0.33	0.39±0.03	0.62±0.04	0.62±0.04	0.59±0.07	0.69±0.05	.3294
Northwards		0.25±0.01	0.19±0.02	0.24±0.09	0.23±0.08	0.71±0.07	**.0000**
Southwards		0.22±0.03	0.41±0.01	0.43±0.04	0.37±0.02	0.70±0.06	**.0001**
Westwards		0.34±0.03	0.39±0.01	0.34±0.06	0.37±0.05	0.69±0.05	**.0000**

Table 4.4 Nutrient levels in water levels over the three months period

Parameter	Site	Experimental sites (n=90)				ANOVA (p-value)
		Eastwards	Northwards	Southwards	Westwards	
Total phosphates	Experimental	1.43±0.76	1.22±0.66	1.40±0.76	1.02±0.42	6.92, *p*= **.0002**
	Control	1.25±0.72	1.24±0.72	1.26±0.71	1.26±0.71	0.00, *p*= .9999
Total nitrates	Experimental	0.58±0.43	0.32±0.25	0.42±0.35	0.42±0.24	9.96, *p*= **.0000**
	Control	0.69±0.35	0.71±0.37	0.70±0.36	0.69±0.35	0.01, *p*= .9991

Additionally, total nitrate concentrations varied greatly depending on the direction, with the highest concentrations being found in the east, north, south, and west directions at the 200M (control) sampling location (Table 4.4). Overall, the overall nitrate levels in the fish cage were lower than those in the open waters, which served as the control site. Similar findings were made by an earlier study in Lake Malawi, which discovered that total nitrates had minimal effect on cage culture in the area (Gondwe *et al*., 2011b). Despite the high fish population in the fish cage farms, they discovered little to no spatial and variations in nitrate (NO_{3-}) and particulate nitrogen (PN) in the water column. Strong bottom currents and wild fish populations were credited by Gondwe *et al*. (2011b) with helping to disperse nutrients and consume cage effluents, respectively. The results of the current study call for more frequent sampling during the stratification and mixing phases in order to identify potential nutrient sources or changes in locations with active cage aquaculture and strong water currents.

4.2.2. Spatial variation of total phosphates in water samples

The ideal and productive phosphorus levels for fish cage farming are between 0.05 to 2.0 mg/l, according to Bhatnagar *et al*. (2004). Total phosphate levels in the current study ranged from 1.25±0.02 to 1.26±0.06 mg/l in the control sites and from 0.92±0.05 to 1.73±0.02 in the experimental sites, indicating that the mean total phosphate levels were relatively higher at experimental sites compared to control sites with the exception of the Westward direction which was lower (One-Way ANOVA, $F_{(3, 356)}$ =6.92, *p*= .0002) (Table 4.4). The values obtained from every site fell within the Piper *et al*. (1982) published standards range, making them appropriate for fish production. Even though they were above the 0.1 mg/l permissible level for fish breeding water set by US public health standards (Di, 2002), the levels of phosphates in the water samples used in the current study were generally low. As a result, they are not deemed suitable for human consumption without prior treatment. Considering spatial variations, the findings showed that total phosphate levels were significantly different across the four sides of the cage with the lowest levels being recorded in the westward side of the cage and highest in the eastward side of the cage in the experimental sites (Table 4.4). Further, the Scheffe's post hoc test showed that total phosphates varied significantly in all the four directions. This might have been caused by the activities in the fish cage. The inclusion of some of the nutrients in the feed is linked to the relatively high phosphorus concentrations in the vicinity of fish cages.

The results of the current study are consistent with other investigations in tropical lakes utilized for caged fish farming, which found higher levels of phosphorus and chlorophyll-a in areas with fish cages (Beveridge, 2008; Guo and Li, 2003). Beveridge (2008) asserts that the tilapia fish species only absorbs 17.4% of the supplied phosphorus in fish feed, with the remaining percentage typically being lost to the environment, primarily to the water column and sediments. In reality, Hkanson *et al*. (1988) estimated that only 20% of the phosphorus (P) available in fish feed is utilised for fish growth and final harvest and that the remaining 80% is lost to the environment in particulate (70%) and dissolved (10%) form. Islam (2005) estimated that 25 kg of phosphorus (P) are released into the environment for every ton of fish produced, and Bristow et al. (2008) looked at the effects of a rainbow trout (Oncorhynchus mykiss) cage farm in the experimental lake area of Canada for the first three years of operation and discovered that the annual input of P from waste (67-100 kg) exceeded the natural budget inputs (4-18 kg).

Studies have also shown that fluctuations in the regional distribution of phosphorus concentrations can occur in lake water, albeit the size of the variations can vary greatly depending on the sampling time or the spatial extents (Mwamburi *et al*., 2020). In their transect survey, which encompassed ten locations sampled monthly between March 2005 and March 2006, Gikuma-Njuru *et al*. (2013) observed no identifiable patterns in total P. However, compared to the shoreline waters, the concentration of dissolved inorganic P was greater in the open waters. Eutrophication, according to Tamatamah *et al*. (2005), has an impact on the entire lake, with air deposition accounting for half of the lake's total phosphorus input (Cornelissen *et al*., 2014; Loiselle *et al*., 2008; Silsbe *et al*., 2006). In addition, the circulation patterns of the lake control important in-lake processes that affect the distribution of substances, nutrients, and even organisms (Mukamburi *et al*., 2020).

A water body is deemed eutrophic (Wetzel 1983), if the total phosphate value is between 20 and 30 mg/l. The total phosphate values in the different sampling points in the present study did not vary significantly and only fluctuated between 0.92 and 1.73 mg/l within the fish cage and surrounding areas, which is far below the levels that can be considered eutrophic thus an indication that the waters around the fish cage have not reached the eutrophic state.

However, it is clear from the present study's overall mean total phosphate concentration of 1.40 mg/l that the concentration of total phosphates in Lake Victoria's coastal and pelagic zones has significantly grown since 1960. While this may not only be attributed to eutrophication, which is not a straightforward linear sequence of nutrient accumulation and environmental degradation, as claimed by Kolding et al. (2008), it may also be caused by accumulation of nutrients from feeds used for fish cage farming, other events in the lake, such as a sudden release of nutrients from decomposing vegetation, algal blooms, and explosive growth of floating aquatic plants like water hyacinth that deplete oxygen and cause fluctuations in a number of parameters in water. According to Okuku *et al*. (2018), changes in the concentrations of phosphate in water are a result of a variety of factors in the aquatic environment, including phytoplankton's active uptake, transformations, sinks, and release/retention within sediments.

4.3. Spatial Variations of Heavy Metals in Water Samples

Fish have the ability to accumulate considerable amounts of heavy metals (El-Nemaki *et al*. 2008), hence it is likely that fish grown in contaminated waters will have heavy metals in their body (Benzer *et al*. 2013; Junianto *et al*. 2017). If the habitat in which fish reside is contaminated with heavy metals, then humans may also be at risk as a result of this contamination through the food chain (Vieira *et al*., 2011; Junejo *et al*., 2019). In this study, the control site's mean levels of iron, copper, and zinc were higher than those at the experimental locations (Table 4.6) This might have been due to the high density of fish at the experimental site which consumed the metals through feeding. Among the principal contaminants that are highly hazardous, persistent, and have a propensity to bioaccumulate in the food chain are lead and cadmium. Both humans and aquatic ecosystems are at risk from them (Kouamenan *et al*., 2020). The levels of Fe in water were highest followed by Cu, then Cd and Pb and lowest in Zn (Table 4.6).

4.3.1. Spatial variability of iron levels in water samples

The amounts of iron in water samples in the present study varied between 43.9±0.1 and 44.2±0.3µg/l in the control sites and from 34.2±0.6 to 46.3±0.9 µg/l in the experimental sites (Table 4.6). In comparison to the experimental site, where there were more fish cage activities, iron levels were significantly higher in the control sites than the respective experimental sites with the exception of the iron levels in the northward direction. Iron and other heavy metals may accumulate in sediments due to natural background concentrations of heavy metals, which are unrelated to the feeds used in aquaculture (Basaran *et al*., 2010). Studies also indicate that iron levels are usually high in nature and could be a thousand times high in sediments compared to water column. Since sediments serve as a substantial repository for all pollutants and dead organic matter (Nguyen *et al*., 2005), Saeed and Shaker's (2008) research of the levels of iron accumulation in water column and sediments found that heavy metals gather higher in sediments than in water column. This may assist to explain why the iron levels in the open seas (the study's control location) were greater than those in the fish cage.

Spatially, iron levels were highest in the Eastwards direction (38.9±0.4 - 46.3±0.9 µg/l) and lowest in the Southwards direction (34.2±0.6 -38.7±0.5 µg/l) (Table 4.6). These concentrations can be regarded as extremely low and fall below allowable limits of Fe in water of 300 g/l as suggested by USEPA (1986). Although the iron levels were relatively low, accumulation over time may exceed acceptable limits hence posing a threat to the aquatic ecosystem. Gordon and Ansa-Asare (2012) found similar low amounts of iron in Lake Volta. A freshwater satellite lake in Kenya with similarly low iron levels supports the findings (Mwamburi, 2009). They suggested that the absence or little intake of this specific heavy metal into the lake may be a contributing factor in the low levels of heavy metals.

Table 4.5 Spatial variations in levels of heavy metal in water (µg/l)

Parameter	Spatial point (distance from center of the cage towards the four corners & open lake)						ANOVA (p-value)
	0 M (center of the cage)	10 M	20 M	30 M	40 M	200 M (Control)	
Lead							
Eastwards	14.7±1.61	14.4±1.59	13.9±1.91	14.4±2.52	14.9±1.39	14.5±1.81	.6528
Northwards		13.4±3.69	14.2±3.56	13.5±3.87	12.9±3.49	14.5±1.75	.5230
Southwards		15.4±3.64	14.5±3.47	13.6±3.58	12.3±4.02	14.3±2.06	.3812
Westwards		15.8±1.37	14.9±1.29	13.3±2.86	14.4±3.22	14.3±1.80	.0386
Zinc							
Eastwards	11.9±1.53	11.3±0.06	12.6±0.41	11.8±0.36	11.7±0.66	12.1±0.55	.4613
Northwards		11.9±0.99	11.3±0.74	12.6±0.72	11.3±0.44	12.2±0.46	.6734
Southwards		11.6±0.22	11.3±0.72	18.3±0.22	15.9±0.70	12.2±0.33	.1057
Westwards		12.6±0.48	13.0±0.10	11.9±0.13	11.1±0.19	12.3±0.61	.1609
Cadmium							
Eastwards	21.9±3.44	21.0±3.69	21.3±2.79	20.7±3.84	21.9±3.44	21.8±3.38	.8280
Northwards		19.9±4.68	20.8±5.61	19.2±4.99	19.6±4.82	21.8±3.46	.3481
Southwards		21.4±5.16	19.9±4.74	19.3±4.93	19.5±5.58	21.8±3.61	.3036
Westwards		18.9±4.49	21.7±4.08	20.1±4.01	19.9±4.48	21.6±3.74	.1652
Iron							
Eastwards	44.1±1.5	38.9±0.4	40.4±0.5	45.1±0.9	46.3±0.9	43.9±0.6	.6764
Northwards		37.9±0.5	36.9±0.5	37.9±0.4	39.6±0.8	44.1±0.4	.4730
Southwards		34.2±0.6	37.8±0.2	38.7±0.5	36.6±0.9	43.9±0.1	.1819
Westwards		41.2±0.6	39.4±0.9	42.3±0.3	42.7±0.3	44.2±0.3	.9321
Copper							
Eastwards	34.9±1.55	32.1±0.67	34.4±0.67	34.7±0.89	34.9±0.25	35.3±0.69	.0119
Northwards		30.2±0.72	29.2±0.51	29.6±0.53	30.6±0.15	35.1±0.72	.0002
Southwards		28.8±1.31	31.8±0.69	31.4±0.98	31.3±0.50	35.0±0.76	.0003
Westwards		31.9±028	33.3±0.42	33.3±0.71	32.9±0.19	35.2±0.64	.0107

Table 4.6. Variations in levels of heavy metal in water during the three months

Parameter		Experimental sites (n=90)				ANOVA (*p-value*)
		Eastwards	**Northwards**	**Southwards**	**Westwards**	
Lead	Experiment	14.5±1.84	13.8±3.33	14.3±3.39	14.6±2.31	1.64, *p*= .1794
	Control	14.1±0.54	14.3±0.61	13.8±0.67	14.1±0.80	0.09, *p*= .9671
Zinc	Experiment	11.9±1.97	11.8±2.76	13.8±9.89	12.1±2.36	2.77, *p*= **.0414**
	Control	10.9±0.41	14.3±0.61	10.8±0.42	10.8±0.71	0.03, *p*= .9942
Cadmium	Experiment	21.4±3.42	20.3±4.76	20.4±4.84	20.6±4.18	1.20, ***p*=** .3095
	Control	19.4±5.2	19.3±5.2	19.4±5.5	18.9±5.57	0.02, *p*= .9972
Iron	Experiment	42.9±15.16	39.3±14.1	38.3±13.5	41.9±14.69	2.10, *p*= .0993
	Control	33.9±23.63	34.3±23.51	34.2±23.4	33.9±23.15	0.00, *p*= .9999
Copper	Experiment	34.2±2.99	30.9±5.54	31.6±5.02	33.3±3.09	10.99, ***p*= .0000**
	Control	36.9±0.54	36.7±0.41	36.6±0.48	36.7±0.40	0.01, *p*= .998

4.3.2. Spatial variability of copper levels in water

When treating cage nets, copper is typically used as an antifouling agent (Nikolaou *et al.*, 2014). The most frequent chemicals used in net cleaning are those that include copper (Shakouri, 2000). Copper levels were significantly higher in the control sites (36.0±0.76-35.3±0.69 µg/l) relative to the experimental sites (28.8±1.31 - 34.7±0.89 µg/l) (t = -4.7955, df=430, *p*= 0.0000) (Table 4.6). This is because there are no fishing activities using copper treated nets at the experimental sites but the activities are carried out in open waters hence the accumulation of copper. From the results, the impact of copper in cage farming is minimal given that the levels in the experimental site where the fish cages were located were lower compared to the control sites – located 200m from the fish cages. A previous study by Winsby (1996) reported almost similar copper concentration levels between a copper treated net and a control net located 700 m away. Buschmann (2002) discovered that cage culture activity was not linked with the rise in dissolved copper concentration in Chilean salmon farms. A research by EAO (1996) found that there was not a significant amount of copper in the water from different lakes in British Columbia, despite the metal being used in antifouling agents and feed in cage culture.

Spatially, the mean copper levels across the four different directions were the highest in the Eastward direction (32.1±0.67 - 34.7±0.89 µg/l) followed by Westward (31.9±028-33.3±0.71 µg/l) then Southward (28.8±1.31 - 31.8±0.69 µg/l) and lowest in the Northwards direction (29.2±0.51 - 30.2±0.72 µg/l) (One-Way ANOVA, $F_{(3,\ 356)} = 10.99$, $p= .0000$). This was confirmed by the Scheffe's post hoc test showing significant differences in copper levels in the four different directions (Table 4.6). The fast rate of dilution of copper, flushing out of residue by the water current, or binding of copper with organic and inorganic material in the water column, which precipitates the metal into the sediment, may all contribute to a reduced risk of environmental consequences. According to numerous studies, copper levels in fish cages were within the acceptable Cu limits in aquatic waters which are consistent with the findings of the current study.

4.3.3. Spatial variability of cadmium levels in water

Spatially, cadmium levels were almost uniform in all four directions as indicated in Table 4.6. There were no significant differences between the Cd levels in the experimental sites and their respective control sites. This was an indicator that fish cage farming had minimum effect on the accumulation of Cd in lake water. However, the data obtained in this investigation indicated that cadmium levels in the water were higher than the 5 g/l threshold that is recommended for freshwater farming (Mélard, 1999). As Mutlu and Kurnaz (2018) have noted, this pollution can be related to the constant usage of nutrients for agricultural purposes near the fish cages. Due to the fact that fish are usually affected by water pollution (Mensoor and Said, 2018), contaminated water has the potentialof increasing the concentrations of heavy metals in fish tissues (Qadir and Malik, 2011; Yasmeen *et al.*, 2016).

4.3.4. Spatial variability of lead levels in water

A comparison of heavy metals in water samples collected from control and experimental sites showed that lead levels did not vary significantly between control and their respective experimental sites. The concentrations of lead did not vary significantly in all the four directions and the different sampling points ($p \geq 0.05$) (Table 4.6). Lead metal is extremely harmful to humans and has no nutritional value. Lead is usually used during the soldering of fish cages although this has minimal effects in water since it is insoluble in water. Fish suffocation and gill damage are two effects of Pb on fish health (Authman *et al*., 2015). Even trace levels of lead can be harmful (Tchounwou *et al*. 2012; Waseem *et al*. 2014). The lack of a substantial difference in lead levels between the control and experimental sites in the current research points to a source other than fish cages. In line with the findings of the current investigation, Mannzhi *et al*. (2021) found that levels of lead in fish meals did not contribute to an upward trend in Pb levels in water or in fish gills. This study was conducted in the Vhembe District of Limpompo Province, South Africa. This was linked to the pH of the water, which regulates metal breakdown and restricts metal absorption into fish tissue.

According to studies, lead typically enters lakes through wastewater from industries like electroplating, electrical, steel, and explosive manufacturers, among others (Acharya *et al*., 2009). This is because the majority of industrial effluents contain lead in higher than average concentrations. Therefore, the industries around Lake Victoria that indiscriminately discharge waste water laden with heavy metals among other pollutants could have contributed to most of the lead levels reported in the present study. Despite this, the lead content was below the upper limits that are permitted for these metals in fish cage farming. This might be because lead tends to accumulate more heavily at the bottom sediments of surface waters, where their concentration is larger than that of the water column (Svobodova, 1993).

4.3.5. Spatial variability of zinc levels in water

To prevent poor growth, increased mortality, cataracts in the eyes, short body dwarfism, and low tissue, zinc must be supplied to fish meals at a rate of 30 to 100 $mgkg^{-1}$ (Maage *et al*. 2001). Spatially, the average zinc level recorded in water samples were highest in the Southwards direction (11.6±0.22-18.3±0.22 µg/l) than the other three directions that were not significantly different from each other (One-Way ANOVA, $F_{(3, 356)}$ = 2.77, p= .0414) (Table 4.6). A comparison of heavy metals in water samples collected from control and experimental sites showed that zinc levels did not vary significantly between control and the respective experimental sites. Saluwa *et al.* (2016) found low quantities of Zn (8.32-11.63 ug/l) in fish and water samples, and the results of the current investigation closely matched their findings. On the other hand, salmon farms in Canada and the US have been observed to have significant zinc concentrations in their sediments and water column. Chou *et al.* (2002) investigated trace metals in sediments around a salmon cage in New Brunswick, Canada, and discovered a sharp spatial increase in zinc concentration in a heavily sedimented area. Brooks and Mahnken (2003) reported zinc concentrations of up to 200 mg/l in sediments around fish cages in British Columbia. Zinc concentrations outside of the cage were typically 2 to 3 times lower, but under anoxic conditions, zinc concentrations reached 25385.7 g/l. In the current experiment, zinc levels in the water column were below the allowed limits recommended by USEPA (1986), hence not harmful to the aquatic environment. Gordon and Ansa-Asare (2012) reported similar low levels of heavy metal in the lake. The outcomes are in line with a freshwater satellite lake in Kenya where Zn levels in the water were extremely low (Mwamburi, 2009). They suggested that the ability of the lake water to dilute the heavy metals near the fish cages may be a contributing factor in the low levels of zinc.

In general, metals-fortified fish diets have been shown to significantly increase the amount of heavy metal contamination in the sediments and water beneath fish cages (Sapkota *et al*., 2008). In the sediments and water columns beneath cage farms in the eastern Mediterranean, elevated concentrations of metals like Cu, Fe, Pb, Zn, and Cd have been discovered (Belias *et al*., 2003; Basaran *et al*., 2010). Researchers Mendiguchia *et al*. (2006) and Sutherland *et al*. (2007) reported increased amounts of heavy metals in lake water and sediments as a result of cultural activities in their subsequent investigations. Heavy metal pollution provides a number of concerns to human health, some of which include neurotoxicity and cancer-causing effects (Sapkota *et al*., 2008). The concentrations of all the heavy metals were nevertheless below WHO-permissible values. This suggests that fish cages are not considerably damaging the lake because of the low mixing of organic and inorganic wastes, the lake's current, and its capacity to mix.

4.4. Heavy Metal Levels in Fish (*Oreochromis niloticus*) Samples

Fish can be seriously threatened by unacceptable heavy metal levels in their ecosystem (Vilizzi and Tarkan, 2016). Fish tissue may change as a result of these high metal concentrations. Indeed, a number of recent studies (Coulibaly *et al*., 2012; Abarghoei *et al*., 2016; Kouamenan *et al*., 2020) have hypothesized that the detrimental impacts of heavy metals may be associated to the changes in fish tissue. While the levels of the two highly toxic heavy metals (lead and cadmium), did not vary in fish obtained from the experimental and control sites in the current study, the concentrations of essential metals like iron, copper, and zinc were higher in fish samples collected from the control point than the experimental sites (Table 4.8). This is mainly due to age of the fish since the age of fish in cages is monitored while those in open waters cannot be monitored. Fish excrement and uneaten feed contain significant levels of phosphate, nitrogen, carbon, and heavy metals compared to the natural sediment (Morrisey *et al*., 2000). Metals such as zinc (Zn), iron (Fe), and copper (Cu) are included into fish feed to fulfill essential mineral requirements (Elnabris *et al*., 2013).

4.4.1. Spatial variability in lead levels in fish samples

There were no significant differences between the lead levels in fish obtained from the experimental and their respective control sites (Table 4.8). There were also no significant differences in the concentrations of lead in the fish obtained from all the four different directions. However, the levels of lead in fish tissue in the study ranged from 12.9±0.49 to 15.5±0.57 µg/l.

Similarly, other researchers have also reported lower levels of lead ranging between 4 µg/l -8 µg/l in Ambon Bay (BTKLPPM, 2008). In comparison to lead levels of 0.48 g/l found in Tilapia nilotica in Soltan *et al*. (2005)'s research of Lake Nasser in Egypt, the mean lead levels found in the current study were substantially higher. The lead concentrations in all fish species in the present study were within the permissible limits of 500ug/l as set by the FAO (1983) and the 400 µg/l set by the EC.

Table 4.7. Heavy metals in fish Gills

Parameter	Spatial point (distance from center of the cage to four corners & open lake)						ANOVA (p-value)
	0 M (center of the cage)	10 M	20 M	30 M	40 M	200 M (Control)	
Lead							
Eastwards	14.6±1.61	14.3±0.79	13.9±0.21	15.0±0.76	15.0±0.35	14.4±0.83	.3832
Northwards		13.3±0.65	14.2±0.56	13.5±0.87	12.9±0.49	14.2±0.57	.4556
Southwards		14.9±0.83	13.9±0.73	13.6±0.61	13.2±0.03	14.5±0.83	.5336
Westwards		15.5±0.57	13.4±0.89	13.7±0.78	14.6±0.29	14.4±0.61	.1171
Zinc							
Eastwards	12.1±1.65	11.8±1.46	12.6±2.48	11.7±2.05	11.6±1.72	12.1±1.60	.6725
Northwards		11.8±2.98	11.3±2.74	12.6±3.72	11.3±2.44	11.9±1.66	.6740
Southwards		11.5±2.17	11.5±2.74	18.1±7.2	15.8±3.8	11.9±1.66	.1286
Westwards		12.8±2.16	12.1±2.96	11.7±3.11	11.0±2.27	11.8±1.65	.3302
Cadmium							
Eastwards	22.1±3.52	21.6±2.99	20.5±3.69	21.9±3.36	20.6±4.07	21.9±3.68	.6470
Northwards		19.7±4.57	20.8±5.61	19.2±4.99	19.6±4.82	21.7±3.73	.2906
Southwards		21.1±5.76	19.5±5.11	19.1±5.19	20.1±4.92	22.1±3.55	.3010
Westwards		21.7±4.04	20.3±4.13	20.5±4.53	20.3±4.17	21.9±3.72	.4157
Iron							
Eastwards	44.2±1.5	40.8±1.1	41.9±1.7	46.5±2.2	42.5±3.3	43.9±3.4	.9060
Northwards		39.5±1.4	36.9±2.5	37.9±3.4	39.6±1.8	44.1±2.1	.6622
Southwards		33.2±1.9	37.9±1.8	38.4±3.9	36.7±2.8	42.3±2.9	.1973
Westwards		43.1±2.0	39.2±1.5	42.4±3.2	42.2±1.4	43.7±2.2	.9381
Copper							
Eastwards	34.9±2.55	33.8±0.97	33.5±0.25	36.3±0.25	33.0±0.35	35.2±0.73	**.0020**
Northwards		31.2±0.47	29.2±0.01	29.6±0.53	30.6±0.15	33.4±0.34	.0558
Southwards		30.2±0.48	31.6±0.90	31.2±0.42	31.3±0.55	34.2±0.23	.2452
Westwards		32.7±0.77	32.5±0.27	33.7±0.27	32.9±0.57	35.2±0.99	.0571

Table 4.8. Heavy metals in fish samples for three month period

Parameter	Site	Experimental sites (n=90)				ANOVA (p-value)
		Eastwards	Northwards	Southwards	Westwards	
Lead	Experimental	14.6±1.78	13.8±3.33	14.1±3.46	14.4±2.59	1.39, *p*= .2454
	Control	14.4±1.83	14.2±1.57	14.5±1.83	14.4±1.61	0.07, p= .9765
Zinc	Experimental	11.9±1.89	11.8±2.77	13.8±9.90	11.9±2.51	2.83, *p*= **.0386**
	Control	12.1±1.60	11.9±1.66	11.9±1.66	11.8±1.65	0.10, p= .9608
Cadmium	Experimental	21.3±3.53	20.3±4.78	20.4±4.95	20.9±4.09	1.11, p= .3442
	Control	21.9±3.68	21.7±3.73	22.1±3.55	21.9±3.72	0.03, p = .9927
Iron	Experimental	43.2±14.98	39.3±14.11	38.1±13.6	42.2±14.6	2.50, p= .0596
	Control	43.9±15.4	44.1±15.06	42.3±14.9	43.7±15.0	0.05, p= .9843
Copper	Experimental	34.3±2.75	30.9±5.54	31.5±5.27	33.3±3.42	11.66, *p*= **.0000**
	Control	35.2±2.73	33.4±6.34	34.2±4.23	35.2±2.98	0.72, p= .5448

4.4.2. Spatial variability in zinc levels in fish samples

Zinc alongside other heavy metals can be found in manufactured fish feeds (Dean *et al.*, 2006; Kalantzi *et al.*, 2013). The levels of Zn in gills of fish obtained from experimental sites did not vary significantly (p>0.05) with the levels of Zn in fish obtained from the control sites (Table 4.8). This could be explained by the fact that nearby wild tilapia also consume feed spilled from fish farms, exposing them to higher concentrations of important metals than wild fish in open waterways coming from distant places (Basaran *et al*., 2010; Ballester-Molto *et al*., 2017). These results are in line with those of Pitta *et al*. (2006), who found that neither the experimental site nor the control site's distance from the cages caused zinc levels to vary much. Zinc is an essential metal that is supplied as a trace element to fish feed since it is required for many biological processes (Yildiz 2008; Fallah *et al*., 2011). Because Lake Victoria has a sizable water surface area and volume and is somewhat deep, the high dilution rates and recycling processes in the lake may have had an impact on the low zinc levels seen in fish from both the experimental location and the control site. Numerous field and laboratory investigations have shown that the concentrations in the rearing medium have little effect on the quantity of zinc that fish acquire in different tissues (Vinagre, 2004). Fish are thought to be at higher levels of the food chain and may absorb significant amounts of certain metals from water (Karadede *et al*. (2004).

In the present study, zinc levels were not significantly different among the fish samples obtained from the four different directions (One-Way ANOVA, $F_{(3, 365)} = 2.83$, p = .0686). According to a number of researchers, a variety of factors, including seasonal changes (Phillips, 1980), fish organs (Gomaa, 1995), age, size, and length of fish (Linde *et al*., 1998; Yousuf *et al*., 2000), and their habitats (Canli and Atli, 2003; Daifullah *et al*., 2003), can influence the rate of accumulation of heavy metals in fish tissues. The relationship between fish length and weight and the accumulation of heavy metals in the same species has already been established (Baptista *et al*., 2019; Yi and Zhang, 2012; Liu *et al*., 2015). Additionally, it was noticed by Yousuf et al. (2000), Canli and Atli (2003), and Karadede *et al*. (2004) that fish have a propensity to absorb contaminants (heavy metals) from their environment at various levels.

4.4.3. Spatial variability of cadmium levels in fish samples

Cadmium is a highly poisonous heavy metal that is totally unnecessary for all living things. As industrialisation increases, environmentalists are increasingly concerned about the buildup of Cd in freshwater bodies like lakes (Drg-Kozak et al., 2019; Abalaka, 2015). The human body can store cadmium from fish, particularly in the kidneys. Kidney injury (damage to the renal tubules), based on present knowledge, is likely the most important health effect (ECDG, 2002) The levels of cadmium in fish samples collected from control site did not vary significantly ($p>0.05$)from those collected from experimental sites (Table 4.8). The levels did also not vary in the fish obtained in all the four directions. In Lake Manzalah, Egypt, Sallam et al. (2019) reported the Cd levels in Nile tilapia (0.024 captured from a cage farm), and they explained these results by blaming a shortage of fresh water supply required to carry waste from the cages to the open lake.

According to studies, wild tilapia can live up to 9 years longer than farmed tilapia, which is harvested six months after it is raised in cages on a lake. Therefore, compared to farmed tilapia, the wild tilapia can accumulate pollutants with long biological half-lives like Cd throughout a longer life span. Research by Hamada et al. (2018) showed positive correlations between tilapia Cd concentrations and age and size. However, we were unable to find any links between heavy metals and fish length in the current investigation. It is also highly likely that the flow of industrial effluents discharged into the lake accumulates more cadmium in the fish flesh in the open waters around the study area compared to those caused directly or indirectly by the fish cages.

4.4.4. Spatial variability of copper levels in fish samples

A crystal-clear indicator of both the concentration of these metals in fish tissue relative to their concentration in water and the propensity of fish muscle to accumulate these metals relative to their abundance in water is typically provided by the bioaccumulation factor for various heavy metals in fish muscle. According to the current analysis, fish tissue had copper levels between 29.2±0.01 µg/l and 36.3±0.25 µg/l (Table 4.8). Geographically, the concentrations of copper in fish samples taken from experimental sites and control sites differed significantly (t= -3.3710, df = 430, p=.0008). The levels of Cu in fish obtained from the experimental sites were lower than those in fish obtained from the respective control sites in all the four directions (t= -3.3710, df = 430, *p*= .0008). The levels of Cu in fish were highest in those obtained from the Eastward direction (33.0±0.35 -36.3±0.25 µg/l), followed by Westward direction (32.5±0.27 - 32.9±0.57 µg/l), then in the Southwards (30.2±0.48-31.6±0.90 µg/l) and lowest in those obtained from the Northward direction (29.2±0.01-31.2±0.47 µg/l). The Scheffe's post hoc test revealed significant differences in copper levels in fish obtained from all the four different directions.

The mean Cu concentrations in the current study were significantly higher than the 0.2–0.5 g/l Cu range that was discovered in *Oreochromis niloticus* from the Winam Gulf over 20 years ago (Ochieng 1987) and the 1.9 g/l Cu mean concentration that was reported in *O. niloticus* samples from the Mwanza Gulf of Lake Victoria in Tanzania by Kishe and Machiwa (2003). However, the amounts in this study were far lower than the EC and FAO allowed limits of Cu, which are 10,000 g/g and 30,000 g/g, respectively. The mean Cu concentrations in the current study were significantly higher than the range of 0.2-0.5 g/l Cu discovered in *Oreochromis niloticus* from

Winam Gulf over 20 years ago (Ochieng 1987) and a mean concentration of 1.9 g/l Cu reported by Kishe and Machiwa (2003) in *Oreochromis niloticus* sampled from Mwanza Gulf of Lake Victoria in Tanzania. However, the amounts in this study were far lower than the EC and FAO allowed limits of Cu, which are 10,000 g/g and 30,000 g/g, respectively.

4.4.5. Spatial variability of iron levels in fish samples

In the present study, the iron levels in fish samples ranged between 33.2±1.9 and 46.5±2.2 µg/l (Table 4.8). The levels of iron in fish obtained from the control sites were significantly higher than those in fish from the respective experimental sites. The order of the concentration of iron was that it was highest in fish obtained Eastwards (40.8±1.1 - 46.5±2.2 µg/l) > Westwards (39.2±1.5 - 43.1±2.0) > Northwards (36.9±2.5 - 39.6±1.8 µg/l) > Southwards (33.2±1.9 - 38.4±3.9 µg/l). The reason why the Fe concentration levels found in the present study were significantly higher than those found in *Oreochromis niloticus* from the Winam Gulf in a previous study by Ochieng (1987), ranging from 1.0 to 6.4 µg/g dry weight, can be attributed to the current level of lake pollution and increased uptake and accumulation of the metal by fish recently.

CHAPTER FIVE

CONCLUSION, RECOMMENDATIONS AND SUGGESTIONS FOR FUTURE STUDIES

5.1. Conclusions

There were statistically no significant differences in temperature, turbidity, BOD and conductivity between the experimental and their respective control sites, while pH and DO were higher in the control sites relative to experimental sites.

The levels of total nitrates were greater in the control water samples as compared to those obtained from the experimental sites, while those of phosphates were higher in the experimental sites compared to the control sites.

The concentrations of Cd, Pb and Zn did not vary significantly between water samples obtained from control and experimental sites while, the quantities of Fe and Cu were greater in the water obtained from the control sites compared to the experimental sites.

The quantities of Pb, Zn and Cd in fish obtained from the experimental sites were similar to those obtained from fish in the respective control sites. Levels of Cu and Fe obtained from fish in the control sites were greater than those obtained from fish in the experimental sites.

5.2 Recommendations

- There is need for regular monitoring surveys to keep pace with possible environmental changes resulting in fluctuations in water physico-chemical parameters, especially given the fact that historical data indicates fast changing lake ecology because of increased human activities in the lake and lake catchment area. Some active management strategies to prevent fluctuations in physico-chemical parameters could include avoiding overcrowding of fish in cages coupled with frequent sampling for key physico-chemical parameters like DO to detect and arrest any changes in time.

- Given that most nutrients emanate from the catchment areas, there is need for regional coordination between countries surrounding Lake Victoria to ensure that there are coordinated actions to address the common challenges of point and non-point source pollution which contribute to the high nutrient levels in the lake.
- While the levels of heavy metals dissolved in water were still below levels that can be considered harmful or toxic to humans, there is need for more frequent sampling during the stratification and mixing periods to detect possible sources or changes in dissolved heavy metals where cage aquaculture operations are active and with strong water currents given the significant amounts of some heavy metals use in aquaculture operations.
- There is need to monitor the seasonal variations of these parameters and heavy metals in order to ascertain the impact of fish cage in the lake during different seasons.

5.3 Areas for Further Research

- There is need for studies that would incorporate biological and physico-chemical data with socio-economic information of cage fish owners and operators on the methods of waste disposal; perception of possible water contamination; awareness of Lake Victoria environmental management and maintenance policies/best practices and actions that can be taken to preserve the lake.
- The present study adopted quasi-experimental design to obtain information on the spatial variations on water quality and heavy metal bioaccumulation in *O. niloticus* in fish cages and open waters in Usenge, Lake Victoria. Future studies need to explore use of mixed methods design that not only explores the quantitative aspect of the data but also explores insights qualitatively through focus group discussions and key informant interviews with different stakeholders around the lake.

REFERENCES

Abalaka SE (2015) Heavy metals bioaccumulation and histopathological changes in Auchenoglanis occidentalis fish from Tiga dam, Nigeria. J Environ Health Sci Eng 13:67. https://doi.org/10.1186/s40201-015-0222-y

Abarghoei, S., Hedayati, A., Ghorbani, R., Miandareh, H. K. and Bagheri, T. (2016). Histopathological effects of waterborne silver nanoparticles and silver salt on the gills and liver of gold fish *Carassius auratus*. *International Journal of Environmental Science Technology*,13:1753 1760.https://doi.org/10.1007/s13762-016-0972-9

Abayechaw, D., & Dikr, W. (2023). Key to Life, Risks and Cycle of Nitrogen. *Cross Current Int J Agri Vet Sci*, *5*(4), 43-48.

Acharya, J.; Sahu, J.N.; Mohanty, C.R.; Meikap, B.C. (2009). Removal of lead(II) from wastewater by activated carbon developed from Tamarind wood by zinc chloride activation. *Chemical Engineering Journal*. 149:249-262, https://doi.org/10.1016/j.cej.

Adekunle, A.S. (2008). Impacts of Industrial Effluent on Quality of Well Water within Asa Dam Industrial Estate, Ilorin, Nigeria. Nature and Science, 6:1-5.

Agyei, B. P. (2022). *Sustainability of pond and cage fish farming systems in the Ashanti, Bono, Eastern and Volta regions in Ghana* (Master's thesis, Norwegian University of Life Sciences).

Ahmad, A., Abdullah, S. R. S., Hasan, H. A., Othman, A. R., & Ismail, N. I. (2021). Aquaculture industry: Supply and demand, best practices, effluent and its current issues and treatment technology. *Journal of Environmental Management*, *287*, 112271.

Akegbejo-Samsons, Y. (2022). Aquaculture and fisheries production in Africa: highlighting potentials and benefits for food security. In *Food Security for African Smallholder Farmers* (pp. 171-190). Singapore: Springer Nature Singapore

Allan, J. D. (2004). Landscapes and riverscapes: the influence of land use on stream ecosystems. *Annu Rev Ecol* 35:257–284

Amankwaah, D., Cobbina, S. J., Tiwaa, Y. A., et al., (2014) Assessment of pond effluent effect on water quality of the Asuofia Stream, Ghana. *African Journal of Environmental Science and Technology* 8(5):306 - 311.

Ameworwor, M. (2014) Impacts of Fish Cage Culture on Water Quality and Selected Commercially Important Fish Stocks in Volta Lake (Stratum II). (Mphil. Thesis). Department of Marine and Fisheries Sciences, University of Ghana, Legon.118pp.

Amisah, S. and Quagrainie, K. K. (2007). Opportunities and challenges for sustainable tilapia production and commercialization in Ghana. *Paper presented at the World Aquaculture Conference,* San Antonio, USA, Nov. 23-28, 2017.

Amoako, J., Karikari, A.Y. & Ansa-Asare, O.D. (2011). Physico-chemical quality of boreholes in Densu Basin of Ghana. *Appl Water Sci*. 1:41–48. https://doi.org/10.1007/s13201-011-0007-0

Anand, A., Krishnan, P., Kantharajan, G., Suryavanshi, A., Kawishwar, P., Raj, U., ... & Babu, D. E. (2020). Assessing the water spread area available for fish culture and fish production potential in inland lentic waterbodies using remote sensing: A case study from Chhattisgarh State, India. *Remote sensing applications: Society and environment*, *17*, 100273.

Anjejo, K. O. (2019). *Cage Fish Farming and Its Effects on Livelihoods of Fisherfolk Within Anyanga Beach, Siaya County, Kenya* (Doctoral dissertation, University of Nairobi).

Antwi, L. A. K. & Ofori-Danson, P. K. (1993) Limnology of a tropical reservoir in Ghana. *Tropical Ecology* 34, 75 – 87.

Apostolaki, E. T., Tsagaraki, T., Tsapaki, M., et al., (2007). Fish farming impact on sediments and macrofauna associated with seagrass meadows in the Mediterranean. *Estuarine, Coastal and Shelf Science* 75:408 - 416.

Araujo, G. S., Silva, J. W. A. D., Cotas, J., & Pereira, L. (2022). Fish farming techniques: Current situation and trends. *Journal of Marine Science and Engineering*, *10*(11), 1598.

Asamoah, E., Nketia, K. A., Sadick, A, Gyembibi K. A., Forkuo, E. K., Ayer, J. and Adjei, E. O. (2015). Water Quality Assessment of Lake Bosomtwe for Irrigation Purpose. *International Journal of Agricultural and Crop Sciences*. 8(3): 366- 372.

Asase, A. (2013). Effects of Stocking Density on the Production of Nile Tilapia (Oreochromisniloticus) in Floating Net Cages on the Volta Lake. (M.Phil. Thesis). Department of Marine and Fisheries Sciences, University of Ghana, Legon. 125pp.

Asmah, R., Karikari, A., Abban, E., Ofori, J. and Awity, L. (2014). Cage fish farming in the Volta Lake and the lower Volta: Practices and potential impacts on water quality. *Ghana Journal of Science*. *54*(1):33–47.

Aura, C. M., Mwarabu, R. L., Nyamweya, C. S., Ongore, C. O., Musa, S., Keyombe, J. L., ... & Njiru, J. M. (2024). Unbundling sustainable community-based cage aquaculture in an afrotropical lake for blue growth. *Journal of Great Lakes Research*, *50*(5), 102410.

Authman M.M.N., Zaki M.S., Khallaf E.A., Abbas H.H. (2015). Use of fish as bio-indicator of the effects of heavy metals pollution. *J. Aquac. Res. Dev.* 6(4):1–13.

Ballester-Molto, M., Sanchez-Jerez, P., Aguado-Gimenez, F. (2017). Consumption of particulate wastes derived from cage fish farming by aggregated wild fish. An experimental approach. *Mar Environ Res*. 130:166–173. doi: https://doi.org/10.1016/j.marenvres.2017.07.014.

Baptista, M., Azevedo, O., Figueiredo, C., Paula, J., Santos, M., Queiroz, N., Rosa, R., Raimundo, J. (2019). Body size and season influence elemental composition of tissues

Basaran, A. K., Aksu, M., & Egemen, O. (2010). Impacts of the fish farms on the water column nutrient concentrations and accumulation of heavy metals in the sediments in the eastern Aegean Sea (Turkey). *Environmental monitoring and assessment*, 162(1-4):439-451.

Bashir, I., Lone, F. A., Bhat, R. A., Mir, S. A., Dar, Z. A., Dar, S. A. (2020). Concerns and Threats of Contamination on Aquatic Ecosystems. Bioremediation and Biotechnology. 27:1–26. doi: 10.1007/978-3-030-35691-0_1. PMCID: PMC7121614.

Belias, C. V., Bikas, V. G., Dassenakis, M. J., and Scoullos, M. J. (2003). Environmental impacts of coastal aquaculture in eastern Mediterranean bays the case of Astakos Gulf. *Greece. Environmental Science and Pollution Research*. *10*(5): 287.

Bergsson, H., Svendsen, M. B. S., & Steffensen, J. F. (2023). Model of Oxygen Conditions within Aquaculture Sea Cages. *Biology*, *12*(11), 1408.

Benzer, S., Arslan, H., Uzel, N., Gül, A. and Yilmaz, M. (2013). Concentrations of metals in water, sediment and tissues of *Cyprinuscarpio* L, 1758 from Mogan Lake (Turkey*)*. *Iranian Journal of Fisheries Sciences*, 12: 45-55.

Beveridge, M. (2008). Cage Aquaculture, 3rd ed. John Wiley & Sons.

Bhatnagar, A. and Devi, P. (2013) Water quality guidelines for the management of pond fish culture. *International Journal of Environmental Sciences* 3:6.

Boonyapookana, B., Parkpian, P., Techapinyawat, S., Delaune, R.D., Jugsujinda, A. (2005). Phytoaccumulation of lead by sunflower (Helianthus annus), tobacco (Nicotiana tabacum), and vetiver (Vetiveria zizanioides). - *J. Environ. Sci. Health* 40: 117-137

Borgå, K., McKinney, M. A., Routti, H., Fernie, K. J., Giebichenstein, J., Hallanger, I., & Muir, D. C. (2022). The influence of global climate change on accumulation and toxicity of persistent organic pollutants and chemicals of emerging concern in Arctic food webs. *Environmental Science: Processes & Impacts*, *24*(10), 1544-1576.

Boyd, C. E. (2018). Aquaculture pond fertilization. *CABI Rev*. 1–12.

Boyd, C. E., Tucker, C. S., McNevin, A., Bostick, K., & Clay, J. (2007). Indicators of resource use efficiency and environmental performance in fish and crustacean aquaculture. *Reviews in Fisheries Science, 15*(4):327–360.

Brčić, J., Einarsson, H., Feekings, J. P., Glemarec, G., Kindt-Larsen, L., Krishnan, P., ... & Yochum, N. (2023). ICES-FAO Working Group on Fishing Technology and Fish Behaviour (WGFTFB).

Bright, C., Mager, S., & Horton, S. (2020). Response of nephelometric turbidity to hydrodynamic particle size of fine suspended sediment. *International Journal of Sediment Research*, *35*(5), 444-454.

Bristow, C. E., Morin, A, Hesslein, R. H., Podemski, C. L. (2008). Phosphorous budget and productivity of an experimental lake during the initial three years of cage aquaculture. *Can J Fish Aquat Sci* 65(11): 2485- 2495.

Brooks, M. K. and Mahnken, C. V. W. (2003). Interaction of Atlantic pacific salmon in the Pacific Northwest environment, III. Accumulation of zinc and copper. *Fisheries Research* 62: 295-305.

Brown, T. W., Chappell, J. A., Boyd, C. E. (2011). A commercial-scale, in-pond raceway system for Ictalurid catfish production. *Aquacult Eng.* 44(3): 72-79.

BTKLPPM. (2013). Kandungan Logam Berat Hg, Cd, Cr, Cu, Pb, dan Zn di Perairan Teluk Ambon. Diakses melalui http://digilib.its.ac.id/public/ITS-Master-11532- 4107205807-Chapter. pdf (12 Desember 2013; Pkl. 22.00 WIT).

Burridge, L., Weis, J. S., Cabello, F., Pizarro, J., Bostick, K. (2010). Chemical use in salmon aquaculture: a review of current practices and possible environmental effects. *Aquaculture*. 306(1):7–23. doi: https://doi.org/10.1016/j.aquaculture.2010.05.020.

Bury, N. and Grosell, M. (2003). Iron acquisition by teleost fish. 135(2), 0–105. doi:10.1016/s1532-0456(03)00021-8.

Buschmann, A. (2002). Environmental impact of Chilean salmon farming: The situation in the Tenth region of the lakes. Terram. www.terram.ch/publication 22.12.2003

Busulwa, H. S. and Bailey, R. G. (2004). Aspects of the physicochemical environment of the. Rwenzori rivers, Uganda‖. *African Journal of Ecology*. 42:87–92.

Butt, A., Khan, M. X., Aihetasham, A., Khan, M. A., Nazli, H., Ramzan, A. (2021). Assessment of water quality of Soan River using physicochemical parameters and aquatic insects diversity. *The Biological Bulletin*. 48(6):813-820.

Cai, S. W., Shen, Z. W., Ni, Z. H., Li, Y. F., Liu, B., Dai, Y., Zhao, J. (2018). Metal Distribution in Water, Sediment, Submerged Plant, And Fish from an Urban River in Zunyi, Southwest of China. *Fresenius Environ. Bull.* 27:1627–1633.

Canfield, J. and Daniel, E. (1983). Prediction of Chlorophyll a concentration in Florida Lakes: The importance of Phosphorus and Nitrogen. Journal of the American Water Resources Association. 19(2): 255-262

Canli, M., Atli, G. (2003). The relationships between heavy metal (Cd, Cr, Cu, Fe, Pb, Zn) levels and the size of six Mediterranean fish species. *Environ Pollut*, 121, 129 –36.

Carlson, R. (1977). A trophic state index for lakes. *Limnology and Oceanography*. 22(2): 361-369.

Carpenter, S.R. (1998). Non point pollution of surface waters with Phosphorus and Nitrogen, *Ecological application*. 8(3):.559-568.

Chapman, D. (1992). Water Quality Assessment; A guide to the use of biota, sediments and water in environmental monitoring. University Press, Cambridge, 585pp.

Chapman, M and Kimistach, V. (1992). A guide to use of biota, sediments and water in environmental monitoring.

Chou, C.L., Haya, K., Paon, L.A., Burridge, L. and Moffatt, J.D. (2002). Aquaculture related metals in sediments and lobsters and relevance to environmental monitoring program rating for near-field effects. *Marine Pollution Bulletin* 44: 1259-1268.

Clottey, N. K. M. (2014). Effect of Microbial Loads on the Physiological Condition and Fecundity of some Key Fish Species of Commercial Importance in Stratum II of the Volta Lake. (MPhil. Thesis). Department of Marine and Fisheries Sciences, University of Ghana, Legon. 105pp

Clottey, N. K. M., Asmah, R., Ofori-Danson, et al., (2016). Impacts of cage culture on physico-chemical and bacteriological water quality in Lake Volta, Ghana, *African Journal of Aquatic Science* 41 (4):473 – 480.

Cole, R. (2002). Impacts of marine farming on wild fish populations. Final Research Report for Ministry of Fisheries Research Project ENV2000/08, Objective One. National Institute of Water and Atmospheric Research, Auckland. CSIR - Water Research Institute (1999) Baseline data and monitoring of pollution on Volta Lake and Kpong Headpond.

Cornel, G. and Whoriskey, F. (1993). The effects of rainbow trout (*Oncorhynchus mykiss*) cage culture on the water quality, zooplankton, benthos and sediments of Lac du Passage, Quebec. *Aquaculture,* 109(2): 101–117.

Cornelissen, I. J. M., Silsbe, G. M., Verreth, J. A. J., Van Donk, E., & Nagerlkerke, L. A. J. (2014). Dynamics and limitations of phytoplankton biomass along a gradient in Mwanza Gulf, southern Lake Victoria (Tanzania). *Freshwater Biology*, 59, 127–141.

Coulibaly, S., Atse, B. C., Koffi, K. M., Sylla, S., Konan, K. J. and Kouassi, N. J. (2012). Seasonal Accumulations of Some Heavy Metal in Water, Sediment and Tissues of Black Chinned Tilapia *Sarotherodon melanotheron* from Biétri Bay in Ebrié Lagoon, Ivory Coast. *Bulletin of Environmental Contamination and Toxicology* 88:571–576. doi.:10.1007/s00128-012-0522-1.

Croijmans, L., De Jong, J. F., & Prins, H. H. T. (2021). Oxygen is a better predictor of macroinvertebrate richness than temperature—a systematic review. *Environmental Research Letters*, *16*(2), 023002.

Curnow, K. (2021). *The Bright Continent: African Art History*. MSL Academic Endeavors.

Daifullah, A. A., Elewa, A. A., Shehata, M. B. and Abdo, M. H. (2003). Evaluation of someheavy metals in water, sediment and fish sam ples from River Nile (Kafr El-Zyatcity), Egypt.A Treatment approach. *African Journal of Environmental Assessmentand management*. 6, 16-31.

Dalzell, D. J. B., Macfarlane, N. A. A. (1999). The toxicity of iron to brown trout and effects on the gills: a comparison of two grades of iron sulfate. *J. Fish Biology* 55:301-315.

Das, S. S., Hossain, M. K., Mustafa, G. M., Parvin, A., Saha, B., Das, P. R. and Moniruzzaman, M. (2017). Physicochemical properties of water and heavy metals concentration of sediments, feeds and various farmed Tilapia (*Oreochromis niloticus*) in Bangladesh. *Fish Aqua J* 8:4. DOI:10.4172/2150-3508.1000232

Dauda, A. B., Ajadi, A., Tola-Fabunmi, A. S., & Akinwole, A. O. (2019). Waste production in aquaculture: Sources, components and managements in different culture systems. *Aquaculture and Fisheries*, *4*(3), 81-88.

Dean, R., Shimmield, T. M., Black, K. D. (2007). Copper, zinc and cadmium in marine cage fish farm sediments: *An extensive survey. 145(1) 0–95.* doi:10.1016/j.envpol.2006.03.050.

Devi, P. A., Padmavathy, P., Aanand, S., et al., (2017). Review on water quality parameters in fresh water cage fish culture. *International Journal of Applied Research* 3(5):114 – 120.

Dhaneesh, K. V., Gopi, M., Ganeshamurthy, R., Kumar, T. A., Balasubramanian, T. (2012). Bio-accumulation of metals on reef associated organisms of Lakshadweep. *Archipelago.* 131(3): 985–991. doi:10.1016/j.foodchem.2011.09.097

Dillon, P. J. and Rigler, F. (1974). A test of a simple nutrient budget model predicting the phosphorus concentration in lake water. *Journal of the Fisheries Board of Canada*. 31(11): 1771-1778.

Drąg-Kozak E, Pawlica-Gosiewska D, Gawlik K, Socha M, Gosiewski G, Łuszczek-Trojnar E, Solnica E, Popek W (2019). Cadmium-induced oxidative stress in Prussian carp (Carassius gibelio Bloch) hepatopancreas: ameliorating effect of melatonin. Environ Sci Pollut Res 26:12264–12279. https://doi.org/10.1007/s11356-019-04595-3

EAO (Environmental Assessment Office of the British Colombia, Canada) (1996). The salmon aquaculturbre review, final report. http://www.interafish.com/laws-andregulations/report_bc 14.11.2003. UNU-Fisheries Training Programme 38

Ebeneezar, S., Linga Prabu, D., & Sajina, K. A. (2023). Feeds and feed management in mariculture.

ECDG. (2002). European Commission DG ENV. E3 Project ENV.E.3/ETU/0058. Heavy Metals in Waste. Final Report.

Eisler, R. (1980). Accumulation of zinc by marine biota. Pages 259-351 in J. O. Nriagu, editor. Zinc in the environment. Part II: health effects. John Wiley & Sons, Inc., New York.

Elnabris, K. J., Muzyed, S. K., & El-Ashgar, N. M. (2013). Heavy metal concentrations in 496 some commercially important fishes and their contribution to heavy metals exposure in Palestinian people of Gaza Strip (Palestine). *Journal of the Association of Arab Universities for Basic and Applied Sciences*, 13(1): 44-51.

El-Nemaki, A. F.; Ali, A. N.; Zeinhom, M. M. and Radwan, A. O. (2008). Impacts of different water resources on the ecological parameters and the quality of tilapia production at El-Sanou *et al.*, 2021 838

Fallah, A. A., Saei-Dehkordi, S. S., Nematollahi, A., Jafari, T. (2011). Comparative study of heavy metal and trace element accumulation in edible tissues of farmed and wild rainbow trout (Oncorhynchus mykiss) using ICP-OES technique. *Microchem J.* 98(2):275–279. doi: https://doi.org/10.1016/j.microc.2011.02.007.

Famoofo, O. O., & Adeniyi, I. F. (2020). Impact of effluent discharge from a medium-scale fish farm on the water quality of Odo-Owa stream near Ijebu-Ode, Ogun State, Southwest Nigeria. *Applied Water Science*, *10*, 1-13.

FAO (2014). The state of world fisheries and aquaculture 2014. Rome, Italy: FAO Fisheries Department, Fishery Information, Data and Statistics Unit.

FAO. (1983). Compilation of legal limits for hazardous substances in fish and fishery products.

FAO. (2002). *Implementation of the International Plan of Action to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing.* FAO Technical Guidelines for Responsible Fisheries. No. 9. Rome.

FAO. (2012). The state of the world fisheries and aquaculture 2010. FAO, Rome. http://www.fao.org/docrep/016/i2727e/i2727e00.htm (accessed 2 Nov 2017)

Fewtrell, L. (2004). Drinking-water nitrate, methemoglobinemia, and global burden of disease: a discussion. *Environ Health Perspect*. 112(14):1371-4. doi: 10.1289/ehp.7216. PMID: 15471727; PMCID: PMC1247562.

Fisheries and Aquaculture Department (2011): FAO Fisheries and Aquaculture Department. Accessed 25, December 2017 http://www.fao.org/fishery/countrysector/naso_ghana/en#tcN900D1

Forstner, U. (1979). Metal transfer between solid and aqueous phases. In: Fo¨ rstner, U., Wittman, G.T.W. (Eds.), Metal Pollution in the Aquatic Environment. Springer-Verlag, Berlin, pp. 197–270.

Franson, M. H. (1995). *Standard methods for the examination of water and wastewater*. (Andrew, D.E., Lenoe S. C., Arnold E.G. eds)19th edition American Public Health Ass. Washington, 936,450,1021-1032

Garcia-Soto, C., Cheng, L., Caesar, L., Schmidtko, S., Jewett, E. B., Cheripka, A., ... & Abraham, J. P. (2021). An overview of ocean climate change indicators: Sea surface temperature, ocean heat content, ocean pH, dissolved oxygen concentration, arctic sea ice extent, thickness and volume, sea level and strength of the AMOC (Atlantic Meridional Overturning Circulation). *Frontiers in Marine Science*, *8*, 642372.

Gavine, F. M., Phillips, M. J., Murray, A. (1995). Influence of improved feed quality and food conversion ratios on phosphorus loadings from cage culture of rainbow trout, *Oncorhynchus rnykiss (Walbaum), in freshwater lakes. 26(7), 483–495.* doi:10.1111/j.1365-2109.1995.tb00939.x

Geitung, L., Wright, D. W., Oppedal, F., Stien, L. H., Vågseth, T., & Madaro, A. (2020). Cleaner fish growth, welfare and survival in Atlantic salmon sea cages during an autumn-winter production. *Aquaculture*, *528*, 735623.

Gikuma-Njuru, P., Guilford, S. J., Hecky, R. E., & Kling, H. J. (2013). Strong spatial differentiation of N and P deficiency, primary productivity and community composition between Nyanza gulf and Lake Victoria (Kenya, East Africa) and the implications for nutrient management. *Freshwater Biology*, 58(11):2237–2252. https://doi.org/10.1111/fwb.12205

Gomaa, M. N. (1995). Recycling study of some heavy metals in the Egyptian aquatic ecosystem. Food Chemistry. 54, 297-303Gurnham, A.S. 1975. Pollutants effect on the fish of fresh water ecosystem. *J. fish. Res. Borad. Canada* 11:920- 925.

Gondwe, M. J. S., Guildford, S. J. and Hecky, R. E. (2011a). Physical-chemical measurements in the water column along a transect through a tilapia cage fish farm in Lake Malawi, *Africa. J Great Lakes Res* 37(1):102- 113.

Gondwe, M. J. S., Guildford, S. J., Hecky, R. E. (2011b). Carbon, nitrogen and phosphorous loadings from Tilapia fish cages in Lake Malawi and factors influencing their magnitude. *J Great Lakes Res*. 37(1):93-101.

Gordon, C. and Ansa-Asare, O. (2012). Water quality assessment of Densu, Birim and Ayensu rivers in the Okyeman area. *West African Journal of Applied Ecology*, *20*(3):53–64.

Granberg, K. (1970). Seasonal fluctuations in numbers and biomass of the plankton of Lake Pääjärvi, southern Finland. *Annales Zoologici Fennici*, JSTOR (1970).

Guo, L., Li, Z., (2003). Effects of nitrogen and phosphorus from fish cage-culture on the communities of a shallow lake in middle Yangtze river basin of China. *Aquaculture, Amsterdam* 226 (1–4), 201–212.

Gupta, M., Haque M. and Khan, M. (2012). Growth performance of tilapia fingerling in cage in ponds managed by *Adivasi* households: An assessment through length-weight relationship. J. Bangladesh Agricultural University. 10(1): 149–155, ISSN 1810-3030.

Håkanson L, Ervik A, Makinen T, Moller B (1988) Basic conceptsconcerning assessments of environmental effects of marine fishfarms. Nordic Council of Ministries. Nord 90

Håkanson, L., Ervik, A., Makinen, T., Moller, B. (1988). Basic concepts concerning assessments of environmental effects of marine fish farms. Nordic Council of Ministries. Nord 90.

Hamada, M., Elbayoumi, Z., Khader, R., Elbagory, A. (2018). Assessment of heavy metal concentration in fish meat of wild and farmed nile tilapia (Oreochromis Niloticus), Egypt. Alexandria. *J Vet Sci*. 57:30. doi:https://doi.org/10.5455/ajvs.295019

Hao, Z., Chen, L., Wang, C., Zou, X., Zheng, F., Feng, W., Zhang, D., Peng, L. (2019). Heavy metal distribution and bioaccumulation ability in marine organisms from coastal regions of Hainan and Zhoushan, China. *Chemosphere* 226:340–350.

Harrison, W. G., Perry, T. & Li, W. K. W. (2005). Ecosystem indicators of water quality, Part I. Plankton biomass, primary production and nutrient demand. In: Hargrave, B.T. (ed) Environmental effects of marine finfish aquaculture. Handbook of Environmental Chemistry, Vol 5M. Springer-Verlag, Berlin, 59 – 82pp.

Hilal, A. A., and Ismail, N. S. (2008). Heavy Metals in Eleven Common Species of Fish from the Gulf of Aqaba, Red Sea. *Jordan Journal of Biological Sciences*. 1 (1):13 - 18

Hocaoğlu-Özyiğit, A., & Genç, B. N. (2020). Cadmium in plants, humans and the environment. *Frontiers in Life Sciences and Related Technologies*, *1*(1), 12-21.

Hooda. P. S., Edwards, A. C., Anderson, H. A. and Miller, A. (2000). A review of water quality concerns in livestock farming areas. *The science of total environment*. 250:143-167.

Hoque, Yamen M.; Tripathi, Shivam; Hantush, Mohamed M.; Govindaraju, Rao S. (2016). *Aggregate Measures of Watershed Health from Reconstructed Water Quality Data with Uncertainty. Journal of Environment Quality, 45(2), 709–*. doi:10.2134/jeq2015.10.0508

Horne, M. T., Dunson W. A. (1995). The interactive effects of low pH, toxic metals, and DOC on a simulated temporary pond community. *Environ Pollut.* 89:155–161.

Huser, B. J., Bajer, P. G., Kittelson, S., Christenson, S., & Menken, K. (2022). Changes to water quality and sediment phosphorus forms in a shallow, eutrophic lake after removal of common carp (Cyprinus carpio). *Inland Waters*, *12*(1), 33-46.

Ioannidou, V., Stefanakis, A. (2020). The use of constructed wetlands to mitigate pollution from agricultural runoff. In: *Contaminants in Agriculture, Springer*. 233–246.

Islam, M. J., Kunzmann, A., & Slater, M. J. (2022). Responses of aquaculture fish to climate change-induced extreme temperatures: A review. *Journal of the World Aquaculture Society*, *53*(2), 314-366.

Islam, M. S. (2005). Nitrogen and phosphorous budget in coastal and marine cage aquaculture and impacts of effluent loading on ecosystem: review and analysis towards model development. *Marine Poll Bull* 50(1): 48-61.

Jain, N., Yevatikar, R., & Raxamwar, T. S. (2022). Comparative study of physico-chemical parameters and water quality index of river. *Materials Today: Proceedings*, *60*, 859-867.

Jain, P., Sharma, J. D., Sohu, D., et al., (2005). Chemical Analysis of drinking water of Villages of Sangener Tehsil, Juipur District. *International Journal of Environmental Science and Technology* 2 (4), 373 - 379.

Jiwyam W. (2012). Extensive net cage culture of Nile Tilapia (*Oreochromis niloticus*) fingerlings in nutrientenriched pond. *Our Nature*. 10:61-70.

Jordão, C. P., Pereira, M. G., And Pereira J. L. (2002). Metal Contamination of River Waters and Sediments from Effluents of Kaolin Processing in Brazil. *Water, Air, and Soil Pollution* 140: 119–138.

Junejo, S. H., Baig, J. A., Kazi, T. G. and Afridi, H. I. (2019). Cadmium and Lead Hazardous Impact Assessment of Pond Fish Species. *Biological Trace Element Research*, 191: 502–511.doi: 10.1007/s12011-018-1628-z.

Junianto, A., Zahidah H. &Apriliani I. M. (2017). Evaluation of heavy metal contamination in various fish meat from Cirata Dam, West Java. Indonesia. Aquaculture, Aquarium, Conservation & Legislation-*International Journal of the Bioflux Society*, 10(2):241-246.

Kalantzi, I.; Shimmield, T. M.; Pergantis, S. A.; Papageorgiou, N.; Black, K. D. and Karakassis, I. (2013). Heavy metals, trace elements and sediment geochemistry at four Mediterranean fish farms. *Science of the Total Environment*. 444: 128–137.

Karadede, H., Oymak, S.A., Unlu, E. (2004). Heavy metals in mullet, Liza abu, and catfish,Silurus triostegus, from the Atatu ̈rk Dam Lake (Euphrates), Turkey, Inivronment international. 30, 183-188.

Karikari, A. Y., Akpabey, F. & Abban, E. K. (2013) Assessment of water quality and primary productivity characteristics of Volta Lake in Ghana. *Academia Journal of Environmental Sciences* 1(5):88 - 103.

Kazmi, S. S. U. H., Wang, Y. Y. L., Cai, Y. E., & Wang, Z. (2022). Temperature effects in single or combined with chemicals to the aquatic organisms: an overview of thermo-chemical stress. *Ecological Indicators*, *143*, 109354

KEBS (1996). Kenya Bureau of Standards. Government printer Nairobi. KS 05-459:part 1 pg 6. ICS 13:06020

Keyombe, J., Waithaka, E. (2019) Analysis of some aspects of water quality of Lake Naivasha. *Int J Chemical Lifesci* 6(1):2001–2005.

Khatri, N., Tyagi, S. (2015). Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. Frontiers Life Sci. 8(1):23–39.

Kibria, G., Nugegoda, D., Fairclough, R., et al., (1998). Can nitrogen pollution from aquaculture be reduced? *NAGA, the ICLARM Quarterly* 21:17 - 25.

Kishe-Machumu, M. A., van Rijssel, J. C., Wanink, J. A., and Witte, F. (2015). Differential recovery and spatial distribution pattern of haplochromine cichlids in the Mwanza Gulf of Lake Victoria. *Journal of Great Lakes Research*, 41: 454–462. https://doi.org/10.1016/j. jglr.2015.03.005

Kishe-Machumu, M. and Machiwa, J. (2003). Distribution of heavy metals in sediments of Mwanza Gulf of Lake Victoria, Tanzania. *Environ Int* 28:619–625. https://doi.org/10.1016/S0160-4120(02)00099-5

Kolda, A., Gavrilović, A., Jug-Dujaković, J., Ljubešić, Z., El-Matbouli, M., Lillehaug, A., ... & Kapetanović, D. (2020). Profiling of bacterial assemblages in the marine cage farm environment, with implications on fish, human and ecosystem health. *Ecological indicators*, *118*, 106785.

Kolding, J., van Zwieten, P., Mkumbo, O. C., Silsbe, G., & Hecky, R. (2008). Chapter 19: Are the Lake Victoria fisheries threatened by exploitation or eutrophication? Towards an ecosystem based approach to management. In G. Bianchi, & H. R. Skjoldal (Eds.), The ecosystem approach to fisheries (pp. 309–354). Rome, Italy: FAO.

Kouamenan, N. M., Coulibaly, S., Atse, B. C. and Goore, B. G. (2020). Human Health Risk Assessment and Effects some Heavy Metals in the Tissue of Two Species of Cichlidae (*Hemichromis fasciatus* and *Tilapia zillii* × *Tilapia guineensis*) from the Western Part of the Ebrie Lagoon, Côte D'Ivoire, *International Journal of Science and Research,* 9(4): 160 – 167.

Kumar, A., Tripathi, V. K., Sachan, P., Rakshit, A., Singh, R. M., Shukla, S. K., ... & Panda, K. C. (2022). Sources of ions in the river ecosystem. In *Ecological Significance of River Ecosystems* (pp. 187-202). Elsevier.

Kuzovkina, Yulia A.; Knee, M., Quigley, M. F. (2004). Cadmium and Copper Uptake and Translocation in Five Willow Species. *International Journal of Phytoremediation*, 6(3):269–287. doi:10.1080/16226510490496726.

Lehtinen, K., Klingstedt, G. (1983). X-ray microanalysis in the scanning electron microscope on fish gills affected by acidic, heavy metal containing industrial effluents. *Aquat Toxicol.* 3:93-102.

Li, X., Zhang, J., Gong, Y., Liu, Q., Yang, S., Ma, J., ... & Hou, H. (2020). Status of copper accumulation in agricultural soils across China (1985–2016). *Chemosphere*, *244*, 125516.

Linde, A. R., Sanchez-Galan, S., Izquierdo, J. I., Arribas, P., Maranon, E., Garcy, V. E. (1998). Brown Trout as biomonitor of heavy metal pollution: effect of age on the reliability of the assessment. *Ecotoxicol Environ Saf*. 40:120–125.

Liu, J., Xu, X., Ding, Z., Peng, J., Jin, M., Wang, Y., Hong, Y., Yue, W. (2015). Heavy metals in wild marine fish from South China Sea: levels, tissue- and species-specific accumulation and potential risk to humans. *Ecotoxicology* 24:1583–1592.

Loiselle, S. A., Azza, N., Cozar, A., Bracchini, L., Tognazzi, A., Dattilo, A., & Rossi, C. (2008). Variability in factors causing light attenuation in Lake Victoria. *Freshwater Biology*. 53:535–545. https://doi. org/10.1111/j.1365-2427.2007.01918.x

Loucks D. P. (1997). Quantifying trends in system sustainability. *Hydrol. Sci. J.-J. Des Sci. Hydrol*. 42: 513–530. 10.1080/02626669709492051.

Lubembe, S. I., Okoth, S., Hounsounou, H. R., Turyasingura, B., Moenga, K. O., & Mwalughali, T. B. (2022). Is Aquaculture a Success? Evidence from Africa. *East African Journal of Agriculture and Biotechnology*, *5*(1), 223-237.

LVEMP, (2002). Lake Victoria Environmental Management Project phase 1, water quality an ecosystem management component, preliminary findings of study conducted on Lake

Maage, A., Julshamn, K. and Berg, G. K. (2001). Zinc gluconate and zinc sulphate as dietary zinc source for Atlantic salmon. *Aquaculture Nutrition* 7: 183-187.

Mackay, A. W., Ryves, D. B., Morley, D. W., Jewson, D. H., Rioual, P. (2006). Assessing the vulnerability of endemic diatom species in Lake Baikal to predicted future climate change: a multivariate approach. *Glob Change Biol* 12:2297–2315. doi:10.1111/j.1365-2486.2006.01270.x

Majiwa, J. G., Magunda, M. M. and Musitwa, F. (2001). Soil and Nutrient losses from major agricultural land practices in Lake Victoria basin. Paper presented at regional scientific conference, Kisumu, Kenya.

Masindi, V., Muedi, K. L. (2018). Environmental Contamination by Heavy Metals. *Heavy Metals*. doi: 10.5772/intechopen.76082.

Maqsood, Q., Hussain, N., Mumtaz, M., Bilal, M., & Iqbal, H. M. (2022). Novel strategies and advancement in reducing heavy metals from the contaminated environment. *Archives of Microbiology*, *204*(8), 478.

Mati, B. M., Mutie, S., Home, P., Mtalo, F., Gadain, H. (2005). Land use changes in the trans-boundary Mara Basin: A threat to pristine wildlife sanctuaries in East Africa.) 8th International River Symposium. Brisbane, Australia.

Matsumura –Tundusi, T and Tundis J. G. (2005). Plankton richness in eutrophic reservoir (Barva Banita reservoir Brazil) *Hydrologia*. 542:367-378.

McCartney, B. A. (2010). Evaluation of Water Quality and Aquatic Ecosystem Health in the Mara River Basin, East Africa.), Florida International University.

Mélard C. (1999). Bases biologiques de l'aquaculture: Notes de cours. Université de Liège (Belgique): Centre de Formation et de Recherche en Aquaculture, 238 p.

Memet, V. (2019). Impacts of cage fish farms in a large reservoir on water and sediment chemistry. *Environmental Pollution, 252:1448–1454.* doi:10.1016/j.envpol.2019.06.090.

Mensoor, M. and Said, A. (2018). Determination of Heavy Metals in Freshwater Fishes of the Tigris River in Baghdad. *Fishes*, 3(2):23. Doi: 10.3390/fishes3020023

Mishra, R. K. (2023). Fresh water availability and its global challenge. *British Journal of Multidisciplinary and Advanced Studies*, *4*(3), 1-78.

Miescher, S. F. (2021). Ghana's Akosombo Dam, Volta Lake Fisheries & Climate Change. *Daedalus*, *150*(4), 124-142.

Mishra, S., Bharagava, R. N., More, N., Yadav, A., Zainith, S., Mani, S., & Chowdhary, P. (2019). Heavy metal contamination: an alarming threat to environment and human health. *Environmental biotechnology: For sustainable future*, 103-125.

Mitra, S., Chakraborty A. K., Tareq, A. M., Emran, T. B., Nainu, F., Khusro, A., Idris, A. M., Khandaker, M. U., Osman, H., Alhumaydhi, F. A., Simal-Gandara, J. (2022). Impact of heavy metals on the environment and human health: Novel therapeutic insights to counter the toxicity, *Journal of King Saud University - Science*, 34(3)101865. https://doi.org/10.1016/j.jksus.2022.101865.

Mo, Y., Zhang, L., Zhao, X., Li, J., & Wang, L. (2022). A critical review on classifications, characteristics, and applications of electrically conductive membranes for toxic pollutant removal from water: Comparison between composite and inorganic electrically conductive membranes. *Journal of Hazardous Materials*, *436*, 129162

Morrisey, D., Gibbs, M., Pickmere, S., and Cole, R. (2000). Predicting impacts and recovery of marine-farm sites in Stewart Island, New Zealand, from the Findlay–Watling model. *Aquaculture*, 185(3-4), 257-271.

Mukhethwa P. Mannzhi;Joshua N. Edokpayi;Olatunde S. Durowoju;Jabulani Gumbo;John O. Odiyo; (2021). *Assessment of selected trace metals in fish feeds, pond water and edible muscles of Oreochromis mossambicus and the evaluation of human health risk associated with its consumption in Vhembe district of Limpopo Province, South Africa. Toxicology Reports.* doi:10.1016/j.toxrep.2021.03.018

Munguti, J. M., Kim, J. D., & Ogello, E. O. (2014). An overview of Kenyan aquaculture: Current status, challenges, and opportunities for future development. Journal of Fisheries and Aquatic Science, 17(1), 1–11.

Munzuroglu, O., Geckil, H. (2002). *Effects of Metals on Seed Germination, Root Elongation, and Coleoptile and Hypocotyl Growth in Triticum aestivum and Cucumis sativus. 43(2), 203–213.* doi:10.1007/s00244-002-1116-4

Musa, S., Aura, C. M., & Okechi, J. K. (2022). Economic analysis of tilapia cage culture in Lake Victoria using different cage volumes. *Journal of Applied Aquaculture*, *34*(3), 674-692.

Murdoch, T., Cheo M. and OLaughlin K. (2001). Stream keeper's field guide: Watershed Inventory and Stream Monitoring Methods.

Mutlu, E. and Kurnaz, A. (2018). Assessment of physicochemical parameters and heavy metals in Celte Pond water. *Indian Journal of Geo Marine Sciences*. 47(06): 1185 – 1192.

Mwamburi J, Basweti G, Owili M, Babu J, Wawiye P. (2020). Spatio-temporal trends of nutrients and physico-chemical parameters on lake ecosystem and fisheries prior to onset of cage farming and re-opening of the Mbita passage in the Nyanza Gulf of Lake Victoria. *Lakes & Reserv*. 00:1–22. https://doi.org/10.1111/lre.12329.

Mwamburi, J., Yongo, E., Omwega, R., & Owiti, H. (2021). Fish cage culture in Lake Victoria (Kenya): Fisher community perspectives on the impacts and benefits for better sustainable management. *Int J Fish Aquat Stud*, *9*, 23-29.

Mwamburi, J. (2009). Trace metal concentration in water and sediments of satellite lakes within Lake Victoria (Kenya) basin. *Lakes & Reservoirs: Research & Management*, *14*(3), 203–220.

Mwamburi, J. and Oloo, N. F. (1996). The distribution and concentration levels of trace metals in water and sediments of Lake Victoria, Kenya. *Afr J Trop Hydrobiol Fish* 7:37–48. Https://Doi.Org/10.4314/Ajthf.V7i1. 1381

Mawundu, S. (2024). *Ecological Carrying Capacity And Growth Performance Of Nile Tilapia (Oreochromis Niloticus) In Cage Aquaculture Within Kadimo Bay, Lake Victoria, Kenya* (Doctoral dissertation, University of Eldoret).

Mwebaza-Ndawula, L., Kiggundu, V., Magezi, G., Naluwayiro, J., Gandi-Pabire, W., Ochaya, H. (2013). Effects of cage fish culture on water quality and selected biological communities in northern Lake Victoria, Uganda. UJAS. 14:2-19.

Namaemba, C., Sibiko, K. W., & Ogello, E. O. (2022). Factors Affecting Productivity and Profitability of Cage-Fish Farming in Siaya County, Kenya.

Namdev, G. R., Bajpai, A., Malik, S. (2011). Assessment of chemical fertilizers on the quality of water at Hathaikheda reservoir in Bhopal (M.P.). International Journal of Pharma and Bio Sciences. 2(3):264- 268.

NAS (1977). National Academy of Sciences, drinking water and health Vol 2 Washington DC printing and publishing office, National Academy of Sciences.

Nash, C. E. (editor). (2001). The net-pen salmon farming industry in the Pacific Northwest. U.S. Dept. of Commer., NOAA Tech. Memo. NMFS-NWFSC-46.

Nassali, J., Yongji, Z., & Fangninou, F. F. (2020). A systematic review of threats to the sustainable utilization of transboundary fresh water lakes: a case study of Lake Victoria. *International Journal of Scientific and Research Publications (IJSRP), 10*(02)

Neubauer, K. R., Wolf, R. E. (2004). Typical regulated elements and allowable limits for drinking water in the United Kingdom, (NS30), European Union (EU) and United States of America (USA). PerkinElmer, Inc. USA, 2004.

Nezlin N. P., Kamer K. Hyde J. and Stein E. D. (2009). Dissolved oxygen dynamics in a eutrophic estuary, Upper Newport Bay, California. *Estuarine, Coastal and Shelf Science*. 82:139–151.

Ngugi, C. C., Bowman, J. R. and Omolo, B. O. (2007). *A new Guide to Fish Farming in Kenya.* Corvallis: Aquaculture Collaborative Research Support Program.

Nguyen, H. L., Leermakers, M., Osán, J., Török, S. and Baeyens, W. (2005). Heavy metals in Lake Balaton: water column, suspended matter, sediment and biota. *Science of the Total Environment*. 340(1-3):213-230.

Nikolaou, M., Neofitou, N., Skordas, K., Castritsi-Catharios, I., & Tziantziou, L. (2014). Fish farming and anti-fouling paints: A potential source of Cu and Zn in farmed fish. *Aquaculture Environment Interactions*, *5*(2), 163–171.

Njiru, J. M., Aura, C. M., & Okechi, J. K. (2019). Cage fish culture in Lake Victoria: A boon or a disaster in waiting?. *Fisheries Management and Ecology*, *26*(5), 426-434.

Noman, M. A., Feng, W., Zhu, G. *et al.* (2022). Bioaccumulation and potential human health risks of metals in commercially important fishes and shellfishes from Hangzhou Bay, China. *Sci Rep*. 12: 4634. https://doi.org/10.1038/s41598-022-08471-y

Noori, R., Berndtsson, R., Hosseinzadeh, M., Adamowski, J. F., Abyaneh, M. R. (2019). A critical review of the application of the National Sanitation Foundation Water Quality Index. *Environ Pollut.* 244:575–587

Nsonga A. (2014). Indigenous fish species a panacea for cage aquaculture in Zambia: A case Kambashi outgrowing scheme. *IJFAS.* 2(1):102-105.

Nyakundi, J. K., Njiru, J. M., Mwayuli, G. A. and Olilo, C. (2015). Effects of Point Source Pollution on Water Quality, Phytoplankton Diversity and Abundance in Lake Victoria, Kenya. *International Journal of Farming and Allied Sciences*. 2:57-64.

Nyanti, L., Hii, K. M., Sow, A., et al., (2012). Impacts of aquaculture different depths and distances from cage culture sites in Batang Ai Hydroelectric Dam Reservoir, Sarawak, Malaysia. *World Applied Science Journal*, ISSN 1818- 4952 19 (4):451 – 156.

Obiero, K. O., Waidbacher, H., Nyawanda, B. O., Munguti, J. M., Manyala, J. O., & Kaunda-Arara, B. (2019). Predicting uptake of aquaculture technologies among smallholder fish farmers in Kenya. *Aquaculture International*, *27*, 1689-1707.

Ochieng, E. N. (1987). Limnological aspects and trace elements analysis of some Kenyan natural inland waters. MSc. Thesis. University of Nairobi, Kenya, p 295

Ogidi, O. I., & Akpan, U. M. (2022). Aquatic biodiversity loss: impacts of pollution and anthropogenic activities and strategies for conservation. In *Biodiversity in Africa: potentials, threats and conservation* (pp. 421-448). Singapore: Springer Nature Singapore.

Oglesby, R. T. (1977). Relationships of fish yield to lake phytoplankton standing crop, production, and morphoedaphic factors. *Journal of the Fisheries Board of Canada*. 34(12): 2271-2279

Okereafor, U., Makhatha, M., Mekuto, L., Uche-Okereafor, N., Sebola, T., & Mavumengwana, V. (2020). Toxic metal implications on agricultural soils, plants, animals, aquatic life and human health. *International journal of environmental research and public health*, *17*(7), 2204.

Okuku, E. O., Tole, M., & Bouillon, S. (2018). Role of a cascade of reservoirs in regulating downstream transport of sediment, carbon and nutrients: Case study of tropical and arid climate Tana River basin. *Lakes & Reservoirs: Science, Policy and Management for Sustainable Use*, 23:43–55. https://doi.org/10.1111/lre.12206

Ontumbi, G. M. (2020). *Effects of geological variability and selected physical parameters of water quality on fluoride levels in river njoro catchment, Kenya* (Doctoral dissertation, University of Eldoret).

Onyari J, Wandiga S (1989) Distribution of Cr, Pb, Cd, Zn, Fe and Mn in Lake Victoria sediments, East Africa. *Bull Environ Contam Toxicol* 42:807–813. https://doi.org/10.1007/BF01701619 O

Orina, P. S.., Ogello, E., Kembenya, E., Githukia, C., Musa, S., Ombwa, V., Mwainge, V. M., Abwao, J., Ondiba RN and Okechi J. K. (2018). State of Cage Culture in Lake Victoria, Kenya.

Osei, L. K., Asmah, R., Aikins, S., Karikari, A. Y. (2019). Effects of Fish Cage Culture on Water and Sediment Quality in the Gorge Area of Lake Volta in Ghana: A Case Study of Lee Fish Cage Farm. *Ghana Journal of Science, 60(1), 1–*. doi:10.4314/gjs.v60i1.1

Otieno, A., Gathuru, G., & Kitur, E. (2017). Physico-Chemical Properties of River Kisat, Lake Victoria Catchment, Kisumu County, Kenya.

Otieno, M. O. (2020). *Factors Affecting Performance and Functionality of Rural Market Centers in Central Alego Ward, Siaya County-Kenya-a Study of Boro, Ndere and Ratuoro Markets* (Doctoral dissertation, University of Nairobi).

Otieno, N. E., & Shidavi, E. (2022). Effectiveness of physical barriers and enhanced fertilization in controlling predation on tilapia and catfish aquaculture systems by four piscivorous water bird families. *Frontiers in Sustainable Food Systems*, *6*, 1018064

Orinda, M., Okuto, E., & Abwao, M. (2021). Cage fish culture in the lake victoria region: Adoption determinants, challenges and opportunities. *International Journal of Fisheries and Aquaculture*, *13*(2), 45-55.

Outa, J. O., Kowenje, C. O., Plessl, C. *et al.* (2020). Distribution of arsenic, silver, cadmium, lead and other trace elements in water, sediment and macrophytes in the Kenyan part of Lake Victoria: spatial, temporal and bioindicative aspects. *Environ Sci Pollut Res*. 27: 1485–1498. https://doi.org/10.1007/s11356-019-06525-9

Pailan, G. H., & Biswas, G. (2022). Advances in Nutrient Resource Management for Fisheries and Aquaculture. In *Agriculture, Livestock Production and Aquaculture: Advances for Smallholder Farming Systems Volume 2* (pp. 291-311). Cham: Springer International Publishing.

Peuranen, S., Vuorinen, M. P. J., Hollender, A. (1994). The effects of iron, humic acids and low pH on the gills and physiology of Brown Trout (*Salmo trutta*). *Ann. Zool. Fennici* 31: 389-396.

Philips, M. J. (1994). Aquaculture and the environment, striking a balance, INFOFISH AQUATECH "94", 29-31 August, 1994, Colombo, Sri Lanka.

Phillips, D. J. (1980). Quantitative aquatic biological indicators, Applied Scienc ePublishers, London, UK.

Pillay, T.V. R. (1990). Basic of Aquaculture, and History of Aquaculture and its Present State. In: Aquaculture Principles and Practice. Fishing News Books. pp. 4,5, 7, 9, 39-43.

Pinheiro, J. P. S., Windsor, F. M., Wilson, R. W., & Tyler, C. R. (2021). Global variation in freshwater physico-chemistry and its influence on chemical toxicity in aquatic wildlife. *Biological Reviews*, *96*(4), 1528-1546.

Piper, R. G., I. B. McElwain, L. E. Orme, J. P. McCraren, L. G. Flower, and J. R. Leonard (1982). Fish hatchery management. U. S. Fish and Wildlife Service, Washington, D. C.

Pollit, E., Kotchabhakodi, N.J., Missel, L., Valyasevi, A. (1989). Iron deficiency and educational achievement in Thailand. *Journal of American Clinical Nutrition*.50:687-697.

Prakash, S. (2021). Impact of Climate change on Aquatic Ecosystem and its Biodiversity: An overview. *International Journal of Biological Innovations, 3*(2).

Prasad, M. N.V. (2007). Aquatic plants for phytotechnology. In S. N. Singh and R.D. Tripathi (eds) Environmental Bioremediation technologies. *Springer*. Pp. 257-274.

Qadir, A. and Malik, R. N. (2011). Heavy metals in eight edible fish species from two polluted tributaries (Aik and Palkhu) of the River Chenab, Pakistan. Biological Trace Element Research, 143(3): 1524–1540.

Rehman, A. U., Nazir, S., Irshad, R., Tahir, K., ur Rehman, K., Islam, R. U., & Wahab, Z. (2021). Toxicity of heavy metals in plants and animals and their uptake by magnetic iron oxide nanoparticles. *Journal of Molecular Liquids*, *321*, 114455.

Rahman, Z., & Singh, V. P. (2019). The relative impact of toxic heavy metals (THMs)(arsenic (As), cadmium (Cd), chromium (Cr)(VI), mercury (Hg), and lead (Pb)) on the total environment: an overview. *Environmental monitoring and assessment*, *191*, 1-21.

Romana-Eguia, M. R. R., Eguia, R. V., & Pakingking Jr, R. V. (2020). *Tilapia culture: The basics*. Aquaculture Department, Southeast Asian Fisheries Development Center.

Rawson, D. (1956). Algal indicators of trophic lake types. Limnology and Oceanography. 1(1): 18-25.

Riasi MS, Teklitz A, Shuster W, Nietch C, Yeghiazarian L, (2018). Reliability-based water quality assessment with load resistance factor design: application to TMDL. *J. Hydrologic Eng*. 23: 1–10. 10.1061/(ASCE)HE.1943-5584.0001722.

Ross, L. G. (2000). Environmental physiology and energetics. In: Beveridge MCM, McAndrew BJ (Eds.), Tilapias: Biology and Exploitation, Fish and Fisheries Series 25, Kluwer Academic Publishers, Dordrecht, The Netherlands. pp. 89-128.

Russell, A., Grotz, P., Kriesemer, S., & Pemsl, D. (2008). Recommendation domains for pond aquaculture: Country case study: Development and status of freshwater aquaculture in Malawi. Penang, Malaysia: The WorldFish Center. WorldFish Center Studies & Reviews No. 1869. 52 pp.

Ryding, S. O. and Forsberg, C. (1980). Short-term load-response relationships in shallow, polluted lakes. *Hypertrophic ecosystems*, Springer, pp. 95-103

Saeed, S. M. and Shaker, I. M. (2008). Assessment of heavy metals pollution in water and sediments and their effect on *Oreochromis niloticus* in the northern delta lakes, Egypt. Paper presented at the 8th international symposium on Tilapia in Aquaculture.

Safitri, R., Setyana, Y., Miranti, M., Rossiana, N., Indrawati, I., Rejeki, S., & Nurhayati, J. (2019). Biodegradation of leachate by consortium of microorganism indigenous

Sallam KI, Abd-Elghany SM, Mohammed MA (2019). Heavy metal residues in some fishes from Manzala Lake, Egypt, and their health-risk assessment. J Food Sci 84:7. https://doi.org/10.1111/1750-3841.14676

Saluwa Y., Yakubu S.I., Garba M., Usman M., Yakasai I.A. (2016). Content of some heavy metals in compound fish feed in Northern Nigeria. *Int. Res. J. Pharm. 7(11):19–22. doi: 10.7897/2230-8407.0711122*

Santhosh, B. and Sing, N. P. (2007). Guidelines for water quality management for fish culture in Tripura, ICAR research complex for NEH region, Publication no. 29. Tripura Centre, Lembucherra–799210.Tripura (west).

Sapkota, A., Sapkota, A. R., Kucharski, M., Burke, J., McKenzie, S., Walker, P., & Lawrence, R. (2008). Aquaculture practices and potential human health risks: current knowledge and future priorities. *Environment international*, 34(8):1215-1226.

Sarang A, Vahedi A, Shamsai A, (2008). How to quantify sustainable development: a Risk-based approach to water quality management. *Environ. Manage*. 41, 200–220. 10.1007/s00267-007-9047-5.

Sekhar, K., Chary, N., Kamala, C., Raj, D., Rao, A. (2004). Fractionation studies and bioaccumulation of sediment-bound heavy metals in Kolleru lake by edible fish. *Environ. Int.* 29:1001–1008.

Shaalan, M., El-Mahdy, M., Saleh, M., & El-Matbouli, M. (2018). Aquaculture in Egypt: insights on the current trends and future perspectives for sustainable development. *Reviews in Fisheries Science & Aquaculture*, *26*(1), 99-110.

Shakouri Heinig, C. S. (2000). The impact of salmon aquaculture: The difficulties of establishing acceptability limits and standards. Report presented to Aquaculture/Environment Workshop. University of Massachusetts, Boston, USA. Jan. 11-13,2001.

Sharma, P., Dubley, R. S. (2004). Ascorbate peroxidase from rice seedlings: properties of enzyme isoforms, effects of stresses and protective roles of osmolytes. *Plant Sci.* 167:541-550.

Silsbe, G. M., Hecky, R. E., Guildford, S. J., & Mugidde, R. (2006). Variability of chlorophyll-a and photosynthetic parameters in a nutrient-saturated tropical great lake. *Limnology and Oceanography*. 51:2052–2063. https://doi.org/10.4319/lo.2006.51.5.2052

Soltan, M. E., Moalla, S. M. N., Rashed, M. N., Fawzy, E. M. (2005). Physicochemical characteristics and distribution of some metals in the ecosystem of Lake Nasser, Egypt. *Toxicol Environ Chem*. 87(1–4):167–197

Soto, D., Norambuena, F. (2004). Evaluation of salmon farming effects on marine systems in the inner seas of southern Chile: a large-scale mensurative experiment. *J Appl Ichthyol*. 20:493-501.

Southern Cooperative Series Bulletin, (2000). Methods of phosphorus analysis for soil sediments residuals and waters. Throckmorton plant science Ctr. Kansas State University. Manhattan ISBN: 1-58161-396-2.

Spellman, F.R. (2013). Handbook of Water and Wastewater Treatment Plant Operations (3rd ed.). CRC Press. https://doi.org/10.1201/b15579.

Srivaro, S., Börcsök, Z., & Pásztory, Z. (2021). Temperature dependence of thermal conductivity of heat-treated rubberwood. *Wood Material Science & Engineering*.

Sutherland, T., Petersen, S., Levings, C. and Martin, A. (2007). Distinguishing between natural and aquaculture-derived sediment concentrations of heavy metals in the Broughton Archipelago, British Columbia. *Marine Pollution Bulletin*, *54*(9):1451–1460.

Svobodova, Z., Lloy, R., Machova, J. and Vykusova, B. (1993). Water quality and fish health. EIFAC, technical paper 54, FAO, Rome, p. 71.

Tamatamah, R. A., Hecky, R. E., & Duthie, H. C. (2005). The atmospheric deposition of phosphorus in Lake Victoria (East Africa). *Biogeochemistry,* 73:325–344.

Tamot P, Mishra R, Samdutt. Water Quality Monitoring of Halali Reservoir with Reference to cage Aquaculture as a Modern Tool for Obtaining Enhanced Fish Production. In: Proceedings of Taal 2007: the 12th World Lake Conference. 2008, 318-324. 68.

TANDEL, M. A. (2023). *fulfilment of the requirements for the Degree of* (Doctoral dissertation, WEST BENGAL UNIVERSITY OF ANIMAL AND FISHERY SCIENCES).

Tchounwou, P. B, Yedjou, C. G., Patlolla, A. K., Sutton, D. J. (2012). Heavy metal toxicity and the environment. *Exp Suppl*. 101:133–164. doi:10.1007/978-3-7643-8340-4_6.

Teklitz, A., Nietch, C., Riasi, M. S., Yeghiazarian, L. (2020). Reliability Theory for Microbial Water Quality and Sustainability Assessment. *Journal of Hydrology. 125711*-doi:10.1016/j.jhydrol.2020.125711.

Temporetti, P., Alonso, M., Baffico, G., Diaz, M., Lopez, W., Pedrozo, F., & Vigliano, P. (2001). Trophic state, fish community and intensive production of salmonids in Alicura Reservoir (Patagonia, Argentina). *Lakes & Reservoirs: Research & Management, 6*(4), 259–267.

Tepe, Y., Turkmen, A., Mutlu, E. and Ates, A. (2005). Some physico-chemical characteristics of Yarselli Lake, Turkey. *Turk. J. Fish. aquat. Sci*. 5: 35–42.

Tibebe, D., Kassa, Y., Melaku, A., Lakew, S. (2019). Investigation of spatio-temporal variations of selected water quality parameters and trophic status of Lake Tana for sustainable management, Ethiopia. *Microchem J*. 148:374–384.

Tičina, V., Katavić, I., & Grubišić, L. (2020). Marine aquaculture impacts on marine biota in oligotrophic environments of the Mediterranean Sea–a review. *Frontiers in marine science*, *7*, 217.

UNAEZE, C. H. (2023). CHEMOMETRIC CHARACTERISATION OF SOME HEAVY METALS AND PHYSICOCHEMICAL PROPERTIES OF SELECTED WATERBODIES IN MINNA, NIGER STATE, NIGERIA.

Udayanga, L., Ranathunge, T., Iqbal, M. C. M., Abeyewickreme, W., & Hapugoda, M. (2019). Predatory efficacy of five locally available copepods on Aedes larvae under laboratory settings: An approach towards bio-control of dengue in Sri Lanka. *PLoS One*, *14*(5), e0216140.

UNEP, (2006). Global Environment Outlook 3: Land degradation – Africa. Available at: http://www.grida.no/geo/geo3/english/149.htm [Access date: 25.08.2022].

UN-Habitat (United Nations Human Settlements Programme). (2005). Financing Urban Shelter: Global Report on Human Settlements 2005. London/Nairobi, Earthscan/UN-Habitat — 2006. Meeting Development Goals in Small Urban Centres: Water and Sanitation in the World's Cities. Nairobi/London, UN-Habitat/Earthscan. http://www.unhabitat.org/content.asp?typeid=19&catid=555&cid=5369

United States Environmental Protection Agency (USEPA) (1986). *Quality criteria for water*. EPA 440/5-86-001. May 1986. Washington, DC: Office of water regulations and standards.

Van Dam AA, Pauly D (1995) Simulation of the effects of oxygen onfood consumption and growth of Nile tilapia, Oreochromis niloticus(L). Aquac Res 26(6): 427–440.26.

Varol, M. (2020). Spatio-temporal changes in surface water quality and sediment phosphorus content of a large reservoir in Turkey. *Environ Pollut* 259:113860.

Varol, Memet. "Impacts of cage fish farms in a large reservoir on water and sediment chemistry." *Environmental Pollution* 252 (2019): 1448-1454.

Vasconcellos, M., Barone, M., & Friedman, K. (2018). A country and regional prioritisation for supporting implementation of CITES provisions for sharks. *FAO Fisheries and Aquaculture Circular*, (C1156), I-182

Vasistha, P., & Ganguly, R. (2020). Water quality assessment of natural lakes and its importance: An overview. *Materials Today: Proceedings*, *32*, 544-552.

Vieira, C., Morais, S., Ramos, S., Delerue-Matos, C. and Oliveira M. (2011). Mercury, cadmium, lead and arsenic levels in three pelagic fish species from the Atlantic Ocean: intra-and inter-specific variability and human health risks for consumption. *Food and Chemical Toxicology*, 49(4): 923 – 932.

Vilizzi, L. and Tarkan, A. S. (2016). Bioaccumulation of metals in common carp (*Cyprinus carpio L.*) from water bodies of Anatolia (Turkey): a review with implications for fisheries and human food consumption. *Environmental Monitoring and Assessment*, 188(4):24. doi: 10.1007/s10661-016-5248-9 841

Vinagre, C., França, S., Costa, M.J. and Cabral, H.N., 2004. Accumulation of heavy metals by flo under, *Platichthys flesus* (Linnaeus 1758), in a heterogeneously contaminated nursery area. Marine Pollution Bulletin, 49,1109 -1113

Vollenweider, R. A. (1976). Advances in defining critical loading levels for phosphorus in Lake Eutrophication. Memorie dell'Istituto Italiano di Idrobiologia, Dott. Marco de Marchi Verbania Pallanza (1976).

Walakira, J. K., Hinrichsen, E., Tarus, V., Langi, S., Ibrahim, N. A., Badmus, O., ... & Baumüller, H. (2023). Scaling aquaculture for food security and employment in Africa–Insights from Egypt, Kenya and Nigeria.

Wang, Q., Liao, Z., Yao, D., Yang, Z., Wu, Y., & Tang, C. (2021). Phosphorus immobilization in water and sediment using iron-based materials: a review. *Science of the Total Environment*, *767*, 144246

Wang, Q., Zhao, R., Li, Q. S., Cui, M. S., Zhang, Y., & Li, J. T. (2022). Cyprinus carpio (common carp). *Trends in Genetics*, *38*(3), 305-306.

Waseem, A., Arshad, J., Iqbal, F., Sajjad, A., Mehmood, Z., Murtaza, G. (2014). Pollution status of Pakistan: a retrospective review on heavy metal contamination of water, soil, and vegetables. *Biomed Res Int*. (2014:813206. doi:10.1155/2014/813206

Welch, E. B. (1980). Ecological Effects of Waste Water. Cambridge University Press, New York. p. 337

Wetzel, R.G. (1983). Limnology. 2nd Ed. Saunders College Publishing, Philadelphia

Wetzel, RG., Likens, GE. (2006). Limnological analysis. New York: SpringerVerlag

White, P. G. (2021). Environmental Management of Fish Cage Aquaculture. *Journal of the Indian Society of Coastal Agricultural Research*, *39*(2).

WHO (World Health Organization) (1989). Guidelines for drinking water quality. International programme on chemical safety. (UNEP, ILO. WHO). vol 1.

WHO (World Health Organization) (1998). Guidelines for drinking water quality. International programme on chemical safety. (UNEP, ILO, WHO).vol 1

WHO (World Health Organization) (2004). Global Water Supply and Sanitation Assessment 2004 Report. World Health Organization, Geneva. URL.

WHO. (1995). Inorganic lead. Environmental Health Criteria 165. World Health Organization, International Program on Chemical Safety (IPCS), Geneva, Switzerland.

Winsby, M., Sander, B., Archibald, D., Daykin, M., Nix, P., Taylor, F.J.R. and Mundy, D. (1996). The environmental effects of salmon net-cage culture in British Colombia.

World Health Organization (2011). Guidelines for Drinking-water Quality FOURTH EDITION. (http://www.who.int)www.googglemaps.com)

Xie, Q., Qian, L., Liu, S., Wang, Y., Zhang, Y., & Wang, D. (2020). Assessment of long-term effects from cage culture practices on heavy metal accumulation in sediment and fish. *Ecotoxicology and environmental safety*, *194*, 110433

Xu, J., Jiang, Y., Zhao, Z., Zhang, H., Peng, W., Feng, J., ... & Xu, P. (2019). Patterns of geographical and potential adaptive divergence in the genome of the common carp (Cyprinus carpio). *Frontiers in Genetics*, *10*, 660.

Yadav, A., Gopesh, A., Pandey, R. S., Rai, D. K., Sharma, B. (2007). Fertilizer industry effluent induced biochemical changes in fresh water teleost, Channa striatus (Bloch). *Bulletin of Environmental Contamination and Toxicology*. 79: 588-595.

Yasmeen, K., Mirza, M. A., Khan, N. A., Kausar, N., Rehman, A-U. and Hanif M (2016). Trace metals health risk appraisal in fish species of Arabian Sea. *Springer Plus* 5(1): 859, 7 p. doi: 10.1186/s40064-016-2436-6

Yee, L. T., Paka, D. D., Nyanti, L., Ismail, N., Emang, J. J. (2012). Water Quality at Batang Ai Hydroeletric Reservoir (Sarawak, Malaysia) and Implications for Aquaculture. *International Journal of Applied Science and Technology*. 2(6):23-30

Yi, Y., Zhang, S. (2012). Heavy metal (Cd, Cr, Cu, Hg, Pb, Zn) concentrations in seven fish species in relation to fish size and location along the yangtze river. *Environ. Sci. Pollut. Res*. 19:3989–3996.

Yildiz, M. (2008). Mineral composition in fillets of sea bass (*Dicentrarchus labrax*) and sea bream (*Sparus aurata*): a comparison of cultured and wild fish. *J Appl Ichthyol*. 24(5):589–594. doi: https://doi.org/10.1111/j.1439-0426.2008.01097.x.

Yousuf, M. H, El-Shahawi, M. S., Al- Ghais, S. M. (2000). Trace metals in liver, skin and muscle of *Lethrinus lentjan* fish species in relation to body length and sex. *Sci Total Environ.* 256:87– 94.

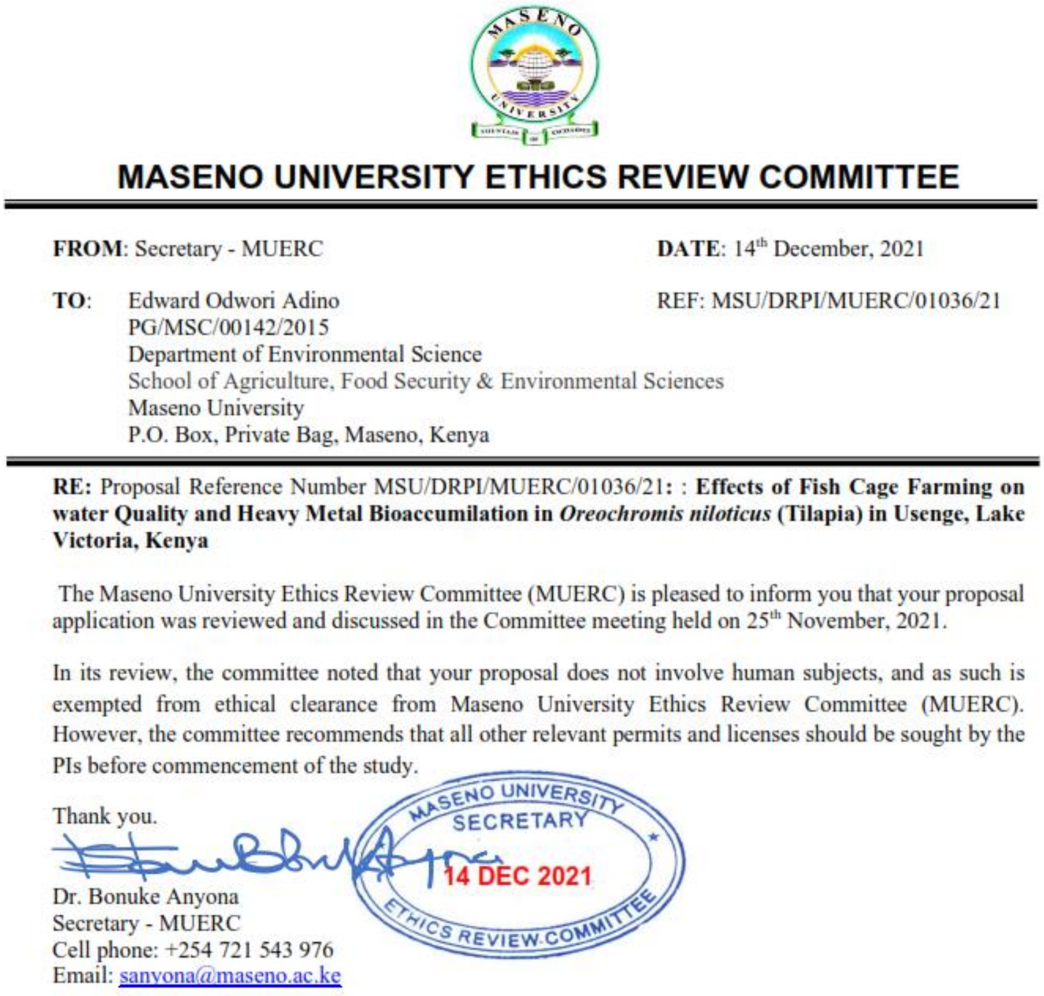
Yovita J. M. (2007). “The effects of Dissolved Oxygen on fish growth in aquaculture”, Kingolwira National Fish Farming Centre, Fisheries Division Ministry of Natural Resources and Tourism, Tanzania, 2007, pp.30

Yu, J., & Liu, J. (2023). Policies in the development of offshore cage aquaculture in China: evolution, performance, and prospects. *Reviews in Fisheries Science & Aquaculture*, *31*(2), 216-232.

Zanatta, A. S., Perbiche-Neves, G., Ventura, R., Ramos, I. P., Carvalho, E. D. (2010). Effects of a small fish cage farm on zooplankton assemblages (Cladocera and Copepoda: Crustacea) in a sub-tropical reservoir (SE Brazil). *Pan American Journal of Aquatic Sciences*. 5(4):530-539.

APPENDICES

APPENIX 1.ETHICS LETTER



MASENO UNIVERSITY ETHICS REVIEW COMMITTEE

FROM: Secretary - MUERC

DATE: 14th December, 2021

TO: Edward Odwori Adino
PG/MSC/00142/2015
Department of Environmental Science
School of Agriculture, Food Security & Environmental Sciences
Maseno University
P.O. Box, Private Bag, Maseno, Kenya

REF: MSU/DRPI/MUERC/01036/21

RE: Proposal Reference Number MSU/DRPI/MUERC/01036/21**: : Effects of Fish Cage Farming on water Quality and Heavy Metal Bioaccumilation in *Oreochromis niloticus* (Tilapia) in Usenge, Lake Victoria, Kenya**

The Maseno University Ethics Review Committee (MUERC) is pleased to inform you that your proposal application was reviewed and discussed in the Committee meeting held on 25th November, 2021.

In its review, the committee noted that your proposal does not involve human subjects, and as such is exempted from ethical clearance from Maseno University Ethics Review Committee (MUERC). However, the committee recommends that all other relevant permits and licenses should be sought by the PIs before commencement of the study.

Thank you.

MASENO UNIVERSITY
SECRETARY
14 DEC 2021
ETHICS REVIEW COMMITTEE

Dr. Bonuke Anyona
Secretary - MUERC
Cell phone: +254 721 543 976
Email: sanyona@maseno.ac.ke

APPENDIX 2: ANALYSYS OF PHYSICO-CHEMICAL PARAMETERS

Table A 1: Comparison of the current study with LVEMP data (2000-2005) and historical data (1960 - 1961)

Physico-chemical parameters	1960 - 61		2000 - 2005		Present study	
	M	SD	M	SD	M	SD
Temperature (^{0}C)	25.32	1.17	24.99	0.61	24.75	1.45
Dissolved Oxygen (mg/l)	5.83	1.18	6.02	1.03	14.81	2.39
Electrical Conductivity (µS/cm)	111.00	29.46	101.05	12.07	79.56	13.35
Ph	8.43	0.35	7.91	0.46	7.40	0.21
Turbidity (NTU)	2.75	1.03	9.11	6.68	35.28	4.07
T. Phosphate (mg/l)	0.05	0.01	0.15	0.04	1.27	0.70
T. Nitrate (mg/l)	1.12	0.60	1.00	0.41	0.44	0.34

Note: LVEMP – Lake Victoria Environmental Project; M – Mean; SD – Standard Deviation

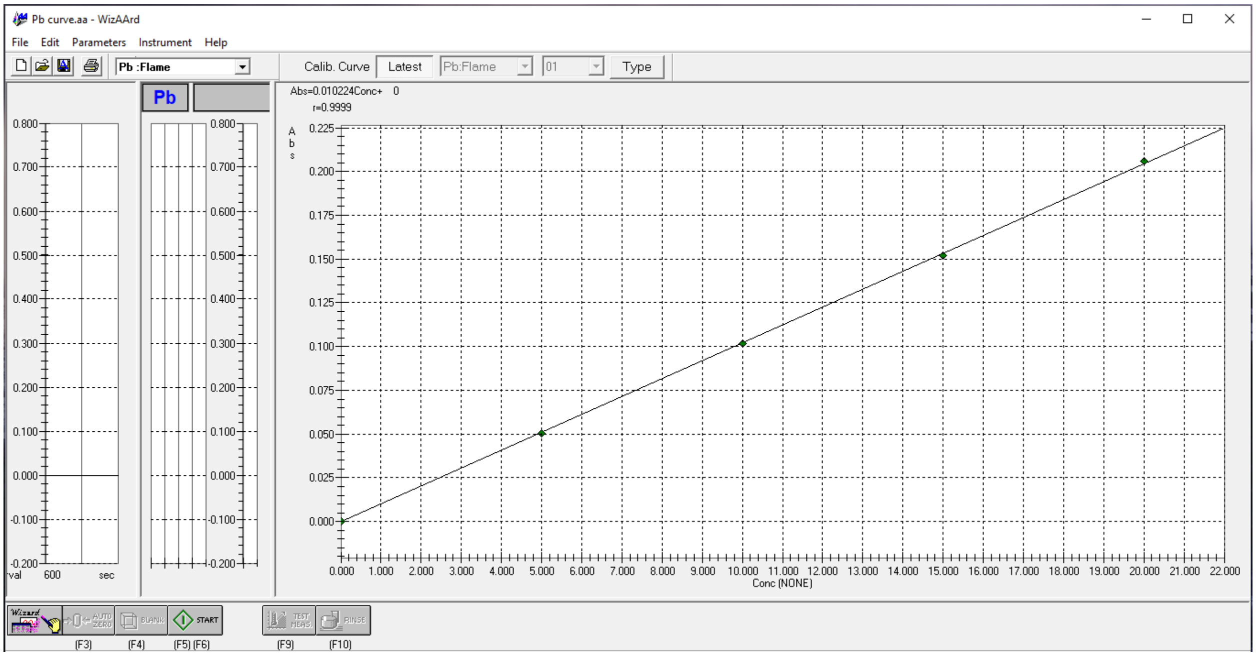
APPENDIX 3: CONTROL AND EXPERIMENTAL BREAKDOWN OF PHYSICO-CHEMICAL PARAMETERS OF WATER IN USENGE (L. VICTORIA)

Table A 2: Breakdown of control and experimental physico-chemical parameters of water in Usenge (L. Victoria)

Site	Groups		Turbidity (NTU)	pH	Dissolved Oxygen	Electrical Conductivity (µS/cm)	Biological Oxygen Demand (BOD)	Temperature (^{0}C)	T. Phosphate (mg/L)	T. Nitrate (mg/L)	Lead in water (ug/L)	Zinc in water (ug/L)	Cadmium in water (ug/L)	Iron in water (ug/L)	Copper in water (ug/L)	Lead in fish (ug/L)	Zinc in fish (ug/L)	Cadmium in fish (ug/L)
Site 1: Eastwards	Control point (200m)	M	35.00	7.47	14.81	85.58	0.26	25.14	1.24	0.69	0.56	0.19	0.01	0.19	0.57	0.07	12.07	0.01
		SD	3.40	0.20	2.42	6.99	0.13	0.81	0.69	0.33	0.06	0.02	0.00	0.07	0.04	0.01	1.65	0.00
	Upto 30m	M	35.65	7.46	15.60	83.29	0.23	25.39	1.48	0.56	0.55	0.19	0.01	0.19	0.56	0.07	11.93	0.01
		SD	3.74	0.24	2.43	9.38	0.14	1.09	0.78	0.45	0.07	0.03	0.00	0.07	0.05	0.01	1.96	0.00
	Total	M	35.52	7.46	15.44	83.75	0.24	25.34	1.43	0.58	0.55	0.19	0.01	0.19	0.56	0.07	11.96	0.01
		SD	3.67	0.23	2.44	8.97	0.14	1.04	0.76	0.43	0.07	0.03	0.00	0.07	0.05	0.01	1.89	0.00
Site 2: Westwards	Control point (200m)	M	35.00	7.47	14.81	85.58	0.26	25.14	1.24	0.69	0.56	0.19	0.01	0.19	0.57	0.07	12.07	0.01
		SD	3.40	0.20	2.42	6.99	0.13	0.81	0.69	0.33	0.06	0.02	0.00	0.07	0.04	0.01	1.65	0.00
	Upto 30m	M	34.27	7.43	15.47	71.67	0.26	24.78	0.97	0.36	0.55	0.19	0.01	0.18	0.54	0.07	11.91	0.01
		SD	3.23	0.20	1.86	21.37	0.14	1.63	0.47	0.16	0.09	0.04	0.00	0.06	0.05	0.01	2.69	0.00
	Total	M	34.41	7.43	15.33	74.45	0.26	24.86	1.02	0.42	0.55	0.19	0.01	0.18	0.54	0.07	11.94	0.01
		SD	3.26	0.20	1.99	20.13	0.14	1.50	0.53	0.24	0.09	0.04	0.00	0.06	0.05	0.01	2.51	0.00

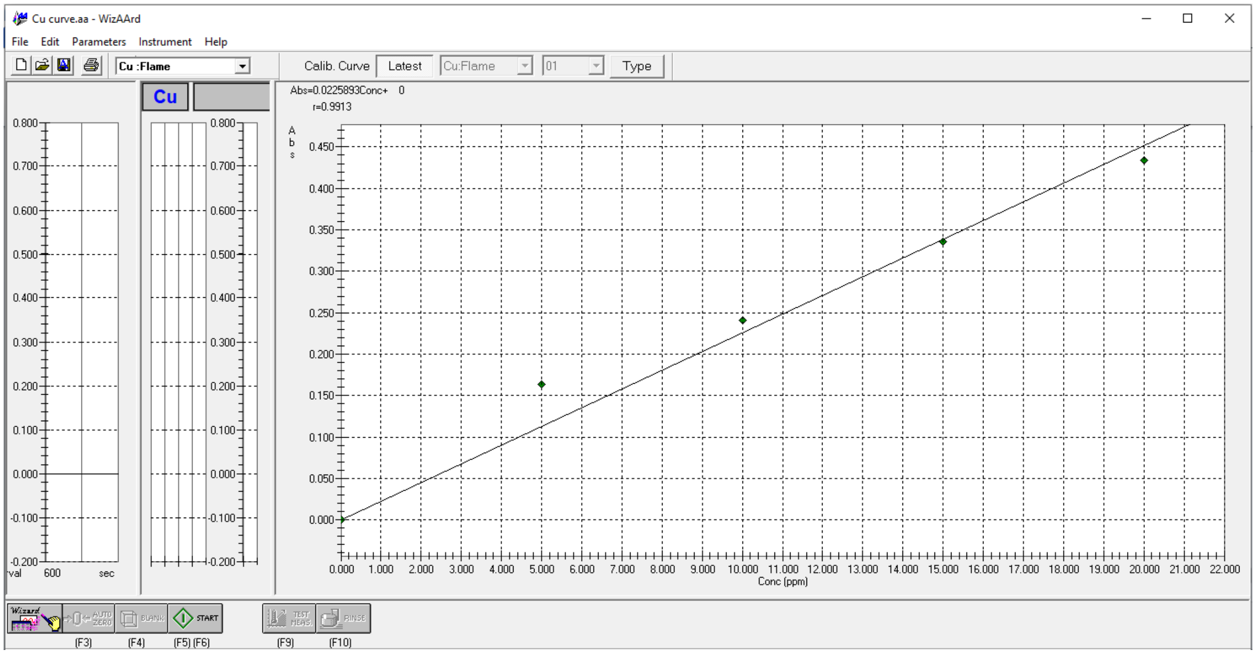
Site 3: Northwards	Control point (200m)	M	35.00	7.47	14.81	85.58	0.26	25.14	1.24	0.69	0.56	0.19	0.01	0.19	0.57	0.07	12.23	0.01
		SD	3.40	0.20	2.42	6.99	0.13	0.81	0.69	0.33	0.06	0.02	0.00	0.07	0.04	0.01	1.65	0.00
	Upto 30M	M	35.20	7.34	14.39	79.75	0.28	24.45	1.45	0.36	0.54	0.23	0.01	0.16	0.50	0.07	14.21	0.01
		SD	2.99	0.19	2.26	10.24	0.14	2.03	0.78	0.32	0.14	0.18	0.00	0.06	0.08	0.02	11.02	0.00
	Total	M	35.16	7.36	14.48	80.92	0.27	24.59	1.40	0.42	0.54	0.22	0.01	0.17	0.52	0.07	13.81	0.01
		SD	3.05	0.20	2.28	9.92	0.14	1.87	0.76	0.35	0.13	0.16	0.00	0.06	0.08	0.02	9.90	0.00
Site 4: Southwards	Control point (200m)	M	35.00	7.47	14.81	85.58	0.26	25.14	1.24	0.69	0.56	0.19	0.01	0.19	0.57	0.07	12.22	0.01
		SD	3.40	0.20	2.42	6.99	0.13	0.81	0.69	0.33	0.06	0.02	0.00	0.07	0.04	0.01	1.65	0.00
	Upto 30M	M	36.29	7.29	13.77	77.49	0.24	23.99	1.21	0.23	0.51	0.19	0.01	0.17	0.49	0.07	11.73	0.01
		SD	6.10	0.14	2.52	9.28	0.13	2.08	0.65	0.09	0.14	0.05	0.00	0.06	0.09	0.02	2.99	0.00
	Total	M	36.03	7.33	13.97	79.11	0.25	24.22	1.22	0.32	0.52	0.19	0.01	0.17	0.51	0.07	11.83	0.01
		SD	5.67	0.17	2.53	9.41	0.13	1.95	0.66	0.25	0.13	0.04	0.00	0.06	0.09	0.02	2.77	0.00
Total	Control point (200m)	M	35.00	7.47	14.81	85.58	0.26	25.14	1.24	0.69	0.56	0.19	0.01	0.19	0.57	0.07	12.15	0.01
		SD	3.33	0.20	2.37	6.84	0.13	0.80	0.68	0.32	0.06	0.02	0.00	0.07	0.04	0.01	1.62	0.00
	Upto 30m	M	35.35	7.38	14.81	78.05	0.25	24.65	1.28	0.38	0.54	0.20	0.01	0.17	0.52	0.07	12.45	0.01
		SD	4.24	0.21	2.39	14.14	0.14	1.82	0.71	0.31	0.11	0.10	0.00	0.06	0.08	0.02	6.00	0.00
	Total	M	35.28	7.40	14.81	79.56	0.25	24.75	1.27	0.44	0.54	0.20	0.01	0.18	0.53	0.07	12.39	0.01
		SD	4.07	0.21	2.39	13.35	0.14	1.68	0.70	0.34	0.11	0.09	0.00	0.06	0.07	0.01	5.42	0.00

APPENDIX 4.AAS LEAD CALIBRATION CURVE



Abs=0.010224Conc+ 0
r=0.9999

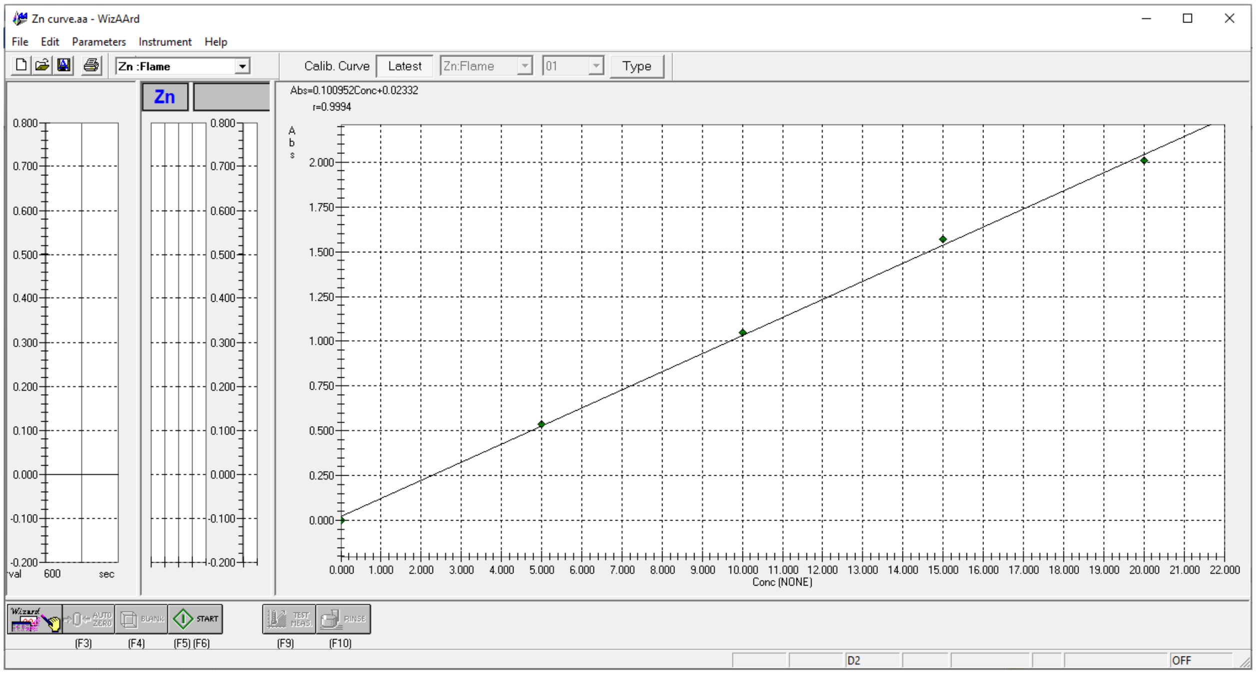
APPENDIX 5.AAS COPPER CALIBRATION CURVE



Abs=0.0225893Conc+ 0

r=0.9913

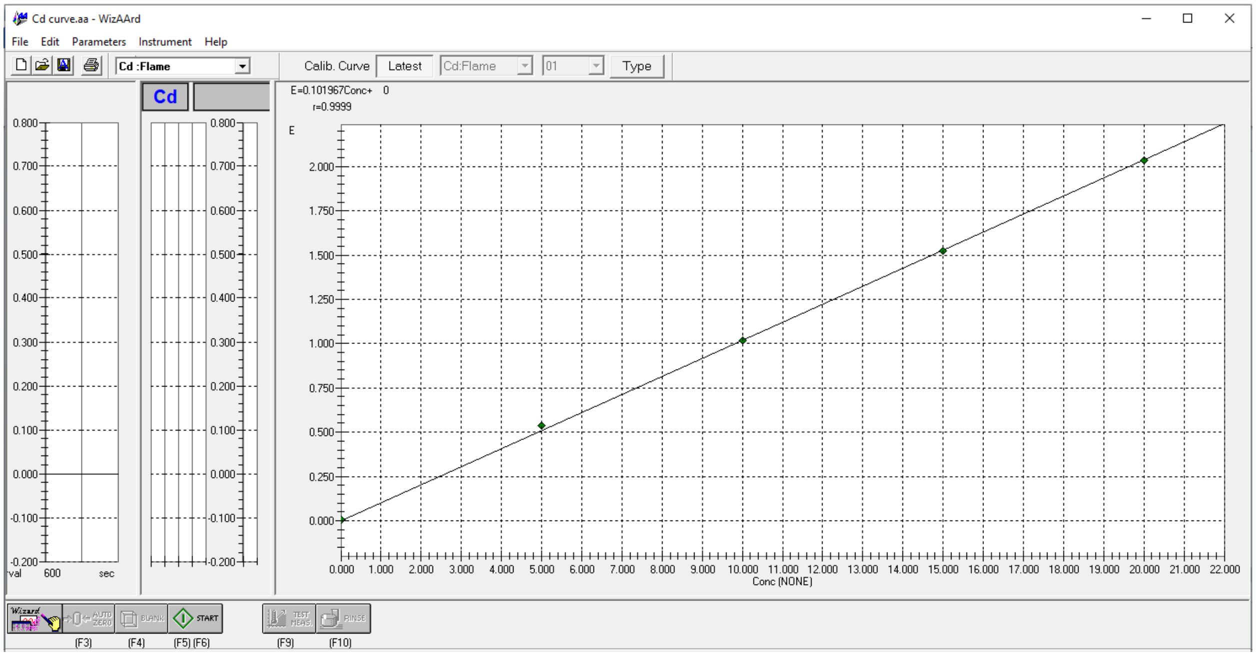
APPENDIX 6.AAS ZINC CALIBRATION CURVE



Abs=0.100952Conc+0.02332

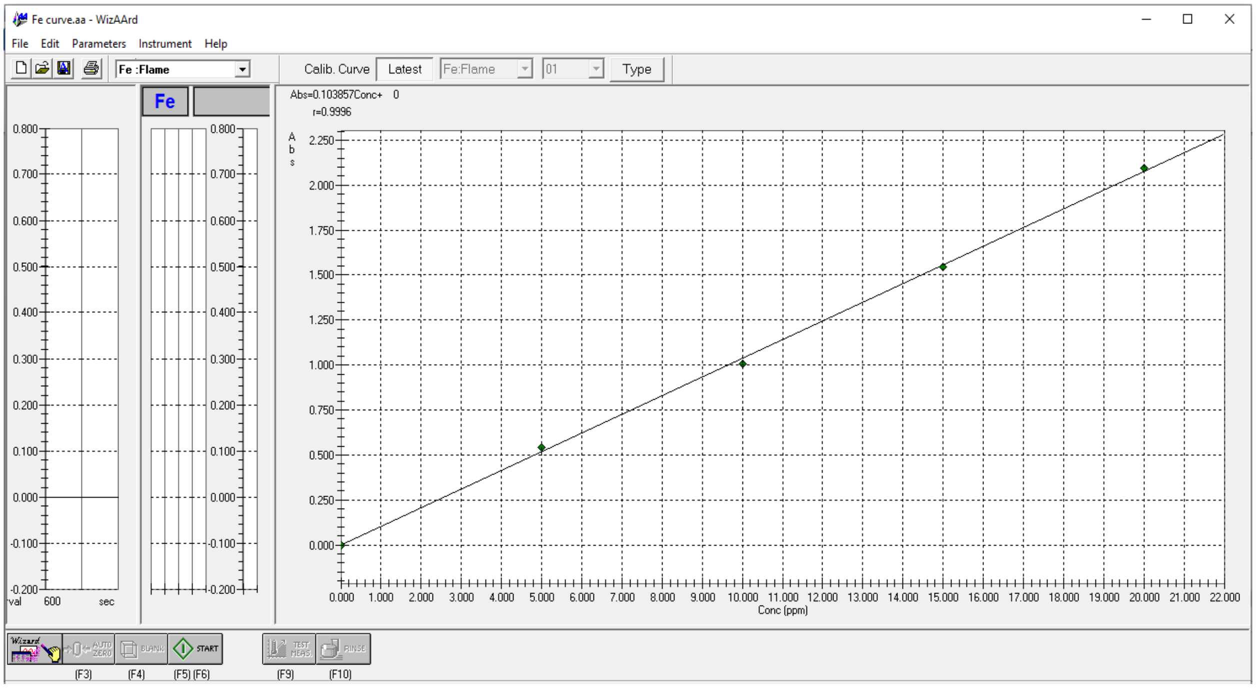
r=0.9994

APPENDIX 7.AAS CADMIUM CALIBRATION CURVE



E=0.101967Conc+ 0
r=0.9999

APPENDIX 8.AAS IRON CALIBRATION CURVE



Fe curve.aa - WizAArd

Fe :Flame

Calib. Curve Latest Fe:Flame 01

Abs=0.103857Conc+ 0

r=0.9996