COMPARATIVE STUDY ON THE LIMNOLOGICAL STATUS OF FIVE ETHIOPIAN SODA LAKES AND LAND USE LAND COVER CHANGES IN THEIR CATCHMENTS

SCHOOL OF GRADUATE STUDIES

A DISSERTATION SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY IN THE DEPARTMENT OF ZOOLOGICAL SCIENCES (AQUATIC SCIENCES, FISHERIES AND AQUACULTURE STREAM)

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Comparative Study on Comparative Study on the Limnological Status of Five Ethiopian Soda Lakes and Land Use Land Cover Changes in their Catchments

By: Hana Melese

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in the Department of Zoological Sciences (Aquatic Sciences, Fisheries and Aquaculture Stream)

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DECLARATION

I declare that this dissertation, entitled: Comparative Study on the Limnological Status of Five Ethiopian Soda Lakes and Land Use Land Cover Changes in their Catchments has been composed by myself and has not been submitted for any other degree or qualification. The work complies with the regulations of the University and meets the accepted standards regarding originality and quality.

Hana Melese: Signature ___________________ Date________________

ABSTRACT

Soda lakes are productive natural ecosystems with considerable biological and socio-economic importance presently facing threats due to anthropogenic and natural activities. The research was conducted in five soda lakes of Ethiopia: Abijata, Arenguade, Beseka, Chittu, and Shala. The objective of this study was to investigate comparative spatio-temporal variations of physico-chemical properties, biological and Land Use Land Cover (LULC) changes in comparison with their historical data. Physico-chemical and biological data were collected from central (open-water) sampling sites of each lake from January to December 2020, four times in different seasons (Dry, Pre-rainy, Rainy, Post-rainy).

All physico-chemical factors exhibited significant differences between seasons (ANOVA, $P < 0.05$), except the salinity in Lake Shala. The concentrations of physicochemical parameters were generally high during the dry seasons in the studied lakes due to the low incidence of rainfall, caused by recurrent drought, resulting in higher evapotranspiration rates as they are characterized by a long dry season. Lakes Arenguade and Beseka showed considerable decrease in conductivity, alkalinity and salinity, compared to data from the 1960s and 1990s, which might be attributed to dilution effect. The same parameters showed slightly increasing trend in Lake Arenguade which might be due to high evaporation rate. In general, the physicochemical parameters of the study lakes showed temporal variations, which could be attributed to the dilution effect, evaporation, and hydrological characteristics of the Ethiopian Rift Valley.

Lake Chittu had the highest chlorophyll-a concentration, followed by Lake Arenguade, Beseka and Shala. Chlorophyll-a concentrations generally increased during the post rainy and dry seasons. The results of multiple linear regression (LR) models were high for lakes Arengude, Beseka and Chittu. Lakes Shala and Beseka had the highest number of phytoplankton taxa, with both taxa composition and abundance dominated by Bacillariophyceae. Cyanoprokaryota, particularly Limnospira fusiformis, predominated in the abundance of lakes Arenguade and Chittu. Water temperature, Secchi depth, turbidity, electrical conductivity, soluble reactive phosphorus, nitrate and silica significantly influenced the phytoplankton community structure. Long-term trend analysis revealed changes in phytoplankton biomass and lake taxonomic composition. The alteration in phytoplankton biomass and species composition of the lakes could be attributed to three factors: frequent high-velocity explosions conducted for seismological studies in the past. This impact may have caused a dramatic increase in lake level in the case of Lake Beseka leading to a drop in nutrient concentration; climate change and salt content. Our findings suggest that phytoplankton composition, biomass, and abundance varied according to seasonal fluctuations, emphasizing the possible effects of anthropogenic and natural causes on their community structure.

The greatest numbers of zooplankton were noted for Lake Shala followed by Beseka, Chittu and Arenguade. Rotifers dominated all four lakes in terms of species richness whereas, cladocerans occurred rarely. The abundance of zooplankton in Lake Arenguade and Chittu was high during the wet season (July), while in Lakes Beseka and Shala it was high during the post-rainy (November) and dry seasons (January), respectively. The variations in the abundances of the zooplankton community were significantly explained by water temperature, DO, EC, nitrate, SRP, and turbidity according to Redundancy Analysis (RDA).

Land use and land cover (LULC) changes around the catchment of lakes Abijata, Beseka, Chittu and Shala have been significant over the last 40 years, reflecting broader environmental and socio-economic trends. Lake Beseka, agricultural land, and settlement areas have shown a consistent increase in the land use classes within the Lake Beseka catchment. Conversely, there has been a decline in the extent of dry land. Although the natural vegetation in the catchment area has displayed a tendency to grow, it experiences constant fluctuations due to alterations in land use and the expansion of water bodies. There has been an increase in agricultural land and settlements in the region, while dry land in the vicinity of the three lakes (Abijata, Chittu, and Shala) has been decreasing. The sizes of lakes Chittu and Shala have remained fairly consistent with minor fluctuations. Lake Abijata experienced a notable decrease in size between 1984 and 2004, but has since returned to its initial size. These changes were primarily driven by agricultural expansion, deforestation, and the demands for a growing population.

This study is the first to record the spatio-temporal variability of physico-chemical properties, plankton and Land Use- Land Cover (LULC) changes in five separate Ethiopian soda lakes. However, there is a need for more comprehensive research that integrates multiple ecological and environmental factors for the sustainable management and conservation strategies.

Keywords/phrases: Alkaline, Chlorphyll-a, Abundance, RDA analysis, Remote sensing

DEDICATION

I dedicate my dissertation work to my mother, AMSALE NEWAY MINDAYE, who has been the architect of my successes and the comfort in my struggles throughout my life and my PhD journey. Your spiritual guidance is a beacon that shines through the fog of life's complexities. Your prayers, whispered in the quiet corners of the day, become the silent guardians of my paths. Your strength is the bedrock upon which I stand, your wisdom the compass that guides me through life's complexities. This dedication is but a small token of my gratitude for the endless sacrifices you've made and the limitless love you have given me. To my mother, the unsung heroine of my world, thank you for every lesson, every sacrifice, and every moment of unwavering support. Love you mom and may you live a long life!

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LIST OF ABBREVIATIONS

ALOS PALSAR	Advanced Land Observing Satellite Phased Array type L-band Synthetic Aperture Radar
ANOVA	Analysis of Variance
APHA	American Public Health Association
ASLNP	Abijata-Shala Lakes National Park
Chl a -	Chlorophyll a
DCA	Detrended Correspondence Analysis
DO	Dissolved Oxygen
EC	Electrical Conductivity
ENMA	Ethiopian National Meteorological Agency
RDA	Redundant Analysis
SD	Standard Deviation
SRP	Soluble Reactive Phosphorus
TP	Total Phosphorus
USGS	United States Geological Survey

CHAPTER 1: GENERAL INTRODUCTION

1.1. Background

The lake ecosystems are inland water bodies formed by a variety of habitats combined with physical, chemical and biological processes (Bhateria and Jain, 2016; Valiente *et al.*, 2022). Hammer (1986) classified lake waters as fresh water lakes with salinities up to 500 mg l^{-1} or less and inland saline lakes with salinities ranging from 3 to 50 g l^{-1}. Depending on their salinity, saline lakes are categorized in three major groups. These are hyposaline (salinities~3-20 g l^{-1}), mesosaline (salinities~20-50 g l^{-1}), and hypersaline (salinities $\geq$50 g l^{-1}). Additionally, saline lakes are categorized as thalassohaline or athalassohaline based on whether the water originated from seawater or not (Zadereev, 2018).

Soda lakes are saline and alkaline lakes where there is a high concentration of carbonates as a major dissolved anion (Jones and Grant, 1999; Sorokin *et al.*, 2015). They are relatively closed systems compared to running waters or terrestrial habitats and are therefore excellent sensors of environmental changes. Climate change and catchment activities such as water course diversion, dredging, or excessive pumping of surface freshwater or ground water threaten the “good” ecological status of saline lakes (Williams, 2002).

Around the world, most soda lakes are primarily found in dry and semi-arid regions like the Kulunda Steppe in South Siberia (Russia), the rain-shadowed areas of California and Nevada, and the Rift Valley in East Eastern Africa. They are formed in depressions where ground water is rich in carbon dioxide and sodium from sodium-rich rocks, but poor in magnesium and calcium (Jones and Grant, 1999). Soda lakes are more abundant in the Eastern Rift Valley stretching from the Red Sea through Ethiopia and Kenya to Tanzania (Matagi, 2004; Schagerl and Renaut, 2016) Soda lakes are often considered to be an "extreme" aquatic environment, because of their exceptionally high alkalinity and salinity. However, they are also recognized as highly productive natural ecosystems (Schagerl and Renaut, 2016) and possess significant economic and non-economic benefits, making them remarkable natural resources. The economic value of soda lakes includes touristic attraction due to their natural beauty and diversity of animal and plant life. They are also recognized as sources of useful minerals like table salt (Sodium chloride), which comes from them. Lake Abijata is commercially exploited for soda ash production (Dagnachew Legesse *et al.*, 2004), while saline Lake Afdera serves as the primary source of edible salt (Abebe Getahun, 2001). Additionally, they are home to a diverse range of species that can be consumed by humans or other animals. For instance, they are particularly significant due to their ability to support the growth of a unique cyanobacterial community known as *Arthrospira fusiformis* (=*Limnospira fusiformis*), which has a high composition of protein (up to 70%) and a diverse range of amino acids. The existence of *Limnospira fusiformis* as a unialgal colony in Lake Chittu gives promising future for the extraction of these natural products from the lake (Tadesse Ogato *et al.*, 2014).

Many aquatic and water-related bird species use soda lakes as feeding, nesting, and refuge areas, which contributes to their non-economic ecological values. They also sustain exceptionally high rates of aquatic primary production, making them one of the most productive ecosystems on the planet (Elizabeth Kebede *et al.*, 1994). Moreover, these lakes hold scientific and educational significance in various fields including ecology, physiology, evolutionary biology, palaeoliminology, hydrology, and geochemistry. The two nearby lakes, Abijata and Shala, are particularly important for wildlife, as they support a diverse bird population consisting of over 360 resident and migratory species (Matagi, 2004).

Several authors have examined the limnological characteristics of a number of Ethiopian soda lakes at different points in time, each focusing on different lakes in the past. However, comparative limnological studies to assess the biological integrity of several lakes connected to temporal patterns are essentially scarcer in the majority of previous surveys. This study aims to address the knowledge gap indicated above by providing up-to-date information on limnological properties. The research was conducted to examine the hypothesis that the physico-chemical characteristics, diversity, and community compositions of phytoplankton, zooplankton, and the land use and land cover (LULC) of Ethiopian soda lakes (Abijata, Arenguade, Beseka, Chittu and Shala) have remained consistent over time due to natural and anthropogenic effects. The findings of this study are important as they enhance our understanding of the limnological features that contribute to the overall ecology of soda lakes. Besides, knowledge on their limnological status can be used as an important tool to establish appropriate management strategies.

1.2. Statement of the Problem

Ethiopia's soda lakes are essential ecosystems that provide home to a diverse range of organisms. Recent research, however, indicates that a number of factors are endangering these ecosystems. Understanding their limnological status can be a valuable tool in developing appropriate management plans for them.

Presently, soda lakes in Ethiopia are facing threats due to anthropogenic and natural activities. Anthropogenic activities such as deforestation, agricultural expansion, livestock grazing, soda ash extraction, and upstream irrigation have led to a decrease in water levels and surface area, altering the physico-chemical and biological conditions of these ecosystems. These changes have had a detrimental impact on biodiversity, with shifts in phytoplankton community structures and reductions in zooplankton populations, leading to the collapse of fisheries and the migration of bird species to nearby lakes (Hadgembes Tesfay, 2006).

For instance, human activities like soda ash extraction and upstream water diversion for irrigation are causing a drop-in water level in lakes like Abijata. This leads to increased salinity, changes in the lake's living organisms (biotic structure), and even fish population collapse (Dagnachew Legesse *et al*., 2004; Solomon Wagaw *et al*., 2019).

Conversely, Lake Beseka has seen a tenfold increase in size over the past three decades. This suggests a change in its water chemistry, with a decrease in total dissolved salts and electrical conductivity. The cause is likely a combination of factors, including hot spring discharge; climate change, increased groundwater inflow, and irrigation return water. This dilution has led to a decrease in the lake's total ionic concentration and a shift in the types of plankton present (Zinabu G/Mariam, 2002; Haile Shishaye, 2017; Umer *et al*., 2020).

The Central Rift Valley (CRV) where these lakes are located is a diverse ecosystem facing significant pressure from human activities. A growing population, unsustainable farming practices, insecure land tenure systems, poverty, and climate change are all contributing to Land Use/Land Cover (LULC) changes (Wolde Mekuria *et al*., 2021).

Plankton communities are sensitive to environmental changes, reflecting the physical, chemical, and biological health of the lake. Studying their abundance and composition provides valuable insights into the lake's ecological balance (Wetzel and Likens, 2000). Land use/Land cover (LULC) changes can disrupt the delicate balance of lake ecosystems, affecting both the physico-chemical variables and the biological communities within them (Liu et al., 2017).

Regular monitoring of water quality is essential to understand the current status and long-term trends of these soda lakes. This information is critical for developing effective management strategies to ensure their health and continued ecological services. The scope of this study was to fill in the gaps in the soda lakes' limnological dynamics by comparing the findings with those of earlier investigations to understand the current conditions and long-term trends for effective management of the lakes.

1.3. Objectives of the Study

1.3.1. General Objective

The general objective of this study was to determine limnological status of five soda lakes of Ethiopia (Abijata, Arenguade, Beseka, Chittu and Shala) and compare the spatio-temporal changes among these lakes in comparison with their historical data to identify trends of change

1.3.2. Specific Objectives

The specific objectives of this dissertation research were to:

- assess spatio-temporal variations of physico-chemical parameters of the soda lakes;
- determine the spatio-temporal phytoplankton dynamics in relation to physico-chemical parameters;
- investigate spatio-temporal variations of zooplankton community structure in relation to physico-chemical variables;
- compare physicochemical parameters, phytoplankton and zooplankton limnological data with previous reported data and note any change that may have occurred;
- estimate long term land use and land cover changes around the catchment areas of the lakes using remote sensing and GIS techniques

1.4. Research Questions

The following research questions were set to guide the research:

- Do physico-chemical parameters show significant variation between the seasons and study sites?
- Are there spatial and temporal changes in the phytoplankton community structure in relation to physico-chemical characteristics?
- Are there spatial and temporal changes in the zooplankton community structure in relation to physico-chemical characteristics?
- Are there long-term changes regarding physico-chemical parameters, phytoplankton, and zooplankton in each lake?
- What are the land use and land cover changes (LULC) around the catchment areas in the last 40 years?

1.5. Study Area Description

This research was conducted in five different Ethiopian soda lakes: Abijata, Arenguade, Beseka, Chittu and Shala (Fig. 1.1). Lakes Beseka (Metahara), Chittu, and Shala are all located within the Main Ethiopian Rift system of the Great East African Rift Valley, while Lake Arenguade is located on the western escarpment of the Ethiopian rift system. Arenguade and Chittu are relatively small crater lakes (the former a- maar) (Klemperer and Cash, 2007). Data from the National Meteorological Agency of Ethiopia (ENMA) were used for the monthly rainfall data of the sample year 2020. The morphometric characteristics of the study lakes were described in Table 1.1.

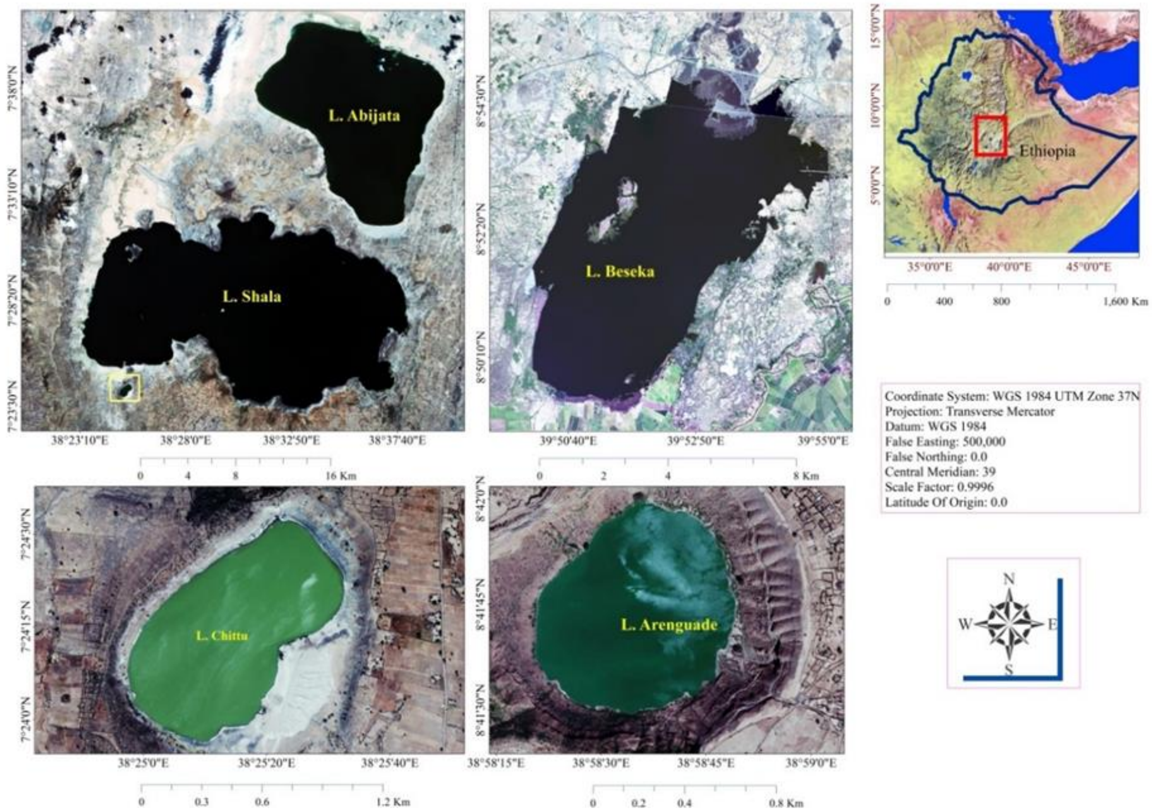


Figure 1. 1. Location map of the study areas indicating the five lakes

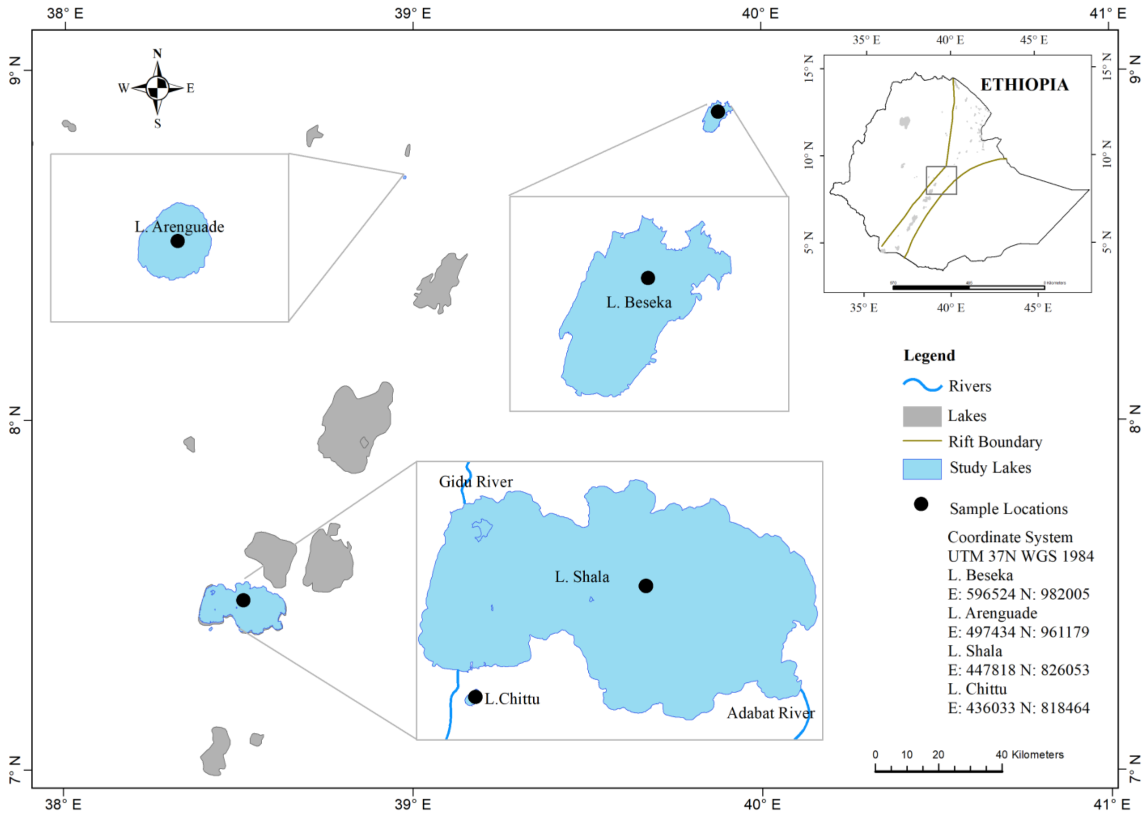


Figure 1. 2. Map of the study lakes showing the sampling sites/locations (black dots)

Table 1. 1. Geospatial and morphometric data of the study Lakes Arenguade, Beseka, Chittu and Shala

Parameter	Arenguade	Beseka	Chittu	Shala
Latitude (N)	8°41.856'	8°51.5'	7°24'	7°28'
Longitude (E)	38°58.796'	39°51.5'	38°25'	38°30'
Altitude (m a. s. l)	1900	952	1600	1560
Area (km^2)	0.54	40	0.8	370
Max. depth (m)	32	11.5	21	266
Mean depth (m)	18.5	6	-	86
Volume (km^3)	0.010	23.31	-	37,000
Catchment area(km^2)	-	401.5 (505)	-	3,920

Data source: (Wood and Talling, 1988), (Elizabeth Kebede *et al.*, 1994), (Tenalem Ayenew, 2004), (Schagerl and Renaut, 2016), (Tadesse Ogato *et al.*, 2015)

Lake Arenguade (also known as Haro Hadho) is situated 45 kilometers south of Addis Ababa. It is a small soda lake which is part of a large group of volcanic, explosion crater lakes known as the Bishoftu crater lakes (Schagerl and Renaut, 2016). The lake has a closed basin with no obvious inlet or outlet. Its crater rim rises about 200 meters above the lake's surface. The average annual temperature is 20.4 ℃; with a mean maximum of 31.6 ℃ and a mean minimum of 11.4 ℃ (EWNHS, 2020) (Figure 1.3). The lake region experiences two rainy seasons: minor (February to April) and major (June to September). The Lake Arenguade region's period is from November to January (Baxter, 2002). It receives water primarily from rainfall that falls directly on its surface and run-off from its small catchments (Misgina Belachew *et al.*, 2012). The mean annual rainfall of this area is 1805 mm (ENMSA, 2020). Lake Arenguade is named (Arenguade means green in Amharic language and Haro Hadho meaning salt lake in Afaan Oromo); for the dense production of the filamentous blue-green alga (*Arthrospira fusiformis*) currently described as *Limnospira fusiformis* by (Nowicka-Krawczyk *et al.*, 2019). The lake is well-known for hosting phytoplankton species of *Limnospira fusiformis*, which is the major food source for lesser (*Phoeniconaias minor,* Geoffroy 1978) and greater flamingos (*Phoeniconaias major* Geoffroy, 1978). Lake Arenguade supports large populations of lesser flamingos, and the calanoid copepod *Lovenula africana* Daday, 1910 which feed on *L. fusiformis.* The Lake, however, is devoid of piscifauna (Misgina Belachew *et al.*, 2012).

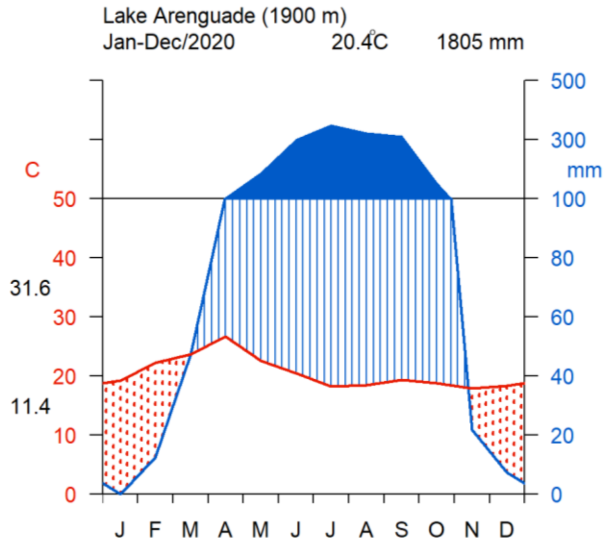


Figure 1. 3. Walter and Lieth climate diagram showing a summary of climate conditions around Lake Arenguade during the year 2020

Lake Beseka (Metahara) is a volcanically dammed, shallow endorheic lake located about 200 Km southeast of Addis Ababa (Tenalem Ayenew, 2004). The surface area of Lake Beseka has grown significantly over the last few decades, from 10.8 km^2 in 1972 to 52.1 km^2 in 2020 (Esayas Gebremichael *et al.*, 2022). Increased ground water inflow from the western part of the watershed (Goerner *et al.*, 2009), increased inflow to the lake in the form of hot springs (Eleni Belay, 2008), lake neotectonism (Megersa Olumana, 2017b) and irrigation return water from the adjacent farms (Tamiru Alemayehu *et al.*, 2006) are some of the reported causes of this expansion. The general climate of the area is semi-arid with a mean annual temperature of 25°C and a total mean annual rainfall of 534 mm (Eleni Belay, 2008). The average annual temperature of Lake Beseka is 24.8 ℃; with a mean maximum of 37.3 ℃ and a mean minimum of 11.6 ℃ (EWNHS, 2020) (Figure 1.4). There are two main seasons in the lake's location: the rainy season (June–August) and the dry season (9 months) (Tamiru Alemayehu *et al.*, 2006). The mean annual rainfall of this area is 742 mm (ENMSA, 2020). As the Lake is situated in the central rift valley region, it is vulnerable to the occurrences of different tectonic and volcanic activities (Megersa Olumana, 2012). Lake Beseka has attractive scenery and supports two commercially important fish species (*Oreochromis niloticus* and *Claries gariepinus*), crocodiles, alligators, and different bird species (Getachew Senbete, 2015).

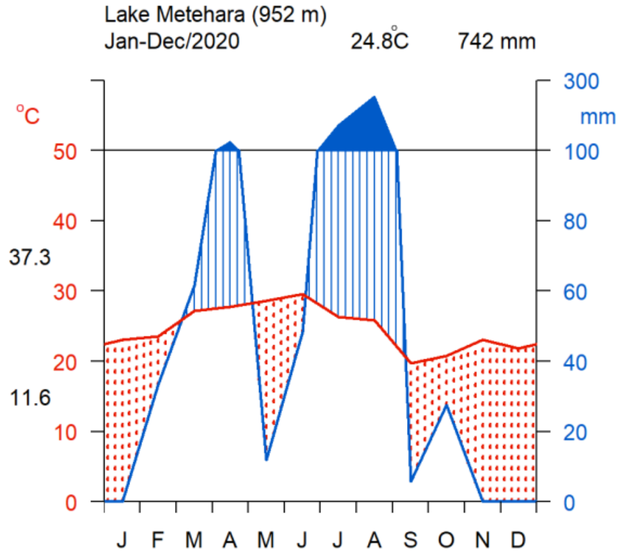


Figure 1. 4. Walter and Lieth climate diagram showing a summary of climate conditions around Lake Beseka (Metehara) during the year 2020

Lakes Chittu and Shala are located some 287 km south of Addis Ababa, within the Abijata-Shala Lakes National Park (Baxter, 2002). Lake Chittu is fed by direct precipitation and a few hot springs on its shores (Tenalem Ayenew and Dagnachew Legesse, 2007) and Shala, is fed by direct precipitation, several hot springs and two rivers (Adabat and Gidu) (Baumann *et al.*, 1975). The lakes' region has semi-arid to sub-humid type of climate with mean annual precipitation and temperature of 600 mm and 25 °C, respectively (Legesse and Ayenew, 2006). The average annual temperature is 18.1 °C; with a mean maximum of 28.4 °C and a mean minimum of 8.0 °C (EWNHS, 2020) (Figure 1.5). The region has two seasons: dry (October to February) and wet (March to September) seasons. The wet season is characterized by a bimodal pattern of rainfall, with minor rainy period extending from March to May and major rainy period from June to September. The mean annual rainfall of this area is 1805 mm (ENMSA, 2020). The region has higher rate of evaporation than precipitation, which causes rainfall deficit (Tadesse Ogato and Demeke Kifle, 2014). Lake Chittu is a cup-shaped Crater Lake surrounded by a crater rim and is situated at about1 km South-West of Lake Shala. Lake Chittu is fed by direct precipitation and a few hot springs around its shore (Ayenew and Legesse, 2007). *L. fusiformis* is an effectively dominant species that normally forms dense blooms. The lake is also a home to thousands of flamingos (Tadesse Ogato and Demeke Kifle, 2014; Girum Faris and Genene Tefera, 2017).

Contrarily, Lake Shala is known for its low phytoplankton productivity with the absence of *L. fusiformis*, and it's predominated by diatoms and cryptomonads (Elizabeth Kebede *et al.*, 1994; Tadesse Ogato and Demeke Kifle, 2017; Solomon Wagaw *et al.*, 2021). Lake Shala and its islands host a significant population of lesser flamingos (*Phoeniconaias minor* Geoffroy), Greater White Pelicans, Cormorants, Storks, and the great cormorants (*Phalacrocorax carbo)* (Tafesse Kefyalew, 2008). It also supports two fish species: *Oreochromis niloticus* and *Aplocheilichthys* sp. (Solomon Wagaw *et al.*, 2022).

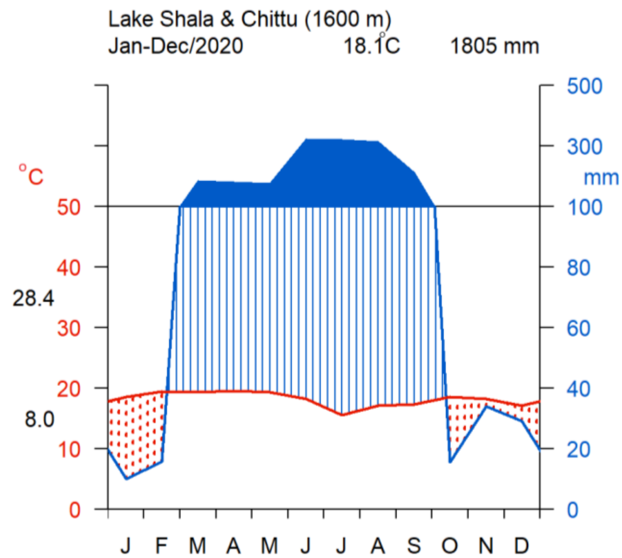


Figure 1. 5. Walter and Lieth climate diagram showing a summary of climate conditions around Lake Shala and Chittu during the year 2020

Lake Abijata is fed by Bulbula and Hora Qallo rivers, draining from lakes Ziway and Langano, respectively (Klemperer and Cash, 2007; Lemma Abera, 2016). Lake Abijata experienced a decrease of around five meters and shrunk by 25% in its size over the last three decades. Its decline is caused by water abstraction for irrigation and soda ash production, land use changes, and climate variability (Tenalem Ayenew, 2002; Tamiru Lemi, 2019). Unlike Lake Abijta which is shrinking, Lake Beseka has grown significantly over the last three decades, with a significant fall in its total ionic concentration compared to 1960s data (Megersa Olumana, 2012; Hana Melese and Habte Jebessa, 2023).

Lakes Abijata and Shala constitute a National Park that Ethiopian Government has nominated as a candidate site for the Ramsar Convention on Wetlands (Negussie *et al.*, 2019). Abijata-Shala Lakes National Park (ASLNP) is a major breeding and feeding area for many species of mammals, an extensive variety of water birds as well as certain rare species of resident and migratory birds (Tafesse Kefyalew, 2008). The park is under severe threat due to deforestation, overgrazing, and agricultural expansion because of rapid population growth (Tadesse Fetahi, 2016; Ayenew Ayalew *et al.*, 2022).

1.6. Dissertation Structure

This dissertation is divided into six chapters. The first chapter provides an overview of the study's background, research gaps, general and specific aims, research questions, and study area. The physico-chemical properties of the four soda lakes are discussed in the second chapter along with a historical trend analysis. In this chapter, the spatio-temporal variations of the physico-chemical parameters were analyzed by comparing them with historical data. The focus was analyzing the physico-chemical parameters of four soda lakes in Ethiopia to identify any trends in change. This chapter has been published:

> Hana Melese and Habte Jebessa (2023). Comparative study on seasonal variations in physic chemical characteristics of four soda lakes of Ethiopia (Arenguade, Beseka, Chitu and Shala). *Heliyon.* **9**(5). DOI: 10.1016/j.heliyon.2023.e16308.

The third chapter details the spatio-temporal dynamics of phytoplankton composition, chlorophyll-a as a proxy for algal biomass, and abundance in relation to environmental parameters in four Ethiopian soda lakes. This chapter has also been published:

> Hana Melese and Habte Jebessa (2024b). Temporal phytoplankton dynamics and environmental variables in four Ethiopian soda lakes. Environmental Systems Research. 13(1): 1-15. DOI: https://doi.org/10.1186/s40068-023-00329-0.

The spatio-temporal patterns of zooplankton communities in relation to environmental factors are shown in the fourth chapter. The manuscript has been submitted to the journal of Heliyon.

The fifth chapter follows, utilizing remote sensing and GIS techniques to predict changes in land cover land use surrounding the catchment region of the four Ethiopian soda lakes during four periods (1984, 1994, 2004, 2014, and 2024).

In the final chapter 6, the thesis concludes the main findings of the study, highlights research gaps and provides recommendations for further research in the study area that could be helpful in establishing improved lake management.

CHAPTER TWO: COMPARATIVE STUDY ON SEASONAL VARIATIONS IN PHYSICO-CHEMICAL CHARACTERISTICS OF FOUR SODA LAKES OF ETHIOPIA (ARENGUADE, BESEKA, CHITU AND SHALA)

2.1. Introduction

Soda lakes are saline and alkaline ecosystems that are thought to have existed since the world's first geological records. They are extreme environments found all over the world, mostly, in arid and semi-arid regions. They are more common in the Eastern Rift Valley, which stretches from the Red Sea to Tanzania via Ethiopia and Kenya (Melack, 1981; Schagerl and Renaut, 2016). They are strongly alkaline aquatic environments with high conductivity (6,000-160,000 μS/cm), extremely high pH (above 9.5), high salinity (>50g l^{-1}) and high alkalinity due to sodium carbonate salt (Hammer, 1986; Jellison *et al.*, 2004; Ventosa and Arahal, 2009).

Since soda lakes are relatively closed systems, they are excellent environmental sensors, sensitive to weather and climate change. Even minor changes have a significant and, in some cases, irreversible impact on the natural character of these lakes (Jellison *et al.*, 2004). Their physical and chemical properties are influenced by local geomorphology, basin characteristics, geochemistry and evaporation (Schagerl and Renaut, 2016). Monitoring water quality of soda lakes has become a high priority for the determination of current conditions and long-term trends for effective water management (Stenger-Kovács *et al.*, 2014).

Ethiopia is rich in soda lakes, which are well-known for their unique diversity, scientific benefits, economic significance and scenic attractions. Presently, these lakes are under threat from both anthropogenic activities and natural events (Hadgembes Tesfay, 2006). A change in the ecology of the catchment, such as water course diversion, sand mining, and water course abstraction are adversely impacting the lakes' ecosystems. On the other hand, climate change is affecting the physicochemical characteristics and biological community structure of the lakes, further complicating their ecology (Williams, 2002; Oduor and Kotut, 2016).

The physicochemical properties of saline lakes naturally fluctuate due to seasonal changes in wet and dry seasons. These changes have a direct impact on the biota that live in saline lakes (Sanders, 2019). Increasing anthropogenic activities, climate change, and the dynamic nature of physicochemical parameters all necessitate the availability of contemporary limnological data. A number of authors have studied the physical and chemical characteristics of some Ethiopian soda lakes (Elizabeth Kebede *et al.*, 1994; Zinabu G/Mariam *et al.*, 2002; Tesfaye Delelegne 2006; Misgina Belachew *et al.*, 2012; Tadesse Ogato, 2015; Haile Shishaye, 2017; Solomon Wagaw *et al.*, 2021). Despite such studies at different times on separate lakes in the past, there are no such coherent studies that show trends in the limnological changes of the Ethiopian Rift Valley soda lakes in recent years. The objective of this study was to compare spatio-temporal variations of the physicochemical properties of four Ethiopian soda lakes in comparison to their historical data and identify trends of change. The results generated by this study will contribute to a better understanding of changes in the lakes' ecosystem to devise effective management strategy and mitigation measures.

2.2. Materials and Methods

2.2.1. Sampling and Analytical Methods

2.2.2. Physicochemical Parameters

Water samples from four Ethiopian soda lakes: Arenguade, Beseka, Chittu and Shala, were taken from offshore sites (open water) (Fig. 1.2) and their geographical position were determined by means of Global Positioning System (GPS). Triplicate samples were collected from the study lakes surrounding each sampling site from 50-100-meter distances from January to December 2020, four times in different seasons (Dry-January, Pre-rainy-June, Rainy-July, Post rainy-November). Over the whole sampling period, a total of forty-eight samples (twelve from each lake) were gathered at midday.

Dissolved oxygen (DO), electrical conductivity (EC), pH and temperature were measured *in-situ* and vertical profiles were determined using a multi-metric probe (HQ40d). Prior to the analysis, the equipment was calibrated at Addis Ababa University's Limnology Laboratory using ionic strength corrected buffers to minimize the effect of ionic strength on pH and DO measurements. The conductivity measured *in-situ* was corrected to conductivity at 25^{o}C using a temperature coefficient of 2.3% per ^{o}C (Talling and Talling, 1965). Depth profiles were determined for three lakes considering their size and depth from 0, 1, 2, 3, 4, 5 m depths (Beseka and Chittu) and from 0, 1, 2, 3, 4, 5, 10, 15, 20 m depths (Shala).

Secchi depth (Z_{SD}) was measured using a standard black and white Secchi disc of 20 cm diameter. The depth of the euphotic zone (Zeu) was calculated in meter from Z_{SD} reading using mathematical relationship: $Z_{eu} \approx 2.7*Z_{SD}$ (Salmaso and Padisák, 2007). Total suspended solids were estimated by weighing Whatman® Glass Microfiber Filters (GF/F), that had been pre-dried at 105°C and calculated using the formula in literature (APHA, 1999). Total (TA) and phenolphthalein alkalinity (PA) were determined by titration of 100 ml of the sample with 0.1 N HCl to the appropriate end point pH using phenolphthalein (PA) and mixed bromocresol green and methyl red indicator for TA according to (Wetzel and Likens, 2000). The levels of dominant ions (HCO_3^- and CO_3^{2-}) were calculated using alkalinity values (Lind, 1979).

Part of the water samples were filtered through Whatman Glass Fibre Filter papers (GF/F) and stored in polyethylene bottles near 4°C for nutrient analyses, which were done within 48–72h of sample collection. Nutrients were analyzed at Limnology Laboratory of Addis Ababa University following the standard methods (APHA, 1999). Ammonium nitrogen **(**NH_3-N) was determined by phenate method; soluble reactive phosphorus (SRP) and total phosphorus (TP) were determined using ascorbic acid method, while total phosphorus (TP), was measured after digesting the unfiltered sample using potassium persulfate. Nitrate (NO_3-N) was determined using sodium-salicylate method and silica (SiO_2) was determined by the Molybdo-silicate method. Total and phenolphthalein alkalinity of the lakes was determined by titration of the sample with 1N HCl to pH = 4.5, using phenolphthalein and bromcresol green indicator solutions (Wetzel and Likens, 2000).

2.3. Data Analysis

Statistical analysis was carried out using the R software (version 4.0.5) (R Core Team, 2020). Significant differences among the results were determined using Kruskal–Wallis method of variance (ANOVA). The data collected were tested for normality using Shapiro-Wilk normality test and transformed to $Log10^{(X+1)}$, where necessary, and differences were considered as significant when $p < 0.05$. Temporal variations in physicochemical parameters were described using bar plots (Sigma plot version 15). Walter and Lieth climate diagrams and line plots for depth profiles were constructed using ggplot2 (climatol and tidypaleo) functions respectively (Villanueva and Chen, 2019).

2.4. Results

2.4.1. Spatial Variation of Physico-chemical Parameters

The spatial variations of physicochemical parameters of the four study lakes are tabulated (Table 2). The highest (25.9 ^{o}C) average water temperature recorded was at Lake Beseka, followed by Lakes Shala and Chittu, and the lowest temperature was recorded at Lake Arenguade. The average pH values recorded were high and showed little variation within the three lakes, whereas a low pH value was recorded in Lake Beseka. The highest measured dissolved oxygen (DO) was (7.36+0.72 mg l^{-1}) measured in Lake Shala, followed by lakes Beseka, and Chittu but very low dissolved oxygen (3.33+0.24 mg l^{-1}) was recorded in Lake Arenguade. Lake Arenguade had the highest turbidity, followed by Beseka and Chittu. Lake Shala, on the other hand, had the lowest turbidity. Secchi disk depth reached a maximum of 1.23cm in Lake Shala and a low of 0.3cm in Lake Arenguade. Lake Chittu had the highest conductivity, alkalinity, and salinity values, followed by Shala. In contrast, Lake Arenguade had the lowest values, followed by Lake Beseka (Table 2). In terms of nutrient concentrations in the lakes, ammonium nitrogen had the highest value (161.93+57.8 µg l^{-1}) in Lake Arenguade and the lowest (56.39+14.69 µg l^{-1}) in Lake Beseka. The minimum and maximum concentrations of nitrate nitrogen were 27.12+7.50 µg l^{-1} (Lake Shala) and 98.36+52.03 µg l^{-1} (Lake Beseka), respectively. Lake Chittu had the highest soluble reactive phosphate (SRP) 1.75+0.34 mgl^{-1} values, followed by Lake Shala and Arenguade. SRP concentrations in Lake Beseka were found to be low (0.44+0.16 mgl^{-1}). Lake Chittu had the highest total phosphorus (TP) concentration (2.41+0.52 mg l^{-1}), followed by Lake Arenguade and Shala, while Lake Beseka had the lowest. The lowest average 27.1±1.72 meql^{-1} (HCO_3^{-}) and 29.53±6.85 meql^{-1} (CO_3^{2-}) was recorded in Lake Beseka followed by Lake Arenguade and Shala. However, the highest average 313.1±71.4 meql^{-1} (HCO_3^{-}) and 279.9±27.4 meql^{-1} (CO_3^{2-}) was recorded in Lake Chittu.

Table 2. 1. Limnological characteristics of the four Ethiopian soda lakes (mean ± sd) and range (min-max) during the present study period

Parameters	Lakes			
	Arenguade	**Beseka**	**Chittu**	**Shala**
Temp (^oC)	22.2±0.55	25.9±0.89	22.8±0.58	22.9±0.6
	21.5-23	24.7-27.5	22.2-23.5	21.9-23.4
pH	10.04±0.34	8.55±0.70	10.46±0.14	10.12±0.37
	9.57-10.41	7.87-9.31	10.2-10.6	9.8-10.7
EC (mS/cm)	5.42±0.167	2.72±0.123	66.9±3.45	26.5±2.94
	5.25-5.65	2.52-2.8	63.5-70.24	23-30.85
DO (mg l^{-1})	3.33±0.24	6.61±0.62	5.44±0.27	7.36±0.72
	3.12-3.66	6.01-7.21	5.14-6	6.63-8.47
Alk (meql^{-1})	50.2±9.22	36.2±3.45	426.7±45.4	305.7±23.27
	42-63.6	32-41.1	375.4-480	282-340
Sal (g l^{-1})	2.91±0.50	1.88±0.48	38.4±7.60	16.78±1.90
	2.1-3.3	1.42-2.38	29.7-45.6	14.4-19.5
Turbidity (NTU)	37.7±4.00	35.9±7.77	30.3±7.66	15.05±4.44
	33.5-42.6	25- 44.5	22-38.7	10.8-22.14
Sechi depth (m)	0.3±0.07	0.46±0.05	0.49±0.08	1.23±0.04
	0.23-0.4	0.39- 0.53	0.42-0.62	1.2-1.3
NO_3–N (μg l^{-1})	40.6±27.31	98.4±52.03	69.5±29.72	27.12±7.50
	9.14-97.71	27.3-164.4	24.86- 112	20.6-40.57
NH_3–N (μg l^{-1})	161.9±57.8	56.4±14.69	113±61.58	89.2±39.2
	83-224.4	44.86-83.4	54.4- 201.6	50.14-148.7
SiO_2 (mg l^{-1})	39.4±11.9	58.4±37.10	2.59±1.01	2.37±0.25
	19.6-49.57	22.9-96.17	1.4- 4.21	2.1-2.87
SRP (mg l^{-1})	1.04±0.27	0.44±0.16	1.75±0.34	1.05±0.50
	0.74-1.47	0.25-0.71	1.37-2.37	0.65-1.9

TP ($mg\ l^{-1}$)	2.08±0.51	1.15±0.33	2.41±0.52	1.59±0.49
	1.48-2.8	0.75- 1.49	1.79- 3.21	1.1- 2.3
HCO_3^- ($meql^{-1}$)	51.34±9.17	27.1±1.72	313.1±71.4	140.73±29.8
	41.3-63	22.8-29.95	224.02-389.6	102.3-170.5
CO_3^{2-} ($meql^{-1}$)	67.6±17.6	29.53±6.85	279.9±27.4	141.82±32.1
	41.6-79.14	24.35-38.96	239.45-299.5	102.27-175.3

2.4.2. Temporal Variation of physico-chemical Parameters

The mean values of seasonal physico-chemical parameters recorded among the lakes during the study period are summarized in figure 5 and 6. With the exception of variation in salinity Lake Shala, all physicochemical variables showed significant differences between the sampling seasons ($p < 0.05$).

Temporal variations in temperature and dissolved oxygen concentration in Lake Arenguade indicated some variability among seasons. Temperature was high in post rainy seasons (23.0 ^oC) and low (21.57 ^oC) in pre-rainy seasons while dissolved oxygen concentration was high (3.66 mg l^{-1}) in pre-rainy seasons. Both electrical conductivity and pH values showed significant differences between sampling seasons. Electrical conductivity was high (5.65 $mScm^{-1}$) in dry and low (5.25 $mScm^{-1}$) in rainy season, whereas pH was high in post rainy season and low in dry season. Salinity results showed high values (3.24 g^{-1}) during the dry season and low (2.10 g l^{-1}) during the rainy season, while alkalinity results showed high values in the pre rainy season and low values in the post rainy season with the mean results of 63.3 $meql^{-1}$,42.0 $meql^{-1}$, respectively, showing significant variations between seasons (Figure 2.1).

In terms of nutrient concentration in Lake Arenguade, nitrate and total phosphorus showed high values (73.9 μg l^{-1}, 2.78 mg l^{-1}) during the dry season, respectively. SRP concentrations were high (1.46 mg l^{-1}) during the rainy season and low (0.75 mg l^{-1}) during pre-rain season. Ammonia concentrations show high values (224.0μg l^{-1}) during the post-rain season and low values (84.4 μg l^{-1}) during the pre-rainy season, and silica concentrations show high values (48.5 mg l^{-1}) during the rainy season and low (20.0 mg l^{-1}) during the pre-rainy season (Figure 6).

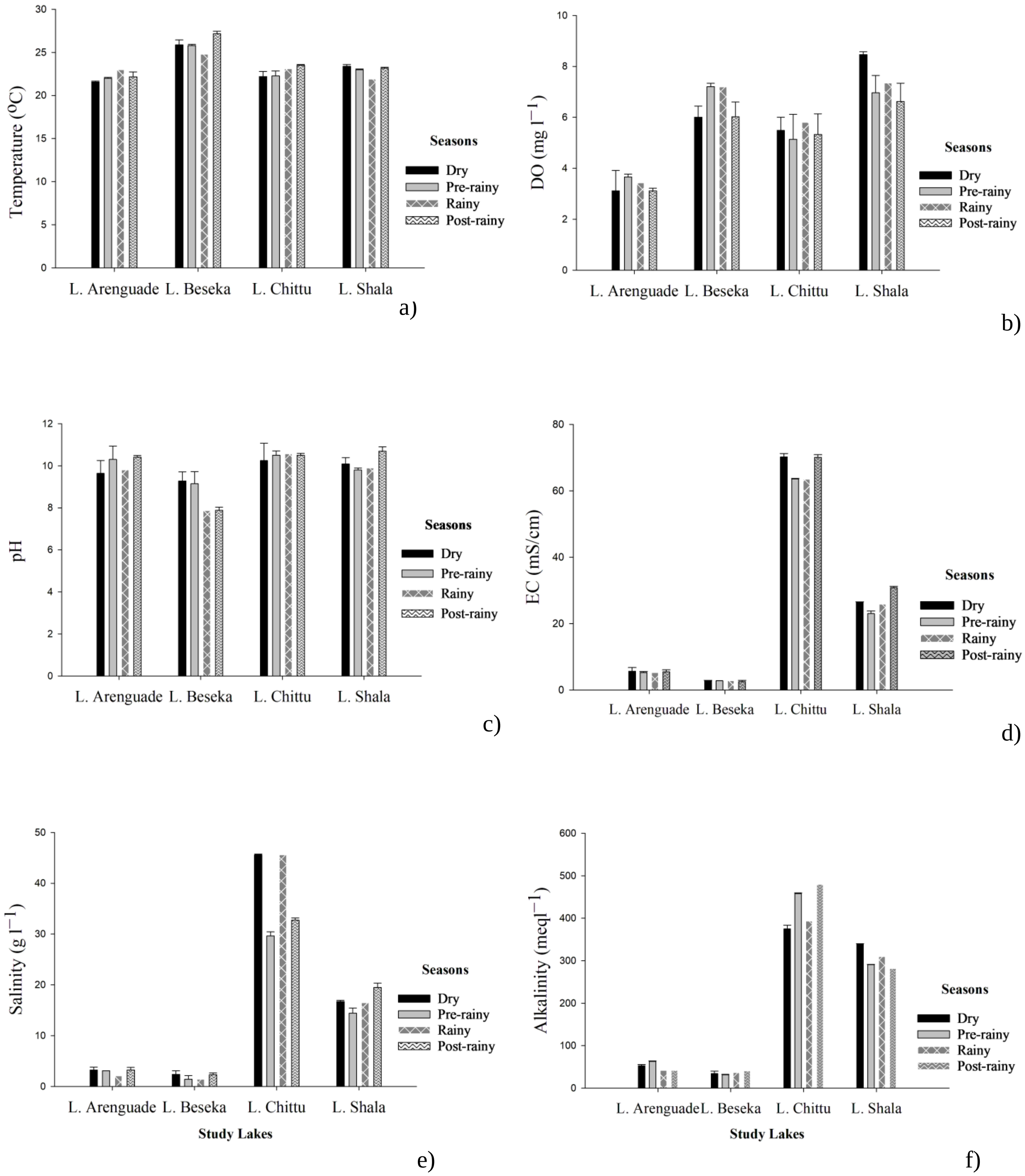


Figure 2. 1. Seasonal variations in a) water temperature, b) dissolved oxygen, c) pH, d) conductivity, e) salinity and f) alkalinity of the study lakes during the study period

In Lake Beseka, physicochemical parameters also showed significant differences between seasons ($p<0.05$). pH values were high (9.28) during the dry season and low (7.87) during the rainy season. Electrical conductivity was higher (2.79 mS/cm) in the pre-rainy season and lower (2.52 mS/cm) in the rainy season. During the post-rainy season, alkalinity was high (41.1 $meql^{-1}$) and salinity were also high (2.38 g l^{-1}) during the dry season (Figure 5). Nitrate concentrations were high (164.4 μg l^{-1}) during the rainy season and low (30.1 μg l^{-1}) during the dry season, while ammonia concentrations were high (80.4 μg l^{-1}) during the post rain season. Both soluble reactive phosphate (SRP) and total phosphate (TP) showed high values (0.66, 1.49 mg l^{-1}) in the dry season and low values (0.26, 0.77 mg l^{-1}) in the rainy season.

In Lake Chittu temperature was high during the post rainy and low during the dry season and dissolved oxygen showed high during the rainy season and low during the pre- rainy season. SRP and Tp showed high values during the dry and during the rainy seasons respectively. In Lake Shala temperature and pH showed higher values during the dry seasons while, dissolved oxygen and alkalinity showed higher values during the rainy season and season low during the post rainy season. In the case of nutrients, ammonia and nitrate were lower during the post rainy season, where as SRP and TP showed higher values during the dry season and lower during the rainy season (Figure 2.2).

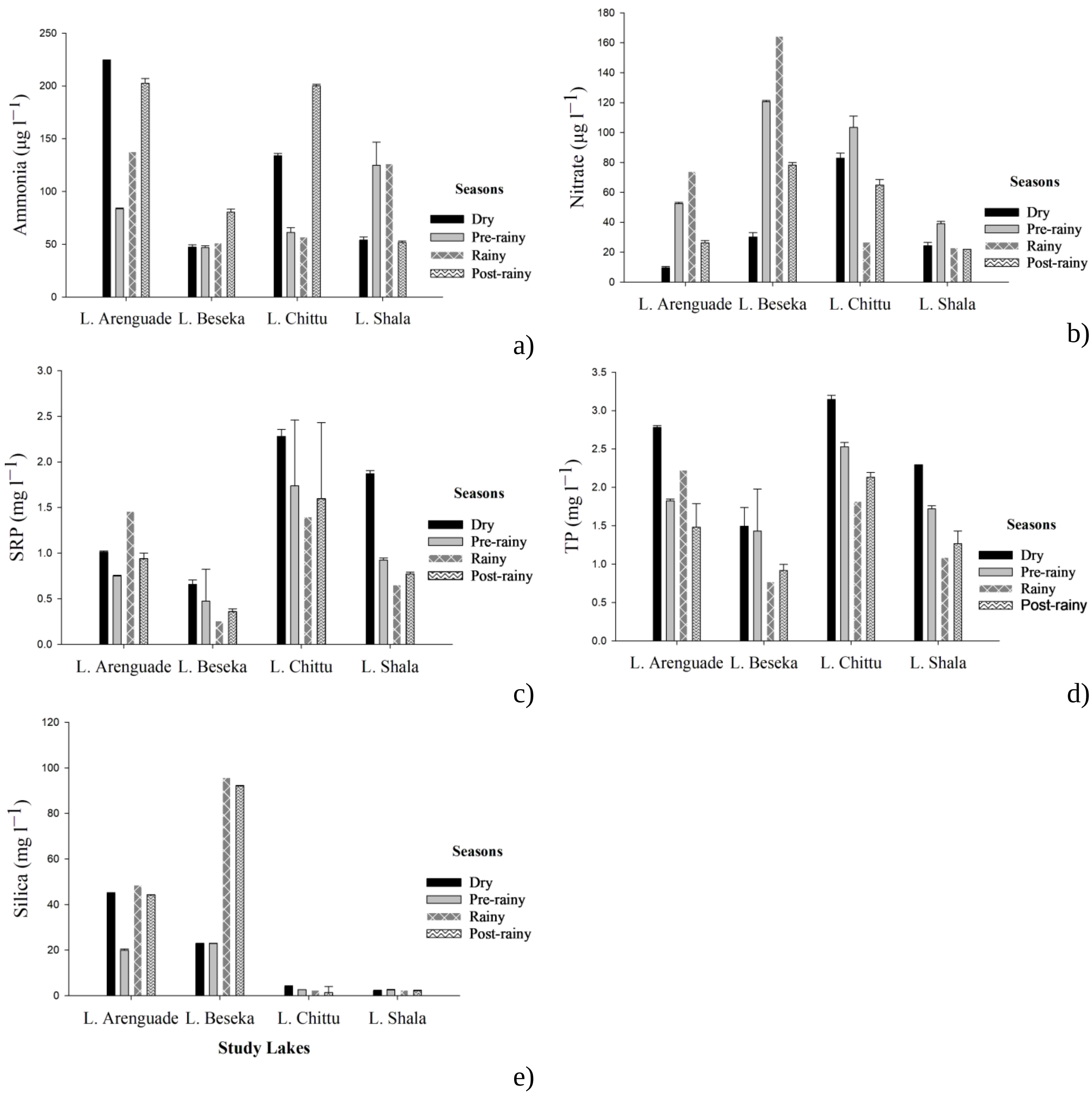
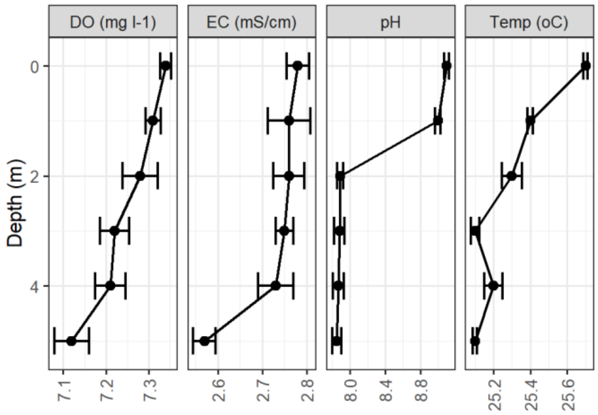


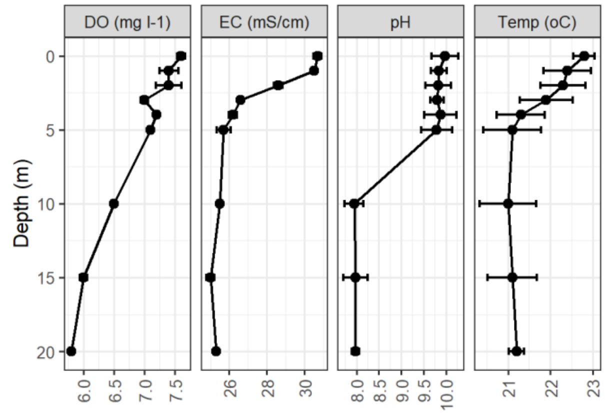
Figure 2. 2. Seasonal nutrient variation in a) ammonia, b) nitrate, c) soluble reactive phosphorus, d) total phosphorus and e) silica of the study lakes during the study period

2.4.3. Depth Profiles of Some Physico-chemical Parameters

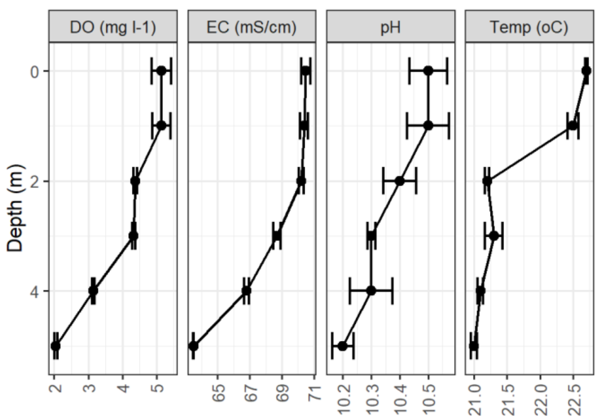
Temperature and DO depth profiles in Lake Beseka exhibited an isothermal pattern with concentrations largely consistent and only slightly dropping below the fifth meter. Depth profiles of pH and conductivity showed some variations with depth, exhibiting decreasing trends (Figure 2.3a). Surface water temperature and DO depth profiles in Lake Shala showed superficial thermal stratification with small temperature gradients. The mean temperature difference between surface water and 20 m depth was slightly higher (1.6±0.25 ^{o}C). pH depth profiles recorded in Lake Shala at depths ranging from 0 to 20 m revealed variations with depth. The pH in the tropogenic zone (above 2 m depths), which was high (9.8) at the surface declined to 7.98 at 20 m depth. Conductivity depth profiles shows variation on the vertical section, first showing a decreasing trend and then increasing at 20 m depth (Figure 2.3b). The vertical distribution of water temperature and DO in the water body Lake Chittu demonstrated superficial stratification. Based on the measured data, the DO concentration in the surface layer (7.6 mg l^{-1}) of Lake Chittu was decreased to (2.05 mg l^{-1}) at the depth 5m. Depth profiles of pH and conductivity of Lake Chittu for depths between 0 and 5m depths indicated small decreasing variability with depth (Figure 2.3c).



a) Lake Beseka



b) Lake Shala



c) Lake Chittu

Figure 2. 3. Dissolved oxygen (DO), Electrical conductivity (EC) and Water temperature depth profiles of the studied lakes

2.5. Discussion

2.5.1. Spatial Variation of Physico-chemical Parameters

In comparison to the other lakes studied, Lake Beseka had the highest surface water temperature. This could be due to the lake's high volcano-tectonic forcing (Esayas Gebremichael *et al.*, 2022). Dissolved oxygen is a critical component of an aquatic ecosystem, determining water quality and supporting aquatic life (Williams, 1998). Dissolved oxygen concentrations below $5 mgl^{-1}$ have a negative impact on aquatic life. Among the studied lakes, Lakes Shala, Beseka, and Chittu had higher dissolved oxygen concentrations, whereas Lake Arenguade had the lowest dissolved oxygen concentration, which was close to $3.3 mgl^{-1}$. This could be due to the lake's altitude and the rapid decomposition of dead algae, as the lake is known to be productive (Talling *et al.*, 1973; Amha Belay *et al.*, 1986; Bhateria and Jain, 2016; Siriwardana *et al.*, 2019). Other researchers also reported very low dissolved oxygen levels (less than 1mg/l) in other East African alkaline saline crater lakes (Nkambo *et al.*, 2015).

Lakes Arenguade, Chittu, and Shala had higher pH, alkalinity, salinity, and electrical conductivity than Lake Beseka. This is due to the three lakes' high evaporation rates (high concentrations of dissolved minerals) and high concentrations of inorganic ions. Previous studies have reported similar results in these and other East African soda lakes (Talling and Talling, 1965; Melack, 1983; Elizabeth Kebede *et al.*, 1994; Tadesse Ogato *et al.*, 2015; Schagerl and Renaut, 2016; Solomon Wagaw *et al.*, 2021). The low pH, alkalinity, salinity and electrical conductivity of Lake Beseka can be explained by dilution due to rapid rise of lake water level (Elizabeth Kebede *et al.*, 1994; Megersa Olumana, 2017a).

Nitrate levels were lower in Lake Arenguade and Shala, which could be attributed to abundance of denitrifying bacteria, which lead to a potential loss of nitrate, aided by the favorable high tropical temperature (Lulit Tilahun, 2010; Lanzen *et al.*, 2013). This finding is consistent with other studies (Wood and Talling, 1988; Tadesse Ogato *et al.*, 2015; Solomon Wagaw *et al.*, 2021). The relatively high level of nitrate concentration in Lake Beseka in comparison to other studied lakes is caused by continuous mixing of the lake and pollution from its catchment area. This may be due to the high amount of nitrate from sediments, decomposition and surrounding agricultural activities entering the lake (Bhateria and Jain, 2016; Wang *et al.*, 2018; Siriwardana *et al.*, 2019). The higher ammonia, SRP and TP in Lake Chittu and Arenguade might be attributed to the predominance of phosphatic mineral-rich rocks, high evaporation rates exceeding precipitation in closed-basin carbonate-rich lakes (Nkambo *et al.*, 2015; Clarisse *et al.*, 2019; Toner and Catling, 2020). Local community produces soda ash near the shore of Lake Chittu to feed their livestock as the salt licks in which animal excreta (cattle and flamingos) are expected to increase the ammonia content of the lake water. The huge number of grazing of livestock around the lakes may also contribute to increase in the nutrient levels through their droppings (Njenga and pollution, 2004; Lodh *et al.*, 2014). Oduor and Schagerl (2007) reported very high mammal population in Lake Nakuru National Park which contributes to the nitrogen levels through droppings in the lake. This finding is consistent with some previous studies (Elizabeth Kebede *et al.*, 1994; Misgina Belachew *et al.*, 2012; Tadesse Ogato *et al.*, 2015). Similarly very high SRP concentrations up to 4 mg l^{-1} and TP concentrations up to 6 mg l^{-1} was recorded from saline-alkaline Lake Bogoria and Lake Nakuru of Kenya (Oduor and Schagerl, 2007b). The low concentrations of ammonia, SRP and TP measured in Lake Beseka may be attributed to lake dilution due to its expansion (Elizabeth Kebede *et al.*, 1994; Megersa Olumana, 2017a). The low concentration of $HCO_3^{-} + CO_3^{2-}$ in Lake Beseka could be attributed to the lake's falling pH trend (Boros and Kolpakova, 2018).

2.5.2. Temporal Variation of Physico-chemical Parameters

The physicochemical parameters of the four lakes, Lake Arenguade, Beseka, Chittu and Shala displayed considerable seasonal variation in relation to its dominant environmental conditions. Temperature is one of the important physical factors, which affects the physical properties, chemical reaction processes and biological activity in water, regulating the rate of photosynthesis in aquatic ecosystem. The higher water temperatures in lakes Beseka and Shala during the dry season could be attributed to high air temperatures (Atobatele and Ugwumba, 2008; Vajravelu *et al.*, 2018; Yu *et al.*, 2021).

The ambient temperature in the Lakes Beseka & Shala region is higher during the dry season (Jan-May). Higher DO concentrations during the rainy season in lakes Arenguade, Beseka and Chittu might be due to higher solubility of oxygen at lower temperature, low biological activity and mixing of surface water with atmospheric oxygen (Domogalla *et al.*, 1926; Ahangar *et al.*, 2012; Bhateria and Jain, 2016; Akagha *et al.*, 2020). However, in Lake Shala the highest amount of DO was recorded during the dry season. During the dry season, increased light penetration enhances photosynthesis in aquatic plants which produces oxygen as a byproduct, contributing to higher DO levels (Bhateria and Jain, 2016). Thus, the current study confirmed previous report on the seasonality of dissolved oxygen in Lake Shala (Solomon Wagaw *et al.*, 2021).

Higher pH values recorded during the post rainy season in Lake Arenguade and in Lakes Beseka and Shala during the dry season might be attributed to the high evaporation rates and photosynthetic activities which decreases CO_2 assimilation (Bhateria and Jain, 2016; Sahoo *et al.*, 2017). The conductivity values indicate that the higher conductivity was observed in dry season in Lakes Arenguade and Chittu, and in Lake Shala during the post rainy season which may be resulted from higher atmospheric temperatures resulting in higher evapotranspiration rates, high rate of decomposition and higher total ionic concentration (Ahangar *et al.*, 2012;

Ngabirano *et al.*, 2016). This result agrees with the report of Solomon Wagaw *et al.* (2021) from Lake Shala and Zinabu G/Mariam (2002) in some Ethiopian rift valley lakes, but contrasts with the report by Tadesse Ogato (2015).

The high level of salinity in the dry season in Lakes Arenguade, Beseka and Shala may be attributed to increased evaporative concentrations of salts due to higher temperatures (Kihwele *et al.*, 2015). This agrees with Solomon Wagaw *et al.* (2021) who reported high salinity level during the dry season in Lake Shala. Alkalinity levels were high during the post-rainy season in Lakes Beseka and Chittu, and during the dry season in Lake Shala. This may likely be caused by high rate of decomposition, which releases CO_2 and results in the addition of carbonate and bicarbonate ions, increasing alkalinity (Jindal and Wats, 2022).

Ammonia concentrations were high in Lakes Arenguade and Beseka after the rainy season and in Lake Chittu during the dry season. There is an agricultural activity surrounding the catchment of Lake Arenguade and Beseka in which nutrients directly released into the lake in the form of runoff and soil erosion during the rainy season and accumulates as the water begins to evaporate during the post rainy and dry seasons (Rasoloariniaina, 2017). During the dry season, the high concentration of nitrate in Lake Arenguade and Shala might be due to runoff from the surrounding area, rich in wild and domestic animal feces, accumulated causing accelerated eutrophication. Since these lakes are closed systems, they tend to accumulate these nutrients. Large number of flamingos, other aquatic birds and livestock are usually observed on the shores of these two lakes (Oduor and Schagerl, 2007b; Umwali *et al.*, 2021).

Phosphate plays a major role in primary productivity in an aquatic ecosystem as it promotes growth for organisms and limits the phytoplankton production. The high concentration of both SRP and TP in Lakes Beseka, Chittu and Shala during the dry season can be attributed to increased temperatures which impact the seasonal retention and release of phosphorus and decay and subsequent mineralization of dead organic matter (Ahangar *et al.*, 2012). In addition, the waves disturb the sediments thereby bringing more phosphate from the sediments (Bhateria and Jain, 2016; Gecheva *et al.*, 2017; Sahoo *et al.*, 2017).

The higher concentration of silicate recorded during the rainy season in Lakes Arenguade and Beseka, during the post rainy season in Lake Shala might be due to the enhanced dissolution of solid silicates. This process is often driven by increased water flow and runoff during these periods (Wood and Talling, 1988). High consumption of silicate by diatoms during the dry season might have contributed to the less availability of silicate concentration during dry seasons (Hilaluddin *et al.*, 2020).

2.5.3. Depth Profiles of Some Physico-chemical Parameters

The water temperature in Lake Beseka's surface layer was impacted by external climatic factors such as wind and the depth profile revealed an isothermal pattern (Chang *et al.*, 2022). Similarly, DO depth profiles show relatively uniform trend which might be due to continuous mixing of the lake. Water temperature and DO depth profiles in Lake Shala showed superficial thermal stratification which might be due to the occurrence of wind-induced turbulent mixing favored by absence of crater walls and vegetation cover from wind action. This result is in accordance with the results by Tadesse Ogato *et al.* (2016). The pH change in the water body was linked to the photosynthesis of aquatic organisms because the enough light at the surface water aided vigorous photosynthesis, which increased the pH. In the bottom, the paucity of light reduced photosynthetic activity, which lowers pH (Chang *et al.*, 2022). The vertical distribution of water temperature and DO in Lake Chittu's water body revealed superficial stratification. The downward trend in DO could be attributed to a dense population of *Arthrospira fusiformis* protecting the light entrance, as well as a poor rate of photosynthesis and organic matter decomposition (Tadesse Ogato *et al.*, 2015).

2.5.4. Long term Selected Physico-chemical Trends

A historical summary of previous studies on selected physicochemical variables of the studied lakes across years for the long-term data from 1961 to 2020 is shown in Fig. 2.4, and showed variations. Comparing the current mean pH to studies conducted in Lake Arenguadé between 1961 and 2012, pH frequently declined from 10.4 (Talling *et al.*, 1973) to 9.48 in 1990s to 9.6 in 2008 (Misgina Belachew *et al.*, 2012) but it showed small increase (10.04) in the present study. Conductivity values for the period 1991 to 2020 also declined regularly from 6.05 mS/cm in the 1990s to 5.5 mS/cm in 2008 and 5.42 mS/cm in the present study. The alkalinity of Lake Arenguade decreased from 51.4 meql^{-1} in the 1960s to 33.5 meql^{-1} in 2008, but the alkalinity values in this study are comparable to the average value of the 1960s (50.2 meql^{-1}). The salinity of Lake Arenguade, has dropped from 5.1 g l^{-1} of the 1960s (Talling *et al.*, 1973) to 2.5 g l^{-1} of 2008 (Misgina Belachew *et al.*, 2012), showing slight increase (2.91 g l^{-1}) in the present study. In general, long-term trends of physicochemical parameters of Lake Arenguade showed a decreasing trend from 1961-2008 but are now slightly increasing. Lake Arenguade is becoming more diluted as a result of frequent high-velocity explosions conducted for seismological research that have altered the lake's water chemistry and plankton diversity (Misgina Belachew *et al.*, 2012). Recurrent drought might be the reason for the current minor increase in physico-chemical features, which enhances evaporation leading to rise in physicochemical parameters (Langbein, 1961; Williams, 2002).

Lake Beseka's pH, conductivity, alkalinity, and salinity, all decreased significantly when compared to 1960s. The mean pH dropped from 9.9 in the 1960s to 9.4 in the 1990s to 8.6 in 2003 and 8.55 in the current study. Similarly, mean conductivity values fell from 72.5 mS/cm (Talling and Talling, 1965) in the 1960s to 7.441 mS/cm (Zinabu and Taylor, 1997) in the 1990s and to 2.72 mS/cm in the present study. The mean alkalinity values have been decreasing from 580 $meql^{-1}$ (Wood and Talling, 1988) in 1970s to 67.6 $meql^{-1}$ in 2020. The lake's salinity has also decreased dramatically, from 56.3 g l^{-1} in the 1970s to 5.3 g l^{-1} in the 1990s and currently to 1.88 g l^{-1}. The increasing water level of the lake may be a contributing factor to the declining trend of the physicochemical parameters of Lake Beseka (Gebremichael *et al.*, 2022). Similar findings were made on Lake Baringo in Kenya, where changes in lake water levels had an impact on the physicochemical characteristics of the lake (Chang *et al.*, 2022).

When compared to previous studies conducted in Lake Chittu from 1971 to 2012 and Lake Shala from 1961 to 2018, the mean pH values showed a slightly increasing trend during the current study, but remained within the ranges found in the previous studies. Mean conductivity values in the present study of Lake Chittu were, generally, higher in contrast to records from the 1990s, which was 50 mS/cm (Elizabeth Kebede *et al.*, 1994) and 66.9 mS/cm in the present study. Lake Chittu's alkalinity decreased t from 573 $meql^{-1}$ (Kebede and Willén, 1996) in 1990s to 426.8 $meql^{-1}$ in 2020, but Lake Shala's alkalinity increased from 200 $meql^{-1}$ (Talling and Talling, 1965) in 1960s to 305.7 $meql^{-1}$ in 2020. In the 1990s, Lake Chittu's mean salinity result was higher (45 g l^{-1}) (Elizabeth Kebede *et al.*, 1994) than it was in the 2010s (37.5 g l^{-1}) (Tadesse Ogato *et al.*, 2015), but it is currently 38.41 g l^{-1}. The results from the 1980s (16.8 g l^{-1}) (Melack, 1983) are comparable to the current mean salinity readings (16.78 g l^{-1}) for Lake Shala, while it was slightly higher in the year 2000(23.15 g l^{-1}) (Zinabu G/Mariam *et al.*, 2002). Very small rises in physico-chemical parameters of Lake Chittu and Shala could be the result of higher evaporative concentrations due to recurrent drought and anthropogenic activities in the catchment (Williams, 2002; Stenger-Kovács *et al.*, 2014).

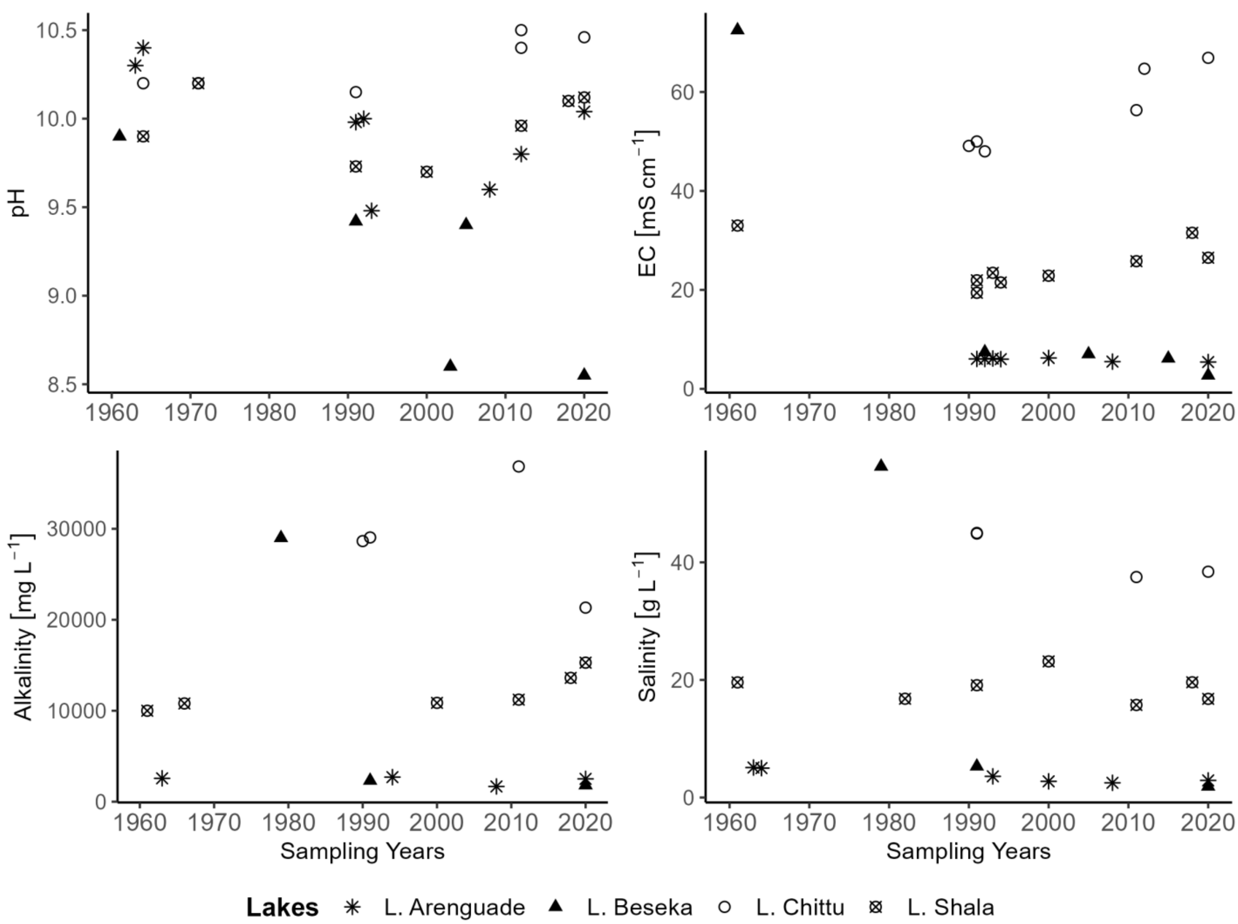


Figure 2. 4. Trends in physico-chemical parameters of studied lakes from 1960 to 2020

CHAPTER THREE: TEMPORAL PHYTOPLANKTON DYNAMICS AND ENVIRONMENTAL VARIABLES IN FOUR ETHIOPIAN SODA LAKES

3.1. Introduction

Soda lakes are highly alkaline aquatic environments where carbonate is a dominant dissolved anion due to evaporative concentration (Schagerl, 2022). They are found worldwide but, abundant in the Eastern Rift Valley, stretching from the Red Sea through Ethiopia and Kenya to Tanzania (Oduor and Schagerl, 2007a; Schagerl and Renaut, 2016). Even if they are often considered as ‘extreme ‘aquatic environments, they are amongst the most productive natural ecosystems and are remarkable natural assets with considerable economic and non-economic values (Valiente Parra *et al.*, 2022). The lakes vary dramatically in terms of hydrology and ecology because of fluctuations both in water level and environmental conditions (Trauth *et al.*, 2010). Due to seasonal changes, saline lakes naturally fluctuate in size, depth, and salinity. These changes have direct effects on the biota that populate the lakes (Harper *et al.*, 2016).

Soda lakes in Ethiopia support a variety of animals including birds, crocodiles, and fish. These lakes have been facing different threats due to anthropogenic and natural activities. Lake Arenguade has undergone considerable change in lake chemistry and dramatic decline in phytoplankton biomass and productivity (Misgina Belachew *et al.*, 2012). Reduction in water level of Lake Abijata might be due to soda ash extraction and upstream diversion that causes high salinization, change in the biota and fish stock collapse (Dagnachew Legesse *et al.*, 2004; Tenalem Ayenew and Dagnachew Legesse, 2007; Solomon Wagaw *et al.*, 2019). Expansion of Lake Beseka triggered dilution and shift in the phytoplankton community of the lake (Goerner *et al.*, 2009; Megersa Olumana, 2017b). Ethiopian Rift Valley Lakes have been in focus of research since the early 1990s (Elizabeth Kebede *et al.*, 1994; Elizabeth Kebede and Willén, 1996; Zinabu G/Mariam *et al.*, 2002).

In recent years, some studies on the composition and structure of phytoplankton have been conducted in Ethiopian soda lakes, on a single lake (Misgina Belachew *et al.*, 2012; Tadesse Ogato and Demeke Kifle, 2014; Tadesse Ogato *et al.*, 2015; Solomon Wagaw *et al.*, 2021).

The main role of phytoplankton in aquatic ecosystems is provision of primary food in most food webs, so that life in there will be sustainable (Vajravelu *et al.*, 2018). It is well known that phytoplankton structure is highly sensitive to environmental alterations (Kawabata *et al.*, 1997; Salm *et al.*, 2009). Changes in the physicochemical parameters of lake water can affect the phytoplankton community structure, and function (Litchman *et al.*, 2010). In addition, phytoplankton structure is influenced by seasons that in turn influence the physicochemical parameters of each lake (Ndebele-Murisa, 2014). In the face of climate change and increasing anthropogenic impact, data concerning trends of changes in phytoplankton abundance and physicochemical alterations can serve as important proxy indicator to prompt appropriate aquatic ecosystem and catchment management strategies.

In almost all former surveys, comparative ecological studies to examine the biological integrity of multiple lakes linked to temporal patterns of phytoplankton community structure and environmental variables is lacking. This study intends to contribute to the above mentioned knowledge gap by presenting timely data of phytoplankton abundance and physicochemical parameters. Furthermore, the findings in this study are important in understanding phytoplankton community structure which gives insight into the ecology of saline lakes and will be useful in maintaining these delicate ecosystems.

3.2. Materials and Methods

3.2.1. Sampling and Analysis

Plankton were collected by plankton net hauls (15µm) and fixed with Lugol's iodine solution. Samples were analyzed by subsampling 1 mL from the 50 mL sample volume and then placing into the Sedgewick rafter counting cell (Hotzel and Croome, 1999). Phytoplankton was then counted with a Nikon inverted light microscope (NIKONTS100, Germany) at a magnification of 40-400x. Diatoms were identified after acid digestion. Samples were boiled with 4ml concentrated hydrochloric acid (HCl 97%) for 30 minutes. Potassium permanganate ($KMnO_4$) solutions were added until sample turns purple. After the samples became cold, distilled water was added and repeatedly rinsed to remove chemicals (Taylor *et al.*, 2007). The phytoplankton taxa were identified using different identification keys (Komárek and Anagnostidis, 2005; Van Vuuren, 2006; Brierley *et al.*, 2007; Bellinger and Sigee, 2010). The phytoplankton abundance calculation was done using the equation in Hotzel and Croome (1999). For the filamentous and colonial algae, the number of cells in 20 filaments and colonies of filamentous and colonial algae was counted, and the mean cell number per filament or colony of a taxon was determined. The number of filamentous or colonial taxa multiplied by the average number of cells per filament or colony was used to determine their abundance.

Chlorophyll-a concentration was used as proxy estimator of phytoplankton biomass. Chlorophyll-a (Chl-a) concentration was analysed spectrophotometrically, using 90% cold acetone as an extraction solvent. Filterable amount of sample was filtered using Whatman Glass Filter Fibre papers (GF/F), and the filters were kept at -4^{o}C for at least 8 hours to aid extraction of pigments. The filters were then ground with a tissue grinder, and the extract was centrifuged at 3000 rpm for 10 minutes after 12 hours of extraction. The supernatant was measured at 665 and 750 nm using a spectrophotometer. Chl-a concentration was calculated according to (Lorenzen, 1967)

3.3. Statistical Analysis

Spatial and temporal variations among results of physicochemical parameters, Chl-a and phytoplankton abundance between seasons, were analyzed using Kruskal–Wallis method of variance (ANOVA) in R software (version 4.3.1) (R Core Team, 2020). Box plots were plotted using ggplot2 package (Villanueva and Chen, 2019). In order to visualize the relationship between environmental variables of the lakes, an ordination plot with a Principal Component Analysis (PCA) using R package FactoMineR was used. PCA with varimax rotation was applied to the 8 selected (eigenvalues >1) environmental variables to identify the variables that have the greatest influence on phytoplankton biomass. Chl a was explained by the PC generated in the PCA in the subsequent Multiple Linear Regression Analyses (LR). Redundancy Analysis [RDA using R package vegan] was also used to examine the effect of environmental variables on the relative abundance of phytoplankton communities (Borcard *et al.*, 2011). Detrended correspondence analysis (DCA) was performed to calculate the lengths of gradient axes and provided the greatest gradient length of 3.34 along the first axis. When the first axis length is between 3 and 4, both linear and unimodal methods can be applied (Lepš and Šmilauer, 2003). So, we decided to use an RDA since the percentage of total variance described by RDA (69.4%) was higher than CCA (62.6%). Prior to analyses, Hellinger transformation (Phytoplankton species data) and environmental variables (except pH) were standardized for normality (Legendre and Gallagher, 2001) and differences were considered as significant when $p < 0.05$. Based on the 999 Monte Carlo permutations, the significance of these RDA model has been evaluated. Multicollinearity between explanatory variables has been tested by the Variance Inflation Factor (VIF<10). As a result, the following variables were added to the model: water temperature, Secchi depth + turbidity + electrical conductivity + soluble reactive phosphorus + nitrate and silica. Similarity Percentage (SIMPER) test using simper function in vegan was performed to determine which phytoplankton taxa contributed significantly to different site types and the similarity among samples at each site (Clarke, 1993). The phytoplankton taxa selected from the simper test were then considered for analysis.

3.4. Results

3.4.1. Description of Environmental Variables

Meteorological data showed a typical seasonal air temperature dynamic, with an increasing trend in the period of dry (December- January) and decreasing trend in wet (July-August) seasons for all lakes which has been clearly described in our previous study (Hana Melese and Habte Jebessa, 2023). The annual rainfall ranged between 0 and 347 mm with a maximum precipitation in June-August (rainy season) and minimum rainfall in November- January (post rainy & dry) (Fig. 3.1A). Overall, 67.2% variance in the environmental variables is explained by the first and second PCA axis (Fig. 3.2B). The first axis explained 42.4% and correlated positively with DO and temperature but negatively with EC and salinity, differentiating Lake Beseka from other lakes. The second axis explains 24.8% of the variation in environmental variables and is strongly associated with turbidity, ammonia and TP.

The values for spatial physicochemical parameters of water samples during the study period were visualized using boxplots in Fig. 3.2. As a supplementary material, temporal results for water quality measurements were provided on appendix 3 (Supplementary Table 1A-D). The concentration of dissolved oxygen and Secchi depth were higher in Lake Shala; whereas, water temperature was higher in Lake Beseka (Fig. 3.2 a, b, f). Lake Chittu had higher pH, conductivity and salinity (Fig. 3.2 c, d, g) and turbidity was higher in Lake Arenguade (Fig. 3.2e). Dissolved oxygen concentration was in the range of 3.12–8.47 mg L^{-1}. Water temperature fluctuated between 21.6 and 27.5 °C with the minimum record in Lake Arenguade, while pH was in the range of 7.9–10.7, indicating alkaline condition. Turbidity and Secchi depth ranged between 10.8–44.5 NTU and 0.23 to 0.62 m, respectively. Electrical conductivity (EC) and salinity ranged between 2.52–70.24 mS cm^{-1} and 1.42–45.6 g L^{-1} , both showing minimum values in Lake Beseka.

Major algal nutrients such as nitrogen forms (NO_3–N and NH_3), SRP, TP and SiO_2 are presented in Fig. 3.3. The concentration of ammonia was higher in Lake Arenguade (Fig. 3.3a). Lake Chittu had higher soluble reactive phosphorus and total phosphorus (Fig. 3.3c, d). Nitrate and ammonia concentrations ranged between 9.14-164.4 μg l^{-1} and 44.86–224.4 μg l^{-1} respectively. Recorded soluble reactive phosphorus and total phosphorus values from all lakes ranged between 0.25–2.37 mg L^{-1} and 0.75–3.21 mg L^{-1} both showing lower concentration in Lake Beseka. Silica values fluctuated between 1.4 to 96.17 mg L^{-1}.

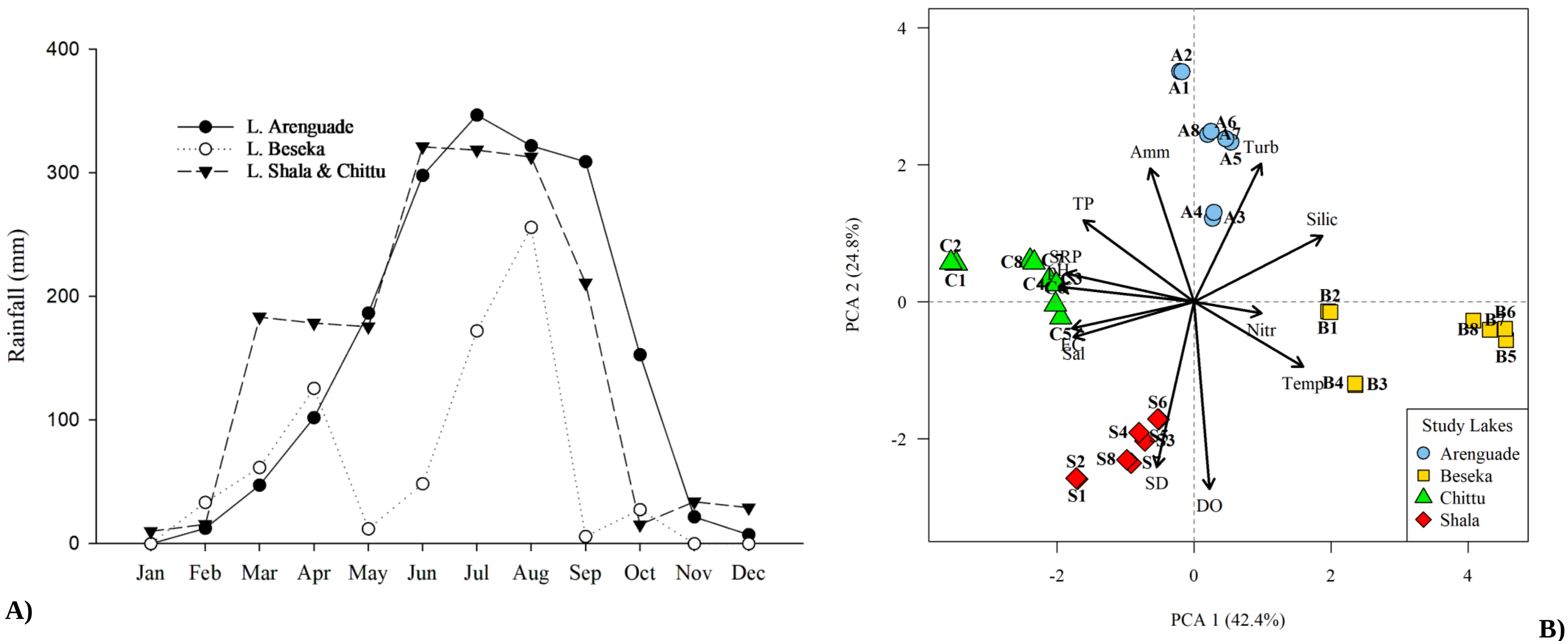


Figure 3. 1. Monthly rainfall data of the three lakes during the study year 2020 (A), Principal Component Analysis (PCA) biplots showing the relationship between environmental variables and lake types during the study periods (B). pH, Temperature (Temp), Dissolved oxygen (DO), Electrical conductivity (EC), Turbidity (Turb), Secchi depth (SD), Salinity (Sal), Soluble reactive phosphorus (SRP), Nitrate (Nitr), Ammonia (Amm), silica (Sil) and Total phosphorus (TP)

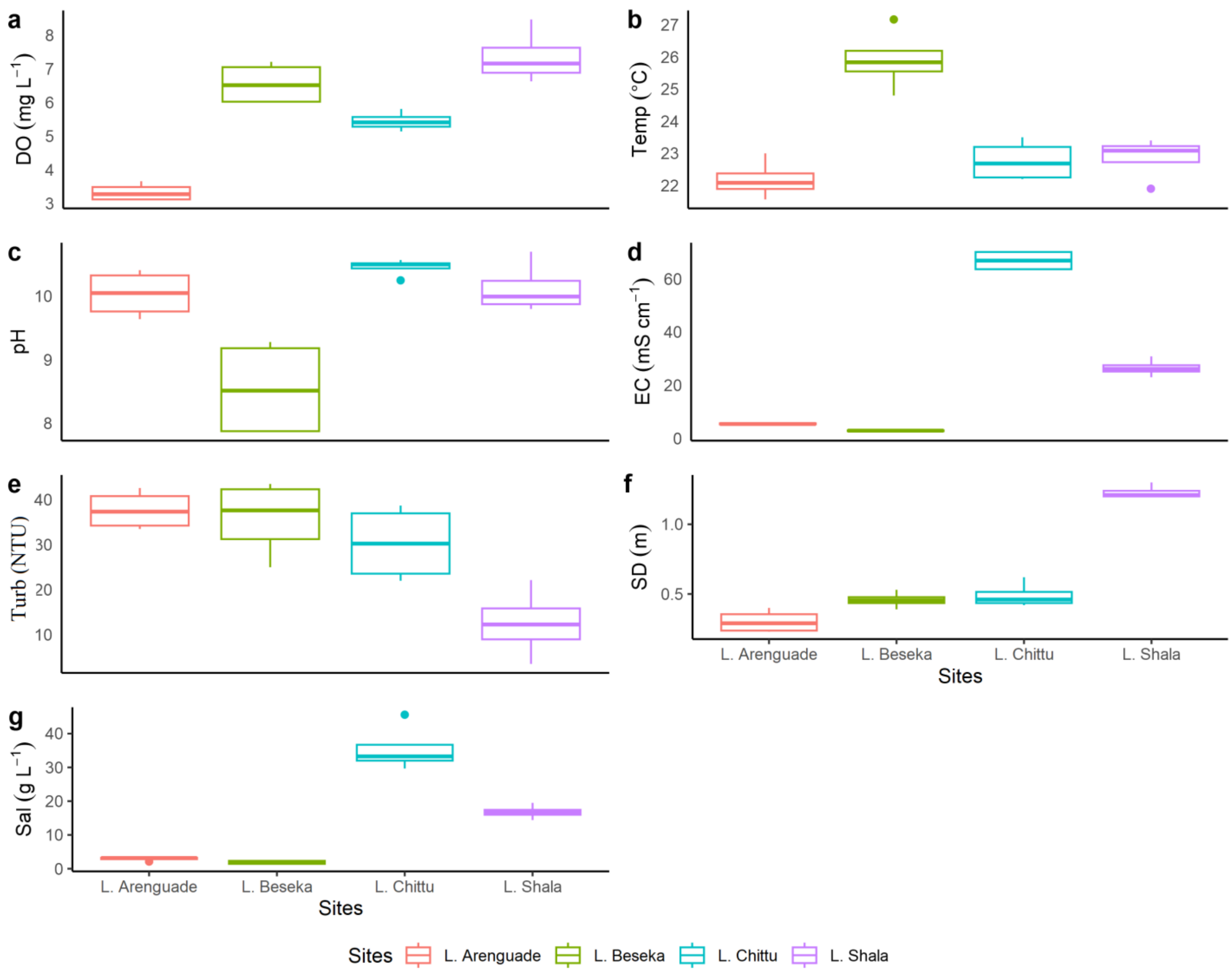


Figure 3. 2. Boxplots depicting the median results in solid lines of environmental variables (a-g); in the four Ethiopian soda lakes (present study). Dissolve oxygen (DO), Temperature (Temp), pH, Turbidity (Turb), Secchi depth (SD), Electrical Conductivity (EC) and Salinity (Sal)

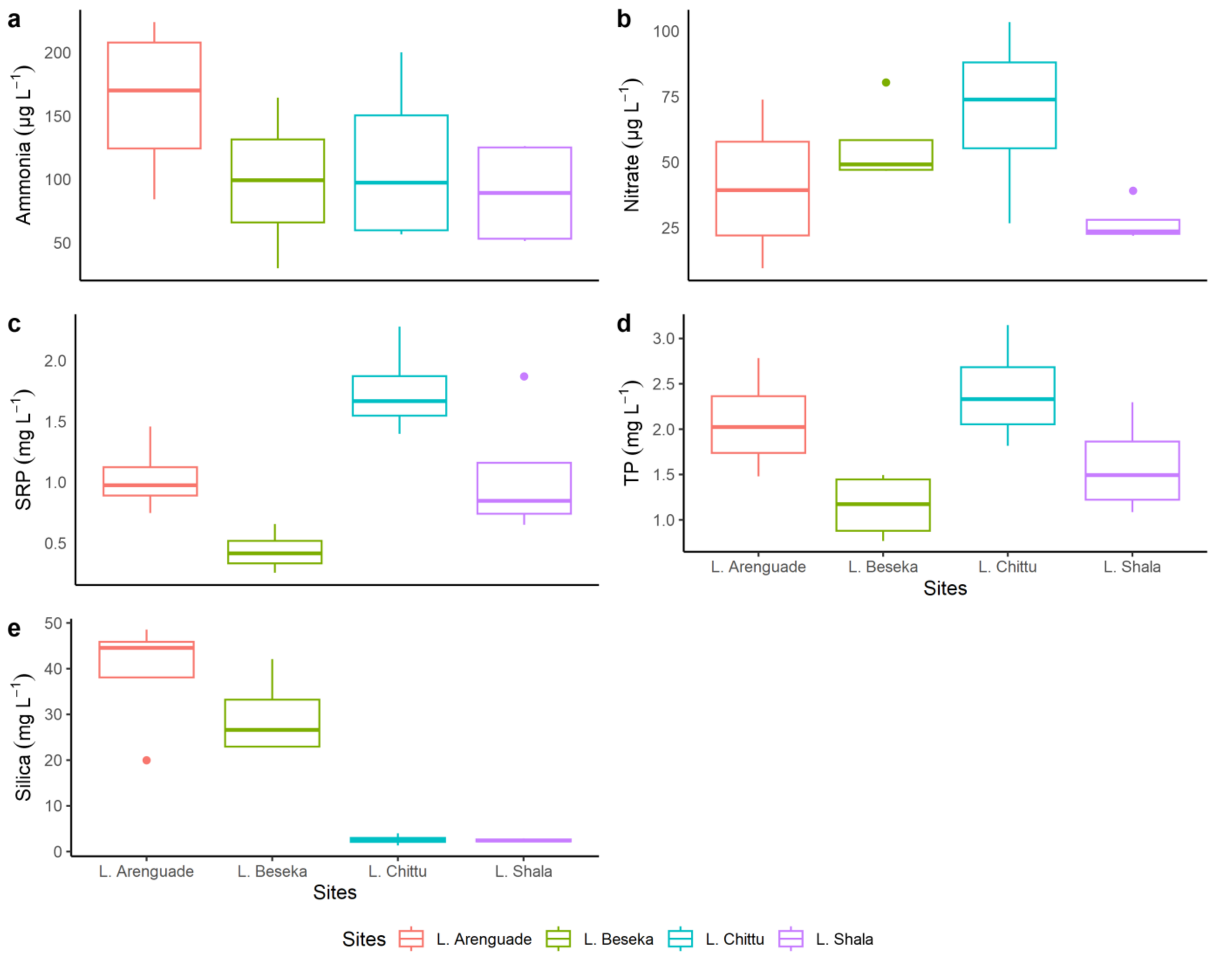


Figure 3. 3. Boxplots depicting the median results in solid lines of algal nutrients (a-e); in the four Ethiopian soda lakes, during the present study period. Ammonia (Amm), Nitrate (Nitr), Soluble reactive phosphorus (SRP), Total phosphorus (TP) and Silica (Sil)

3.4.2. Phytoplankton Species Composition and Abundance

A total of 56 phytoplankton taxa belonging to six classes of phytoplankton, namely, Cyanoprokaryota, Bacillariophyceae, Chlorophyceae, Cryptophyceae, Dinophyceae and Euglenophyceae were recorded from all four lakes (Appendix 3, Supplementary Table 2). Least number of taxa (15) was observed in L. Chittu, followed by L. Arenguade, which had 20 taxa, whereas L. Beseka and L. Shala had 26, and 39 taxa identified, respectively (Table 3.1). A single cryptophyte species was observed in L. Chittu but not in the other three lakes. Appendix 1 contains images of some phytoplankton species that have been identified in the lakes.

Table 3. 1. Checklist of identified phytoplankton taxa in the four Lakes Arenguade, Beseka, Chittu and Shala during the current study period

L. Arenguade	**L. Beseka**	**L. Chittu**	**L. Shala**	
Bacillariophyceae	Bacillariophyceae	Bacillariophyceae	Bacillariophyceae	*Cosmarium depresum*
Achnanthidium minutissimum	*Achnanthidium minutissimum*	*Achnanthidium minutissimum*	*Achnanthidium minutissimum*	*Monoraphidium minutum*
Amphora sp.	*Amphora aequalis*	*Amphora pediculus*	*Amphora veneta*	*Oosystis* sp.
Aulacoseira distans	*Amphora pediculus*	*Cyclotella* sp.	*Amphora pediculus*	*Scenedesmus* sp.
Aulacoseira granulata	*Aulacoseira distans*	*Cymbella affinis*	*Aulacoseira distans*	Cyanoprokaryota
Cyclotella sp.	*Aulacoseira granulata*	*Diatoma* sp.	*Aulacoseira granulata*	*Anabaena* sp.
Cymbella affinis	*Cyclotella* sp.	*Epithemia gibba*	*Ceratoneis arcus*	*Limnospira fusiformis*
Navicula sp.	*Cyclotella meneghiniana*	*Navicula* sp.	*Cyclotella* sp.	*Microcystis aeruginosa*
Nitzschia sp.	*Cymbella affinis*	*Nitzschia* sp.	*Cymbella affinis*	*Raphidiopsis africana*
Pinnularia sp.	*Diatoma* sp.	*Rhopalodia gibberula*	*Diatoma* sp.	Dinophyceae
Rhopalodia gracilis	*Fragilaria* sp.	Chlorophyceae	*Epithemia frickei*	*Peridinium cinctum*
Surirella engleri	*Navicula* sp.	*Cosmarium depresum*	*Epithemia turgida*	Euglenophyceae
Chlorophyceae	*Nitzschia* sp.	*Monoraphidium minutum*	*Fragilaria* sp.	*Euglena* sp.
Coelastrum astroidem	*Rhopalodia gibberula*	Cryptophyceae	*Frustulia rhomboides*	*Phacus* sp.
Cosmarium sp.	*Rhopalodia gracilis*	*Cryptomonas marssonii*	*Gomphonema affine*	
Monoraphidium minutum	Chlorophyceae	Cyanoprokaryota	*Gomphonema minutum*	
Cyanoprokaryota	*Closterium acutum*	*Anabaenopsis abijatae*	*Gomphonema* sp.	
Chroococcus minutus	*Coelastrum astroideum*	*Limnospira fusiformis*	*Gyrosigma obtusatum*	
Limnospira fusiformis	*Desmodesmus communis*	*Spirulina major*	*Navicula* sp.	
Raphidiopsis africana	*Oosystis* sp.		*Nitzschia dissipata*	
Dinophyceae	*Pediastrum duplex*		*Nitzschia* sp.	
Glenodinium sp.	*Scenedesmus bicaudatus*		*Pinnularia* sp.	
Euglenophyceae	*Scenedesmus ellipticus*		*Rhopalodia gibberula*	
Euglena sp.	Cyanoprokaryota		*Rhopalodia gracilis*	
Phacus sp.	*Dolichospermum flos-aquae*		*Stephanodiscus* sp.	
	Raphidiopsis africana		*Surirella engleri*	
	Dinophyceae		Chlorophyceae	
	Peridinium sp.		*Chlorella* sp.	
	Euglenophyceae		*Closterium actum*	
	Euglena sp.		*Coelastrum astroidem*	

Phytoplankton biomass expressed as Chl-a in Lakes Arenguade and Chittu was higher than in Lakes Beseka and Shala (Fig. 3.4). It ranged from 85.5 to 160.0 µg L^{-1} for L. Arenguade, 1.1 to 11.6 µg L^{-1} for Lake Beseka, 103.4 to 174.6 µg L^{-1} for L. Chittu and 5.4 to 35.6 µg L^{-1} for L. Shala. Generally, the spatial phytoplankton biomass ranged between 1.1–174.6 µg L^{-1} from all lakes. Temporal phytoplankton biomass showed higher values during the rainy and post rainy seasons in Lakes Chittu and Shala respectively. In Lake Beseka, phytoplankton biomass was high during the dry season (January 2020) and as low as 1 µg L^{-1} after the rainy season (November) (Fig. 3.5). Seasonal variations in phytoplankton biomass showed significant variation (p <0.05) in all lakes but phytoplankton abundance shows no significant variation between seasons.

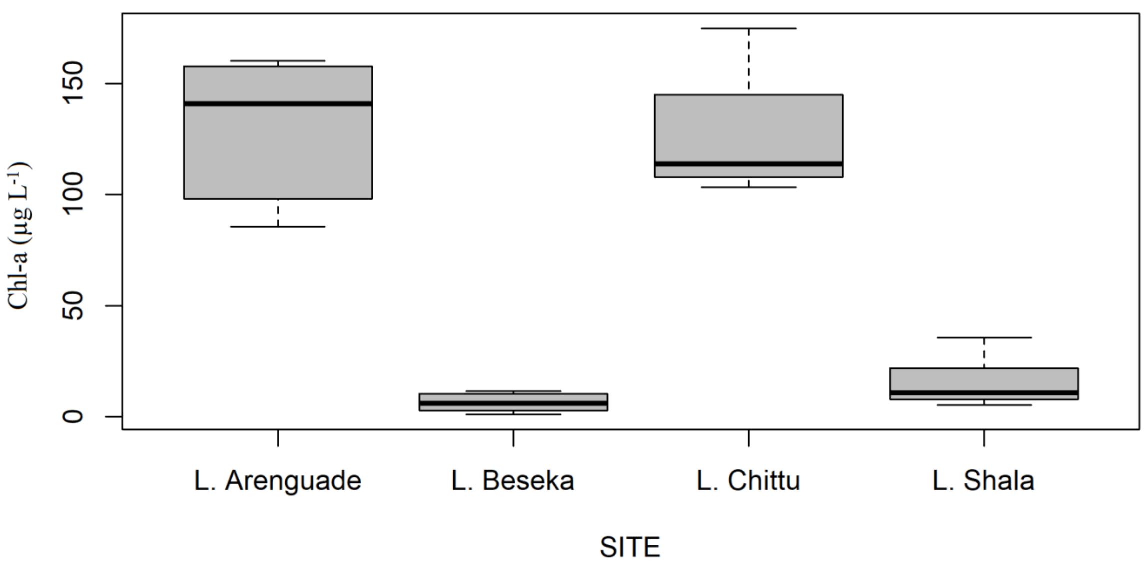


Figure 3. 4. Spatial variations in phytoplankton biomass (Chl-a) during the study period

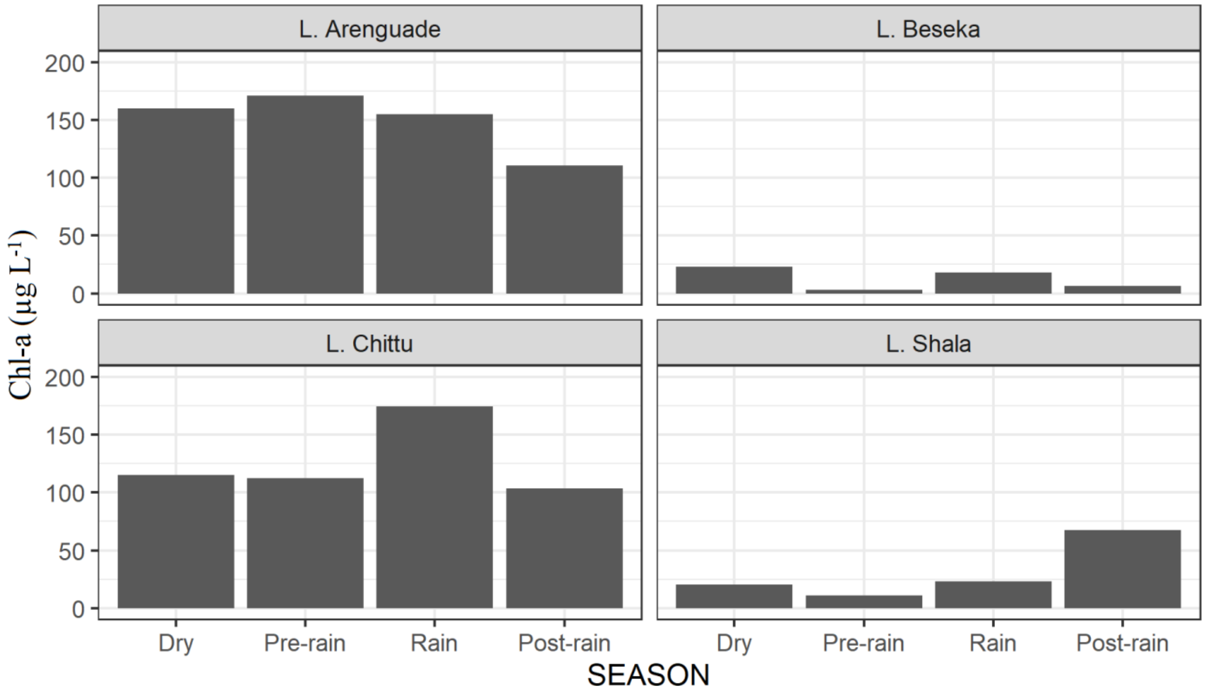


Figure 3. 5. Seasonal variations in phytoplankton biomass (Chl-a) during the study period

3.4.3. Multiple Linear Regression Analysis of Chl-a on Varimax Rotated PC's

Relationship between Chl-a scores and selected PC's obtained from PCA using environmental variables determined by LR analysis to identify the best predictors of phytoplankton biomass. PCA extracted two significant PC's that accounted for 77.1% of the total variation (Appendix 3 Supplementary Table 3). High loadings of ammonia, silica, (negative secchi depth) in PC1 and temperature, turbidity, (negative conductivity) were found in PC2 for L. Arenguade. The LR produced a significant model that described 27.4% of the changes in Chl a caused by PC1 and PC2. PCA for L. Beseka also extracted two PC's that explained 71.3% of the total variation. Temperature, ammonia, (negative conductivity) and nitrate, (negative SRP) were variables with the highest factor loadings in PC1 and PC2 respectively. LR generated a significant model that describes 28.7 % of the Chl a variation due to PC1 & PC2. For L. Chittu, PCA extracted two PC's which explained 79.7 % of the total variation. Conductivity, ammonia, (negative turbidity) in PC1 and silica, SRP, (negative temperature) in PC2 were variables with the highest factor loadings. LR generated a significant model that describes 20.3% of the Chl a variation due to PC1 & PC2. However, PCA for L. Shala, extracted three PC's that explained 90.2 % of the total variation. Secchi depth, nitrate (negative conductivity) in PC1 and temperature, (negative turbidity) in PC2 were variables with the highest factor loadings. SRP was the only variable with high factor loading from PC3. LR produced a significant model that describes only 9.8% of the Chl a variation due to PC1 & PC2 (Supplementary Table 3).

Percentage contribution to the total taxa composition and abundance in the lakes are presented in Fig. 3.6. Bacillariophytes dominated both the taxa composition and abundance of lakes Beseka (58%, 89%) and Shala (64%, 92%), whereas Cyanoprokaryotes dominated the abundance in lakes Arenguade (72%) and Chittu (80%). The maximum total phytoplankton abundance was recorded in L. Arenguade, followed by L. Chittu and Beseka while L. Shala had the lowest. The highest peaks in phytoplankton abundance were observed in November in Lakes Arenguade, Chittu and Shala, and January in Beseka. In Supplementary Table 4, a table showing the temporal trends of phytoplankton groups in each lake is provided. As shown in the table, in Lakes Arenguade and Chittu, the density of cyanoprokaryotes was found to be high in January and November respectively. Bacillariaphytes density has shown higher values during the post rainy season in Lakes Beseka and Shala.

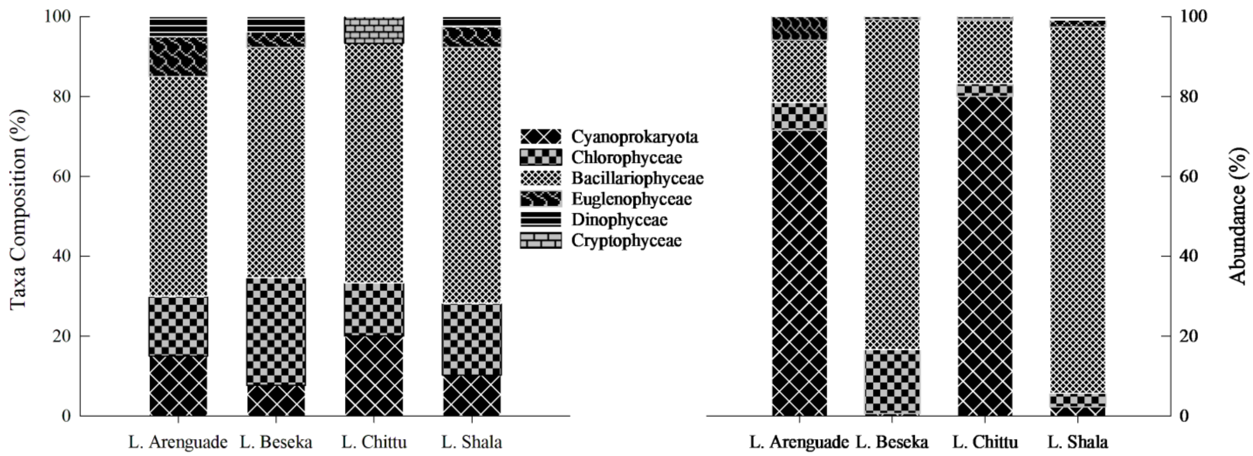


Figure 3. 6. Percentage contribution to the total number of phytoplankton species and abundance of phytoplankton groups in the four study lakes during the present study

3.4.4. Relationships between Phytoplankton Communities and Environmental Factors

The relation of the phytoplankton abundance to environmental factors has been tested by the Redundancy analysis (RDA). Abundance data have been associated with thirteen environmental variables and seven significant ($P<0.05$) environmental variables were identified in to RDA model, using VIF and forward selection method. RDA explained 69.36% of the total variance of the species distribution related to environmental variables for axis one accounting for 52.81% and axis two accounting for 16.55%. Secchi depth, turbidity, electrical conductivity, soluble reactive phosphorus, nitrate and silica are environmental variables that have significant relationships with phytoplankton as shown in Fig. 3.7. *Euglena* sp., *Phacus* sp. and *Raphidiopsis africana* occurrence coincided with increase in turbidity, whereas abundance *of Limnospira fusiformis, Cryptomonas marssonii, Anabaenopsis abijatae* and *Monoraphidium minutum* was associated with SRP concentration (Fig.3.7).

The abundances of most diatoms were positively correlated with nitrite concentrations. *Desmodesmus communis, Dolichospermum flos-aquae, Coelastrum astroidem, Pediastrum duplex and Oosystis* sp. were positively affected by water temperature and negatively affected by conductivity. The majority of the abundances of diatoms showed a positive correlation with lakes Shala and Beseka, whereas *Aulacoseira granulata* tended to be high in Lake Beseka. In L. Chittu, *Limnospira fusiformis* was more abundant, whereas *Raphidiopsis africana* was abundant in L. Arenguade.

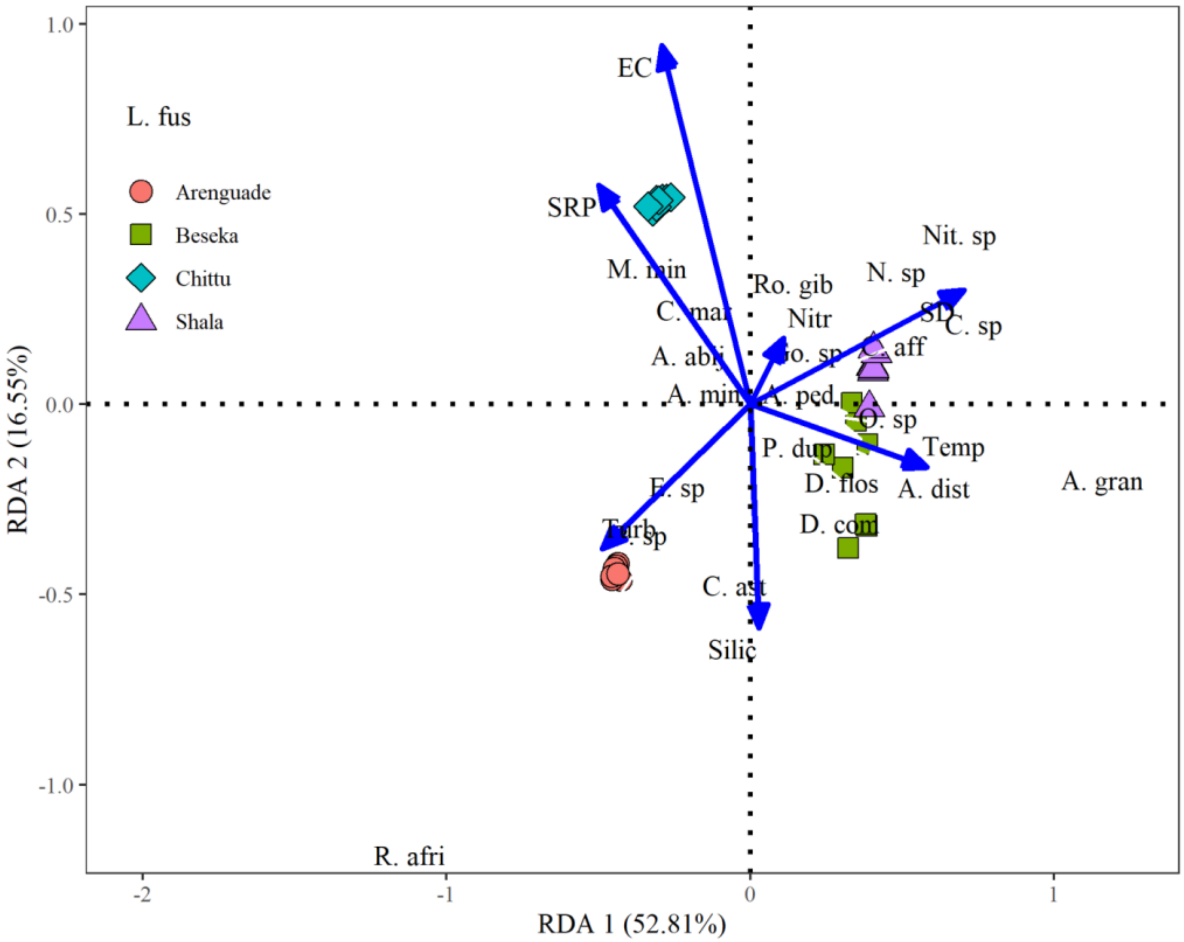


Figure 3. 7. Redundancy Analysis (RDA) triplots, showing relationship between significant environmental variables and phytoplankton communities in four lakes during the study periods. Water temperature (Temp Electrical conductivity (EC), Turbidity (Turb), Secchi dep (SD), Soluble reactive phosphorus (SRP), Nitrate (Nitr) and Silica (Sil). *Limnospira fusiformis (L. fus), Raphidiopsis Africana (R. afri), Anabaenopsis abijatae (A. abij), Dolichospermum flos-aquae (D. flos), Monoraphidium minutum (M. min), Oosystis sp. (O. sp), Coelastrum astroidem (C. ast), Achnanthidium minutissimum (A. min), Cryptomonas marssonii (C. mar), Cyclotella sp. (C. sp), Cymbella affinis (C. aff), Aulacoseira granulate (A.gran), Desmodesmus communis (D. com), Aulacoseira distans (A. dist), Navicula sp. (N. sp), Euglena sp. (E. sp), Phacus sp. (P.sp), and Nitzschia sp. (Nit. Sp), Amphora pediculus (A. ped), Rhopalodia gibberula (Ro.gib), Gomphonema sp. (Go. Sp), Pediastrum duplex (P. dup).*

3.5. Discussion

This comparative study of phytoplankton patterns in four Ethiopian soda lakes provided further insights into their ecology and highlighted the need for careful management of these fragile ecosystems. High turbidity and reduced secchi transparency in Lake Arenguade can be caused by high algal density and shallow depth of the lake (Padisak and Naselli-Flores, 2021). Lake Shala's higher dissolved oxygen concentration and Secchi depth, and lower turbidity compared to the other lakes, could be attributed to: atmospheric mixing with surface water by convective currents due to the lake's atelomictic nature (Akagha *et al.*, 2020; Padisak and Naselli-Flores, 2021); and surface temperatures (Sahoo *et al.*, 2017). These findings are consistent with observations made by Tadesse Ogato and Demeke Kifle (2017) and Solomon Wagaw *et al.* (2021).

The high number of phytoplankton taxa in lakes Shala and Beseka might be associated with less extreme conditions (Diego *et al.*, 2015). For example, Lake Beseka is undergoing consistent changes in its chemical composition which shows decline in pH, alkalinity, salinity and electrical conductivity due to lake expansion causing dilution (Hana Melese and Habte Jebessa, 2023) that may be beneficial for phytoplankton diversity. It is known that circumneutral pH favors high phytoplankton diversity than extreme pH ranges on both sides (Fang *et al.*, 2018). Different phytoplankton species exhibit varying tolerances to pH extremes (Fang *et al.*, 2018). Some species have evolved mechanisms to cope with acidic or alkaline environments, but these adaptations may come at a cost in terms of growth efficiency or competitive ability (Elizabeth Kebede, 1997).

The presence of a higher concentration of Chl-a in L. Chittu, followed by L. Arenguade, could be attributed to their shallow depth, which could result in regeneration and resuspension of nutrients from the bottom sediments, resulting in an increased abundance of cyanobacteria, particularly *L. fusiformis,* which is a major contributor to phytoplankton biomass and primary productivity (Okoth *et al.,* 2009; DeLong *et al.*, 2014; Mhlanga *et al.,* 2017). The high Cattle population and bird droppings dumped on lake shores also predicted to contribute to increased source of nutrients in these lakes (Hana Melese and Habte Jebessa, 2023). The result of this study is aligned with the report by Tadesse Ogato and Demeke Kifle (2014) in L. Chittu and Misgina

Belachew *et al.* (2012) in L. Arenguade. (Okoth *et al.*, 2009) similarly, high Chl-a concentrations reported in shallow (up to 1m depth) alkaline-saline Lake Nakuru, Kenya.

Generally, Chl-a concentrations have increased during the post rainy and dry season, which may be due to high light intensity and rising temperatures in January, that tended to stimulate photosynthetic activities and increased phytoplankton population density as a possible result of high nutrient concentrations due to high evaporation rates (Amin, 2006; Carvalho *et al.*, 2016; Sahoo *et al.*, 2016; Awortwi *et al.*, 2018). Similarly, higher temperatures in Kenya's Rift Valley alkaline saline lakes have stimulated the biomass of phytoplankton (Schagerl and Oduor, 2008). Additionally, during the dry period, blooms of cyanobacteria were observed in the saline lakes of the Nhecolndia region of Brazil, contributing considerably to the biomass of phytoplankton (Costa *et al.*, 2016).

The temporal Chl-a changes observed in these lakes was consistent with certain environmental factors. The results of LR models are high for lakes Arengude, Beseka and Chittu. In the catchments of Lakes Arenguade and Chittu, huge cattle and bird populations can contribute to increased nutrient concentrations in the lakes by flushing excrement into the lakes (Hana Melese and Habte Jebessa, 2023). Lake Beseka is not a stabilized lake, as the lake's surface area and level have increased and human encroachment on its watershed has increased. These anthropogenic activities still control the environmental activities of lakes and generally influence phytoplankton biomass.

The abundance of lakes Beseka and Shala were dominated by high percentage composition of Bacillariophytes. This might be attributed to their tolerance to a wide range of environments and lower size range of edibility by the top grazers or filter feeders (Stenger-Kovács *et al.*, 2014; Padisak and Naselli-Flores, 2021). Again, high nitrate concentrations in L. Beseka may have favored diatom population expansion, as these species are good phosphorus competitors but weak nitrogen competitors (Donald *et al.*, 2013).

The result of this study is consistent with the study by Elizabeth Kebede and Willén (1996), Tesfaye Delelegne (2006), Zinabu G/Mariam (2002) and Solomon Wagaw *et al.* (2021) but not with Tadesse Ogato and Demeke Kifle (2017), reported dominance of cryptomonads in Lake Shala. The dominance of diatoms has been reported by different previous researchers in different alkaline-saline lakes in Ethiopia, such as Lake Abijata (Tewodros Kumssa and Afework Bekele, 2014).

Cyanoprokaryotes dominated the abundance of lakes Arenguade and Chittu, which might be attributed to their dominance in nutrient rich systems, especially, elevated phosphorus concentrations (Attayde and Hansson, 1999). Among cyanoprokaryotes, *Limnospira* species largely dominated the abundance of both lakes. These species have a special physiological adaptation to high pH, salinity, and nutrient concentrations (Costa *et al.*, 2016). The fact that these lakes are preferred habitats for a large number of Lesser Flamingos, feeding on *L. fusiformis* (Spirulina) has been known since the 1980s. Similarly, dominance of Cyanobacteria has been reported for tropical soda lakes (Schagerl and Oduor, 2008; Ballot *et al.*, 2009; Ndebele-Murisa *et al.*, 2010; Mhlanga *et al.*, 2017; Koskei *et al.*, 2019), soda lakes of the Kulunda steppe, China (Wen *et al.*, 2005) and also saline lakes of the Nhecolndia region of Brazil (Costa *et al.*, 2016). The higher peak values of phytoplankton abundance observed in lakes Arenguade, Chittu and Shala during the post-rainy season could be attributed to stable nutrient concentration after runoff introduced high nutrient levels into the lakes. Nutrient concentration in a water body is the main factor affecting the growth of phytoplankton (He *et al.*, 2022). The high relative abundance of Bacillariophytes during the post-rainy season could be attributed to more stable hydrographic factors (e.g., temperature), increased nutrition availability due to runoff from the catchments during the rainy season (Vajravelu *et al.*, 2018; Zhang *et al.*, 2019), and a substantial increase in transparency (Simiyu *et al.*, 2022). The dominance of cyanoprokaryotes and chlorophytes in cell densities during rainy periods could be attributed to high precipitation recorded during the rainy season (June-August 2020), resulted in high terrestrial run off from the catchment in to the lake which can stimulate growth of phytoplankton populations (Rao *et al.*, 2018). This observation is in line with the findings of Tadesse Ogato and Demeke Kifle (2017) for L. Shala.

Different responses to the main physicochemical drivers have been observed for the abundance of plankton and biomass dynamics. RDA models indicated that the main drivers of phytoplankton abundance have been significantly influenced by water temperature, dissolved oxygen, chlophyll-a, Secchi depth, turbidity, electrical conductivity, soluble reactive phosphorus, nitrate and silica during the present study. Water temperature has a direct effect on phytoplankton by affecting their physiology and metabolism (Li *et al.*, 2021). An increase in water temperature increases phytoplankton nutrient uptake, increasing phytoplankton growth rates (Thomas and Litchman, 2016). In this study, water temperature was the key driving factor, affecting abundance of *D. communis, D. flos-aquae, C. astroidem* and *Oosystis* sp., positively and conductivity affected them negatively. This could be attributable to adaptation of Chlorophytes to relatively higher temperatures and their restriction to low conductivity (Frau *et al.*, 2021). This is in comparable with other studies in Kenyan Rift Valley Lakes, where conductivity has a negative impact on abundance of chlorophytes (Schagerl and Oduor, 2008). *Euglena* sp., *Phacus* sp. and *R. africana* occurrence coincided with increase in turbidity since they are especially common in decomposing organic matter-rich systems (Koskei *et al.*, 2019). *L. fusiformis, C. marssonii,* and *M. minutum* abundance was related to both Chl-a and Soluble Reactive Phosphorus (SRP) concentration. This might be due to the fact that high Cyanoprokaryotes contribution to the phytoplankton biomass and an increase in the supply of SRP may also be supporting the abundance of phytoplankton (Ndebele-Murisa *et al.*, 2010; Trombetta *et al.*, 2019). The majority of abundances of diatoms showed positive correlations with lakes Shala and Beseka, whereas *A. granulate* tended to be high in L. Beseka, which indicated the diatoms dependency on mixing to get nutrients from bottom sediments (Yang *et al.*, 2016). In L. Chittu, *L. fusiformis* was more abundant, whereas *R. africana* was abundant in L. Arenguade. The extreme dominance in the abundance of *L. fusiformis* in L. Chittu might be due to their ability to regulate their buoyancy, tolerance level to wide salinity concentration and its ability to cope with very low light intensity (Okechukwu I, 2009; Schagerl *et al.*, 2015; Bernard *et al.*, 2019).

3.5.1. Trends in Phytoplankton biomass and composition changes in the studied lakes

According to Wood and Talling (1988), the phytoplankton species that represented L. Arenguade were *L. fusiformis* (dominant), *Glenodinium* sp., and *Chroococcus minutus*. A report by Misgina Belachew *et al.*, 2012, concluded that *Anabaenopsis elenkinii* and *L. fusiformis* codominated, while *Chroococcus minutus* constituted to the lakes phytoplankton. In general, Chl-a concentrations in L. Arenguade showed a decreasing trend when compared to the 1960s (Table 2). This could be due to changes in the lake's physico-chemical characteristics (Hana Melese and Habte Jebessa, 2023), which might be to the result of frequent high-velocity explosions, conducted for seismological studies causing changes in the phytoplankton community structure (Misgina Belachew *et al.*, 2012). Agricultural runoff and sewage disposal are major pollutants in Lake Beseka (Umer *et al.*, 2020).

Cyanoprokaryotes, particularly *L. fusiformis*, predominated Lake Beseka in the 1960s. *Oscillatoria* sp. and *Anabaenopsis arnoldii* were also reported in the phytoplankton of Lake Beseka (Wood and Talling, 1988). The previous dominant phytoplankton species *L. fusiformis*, has been completely eradicated, and the phytoplankton population has shifted from cyanobacteria to diatoms. As compared to the 1970s, the change in Chl-a concentrations showed a decreasing trend (Table 3.2) and the number of phytoplankton taxa increased. This change in phytoplankton biomass and species composition of the lake may be associated with a drastic increase in lake volume, changing the lake's physico-chemical parameters. Hana Melese and Habte Jebessa (2023) pointed out a significant drop in the lake's pH, conductivity, alkalinity, and salinity in their prior study. This could result in dilution, which could have an impact on the Lake's phytoplankton community. Increased dilution resulted in a decrease in nutrient content and an increase in phytoplankton taxa (Angom, 2011). Previous research on Lake Kilole by Brook Lemma (2003) also revealed changes in the phytolankton community, including the replacement of *L. fusiformis*, which was previously dominating, with other species caused by the dilution of the lake water after the diversion of River Mojo into the lake. Furthermore, changes in phytoplankton composition, which was previously dominated by *L. fusiformis*, have been observed from other East African Rift Valley Lakes, with another cyanobacterium species codominating the lake's phytoplankton (Ballot *et al.*, 2004; Schagerl and Oduor, 2008; Krienitz and Kotut, 2010; Schagerl *et al.*, 2015).

L. fusiformis was the only species represented in L. Chittu in 1960s. More recently, other studies reported that *Aomoeoneis spaerophora*, *Cyclotella*, *Navicula*, *Nitzschia*, *Rhopalodia and Synedra*. *C. marssonii* and *C. obovata* exist in Lake Chittu (Tadesse Ogato *et al.*, 2015), (Solomon Wagaw *et al.*, 2021), clearly demonstrated long-term trends of change in phytoplankton community structures due to increasing degradation of the water chemistry caused by salt content. Long-term phytoplankton biomass and species composition analysis revealed changes in phytoplankton composition and community structure.

Table 3. 2. Phytoplankton biomass measured as Chl-a concentration over the last few decades in study

Lakes	Chl-a (μg L^{-1})	Sampling Years	References
L. Arenguade	400-5000	1964-66	(Wood and Talling, 1988)
L. Arenguade	292	March – October 1993	(Habte Jebessa, 1994)
L. Arenguade	422	1989 -1993	(Zinabu and Taylor, 1997)
L. Arenguade	160	2008 - 2009	(Misgina Belachew *et al.*, 2012)
L. Arenguade	**130**	**2020**	**This study**
L. Beseka	29	1989 -1993	(Zinabu G/Mariam and Taylor, 1997)
L. Beseka	26.7	March-May 1991	(Elizabeth Kebede *et al.*, 1994)
L. Beseka	9.4	2004- 2005	(Tesfaye Delelegne 2006)
L. Beseka	**6.33**	**2020**	**This study**
L. Chittu	2600	Aug. 1966	(Wood and Talling, 1988)
L. Chittu	224	1989 -1993	(Zinabu G/Mariam and Taylor, 1997)
L. Chittu	145.5	March-May 1991	(Elizabeth Kebede *et al.*, 1994)
L. Chittu	72-234	Feb. 2012- Jan. 2013	(Tadesse Ogato *et al.*, 2015)
L. Chittu	**126.4**	**2020**	**This study**
L. Shala	5	Oct. 1966	(Wood and Talling, 1988)
L. Shala	7.1	1989 -1993	(Zinabu and Taylor, 1997)
L. Shala	16.6	Feb. 2012- Jan. 2013	(Tadesse Ogato and Demeke Kifle, 2017)
L. Shala	15.8	March-May 1991	(Elizabeth Kebede *et al.*, 1994)
L. Shala	17.1	Jan.- Dec. 2018	(Solomon Wagaw *et al.*, 2021)
L. Shala	**15.2**	**2020**	**This study**

CHAPTER FOUR: SEASONAL AND SPATIAL VARIATIONS OF ZOOPLANKTON IN RELATION TO PHYSICO-CHEMICAL VARIABLES IN SODA LAKES OF ETHIOPIA (ARENGUADE, BESEKA, CHITTU AND SHALA)

4.1. Introduction

Soda lakes, are abundant in Africa's Eastern Rift Valley, hold immense ecological and economic values (Jellison *et al.*, 2004). They are more abundant in the Eastern Rift Valley, which stretches from the Red Sea through Ethiopia and Kenya to Tanzania (Schagerl and Renaut, 2016). However, they face threats from anthropogenic activities in their catchments and climate change (Schagerl, 2022). These factors can alter the lakes' physicochemical characteristics, biological community structure, and water levels of the lakes. Furthermore, climate change is complicating their ecosystem by causing enormous fluctuations in their water levels (Oduor and Kotut, 2016). Understanding the interactions between zooplankton, phytoplankton, and the environment is crucial for managing these unique ecosystems.

For many years, limnology of soda lakes has been the subject of extensive research. Early studies (1960s) indicate these Ethiopian soda lakes had high physico-chemical values: pH > 9, salinity > 5 g L^{-1}, conductivity > 6 mS cm^{-1}, and alkalinity > about 2.5 $meql^{-1}$ (Talling and Talling, 1965). With the exception of Lake Shala, cyanoprokaryotes, particularly *Limnospira fusiformis*, predominated in phytoplankton production in those lakes in the 1980s (Wood and Talling, 1988). Misgina Belachew *et al.* (2012) linked a decline in Lake Arenguade's phytoplankton biomass and productivity to a dilution of key chemical properties like salinity, conductivity, and alkalinity. Furthermore, phytoplankton biomass (as Chl-a concentrations) in L. Arenguade decreased as compared to the 1960s (Hana Melese and Habte Jebessa, 2024b). Underwater explosions of seismic experiments have been suggested to be the primary cause of the lake's limnological changes (Misgina Belachew *et al.*, 2012).

Likewise, the physico-chemical characteristics of Lake Beseka reveal a deteriorating trend compared to prior investigations from the 1960s (Hana Melese and Habte Jebessa, 2023; Hana Melese and Habte Jebessa, 2024a). *L. fusiformis*, the previous dominant phytoplankton species (Wood and Talling, 1988), has been fully smashed (Zinabu G/Mariam, 2002). The phytoplankton population in Lake Beseka shifted from cyanobacteria to diatoms, despite the fact that the number of phytoplankton taxa indicated a growing trend from earlier researches (Hana Melese and Habte Jebessa, 2024a). Moreover, the change in Chl-a concentrations showed decreasing trend, while the number of phytoplankton taxa increased (Hana Melese and Habte Jebessa, 2024b). These changes in limnological properties have been attributed to dilution induced by the lake's increased size and area (Hana Melese and Habte Jebessa, 2024a).

In the 1960s, *L. fusiformis* was the only species represented in L. Chittu; however, several algae species have been found in recent investigations (Tadesse Ogato *et al.*, 2015). Even though East African soda lakes are recognized for their dense production of the Cyanoprokaryotes *L. fusiformis* (Schagerl and Oduor, 2008), Lake Shala has so far been devoid of this species. However, Solomon Wagaw *et al.* (2021) reported the sparse distribution of the species in the lake.

Zooplankton plays a key role in the aquatic food chain, transferring energy from primary producers to higher trophic levels such as fish (Beaver and Havens, 1996). Due to their short life cycle and rapid adaptation to environmental changes, they are sensitive indicators of the environment's response to various disturbances (Manickam *et al.*, 2017). Zooplankton diversity and abundance serve as effective indicators of aquatic ecosystem health (Melack, 1983). Therefore, quantifying changes in their community structure is crucial for understanding ecosystem condition.

Independent studies have been conducted on the dynamics of zooplankton species and abundances in the current study lakes. Copepods have been identified as the major zooplankton in soda lakes (Green, 1993; Seyoum Mengistou, 2016). *Lovenula Africana* (*Paradiaptomus africanus*) was the most common Copepod species in Lake Arenguade (Afeworki Ghebrai, 1992; Habte Jebessa, 1994), and *Brachionus dimidiatus* was the most common Rotifer (Green and Mengestou, 1991). Rotifers are the most diverse zooplankton in soda lakes and the genera *Branchionus*, *Lecane*, *Trichocerca*, *Hexarthra*, and *Asplanchna* represent the most diversified zooplankton (Seyoum Mengistou, 2016; Tadesse Ogato *et al.*, 2016; Solomon Wagaw *et al.*, 2023). Cyclopoids and Cladocerans were rarely represented in the lakes (Seyoum Mengistou, 2016). The changes in physico-chemical parameters and phytoplankton community described above may have altered the structure and composition of zooplankton in the lakes. Based on the above limnological information, the study of zooplankton communities in relation to environmental variables on multiple lakes with temporal variation was deemed necessary. Thus, the objective of this study was to examine the spatial and temporal patterns of zooplankton communities in relation to environmental conditions and compare them to historical data to find trends of change in these four Ethiopian soda lakes.

4.2. Materials and Methods

4.2.1. Zooplankton Sampling

Zooplankton samples were collected by vertically hauling 30μm plankton net from 5m to the surface of lakes Beseka and Chittu and 20m to the surface of Lake Shala. After collection, samples were placed in a 250 ml labeled plastic container and fixed with 5% formaldehyde. Zooplankton were identified in the laboratory to the lowest taxonomic units possible using relevant taxonomic keys. Specifically, Crustaceans were identified according to Korovchinsky (1992), Cladocerans according to Dumont and Smirnov (1996), Copepods using Defaye (1988) and Rotifers according to Fernando (2002), Koste (1978) and Segers (1995). Counting was made from subsamples using a plankton counting chamber mounted under an inverted microscope. Zooplankton abundance was reported as the number of individuals per liter.

4.3. Statistical Analyses

Temporal variations among results of physicochemical parameters, Chl-a biomass and zooplankton abundance between seasons were analyzed using Kruskal–Wallis method of variance (ANOVA) in R software ((version 4.3.1) (R Core Team, 2020). Redundancy Analysis [RDA using R package vegan] was also used to examine the effect of environmental variables on the abundance of zooplankton communities (Borcard *et al.*, 2011). Prior to analyses, Hellinger transformation (zooplankton species data) and environmental variables (except pH) were standardized for normality (Legendre and Gallagher, 2001) and differences were considered as significant when $p < 0.05$. Based on the 999 Monte Carlo permutations, the significance of these RDA model has been evaluated. Multicollinearity between explanatory variables has been tested by the Variance Inflation Factor (VIF<10). As a result, the following variables were added to the model: water temperature + dissolved oxygen + turbidity + electrical conductivity + soluble reactive phosphorus and nitrate. Twenty three zooplankton taxa were taken into account for RDA analysis.

4.4. Results

4.4.1. Physico-chemical Characteristics

The spatial and seasonal physico-chemical results (mean± sd) during the study period are presented in Tables 1 and 2, respectively. Lake Arenguade has the lowest water temperatures and dissolved oxygen levels, followed by Chittu. While, Lakes Shala and Beseka had the highest recorded water temperatures and DO levels. Lake Beseka has the lowest pH, conductivity (EC), and salinity, followed by Arenguade. However, Lake Chittu had the highest pH, EC, and salinity, followed by Shala (Table 4.1). Regarding nutrient concentrations in the lakes, Lake Arenguade had the greatest ammonium nitrogen concentration, while Lake Beseka had the lowest. The lowest and highest nitrate nitrogen concentrations were measured in Lakes Shala and Beseka. Lake Chittu showed the greatest soluble reactive phosphate (SRP, followed by Lake Shala and Arenguade. Lake Chittu has the greatest concentrations of total phosphorus (TP, followed by Lakes Arenguade and Shala. SRP and TP concentrations in Lake Beseka were found to be low (Table 4.1). The physicochemical parameters of four lakes (Lake Arenguade, Beseka, Chittu, and Shala) showed dynamic seasonal change in connection to their dominating environmental parameters (Table 4.2). Except for variation in the salinity of Lake Shala, all other physicochemical parameters demonstrated significant temporal variations ($P < 0.05$).

Table 4. 1. Mean value (± sd) of physicochemical parameters in four Ethiopian soda lakes during the present study period (L.A: Arenguade; L.B: Beseka; L.C: Chittu; L.S: Shala; Temp: Temperature; EC: Electrical Conductivity; DO: Dissolved Oxygen; Sal: Salinity)

Season	Physico-chemical parameters									
	Temp (°C)	**PH**	**EC** (mS/cm)	**DO** (mg l^{-1})	**Sal** (g l^{-1})	**NO_3–N** (µg l^{-1})	**NH_3–N** (µg l^{-1})	**SiO_2** (mg l^{-1})	**SRP** (mg l^{-1})	**TP** (mg l^{-1})
L. A	22.2± 0.55	10.04±0.34	5.42±0.17	3.33± 0.24	2.91± 0.50	40.6±27.31	161.9±57.8	39.4± 11.9	1.04 ± 0.27	2.08 ± 0.51
L. B	25.9± 0.89	8.55 ± 0.70	2.72±0.12	6.61± 0.62	1.88± 0.48	98.4±52.03	56.4±14.69	58.4±37.1	0.44 ± 0.16	1.15 ± 0.33
L. C	22.8± 0.58	10.46±0.14	66.9±3.45	5.44± 0.27	38.4± 7.60	69.5±29.72	113± 61.58	2.59± 1.01	1.75 ± 0.34	2.41 ± 0.52
L. S	22.9 ± 0.6	10.12±0.37	26.5±2.94	7.36± 0.72	16.8±1.90	27.12±7.50	89.2 ± 39.2	2.37± 0.25	1.05 ± 0.50	1.59 ± 0.49

Table 4. 2. Mean value (± sd) of physicochemical parameters the four Ethiopian soda lakes during the present study period

Season	Physico-chemical parameters									
	Temp (°C)	**PH**	**EC** (mS/cm)	**DO** (mg l^{-1})	**Sal** (g l^{-1})	**NO_3–N** (µg l^{-1})	**NH_3–N** (µg l^{-1})	**SiO_2** (mg l^{-1})	**SRP** (mg l^{-1})	**TP** (mg l^{-1})
Lake Arenguade										
Dry	21.6 ±0.12	9.64±0.61	5.65±1.09	3.12±0.80	3.24±0.58	9.61±0.83	224.0 ±0.83	45.0±0.31	1.01±0.02	2.78±0.03
Pre-rain	22.0 ±0.10	10.3±0.64	5.30±0.25	3.66±0.13	3.08±0.09	52.5±0.83	83.5±0.82	20.0±0.47	0.75±0.01	1.82±0.02
Rain	23.0 ±0.08	9.8±0.72	5.25±0.32	3.43±0.47	2.10±0.21	73.9±21.8	137.8±2.82	48.5±1.77	1.46±0.60	2.22±0.02
Post-rain	22.2 ±0.60	10.4±0.08	5.50±0.55	3.12±0.10	3.23±0.50	73.9±21.8	137.8±2.82	48.5±1.77	1.46±0.60	2.22±0.02
Lake Beseka										
Dry	25.9 ±0.58	9.28±0.44	2.78±0.12	6.01±0.43	2.38±0.70	30.1±2.85	47.2±2.18	22.9±0.08	0.66±0.05	1.49±0.24
Pre-rain	25.8 ±0.12	9.15±0.56	2.79±0. 54	7.21±0.13	1.42±0.72	120.6±0.8	46.8±1.65	22.9±0.08	0.47±0.35	1.43±0.55
Rain	24.8 ±0.10	7.87±0.48	2.8±0.44	7.20±0.33	1.43±0.53	164.4±0.0	51.1±8.71	95.8±0.07	0.26±0.01	0.77±0.04
Post-rain	27.2 ±0.30	7.88±0.16	2.52±0.37	6.03±0.58	2.31±0.35	78.2±1.65	80.4±2.87	92.1±0.07	0.36±0.03	0.92±0.08
Lake Chittu										
Dry	22.2 ±0.60	10.2±0.83	70.24±1.0	5.49±0.52	45.6±0.17	83.0±3.23	134±2.18	4.00±0.38	2.28±0.08	3.15±0.05
Pre-rain	22.3 ±0.58	10.5±0.21	63.6 ±0.10	5.14±0.98	29.7±0.77	103.4±7.6	61.1±4.59	2.64±0.00	1.74±0.72	2.53±0.06
Rain	23.1 ±0.06	10.6±0.58	63.5±0.03	5.81±0.23	45.6±0.77	26.8±2.18	56.8±2.18	2.38±0.33	1.40±0.03	1.82±0.03
Post-rain	23.5 ±0.10	10.5±0.10	70.1±0.82	5.33±0.81	32.8±0.41	64.9±3.78	200±1.43	1.34±2.72	1.60±0.83	2.13±0.07
Lake Shala										
Dry	23.4 ±0.2	10.09±0.3	26.4±0.21	8.47±0.12	16.7±0.23	24.4±2.18	54.0±2.98	2.23±0.14	1.87±0.03	2.30±0.00
Pre-rain	23.0 ±0.09	9.8±0.10	23.0±0.80	6.97±0.68	14.4±1.02	39.1±1.43	124.9±21.8	2.58±0.13	0.92±0.02	1.72±0.04
Rain	21.9 ±0.01	9.9±0.80	25.9±0.00	7.35±0.16	16.5±0.02	23.0±2.98	126.3±1.25	2.46±0.40	0.65±0.70	1.09±0.42
Post-rain	23.2 ±0.12	10.7±0.20	30.9±0.35	6.63±0.72	19.5±0.82	22.0±0.00	51.6±1.43	2.23±0.14	0.77±0.02	1.27±0.17

4.4.2. Zooplankton Taxonomic Composition and Abundance

Table 4.3 displays a checklist of the zooplankton species identified at all the study lakes. The results in this table reveal that the greatest numbers of zooplankton were noted for Lake Shala (20) followed by Beseka (12), Chittu (10) and Arenguade (4). The zooplankton assemblage in all lakes included 25 species in which Rotifera had the highest proportion with 16 taxa and Copepoda with 6 species. However, Cladocerans were the least in terms of species richness and represented by 2 species. The genus *Brachionus*, specifically *B. dimidiatus* and *B. plicatilis,* were found to be prevalent and abundant among the Rotifers in all lakes in the current study. Pictures of a few zooplankton species found in the lakes are included in Appendix 1.

Table 4. 3. List of zooplankton species recorded in the four Ethiopian soda lakes during the study period

Zooplankton species	Study Lakes			
	Arenguade	Beseka	Chittu	Shala
Cladocera				
Diaphanosoma excisum (Sars 1885)	-	-	-	+
Moina micrura (Kurz, 1874)	-	+	-	+
Copepoda				
Calanoida				
Lovenula africana (Daday, 1910)	+	-	-	-
Cycolopoida	-			
Afrocyclops gibsoni ondoensis Kiefer, 1952	-	-	-	+
Mesocyclops (Mesocyclops) kieferi van de Velde, 1984	-	+	-	-
Thermocyclops ethiopiensis (Defaye, 1988)	-	-	-	+
Thermocyclops sp.	-	+	-	-
Harpacticoida	-			
Nitocra lacustris (Schmankevitsch, 1875)	-	-		+
Rotifera	-			
Anuraeopsis fissa (Gosse 1851)	+	-	-	+
Asplanchna sp.	-	-	+	-
Brachionus angularis (Gosse, 1851)	-	+	+	+
Brachionus calyciflorus (Pallas, 1766)	-	+	+	+
Brachionus dimidiatus (Bryce, 1931)	+	+	+	+
Brachionus falcatus (Zacharias 1898)	-	-	-	+
Brachionus plicatilis (Müller, 1786)	+	+	+	+
Brachionus quadridentatus (Hermann, 1783)	-	-	-	+
Brachionus rubens (Ehrenberg, 1838)	-	+	+	+
Brachionus urceolaris (Müller, 1773)	-	-	+	+
Filinia pejleri (Hutchinson, 1964)	-	+	+	+
Hexarthra jenkinae (Beauchamp, 1932)	-	-	-	+
Keratella tropica (Apstein, 1907)	-	-	-	+
Lecane luna (Müller, 1776)	-	+	+	+
Polyarthra vulgaris (Carlin, 1943)	-	+	+	+
Trichocerca pusilla (Jennings, 1903)	-	-	-	-
Trichocerca sp.	-	-	-	+

+, species present; -, species absent.

The mean abundance of zooplankton in Lake Arenguade ranged from 81.6 to 295.8 ind. L^{-1}, with the highest values in July and the lowest in January, and Copepods accounted for 57% of total zooplankton density. Lake Besekas' mean zooplankton abundance ranged from 1012.6-2737.4 ind.L^{-1}, with the highest values in November and the lowest in July, and copepods contributed 63%. In Lake Chittu, zooplankton abundance ranged from 489.6 to 841.58 ind.L^{-1}, with the highest in July and the lowest in January, all contributed only by rotifers. Lake Shala's zooplankton abundance ranged from 507.4 to 902.7 ind. L^{-1}, with the highest values in January and the lowest in June. Rotifers produced 65% of the total zooplankton density (Figure 4.1).

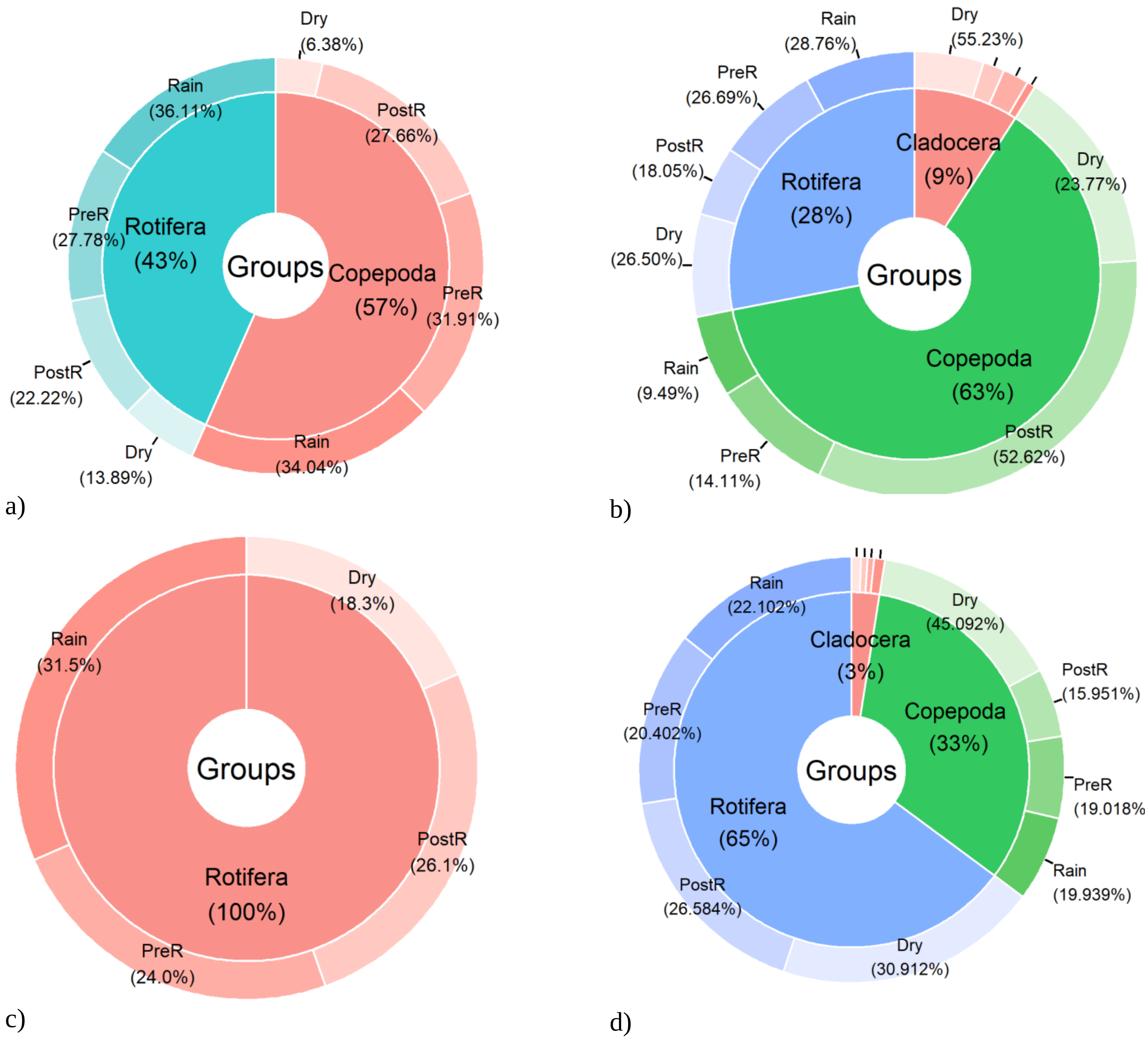


Figure 4. 1. Spatial and seasonal contribution of different zooplankton groups to the total zooplankton abundance (Ind. L-1) observed during the study period; a) L. Arenguade, b) L. Beseka, c) L. Chittu, d) L. Shala

4.4.3. Zooplankton species relations with Environmental parameters

The abundance data of 23 taxa and eleven environmental variables were analyzed using Redundancy Analysis (RDA). The forward selection procedure (VIF) found six significant ($P<0.05$) environmental variables to include in the RDA model (Fig. 4.2). These environmental variables include temperature, DO, EC, nitrate, SRP, and turbidity. The first two axes described 69.21% of taxonomic variation, with the first axis accounting for 48.22% and the second for 20.99% of total variance. Most of the rotifers inhabited areas associated with higher temperature, electrical conductivity, nitrate and SRP. *B. angularis*, *B. calyciflorus*, *B. urceolaris*, *B. rubens* and *B. falcatus*, as well as other rotifers such as *H. jenkinae* and *K. tropical* are associated with higher EC. *B. quadridentatus*, *B. plicatilis* are associated with increasing SRP. In addition, *Thermocyclops* species are related to rising temperatures.

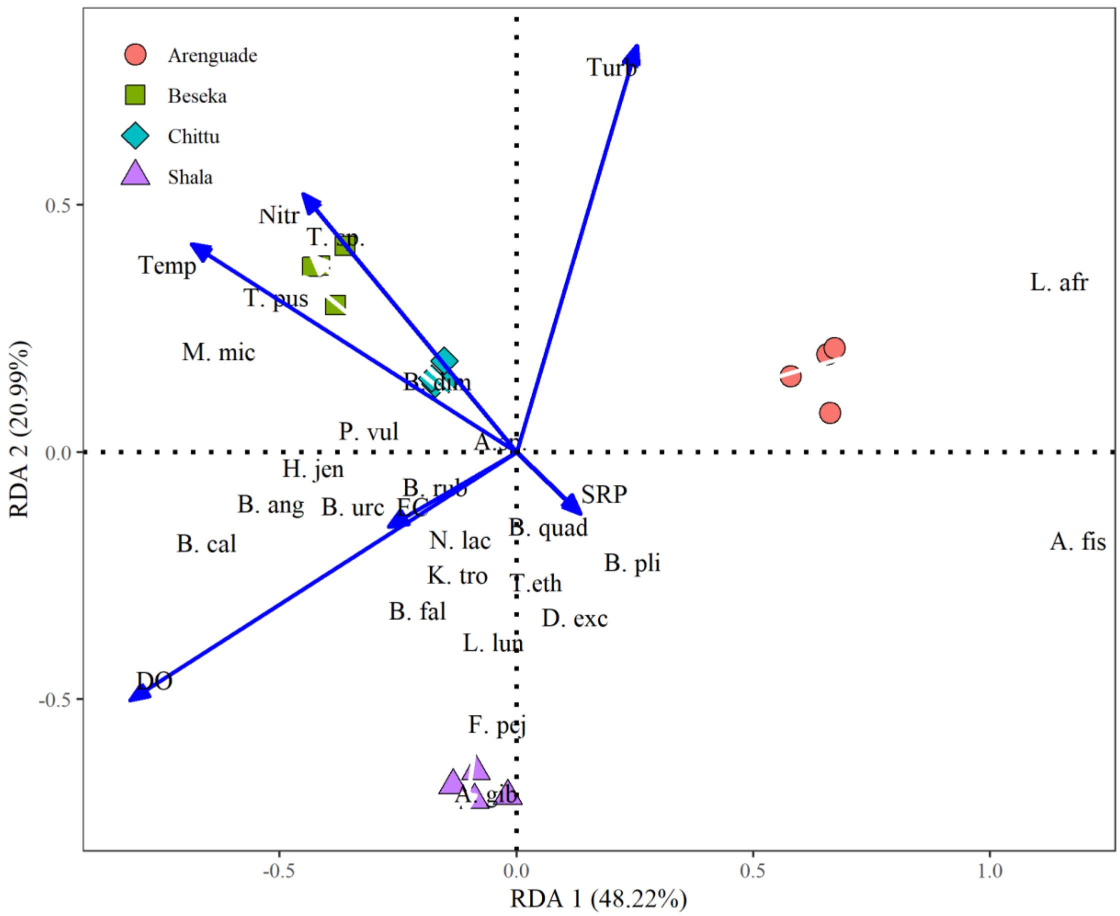


Figure 4. 2. Redundancy Analysis (RDA) triplots, showing relationship between significant environmental variables and zooplankton communities in four lakes during the study periods. Water temperature (Temp), Electrical conductivity (EC), Turbidity (Turb), Dissolved (DO), Soluble reactive phosphorus (SRP) and Nitrate (Nitr). *Diaphanosoma excisum (D. exc), Moina micrura (M. mic), Lovenula Africana (L. afr), Afrocyclops gibsoni (A. gib), Thermocyclops ethiopiensis (T. eth), Thermocyclops sp. (T. sp.), Nitocra lacustris (N. lac), Anuraeopsis fissa (A.sp.), Brachionus angularis (B. ang), Brachionus calyciflorus (B. cal), Brachionus dimidiatus (B. dim), Brachionus falcatus (B. fal), Brachionus plicatilis (B. pli), Brachionus urceolaris (B. urc), Brachionus quadridentatus (B. quad), Brachionus rubens (B. rub), Filinia pejleri (F. pej), Hexarthra jenkinae (H. jen), Keratella tropica (K. tro), Lecane luna (L. lun), Polyarthra vulgaris (P. vul), and Trichocerca pusilla (T. pus).*

4.5. Discussion

The current study found that rotifers dominated all four lakes in terms of species richness whereas, cladocerans occurred rarely. *Brachionus* was discovered to be the most common genus among rotifers. This finding is in accord with work by Green and Mengestou (1991); (Green, 1993); Okoth *et al.* (2011); Burian *et al.* (2014); (Seyoum Mengistou, 2016); Solomon Wagaw *et al.* (2023); and Dhanasekaran *et al.* (2017), who reported rotifers dominance in East African and Indian Soda lakes. Rotifers dominance in species richness may indicate that they have special physiological tolerance of increased salinity, their high tolerance to a variety of environmental factor, a short developmental rate, and the ability to feed or eat a variety of foods (Mustapha, 2010; Tóth *et al.*, 2014). Occurrence of cladocerans may be rare because of the influence of high osmotic pressure, respiration, and filtration rate (Potts and Fryer, 1979; Seyoum Mengistou, 2016).

In contrast to lakes Chittu and Shala, where rotifers made an important contribution, lakes Arenguade and Beseka have substantial percentage of copepod contributions to the overall zooplankton abundances. Such a dominance of rotifers and copepods is a common pattern in tropical water bodies. This could be due to their defense mechanism and the presence of edible phytoplankton as a food source (Hansen and Jeppesen, 1993; Bozkurt and Kara, 2020).

The abundance of zooplankton in Lake Arenguade and Chittu was high during the wet Month (July), while in Lakes Beseka and Shala it was high during the post-rainy (November) and dry seasons (January), respectively. The highest abundance of zooplankton species recorded during July in Lake Arenguade and Chittu could have been caused by the high nutrient loading and sediment suspension caused by runoff, maintains the high productivity of phytoplankton which ultimately supports the growth of zooplankton population (Zhou *et al.*, 2023). Since small closed lakes have a significant catchment area to surface area ratio and are shallow, they are subject to seasonal variations in wind speed and rainfall, which affect plankton populations through water mixing and nutrient loading (Kondowe *et al.*, 2022).

Two species of Rotifera, *B. dimidiatus* and *B. plicatilis*, have been found in zooplankton in all types of lakes because they are cosmopolitan, halobiont and typical inhabitant of inland saline lakes, preferring alkaline soda lakes. This finding is consistent with studies on East African soda lakes conducted by several scholars (Okoth *et al.*, 2011; Oduor and Kotut, 2016).

The variations in the abundances of the zooplankton community were significantly explained by the six environmental parameters. According to RDA data, the majority of rotifers inhabited areas associated with greater levels of SRP, nitrate, electrical conductivity, and temperature. Nutrients, such as nitrogen and phosphorus, affect the community structure of zooplankton by affecting phytoplankton because they act as minerals for their growth that can be grazed by zooplankton, thereby having a pronounced effect on the zooplankton abundance (Mhlanga *et al.*, 2017). Temperature fluctuations have a direct impact on the abundance of rotifers as it affects their reproductive rate, feeding, movement and longevity (Manickam *et al.*, 2017; Zhou *et al.*, 2023). Higher EC is linked to *B. angularis*, *B. calyciflorus*, *B. urceolaris*, *B. rubens*, and *B. falcatus*, as well as other rotifers including *H. jenkinae* and *K. tropical*, *B. plicatilis* and *B. quadridentatus* which are linked to elevated SRP. In saline ecosystems, conductivity appears to provide zooplankton suitable habitats for feeding, growing, and reproducing.

CHAPTER FIVE: COMPARATIVE ANALYSIS OF LAND USE/LAND COVER CHANGES IN THE CATCHEMENT OF ETHIOPIAN SODA LAKES (ABIJATA, ARENGUADE, BESEKA AND SHALA) USING GIS AND REMOTE SENSING

5.1. Introduction

Land Use/Land Cover (LULC) analysis has become an integral part of current approaches to understand how anthropogenic activities interact with the environment and to assess global change at multiple spatio-temporal scales for monitoring environmental changes and managing natural resources (Lambin and Geist, 2008; Poongothai *et al.*, 2014). Land use at different levels is influenced by a range of factors including economic, cultural, political, historical, and land tenure factors (Liu *et al.*, 2017; Panwar *et al.*, 2017). Land use change refers to changes in land use types and their spatial characteristics, which are based on historical processes relating to how people use the land (Su *et al.*, 2015).

Although land use problems are common in both developing and developed worlds, rapid population growth is the most prominent driver of changes to land use across the developing world (Ekaka Azanga *et al.*, 2016). Ethiopia has experienced a significant LULC dynamic due to natural and manmade drivers as a country with one of the largest populations in Africa (Mengistie Kindu *et al.*, 2013; Eyasu Elias *et al.*, 2018; Abebe Tufa *et al.*, 2021). Several studies have identified some of the causes of LULC changes in Ethiopia as deforestation, significant increases in agricultural lands and expansion in built-up areas or settlements, climate change, neo-tectonic movements, industrial lake water use, expansion of invasive species and so on (Efrem Garedew *et al.*, 2009; Mengistie Kindu *et al.*, 2013; Temesgen Habtamu *et al.*, 2013; Belew Bekele *et al.*, 2018; Ayenew Ayalew *et al.*, 2023; Gizaw Abera *et al.*, 2023). LULC changes will have a considerable impact on the sediment, water and nutrients regimes which in turn influence aquatic biota and ecological processes in Lake Ecosystem (Panwar *et al.*, 2017; Wang *et al.*, 2022).

Ethiopia is endowed with a number of aquatic ecosystems, including a number of saline/soda lakes immensely located in the Ethiopian Rift Valley. They are incredible natural assets of considerable economic and noneconomic value (Williams, 2002; Hadgembes Tesfay, 2006). They are recognized as sources of valuable minerals such as table salt (Sodium chloride), which is why commercial exploitation of soda ash in Lake Abijata (Dagnachew Legesse *et al.*, 2004), and edible salt from Lake Afdera is practiced (Abebe Getahun, 2001). Lakes Arenguade and Chittu are also key algal production areas, particularly *Arthrospira fusiformis* (=*Limnospira fusiformis*), providing a potential future for the extraction of these natural products from the lakes (Elizabeth Kebede, 1997; Misgina Belachew *et al.*, 2012; Tadesse Ogato *et al.*, 2014). Moreover, they are known as remarkable places for tourist attraction due to the natural beauty, provide suitable feeding and breeding habitats for numerous birds, fish, animals like crocodiles and have scientific and educational values (Matagi, 2004; Lemma Abera, 2013; Getachew Senbete, 2015; Tadesse Fetahi, 2016; Solomon Wagaw *et al.*, 2019).

Unfortunately, a number of natural and anthropogenic activities are currently threatening these lakes. During the last few decades, some of them witnessed a dramatic decline in Lake level/volume/ area, while others have experienced an increase. Several studies have been carried out, with a specific focus on water resources in Ethiopia's Central Rift Valley Region, to assess the impact of LULC change (Tenalem Ayenew, 2007; Temesgen Habtamu *et al.*, 2013; Eyasu Elias *et al.*, 2018; Wolde Mekuria *et al.*, 2021). For example, Lake Abijata had shown a significant reduction in volume due to increased water usage by a soda ash factory and increased evaporation (Tenalem Ayenew, 2004; Tamiru Alemayehu *et al.*, 2006; Tadesse Fetahi, 2016; Hamere Yohannes *et al.*, 2017; Binyam Tesfaw and Shimelis Girma, 2019). Similarly the surface area of Lake Shala is also reduced by 1.48% in 2015 from its area 0f 1985 (Wondwossen Girmay *et al.*, 2017) which may be due to human encroachment, cattle grazing, uncontrolled water abstraction, and other anthropogenic activities (Tamiru Lemi, 2019). Nevertheless, Lake Beseka (Metehara) is extremely expanded at an alarming rate in surface area and volume over the last decades which thought to be caused by discharge from hot springs, climate variability, groundwater input, and irrigation return water from adjacent farms (Tenalem Ayenew, 2004; Goerner *et al.*, 2009; Megersa Olumana, 2012; Esayas Gebremichael *et al.*, 2022). There is currently no research on the change in land use and land cover, as well as the change in Lake Arenguade's water level. However, there is a scarcity of comparative studies on long-term changes in LULC dynamics of soda lakes; consequently, it is vital to understand land use change and its impacts on ecological deterioration in the lake watershed. So, this study aimed to estimate the land use and land cover changes around the lakes catchment area of four Ethiopian soda lakes over four periods (1984-2024) using remote sensing and GIS techniques.

5.2. Materials and Methods

The current investigation focuses on the analysis of land use and land cover (LULC) for the years 1984, 1994, 2004, 2014, and 2024. The study encompasses four distinct study sites: (1) Lake Beseka, which stands independently, (2) Lake Shala, (3) Lake Chittu, and (4) Lake Abijata, all located within a similar catchment area. However, Lake Arenguade was excluded from this study due to its small catchment size of only $6km^2$. The methodology's complete process is illustrated in Fig. 5.1.

5.2.1. Data Acquisition

Remote sensing platforms are our primary data acquisition hubs in order to collect time series images. Landsat images have been the preferred choice due to their longevity, dating back to 1972. Over the years, Landsat has conducted multiple missions, capturing multi-temporal and multispectral images using advanced cameras and sensors like MSS, TM, ETM, ETM+, OLI/TIRS. The Landsat images collected every 10 years from 1984 to 2024 can be accessed from the USGS website https://earthexplorer.usgs.gov/, ensuring consistency in seasons. Each image is carefully selected to ensure cloud-free and dry conditions, providing clear sky images and avoiding misinterpretation of vegetation due to winter season. Additionally, the ALOS PALSAR DEM with a resolution of 12.5m is utilized to create the watershed of the study area.

5.2.2. Image Processing and Classification

The collected images are projected to WGS 1984 UTM coordinate system, to setup the matching of spatial coverage of the area of interest. Radiometric correction is also applied to enhance the images quality using ENVI software. As part of the image preprocessing, bands with comparable spatial resolution are combined for each image to enhance the raster files. The resulting composite band images are then imported into ArcGIS 10.8 software, where the band order is adjusted to improve the visualization of specific LULC classes. A signature file is generated, containing information about each class, which is utilized by the computer algorithm during the classification process. The Maximum Likelihood Classification method is employed, taking into account both the means and covariances of the class signatures, to assign each cell to one of the classes represented in the signature file (.sig extension).

The delineation of catchment is carried out with the help of the SWAT extension in ArcGIS and the DEM files function in Global Mapper. The catchment encompasses areas that have drainage contribution impacting the hydrology of the study areas. The focus is on five categories of LULC classification: water bodies, agricultural land, natural vegetation, dry land, and settlements, to monitor changes in LULC over time as shown in Table 5.1.

Table 5. 1. Land use/ land cover categories and the corresponding description

LULC Classes	Description
Water Body	Water body: lakes, reservoirs,
Agricultural Land	Cropland, paddy field
Natural Vegetation	Shrub, bushes, sparse vegetation
Settlement	Residential, market, towns, industrial, built-up land
Dry land	Bare land, rugs and volcanic piles, consolidated (gravel, rock); bare area, unconsolidated (sand)

5.2.3. Land Use Land Cover Change (LULC) Analysis

The post-classification image comparison technique was employed to conduct an analysis on land use change. Subsequently, change detection analysis was employed to assess the spatial extent of the various land use and land cover (LULC) classes in each map. The data collected was presented in terms of percentage coverage and square kilometers for each of the study years (1984, 1994, 2004, 2014, and 2024) across the five land use categories. The degree of LULC changes among the five land use categories of the lake watershed was then compared.

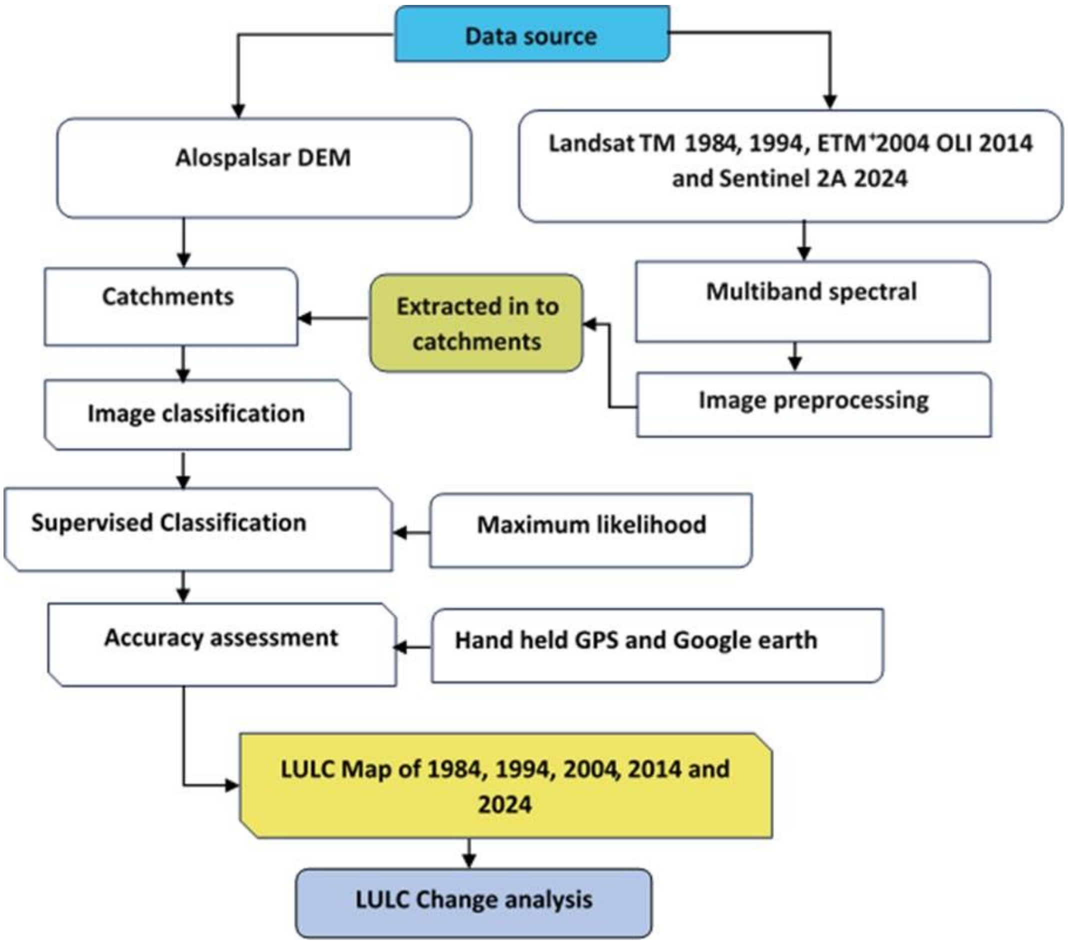


Figure 5. 1. Flow chart methodology of LULC change detection

5.3. Results

5.3.1. Accuracy Assessment

Accuracy assessment in land use and land cover change analysis is a critical step to evaluate the precision of the classification process used in mapping changes over time. It involves comparing the results of the land cover classification from remote sensing data to a set of reference data that is considered to be the ground truth. This comparison helps to identify the proportion of correctly classified pixels and thus, the reliability of the land cover change analysis (MohanRajan *et al.*, 2020). Post-classification accuracy assessment is a critical step in remote sensing and land cover mapping projects. It involves evaluating the precision of the classification results produced by a computer program. This process typically uses a stratified random sampling method, where the number of sample points is proportional to the area of each class within the study region. A confusion matrix is then constructed to calculate the overall accuracy and Kappa coefficient, which provide insights into the agreement between the classified data and the actual ground truth. These metrics are essential for understanding the reliability of the classification and for making informed decisions based on the mapped data. The Kappa statistic, in particular, is a measure of how much better the classification is compared to random chance, accounting for the possibility of agreement occurring by chance (Lillesand *et al.*, 2015). Ground verification was also conducted through the collection of GPS points to validate the findings related to various land use attributes.

Table 5. 2. L. Shala, L. Abijata and L. Chitu LULC Confusion Matrix Result (a (1984, b (1994), c (2004), d (2014), e (2024))

a)

LULC Classes	Natural Vegetation	Agricultural Land	Dry Land	Settlement	L. Abijata	L. Shala	L. Chittu	Total	U. Acc. (%)
Natural Vegetation	**50**	6	1	0	0	0	0	57.00	87.72
Agricultural Land	4	**58**	19	0	0	0	0	81.00	71.60
Dry Land	0	6	**294**	1	0	0	0	301.00	97.67
Settlement	0	2	4	**10**	0	0	0	16.00	62.50
L. Abijata	0	0	1	0	**16**	1	0	18.00	88.89
L. Shala	0	0	1	0	0	**26**	0	27.00	96.30
L. Chittu	0	0	1	0	0	0	**8**	9.00	88.89
Total	54	72	321	11	16	27	8	509.00	
P. Accuracy (%)	92.59	80.56	91.59	90.91	100.00	96.30	100.00		
Tot. Correct Pixels	462.00								
Tot. Created Pixels	509.00								
Overall Acc. (%)	90.77								
Kappa Statistics	0.8431								

b)

LULC Classes	Natural Vegetation	Agricultural Land	Dry Land	Settlement	L. Abijata	L. Shala	L. Chittu	Total	U_Accuracy (%)
Natural Vegetation	**59**	1	2	0	1	0	0	63.00	93.65
Agricultural Land	9	**68**	10	0	0	0	0	87.00	78.16
Dry Land	14	3	**282**	1	0	0	0	300.00	94.00
Settlement	0	2	1	**7**	0	0	0	10.00	70.00
L. Abijata	0	0	0	0	**12**	0	0	12.00	100.00
L. Shala	0	0	0	0	0	**29**	0	29.00	100.00
L. Chittu	1	0	0	0	0	1	**9**	11.00	81.82
Total	83	74	295	8	13	30	9	512.00	
P. Accuracy (%)	71.08	91.89	95.59	87.50	92.31	96.67	100.00		
Tot. Correct Pixels	466.00								
Tot. Created Pixels	512.00								
Overall Acc. (%)	91.02								
Kappa Statistics	0.8536								

c)

LULC Classes	Natural Vegetation	Agricultural Land	Dry Land	Settlement	L. Abijata	L. Shala	L. Chittu	Total	U_Acc. (%)
Natural Vegetation	**44**	1	2	0	2	0	1	50.00	88.00
Agricultural Land	5	**181**	41	0	0	0	0	227.00	79.74
Dry Land	1	2	**173**	0	0	0	0	176.00	98.30
Settlement	0	2	1	**11**	0	0	0	14.00	78.57
L. Abijata	1	0	0	0	**9**	0	0	10.00	90.00
L. Shala	0	0	0	0	0	**31**	0	31.00	100.00
L. Chittu	0	0	0	0	0	0	**8**	8.00	100.00
Total	51	186	217	11	11	31	9	516.00	
P. Accuracy (%)	86.27	97.31	79.72	100.00	81.82	100.00	88.89		
Tot. Correct Pixels	457.00								
Tot. Created Pixels	516.00								
Overall Acc. (%)	88.57								
Kappa Statistics	0.8329								

d)

LULC Classes	Natural Vegetation	Agricultural Land	Dry Land	Settlement	L. Abijata	L. Shala	L. Chittu	Total	U. Acc. (%)
Natural Vegetation	**14**	2	1	0	0	0	0	17.00	82.35
Agricultural Land	0	**215**	19	2	0	0	0	236.00	91.10
Dry Land	0	13	**163**	2	0	0	0	178.00	91.57
Settlement	0	2	1	**13**	0	0	0	16.00	81.25
L. Abijata	0	0	0	0	**12**	0	0	12.00	100.00
L. Shala	0	0	0	0	0	**38**	0	38.00	100.00
L. Chittu	0	0	0	0	0	0	**7**	7.00	100.00
Total	14	232	184	17	12	38	7	504.00	
P. Accuracy (%)	100.00	92.67	88.59	76.47	100.00	100.00	100.00		
Tot. Correct Pixels	462.00								
Tot. Created Pixels	504.00								
Overall Acc. (%)	91.67								
Kappa Statistics	0.8714								

e)

LULC Classes	Natural Vegetation	Agricultural Land	Dry Land	Settlement	L. Abijata	L. Shala	L. Chittu	Total	U. Acc. (%)
Natural Vegetation	**58**	4	0	0	2	0	0	64.00	90.63
Agricultural Land	4	**193**	3	2	0	0	0	202.00	95.54
Dry Land	0	5	**143**	0	0	0	0	148.00	96.62
Settlement	0	2	1	**14**	0	0	0	17.00	82.35
L. Abijata	0	0	0	0	**18**	0	0	18.00	100.00
L. Shala	0	0	0	0	0	**48**	0	48.00	100.00
L. Chittu	0	0	0	0	0		**8**	8.00	100.00
Total	62	204	147	16	20	48	8	505.00	
P. Accuracy (%)	93.55	94.61	97.28	87.50	90.00	100.00	100.00		
Tot. Correct Pixels	482.00								
Tot. Created Pixels	505.00								
Overall Acc. (%)	95.45								
Kappa Statistics	0.9373								

The study site LULC classification accuracy assessment provides an overall accuracy of 90%, 85%, 88%, 87% and 95% for 1984, 1994, 2004, 2014 and 2024 respectively. Similarly, kappa statistics is computed to be 0.90, 0.91, 0.83, 0.87 and 0.93 for the above-mentioned respective years (Table 5.2 a – e).

Table 5. 3. L. Beseka LULC Confusion Matrix Result (f (1984, g (1994), h (2004), i (2014), j (2024))

f)

LULC Classes	Natural Vegetation	Agricultural Land	Dry Land	Settlement	Water Bodies	Total	U. Acc. (%)
Natural Vegetation	**50**	9	0	0	0	59.00	84.75
Agricultural Land	0	**109**	0	0	0	109.00	100.00
Dry Land	7	5	**261**	0	10	283.00	92.23
Settlement	0	2	0	**7**	0	9.00	77.78
Water Bodies	4	12	9	0	**22**	47.00	46.81
Total	61	137	270	7	32	507.00	
P Accuracy (%)	81.97	79.56	96.67	100.00	68.75		
Total Correct Pixels	449.00						
Total Created Pixels	507.00						
Overall Accuracy (%)	88.56						
Kappa Statistics	0.8168						

g)

LULC Classes	Natural Vegetation	Agricultural Land	Dry Land	Settlement	Water Bodies	Total	U. Acc. (%)
Natural Vegetation	**53**	13	0	0	0	66.00	80.30
Agricultural Land	5	**114**	0	3	0	122.00	93.44
Dry Land	0	6	**246**	0	9	261.00	94.25
Settlement	1	0	0	**11**	0	12.00	91.67
Water Bodies	6	8	0	0	**29**	43.00	67.44
Total	65	141	246	14	38	504.00	
P Accuracy (%)	81.54	80.85	100.00	78.57	76.32		
Total Correct Pixels	453.00						
Total Created Pixels	504.00						
Overall Accuracy (%)	89.88						
Kappa Statistics	0.8456						

h)

LULC Classes	Natural Vegetation	Agricultural Land	Dry Land	Settlement	Water Bodies	Total	U. Acc. (%)
Natural Vegetation	**65**	3	0	0	0	68.00	95.59
Agricultural Land	10	**124**	0	0	0	134.00	92.54
Dry Land	4	5	**228**	0	0	237.00	96.20
Settlement	0	3	0	**15**	0	18.00	83.33
Water Bodies	11	0	0	0	**33**	44.00	75.00
Total	90	135	228	15	33	501.00	
P. Accuracy (%)	72.22	91.85	100.00	100.00	100.00		
Total Correct Pixels	465.00						
Total Created Pixels	501.00						
Overall Accuracy (%)	92.81						
Kappa Statistics	0.8945						

i)

LULC Classes	Natural Vegetation	Agricultural Land	Dry Land	Settlement	Water Bodies	Total	U. Acc. (%)
Natural Vegetation	**60**	4	0	0	2	66.00	90.91
Agricultural Land	5	**119**	7	4	0	135.00	88.15
Dry Land	6	8	**226**	0	0	240.00	94.17
Settlement	2	1	0	**16**	0	19.00	84.21
Water Bodies	3	2	0	0	**42**	47.00	89.36
Total	76	134	233	20	44	507.00	
P. Accuracy (%)	78.95	88.81	97.00	80.00	95.45		
Total Correct Pixels	463.00						
Total Created Pixels	507.00						
Overall Accuracy (%)	91.32						
Kappa Statistics	0.8729						

j)

LULC Classes	Natural Vegetation	Agricultural Land	Dry Land	Settlement	Water Bodies	Total	U. Acc. (%)
Natural Vegetation	**62**	3	0	0	1	66.00	93.94
Agricultural Land	3	**125**	14	2	0	144.00	86.81
Dry Land	0	8	**226**	0	0	234.00	96.58
Settlement	0	2	1	**13**	0	16.00	81.25
Water Bodies	0	0	0	0	**45**	45.00	100.00
Total	65	138	241	15	46	505.00	
P. Accuracy (%)	95.38	90.58	93.78	86.67	97.83		
Total Correct Pixels	471.00						
Total Created Pixels	505.00						
Overall Accuracy (%)	93.27						
Kappa Statistics	0.9003						

Lake Beseka’s classification confusion matrix resulted in an overall accuracy of 88% (1984), 89% (1994), 92% (2004), 91% (2014) and 93% respectively while kappa statistics are 0.82 (1984), 0.85 (1994), 0.89 (2004), 0.87 (2014) and 0.90 (2024) respectively as depicted in tables 5.3 f – j.

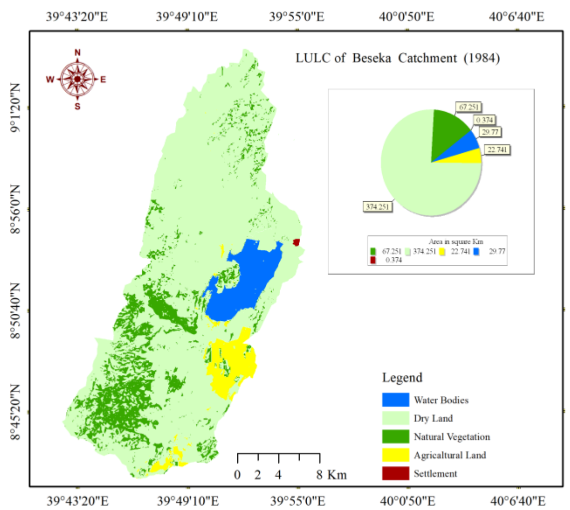
5.3.2. Land use/land Cover Changes of Lake Beseka (1984 −2024)

The maps and pie charts provided below illustrates the variations in land use/land cover over different time periods, indicating the alterations that have occurred within the study sites over a 40-year timeframe. The outputs for classification of the images involved comparing the land use categories by their respective total areas.

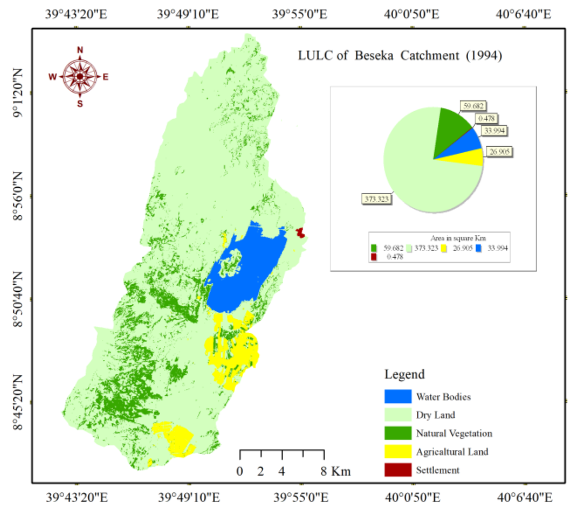
The classified land use maps of Lake Beseka catchment from the year 1984 to 2024 are presented in Fig. 5.2. The figure presents the areal distribution of the land use categories for the years under consideration, at ten-year interval. As presented in Table 5.4 and Figures 5.2, the land use classes that have consistently increased are agricultural water body, land and settlement areas, while there has been a decrease in dry land. The catchment area's natural vegetation exhibited a growing tendency, but due to changes in land use and the increase of water bodies, it is constantly fluctuating. Agricultural land experienced the largest change in land use, rising from 4.60% of the total catchment area (494.87 km2) in 1984 to 26.1% in 2024 followed by water body area that increased from 6.02% in 1984 to 10% in 2024. Additionally, the settlement area rose from 0.08% in 1984 to 0.43% in 2024. However, dry land decreased from 75.7% of the total catchment area in 1984 to 50.22% in 2024 (Table 5.4).

Table 5. 4. Area (Km^2) and percentage of change in different land use/land cover categories in the catchment area of Lake Beseka 1984-2024

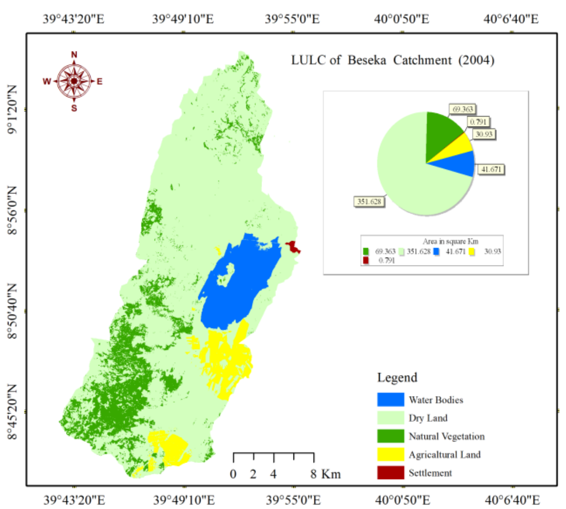
LULC classes	**Years (Area Km^2) %**									
	1984	**%**	**1994**	**%**	**2004**	**%**	**2014**	**%**	**2024**	**%**
L. Beseka	29.77	6.02	33.99	6.88	41.67	8.43	46.71	9.45	49.44	10.00
Dry Land	374.25	75.70	373.32	75.51	351.63	71.12	313.41	63.39	248.29	50.22
Natural Vegetation	67.25	13.60	59.68	12.07	69.39	14.04	69.60	14.08	65.54	13.26
Agricultural Land	22.74	4.60	26.91	5.44	30.93	6.26	63.00	12.74	129.02	26.10
Settlement	0.37	0.08	0.48	0.10	0.79	0.16	1.71	0.35	2.14	0.43


LULC of Beseka Catchment (1984)
39°43'20"E
39°49'10"E
39°55'0"E
40°0'50"E
40°6'40"E
9°1'20"N
8°56'0"N
8°50'40"N
8°45'20"N
N
S
W
E
Legend
Water Bodies
Dry Land
Natural Vegetation
Agricaltural Land
Settlement
0 2 4 8 Km

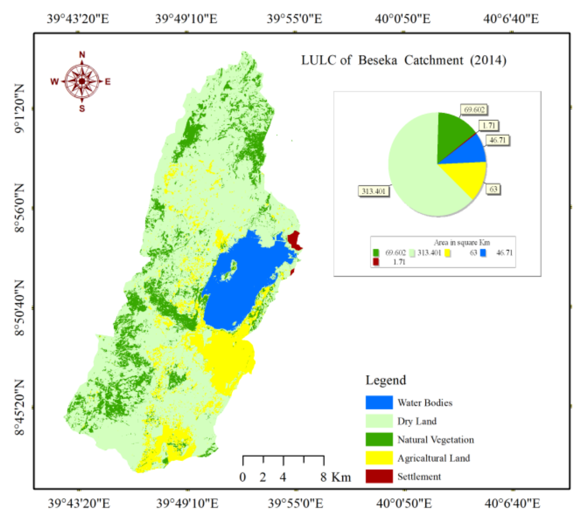
a)


LULC of Beseka Catchment (1994)
39°43'20"E
39°49'10"E
39°55'0"E
40°0'50"E
40°6'40"E
9°1'20"N
8°56'0"N
8°50'40"N
8°45'20"N
N
S
W
E
Legend
Water Bodies
Dry Land
Natural Vegetation
Agricaltural Land
Settlement
0 2 4 8 Km

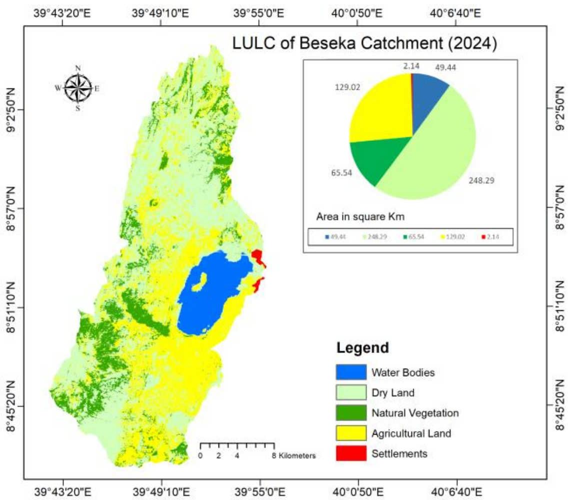
b)


LULC of Beseka Catchment (2004)
39°43'20"E
39°49'10"E
39°55'0"E
40°0'50"E
40°6'40"E
9°1'20"N
8°56'0"N
8°50'40"N
8°45'20"N
N
S
W
E
Legend
Water Bodies
Dry Land
Natural Vegetation
Agricaltural Land
Settlement
0 2 4 8 Km

c)


LULC of Beseka Catchment (2014)
39°43'20"E
39°49'10"E
39°55'0"E
40°0'50"E
40°6'40"E
9°1'20"N
8°56'0"N
8°50'40"N
8°45'20"N
N
S
W
E
Legend
Water Bodies
Dry Land
Natural Vegetation
Agricaltural Land
Settlement
0 2 4 8 Km

d)



e)

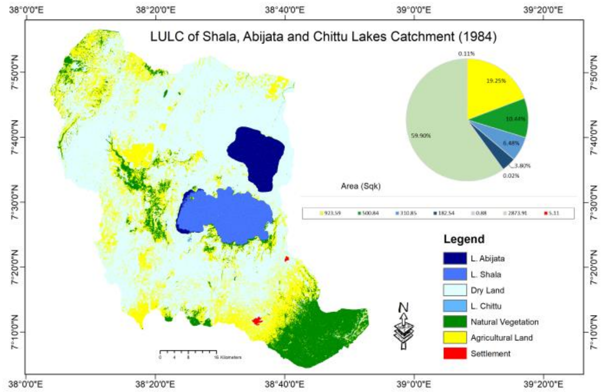
Figure 5. 2. Land-Use Land-Cover Classification Map of Lake Beseka (a-e)

5.3.3. Land use/land Cover Changes of Lakes Abijata, Chittu and Shala ((1984 −2024)

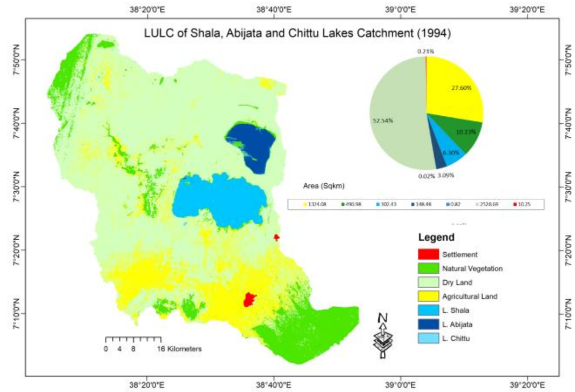
The LULC map for Lake Abijata, Chittu, and Shala catchment areas from 1984 to 2024 has been presented in Table 5.5 and Fig. 5.3. There has been rising trend in the area of agricultural land from 19.25% of the total catchment area (4797.73 km^2) in 1984 to 40.5% in 2024, while settlement areas have also shown a rise from 0.11% in 1984 to 2.37% in 2024. On the other hand, dry land has decreased from 59.9% in 1984 to 34.62% in 2024. The sizes of lakes Chittu and Shala have remained relatively stable with minor changes. Lake Abijata, however, experienced a significant decrease from 3.08% in 1984 to 2.3% in 2004, followed by a slight increase from 2.76% in 2014 to 3.25% in 2024.

Table 5. 5. Area (Km^2) and percentage of change in different land use/land cover categories in the catchment area of lakes Abijata, Chittu and Shala 1984-2024

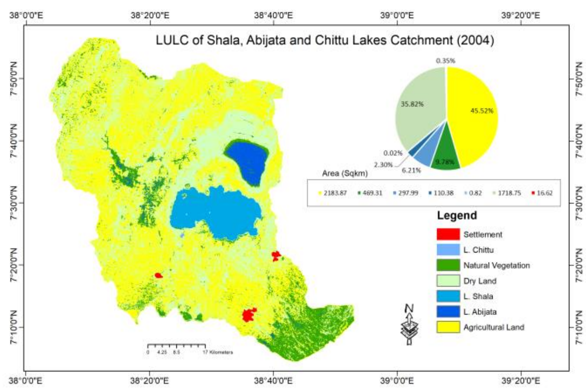
LULC classes	**Years (Area Km^2) %)**									
	1984	**%**	**1994**	**%**	**2004**	**%**	**2014**	**%**	**2024**	**%**
Agricultural Land	923.59	19.25	1324.1	27.6	2183.9	45.52	2429.7	50.6	1944.1	40.5
Natural Vegetation	500.84	10.44	490.98	10.2	469.31	9.782	156.15	3.25	621.82	12.9
L. Shala	310.85	6.48	302.43	6.30	297.99	6.211	303.42	6.32	300.62	6.27
L. Abijata	182.54	3.80	148.48	3.09	110.38	2.301	132.54	2.76	156.01	3.25
L. Chittu	0.88	0.02	0.82	0.02	0.82	0.017	0.69	0.01	0.65	0.01
Dry Land	2873.9	59.90	2521	52.54	1718.7	35.82	1689.75	35.22	1660.89	34.62
Settlement	5.11	0.11	10.25	0.21	16.62	0.346	85.43	1.78	113.68	2.37



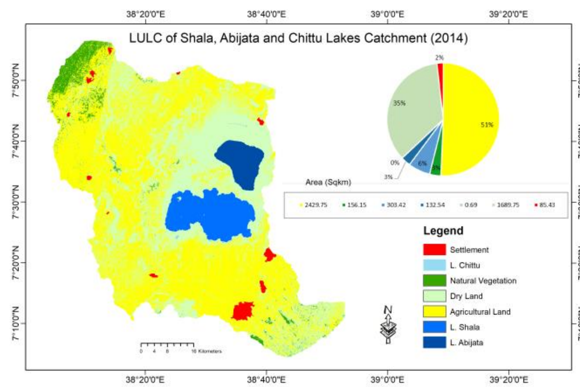
f)



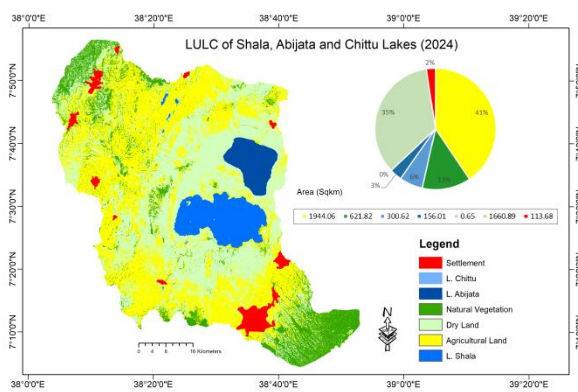
g)



h)



i)



j)

Figure 5. 3. Land-Use Land-Cover Classification Map for lakes Abijata, Chittu and Shala (f-j)

5.4. Discussion

The LULC change detection around the catchment of Lake Beseka revealed a discernible increase in agricultural land, settlements, and water bodies, while there has been a decrease in dry land between 1984 and 2024. This may be attributed to population growth, which leads to various anthropogenic activities like large-scale irrigation development and rising demand for food and housing by the local population. The decline in dry land categories surrounding the lake's catchment area could potentially be attributed to the increasing demand for agricultural land to accommodate the expanding population, resulting in the transformation of dry land areas into farmland and residential areas. Furthermore, the implementation of water-efficient irrigation technologies and the introduction of salt-tolerant crops as part of alternative solutions to address water governance challenges have likely contributed to changes in land use. The results of this research are in line with the studies conducted by Megersa Olumana and Klik (2019) and Tewabe Melkamu *et al.* (2022).

The expansion of Lake Beseka has been significant since the 1960s. This expansion can be attributed to various factors such as groundwater discharge, inflow from hot springs, discharge of hot springs due to tectonic movements, and excess irrigation water entering the lake through subsurface flows. Currently, measures are being taken to manage the rising lake level by discharging water into the Awash River through two canals at the bottom outlet of the lake (Dawit Mekonnen *et al.*, 2022). However, despite these efforts, the lake continues to expand. According to a study by Martínek *et al.* (2021)), the expansion of the lake is directly influenced by the activity of the rift system, which includes the formation of new fractures and faults. These geological features play a crucial role in directing groundwater towards the lake, thereby impacting its size and the local hydrology. Furthermore, recent observations in the Ethiopian Rift have documented basalt eruptions and active crevice formation, providing valuable insights into the processes that could potentially lead to the formation of new ocean basins (Biggs *et al.*, 2021). This expansion has resulted in the submergence of large land areas, consequently affecting land use patterns.

The study's findings around the catchment of lakes Abijata, Chittu and Shala highlights shift in land use patterns, with agricultural land and settlements expanding at the expense of dry land. The presence of a large human population and extensive cattle grazing in the Abijata Shala

National Park can have a significant impact on catchment land use patterns. This can result in the conversion of natural vegetation areas and dry land into agricultural lands, settlements, and grazing land. This result is in agreement with the report by Wondwossen Girmay *et al.* (2017) and Denbel Bedo *et al.* (2022).

The surface area of lakes Chittu and Shala remained relatively stable with slight fluctuations. The enduring stability of these systems is attributed to their unique geological and hydrological features, which efficiently uphold a harmonious balance between water inflows and outflows. The consistent size of lakes Shala could potentially be attributed to the lake's profound volcanic setting, which restricts water loss through seepage. (Tenalem Ayenew, 2001). Additionally, the existence of hot springs and groundwater flux further contribute to this phenomenon, despite the ever-changing climate patterns in the Ethiopian Rift Valley (Tenalem Ayenew and Becht, 2008). Moreover, the water from lakes Chittu and Shala is not utilized for irrigation due to its highly saline nature. On the other hand, Lake Abijata has experienced a significant decrease in size over the past three decades (1984-2004). This might be due to anthropogenic activities such as water abstraction soda ash extraction and feeding rivers and lakes diversion for irrigation purposes. Additionally, natural factors like climate variability also play a significant role. This result is consistent with report by Tenalem Ayenew (2004), Hamere Yohannes *et al.* (2017), Binyam Tesfaw and Shimelis Girma (2019), Ayenew Ayalew *et al.* (2022). Nevertheless, the water level has remained constant between 2014 and 2024, with a slight increase compared to the preceding decades. This could be attributed to natural seasonal variations (water from the rainy season) and groundwater flux to the lake. Though, the findings of Ayenew Ayalew *et al.* (2024) are in contrast to this report.

CHAPTER SIX: GENERAL CONCLUSIONS AND RECOMMENDATIONS

This study assessed the physicochemical properties, plankton, and changes in land use/land cover of soda Lakes Abijata, Arenguade, Beseka Chittu, and Shala. Additionally, it included a discussion on the limnological conditions and conducted a comparison with previous research to provide a thorough analysis. The results have significantly contributed to our understanding of the lakes' limnology. This chapter presents a concise overview of the main findings and proposes recommendations for future research endeavors.

6.1. Conclusions

- ❖ The physico-chemical parameters investigated in the current study showed variability depending on location, season and trends across years. All physicochemical variables showed significant differences between the sampling seasons ($p < 0.05$), except salinity in Lake Shala. The concentrations of physico-chemical parameters were, generally, high during the dry seasons in the studied lakes due to the low incidence of rainfall caused by climate change, resulting in higher evapotranspiration rates as they are characterized by a long dry season. Lakes Arenguade and Beseka showed a considerable decrease in conductivity, alkalinity and salinity compared to data from the 1960s and 1990s but are now showed slightly increasing trend in Lake Arenguade which might be due to high evaporation rate. Long term physico-chemical trend in Lakes Chittu and Shala showed very small rise in physico-chemical parameters which could be a result of higher evaporative concentrations due to climate change and catchment activities.
- ❖ Taxonomic composition, biomass and abundances of phytoplankton groups vary greatly between lakes. A significant seasonal change has been observed in the biomass of phytoplankton on all lakes where concentrations were high during the dry season. Compared to other study lakes, lakes Shala and Beseka had the most diverse phytoplankton taxonomic representation as a result of less extreme environmental conditions and a dilution impact, generated by expansion of Lake Beseka. The LR model showed the relationships between physico-chemical variables and phytoplankton biomass and showed that environmental factors have an influence on Chl-a concentration. The abundance of phytoplankton in lakes Beseka and Shala were dominated by Bacillariophytes (diatoms), whereas Cyanoprokaryotes dominated the abundance of lakes

Arenguade and Chittu. Bacillariophytes formed dominant groups during the pre-rainy season whereas Cyanoprokaryotes and Chlorophytes are dominant during the rainy season. The RDA results show that environmental variables have driven phytoplankton abundance dynamics. Water temperature, Secchi depth, turbidity, electrical conductivity, soluble reactive phosphorus, nitrate, and silica significantly influenced the phytoplankton community structure. Changes in the composition and structure of the phytoplankton community have been observed in the long term analysis of biomass and species composition.

- ❖ Rotifers dominated the zooplankton community of all four lakes in terms of species richness which is a common pattern in tropical water bodies. Cladocerans, on the other hand, had the lowest species richness with only two species. In July, the wet season, Lake Arenguade and Chittu had high zooplankton abundance; in November, the post-rainy season, and January, the dry season, Lakes Beseka and Shala had high zooplankton abundance. Two species of Rotifera, *B. dimidiatus* and *B. plicatilis*, have been found in zooplankton in all sorts of lakes because of their cosmopolitan nature, halobiont tendencies, and preferences for alkaline soda lakes. The RDA results showed that environmental variables explained variations in the abundances of the zooplankton community.
- ❖ The land cover has been significantly modified and transformed into a variety of land use systems to meet human demands. The basin's pattern of land use has undergone significant change as a result of the expansion of agriculture and the construction of more settlements. This has had a severe negative impact on the ecosystem and has wide-ranging ecological degradation of the basins.

6.2. Recommendations

The following recommendations are given considering the findings from the study period.

- ❖ Comprehensive research that considers long-term trends and integrates multiple ecological and environmental factors, which include the study of benthic communities, macrophytes, fish, water birds, crocodiles, and other aquatic organisms, is imperative.
- ❖ A socio-economic study for Land Use/Land Cover (LULC) change of lakes in order to assess the impact of land use changes on the ecological health of the lakes and the

economic implications to establish sustainable land management practices and policies is important.

- ❖ Climatological and hydrological studies using variety of methods, including satellite data analysis, hydrologic modeling, and machine learning techniques should be done to assess how anthropogenic activities and climate variability alter the ecological balance and water chemistry of these unique ecosystems.
- ❖ Ongoing research and satellite observations are crucial for monitoring these ecosystems and guiding conservation strategies.
- ❖ Conservation efforts for these lakes must consider the unique characteristics of each lake, addressing industrial impacts, promoting sustainable land use, and protecting the rich biodiversity that these lakes support.

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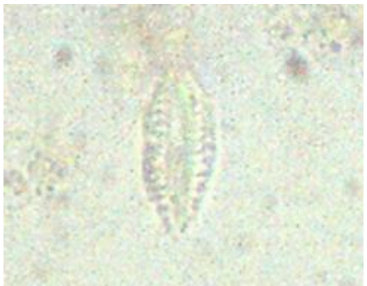
APPENDICES

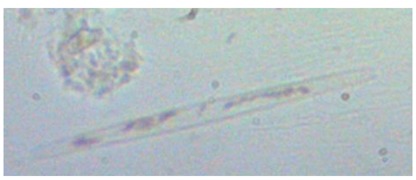
Appendix 1. Some phytoplankton species identified from the study lakes.



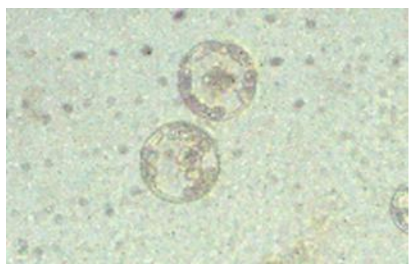
Achnanthidium minutissimum

Aulacosera granulata

Cosmarium sp.

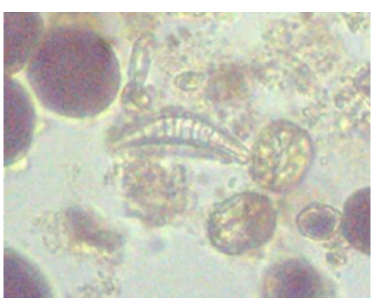


Closterium sp.



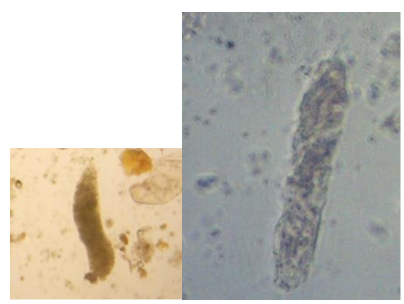
Cyclotella sp.

Epithemia frickei

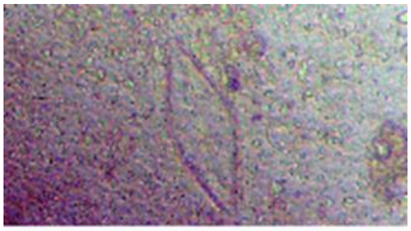


Epithemia gibba

Epithemia turgida



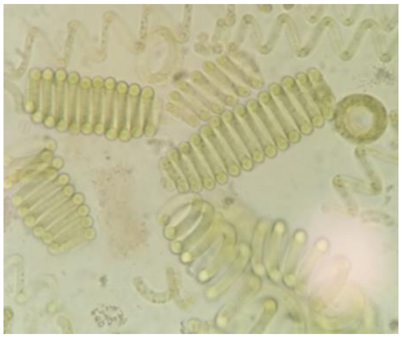
Euglena sp.



Frustula rhomboids

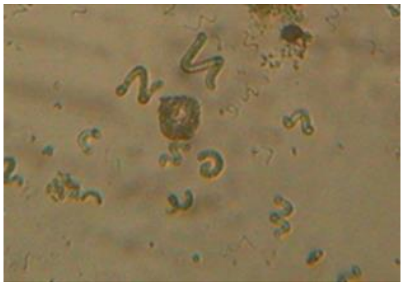
Gomphonema affine

Gomphonema sp.



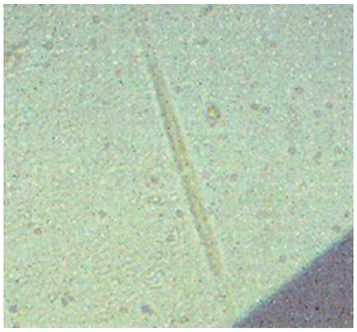
Limnospira fusiformis

Navicula sp.



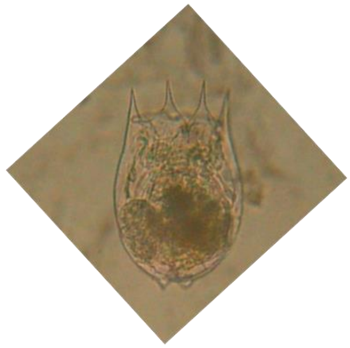
Phacus sp.

Nitzchia sp.



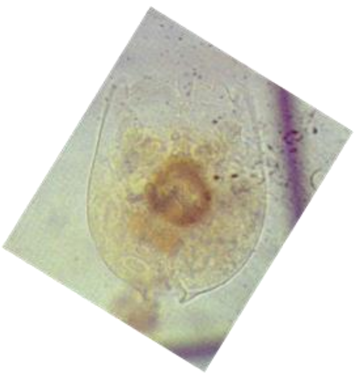
Appendix 2. Some zooplankton species identified from the study lakes.

Brachionus angularis

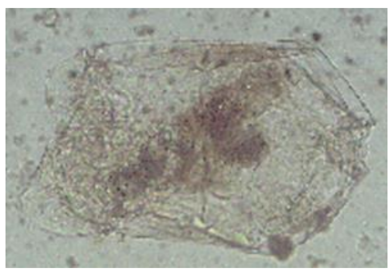


Brachionus calyciflorus

Branchionus dimidiatus



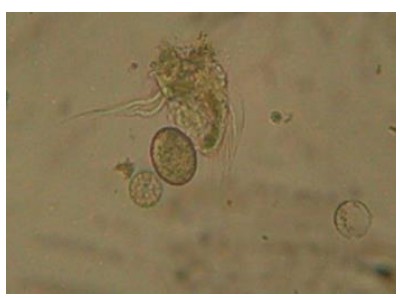
Brachionus plicatilis



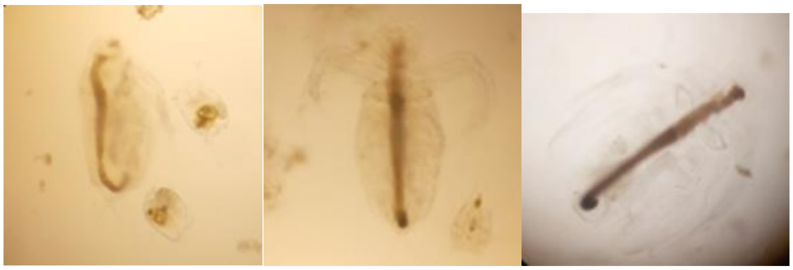
Branchionus rubens

Branchionus plicatilis

Filinia sp.

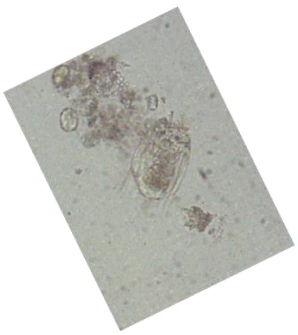


Hexarthra jenkinae

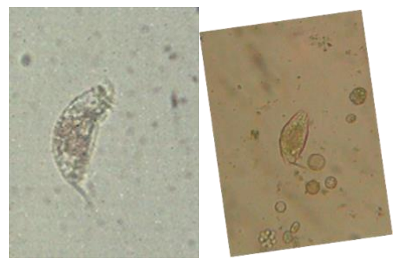


Moina micrura

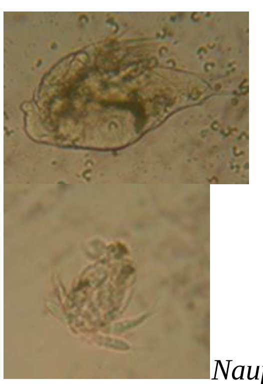
Nitocra lacustris



Polyarthra vulgaris



Trichocerca pusilla



Nauplii

Thermocyclops ethiopiensis

Appendix 3. Supplementary material for chapter three

Table S1. Seasonal variation of environmental characteristics of the four Ethiopian soda lakes (mean ± sd) during the present study period.

A) Lake Arenguade

Season	**Parameters**				
	Temp (°C)	PH	EC (mS/cm)	DO (mg l^{-1})	Sal (g l^{-1})
Dry	21.6 ±0.12	9.64±0.61	5.65±1.09	3.12±0.8	3.24±0.58
Pre-rain	22.0 ±0.1	10.3±0.64	5.30±0.25	3.66±0.13	3.08±0.09
Rain	23.0 ±0.08	9.8±0.72	5.25±0.32	3.43±0.47	2.10±0.21
Post-rain	22.2 ±0.58	10.4±0.08	5.50±0.55	3.12±0.1	3.23±0.5
	NO_3–N (μg l^{-1})	NH_4^+-N (μg l^{-1})	SiO_2 (mg l^{-1})	SRP (mg l^{-1})	TP(mg l^{-1})
Dry	9.61±0.83	224.0±0.83	45.0±0.31	1.01±0.02	2.78±0.03
Pre-rain	52.5±0.83	83.5±0.82	20.0±0.47	0.75±0.01	1.82±0.02
Rain	73.9±21.8	137.8±2.82	48.5±1.77	1.46±0.6	2.22±0.02
Post-rain	26.3±1.43	202.5±4.6	44.1±0.21	0.94±0.06	1.48±0.02

B) Lake Beseka

Season	**Parameters**				
	Temp (°C)	PH	EC (mS/cm)	DO (mg l^{-1})	Sal (g l^{-1})
Dry	25.9 ±0.58	9.28±0.44	2.78±0.12	6.01±0.43	2.38±0.7
Pre-rain	25.8 ±0.12	9.15±0.56	2.79±0. 54	7.21±0.13	1.42±0.72
Rain	24.8 ±0.1	7.87±0.48	2.8±0.44	7.20±0.33	1.43±0.53
Post-rain	27.2 ±0.3	7.88±0.16	2.52±0.37	6.03±0.58	2.31±0.35
	NO_3–N (μg l^{-1})	NH_4^+-N (μg l^{-1})	SiO_2 (mg l^{-1})	SRP (mg l^{-1})	TP(mg l^{-1})
Dry	30.1±2.85	47.2±2.18	22.95±0.08	0.66±0.05	1.49±0.24
Pre-rain	120.6±0.82	46.8±1.65	22.95±0.08	0.47±0.35	1.43±0.55
Rain	164.4±0.00	51.1±8.71	95.8±0.07	0.26±0.01	0.77±0.04
Post-rain	78.2±1.65	80.4±2.87	92.1±0.07	0.36±0.03	0.92±0.08

C) Lake Chittu

Season	Parameters				
	Temp (^oC)	PH	EC (mS/cm)	DO ($mg\ l^{-1}$)	Sal ($g\ l^{-1}$)
Dry	22.2 ±0.6	10.2±0.83	70.24±1.0	5.49±0.52	45.6±0.17
Pre-rain	22.3 ±0.58	10.5±0.21	63.6 ±0.1	5.14±0.98	29.7±0.77
Rain	23.1 ±0.06	10.6±0.58	63.5±0.03	5.81±0.23	45.6±0.77
Post-rain	23.5 ±0.1	10.5±0.1	70.1±0.82	5.33±0.81	32.8±0.41
	NO_3–N ($\mu g\ l^{-1}$)	NH_4^+-N ($\mu g\ l^{-1}$)	SiO_2 ($mg\ l^{-1}$)	SRP ($mg\ l^{-1}$)	TP($mg\ l^{-1}$)
Dry	83.0±3.23	134±2.18	4.00±0.38	2.28±0.08	3.15±0.05
Pre-rain	103.4±7.56	61.1±4.59	2.64±0.0	1.74±0.72	2.53±0.06
Rain	26.8±2.18	56.8±2.18	2.38±0.33	1.40±0.03	1.82±0.03
Post-rain	64.9±3.78	200±1.43	1.34±2.72	1.60±0.83	2.13±0.07

D) Lake Shala

Season	Parameters				
	Temp (^oC)	PH	EC (mS/cm)	DO ($mg\ l^{-1}$)	Sal ($g\ l^{-1}$)
Dry	23.4 ±0.2	10.09±0.3	26.4±0.21	8.47±0.12	16.7±0.23
Pre-rain	23.0 ±0.09	9.8±0.1	23.0±0.8	6.97±0.68	14.4±1.02
Rain	21.9 ±0.013	9.9±0.8	25.9±0.0	7.35±0.16	16.5±0.02
Post-rain	23.2 ±0.12	10.7±0.2	30.9±0.35	6.63±0.72	19.5±0.82
	NO_3–N ($\mu g\ l^{-1}$)	NH_4^+-N ($\mu g\ l^{-1}$)	SiO_2 ($mg\ l^{-1}$)	SRP ($mg\ l^{-1}$)	TP($mg\ l^{-1}$)
Dry	24.4±2.18	54.0±2.98	2.23±0.14	1.87±0.03	2.30±0.00
Pre-rain	39.1±1.43	124.9±21.8	2.58±0.13	0.92±0.02	1.72±0.04
Rain	23.0±2.98	126.3±1.25	2.46±0.4	0.65±0.7	1.09±0.42
Post-rain	22.0±0.00	51.6±1.43	2.23±0.14	0.77±0.02	1.27±0.17

Table S1. List of phytoplankton species with their taxonomic groups identified from four Ethiopian soda lakes (Arenguade Beseka, Chittu & Shala) during the study period.

Bacillariophyceae	**Chlorophyceae**
Achnanthidium minutissimum (Kützing) Czarnecki	*Coelastrum astroideum* De Notaris
Aulacoseira distans (Ehrenberg) Simonsen	*Cosmarium* sp.
Aulacoseira granulata (Ehrenberg) Simonsen	*Monoraphidium minutum* (Nägeli) Kom-Leg
Cymbella affinis Kützing	*Closterium acutum* Brébisson
Rhopalodia gracilis O.Müller	*Desmodesmus communis* (E.Hegewald)
Surirella engleri O.Müller	*Oosystis* sp.
Amphora sp.	*Pediastrum duplex* Meyen
Cyclotella sp.	*Scenedesmus bicaudatus* var. alternans Christjuk
Navicula sp.	*Scenedesmus ellipticus* Corda
Nitzschia sp.	*Cosmarium depressum* var. planctonicum Reverdin
Pinnularia sp.	*Monoraphidium minutum* (Nägeli) Kom-Legnerová
Amphora aequalis Krammer	*Chlorella* sp.
Amphora pediculus (Kützing) Grunow	*Scenedesmus* sp.
Cyclotella meneghiniana Kützing	**Cyanoprokaryota**
Diatoma sp.	*Chroococcus minutus* (Kützing) Nägeli
Fragilaria sp.	*Limnospira fusiformis* (Voronichin) Now-Kraw
Rhopalodia gibberula (Ehrenberg) O.Müller	*Raphidiopsis africana* (Kom & H.Kling) Aguilera
Epithemia gibba (Ehrenberg) Kützing	*Dolichospermum flos-aquae* (Bornet & Flahault)
Amphora veneta Kützing	*Anabaenopsis abijatae* Kebede & Willén
Ceratoneis arcus (Ehrenberg) Kützing	*Spirulina major* Kützing ex Gomont
Epithemia frickei Krammer	*Anabaena* sp.
*Epithemia turgida var.turgida (*Ehrenberg) Kützing	*Microcystis aeruginosa* (Kützing) Kützing
Frustulia rhomboides (Ehrenberg) De Toni	**Dinophyceae**
Gomphonema affine Kützing	*Glenodinium* sp.
Gomphonema minutum (C.Agardh) C.Agardh	*Peridinium* sp.
Gyrosigma obtusatum (Sullivant & Wormley)	*Peridinium cinctum* (O.F.Müller) Ehrenberg
Nitzschia dissipata (Kützing) Rabenhorst	**Cryptophyceae**
Stephanodiscus sp.	*Cryptomonas marssonii* Skuja
Gomphonema sp.	**Euglenophyceae**
	Euglena sp.
	Phacus sp.

Table S2. Results of principal component analysis with eight environmental variables (factor loadings >0.750 are **bold**). Regressions of chl-a on the principal components contain only the significant ($P < 0.05$) coefficient

L.Arenguade	PC1 (41.6 %)	PC2 (31.0 %)	PC3 (25.5%)	Multiple regression analysis Chla= ─ 0.14*PC1 ─ 0.49*PC2 + 0.21
Temp	-0.142	**0.939**	0.301	N=12 R^2=0.95, p≤ 0.018
EC	0.700	**-0.712**	0.21	
Turb	0.100	**0.992**	0.179	
SD	**-0.973**	0.226	0.10	
Ammonia	**0.935**	-0.316	0.152	
nitrate	-0.578	0.711	0.211	
silica	**0.788**	0.283	0.542	
srp	0.201	0.589	**0.778**	
L. Beseka	PC1 (39.2%)	PC2 (32.1%)	PC3 (27.7%)	Chla= ─0.11*PC1 + 0.33*PC2 + 0.04
Temp	**0.874**	-0.311	-0.333	N=12 R^2=0.98, p≤ 0.001
EC	**-0.996**	0.024	0.011	
Turb	-0.145	0.457	**0.984**	
SD	-0.129	0.361	**0.927**	
Ammonia	**0.972**	0.187	0.144	
nitrate	-0.336	**0.940**	0.184	
silica	0.501	0.712	0.491	
srp	-0.208	**-0.950**	-0.162	
L. Chittu	PC1 (46.4%)	PC2 (33.3%)	PC3 (19.5%)	Chla= ─0.31*PC1 + 0.32*PC2 + 0.64 N=12 R^2=0.99, p≤ 0.000
Temp	0.217	**-0.865**	-0.446	
EC	**0.993**	0.105	0.211	
Turb	**-0.976**	-0.200	0.14	
SD	-0.744	0.147	0.658	
Ammonia	**0.949**	-0.305	0.102	
nitrate	0.152	0.344	**0.923**	
silica	-0.12	**0.987**	0.132	
srp	0.502	**0.819**	0.266	
L. Shala	PC1 (41.3%)	PC2 (36.4%)	PC3 (12.5%)	Chla= ─0.33*PC1 -0.26*PC2 + 0.76*PC3+0.12 N=12 R^2=0.98, p≤ 0.001
Temp	0.312	**0.984**	0.170	
EC	**-0.887**	0.293	-0.361	
Turb	-0.113	**-0.959**	-0.254	
SD	**0.973**	0.249	0.152	
Ammonia	0.646	-0.698	-0.150	
nitrate	**0.939**	0.170	0.241	
silica	0.501	-0.311	-0.110	
srp	0.261	0.514	**0.855**	

Table S3. Seasonal variations in mean phytoplankton abundance (Cells/ml) in the studied lakes during the current sampling period

Sites	**Classes**	**Dry**	**Pre-rain**	**Rain**	**Post-rain**
L. Arenguade	Cyanoprokaryota	69000	30466	47600	68000
L. Arenguade	Chlorophyceae	5417	3666.7	4200	8416.7
L. Arenguade	Bacillariophyceae	5455	2288.9	2489	6636.4
L. Arenguade	Euglenophyceae	8833	2083.3	5778	4333.3
L. Beseka	Cyanoprokaryota	583.3	666.7	1000	0
L. Beseka	Chlorophyceae	3476	1333.3	4267	11111
L. Beseka	Bacillariophyceae	9377	7782.6	6159	47747
L. Beseka	Dinophyceae	0	2333.3	1167	0
L. Beseka	Euglenophyceae	0	333.3	0	0
L. Chittu	Cyanoprokaryota	76167	33250	44722	85250
L. Chittu	Chlorophyceae	5833	4333.3	2778	6333.3
L. Chittu	Cryptophyceae	2167	1666.7	1000	2000
L. Chittu	Bacillariophyceae	4524	2976.2	3044	3928.6
L. Shala	Cyanoprokaryota	1222	333.3	1238	1166.7
L. Shala	Chlorophyceae	1222	1333.3	1250	1200
L. Shala	Bacillariophyceae	6611	3849.5	3259	9469.7
L. Shala	Dinophyceae	1167	1500	0	0
L. Shala	Euglenophyceae	0	1666.7	1250	0