STUDIES ON THE LIMNOLOGY, AND BIOLOGY OF NILE TILAPIA, *OREOCHROMIS NILOTICUS* L., IN A TROPICAL SODA LAKE, LAKE SHALA, ETHIOPIA

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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Studies on the Limnology, and Biology of Nile tilapia, *Oreochromis niloticus* L., in a Tropical Soda Lake, Lake Shala, Ethiopia

By: Solomon Wagaw

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: *Studies on the Limnology, and Biology of Nile tilapia, Oreochromis niloticus L., in a Tropical Soda Lake, Lake Shala, Ethiopia* 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.

Solomon Wagaw: Signature ___________________ Date_________________

ABSTRACT

Lake Shala is the deepest, alkaline lake in Ethiopia and is a vital resource having considerable esthetic, economic, scientific and ecological values. However, the lake is under pressure from various anthropogenic activities and climatic change. There is also a plan to expand the Abijata Soda Ash plant to Lake Shala. The purpose of this study was to assess the spatial and seasonal dynamics, and long-term trend of abiotic factors and biological communities in the lake. Physicochemical and biological data were collected from four sites every month from January to December 2018. All physicochemical factors exhibited significant variation among sites and between seasons (ANOVA, $P < 0.05$), except DO, which showed only seasonal variation. Compared with previous studies, long-term increasing trend in pH, alkalinity, salinity, electrical conductivity, NO_3-N, NH_3-N, SRP and TP, and decreasing trend in SiO_2 were observed. These changes might be due to the high evaporation rate in the region, precipitation, accumulation of solutes and saline surface runoff from its degraded catchments.

The phytoplankton community in Lake Shala showed changes with time. During this study, 72 phytoplankton species belonging to Bacillariophyta (55 taxa), Chlorophyta (7 taxa), Cyanophyta (6 taxa), Euglenophyta (2 taxa), Charophyta (1 taxon) and Dinophyta (1 taxon) were recorded. The previous dominance of Cryptophytes in the lake has been replaced by diatoms. The lake also lacked *Arthrospira fusiformis*, but now a few specimens were recorded many times. Zooplankton community structure of Lake Shala (32 species, belonging to rotifers, copepods and cladocerans) has also changed over time, benthic harpacticoids (*Nitocra lacustris*) were replaced by small-bodied and generalist-

feeders rotifers (genus *Brachionus*). Such ecological shifts in phytoplankton and zooplankton communities may be associated with physicochemical changes and ‘atelomixis’ brought about by unusual mixing behavior in deep, tropical lakes. Based on RDA analysis, most phytoplankton and zooplankton species were strongly influenced by nutrients, salinity and electrical conductivity.

The macro-invertebrate community of Lake Shala, was constituted by a few (21) taxa belonging to the Diptera (7), Gastropoda (4), Hemiptera (3), Coleoptera (2), Oligochaeta (2), Argulidae, Arachnida and Corydalidae. Compared with previous data, shifts in macro-invertebrate community structure were observed over the years. The shift might be due to the changes in the water chemistry and recession of the lake littoral zone. The macro-invertebrate taxa richness and abundance were significantly affected by locality ($P < 0.05$), the two shore sites having significantly higher taxa richness and the opposite was true for abundance. Most families were absent from the open water stations and when present, represented by Diptera (Ceratopogonidae and Chironomidae) and Oligochaeta (Tubificidae and Naididae), which were correlated strongly with depth, DO, EC and alkaline-salinity of the lake. These abiotic factors have presumably become altered in the lake due to undetermined stressors.

Previous studies did not report the ecology and biology of fish from Lake Shala and this study is the first to document the biology of tilapia from this lake. *Oreochromis niloticus* had a curvilinear growth pattern ($TW = 0.0104TL^{3.19}$, $R^2 = 0.98$, $n = 343$). The condition factor between sex categories (ANOVA, $P > 0.05$) and sex ratio from the hypothetical distribution of 1:1 ($\chi 2 = 0.47$, $P > 0.05$) were not significant. The breeding seasons, rainy (July) and dry (February) coincided with the increase in phytoplankton abundance and

biomass (*Chl a*). The fecundity ranged between 240 and 1,642 eggs per fish, with a mean fecundity of 806 eggs and correlated with the length and weight of the fish. Analysis of the stomach revealed that 226 (65.9%) fish contained different food items, while 117 (34.1%) had empty stomachs. *O. niloticus* mainly fed on phytoplankton and had phytoplanktivorous feeding habits. Bacillariophyta was identified as the most desired phytoplankton item. The prey items and food habits of *O. niloticus* varied significantly among size classes (ANOVA, $P < 0.05$) and seasons (t-test, $P < 0.05$). Such variations might be associated with seasonal availability of natural food, habitat, and morphological and physiological changes such as increase in the length of the gut and acidity as the fish grow.

This study is the first comprehensive study on the limnology, and biology of *O. niloticus* in Lake Shala. Lake Shala is located in the center of economic development pressure and the physical environment and the biota of the lake are continually changing. Such ecological changes in this deep lake might be due to anthropogenic activities around the lake catchments and internal limnological dynamics (atelomixis). However, continuous investigation on physical environment and biodiversity assessment in Lake Shala is necessary to evaluate the ecological impacts of the upcoming soda ash factory and other external impacts on the limnology of the lake ecosystems.

Keywords/phrases: Atelomixis, Chironomidae, Diatom, Ecological Shift, Lake Shala, Phytoplanktivorus, Rotifers

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LIST OF ABBREVIATIONS

ANOVA	Analysis of Variance
APHA	American Public Health Association
ASLNP	Abijata-Shala Lakes National Park
CANOCO	Canonical community ordination
CF	Condition Factor
Chl a -	Chlorophyll a
DCA	Detrended Correspondence Analysis
DO	Dissolved Oxygen
DW	Dry Weight
EARV	East Africa Rift Valley
EC	Electrical Conductivity
ENMA	Ethiopian National Meteorological Agency
FCF	Fulton Condition Factor
GIIi	Geometric Importance of index
GSI	Gonado-Somatic Indexes
IOPa	Index of Preponderance
m.a.s.l	Meter above sea level
Mm^3	Million metric cube
PPI	Phytoplankton preference index
RDA	Redundant Analysis
SD	Standard Deviation
SRP	Soluble Reactive Phosphorus
TL	Total Length
TP	Total Phosphorus
TW	Total Weight

Chapter One: General Introduction

1.1. Background

Inland saline lakes are found worldwide (Schagerl and Renaut, 2016), but are especially common in regions with volcanic bedrock, including the eastern division of the East African Rift and the western interior of North America (Grant, 2004; Pecoraino *et al.*, 2015). Their development is favored by closed drainage (endorheic) conditions and they are common in the arid (25 to 200 mm annual rainfall) and semi-arid (200 to 500 mm annual rainfall) basins of the world (Hammer, 1986). The global estimated total volume of saline lakes ($104 \text{ X } 10^3 \text{ km}^3$) is comparable to that of freshwaters ($124 \text{ X } 10^3 \text{ km}^3$) (Dodds and Whiles, 2010). Williams (2002) describes these lakes as very significant natural resources with considerable aesthetic, cultural, economic, recreational, scientific, conservation, and ecological values for mankind.

Soda lakes are known for their extreme environmental conditions associated with high pH, carbonate-bicarbonate, alkalinity, and salinity (Deocampo and Renaut, 2016). Also, soda lakes are among the most productive water bodies in the world and are typically earmarked by low biodiversity but high abundance and biomass of both, primary producers and consumers (Oduor and Schagerl, 2007a; Bernard *et al.*, 2019). Some of the East African Rift Valley (EARV) soda lakes are known as ‘flamingo lakes’ by supporting large flocks of lesser flamingos (*Phoeniconaias minor* Geoffroy Saint-Hilaire, 1798) (Krienitz and Kotut, 2010; Kaggwa *et al.*, 2013), and of great economic importance as they attract tourists (Krienitz *et al.*, 2016). Although soda lakes are in an area undergoing significant environmental change resulting from human-induced disturbances and climatic conditions (Tenalem Ayenew and Dagnachew Legesse, 2007; Oduor and Kotut, 2016), there have been limited scientific studies on how biological communities interact with each other and environmental change (physicochemical) in deep inland soda lakes.

The chemical dynamics and composition of the water column of soda lakes are controlled by hydrologic cycles, geochemical and biogeochemical processes (Deocampo and Renaut, 2016; Melack and MacIntyre, 2016). Studies on some EARV soda lakes have shown fluctuations in water chemistry with consequent changes in biological community structure (Oduor and Schagerl, 2007b; Krienitz and Kotut, 2010; Tadesse Ogato and Demeke Kifle, 2017). Fluctuations and shifts in the phytoplankton community composition in the soda lakes of the EARV have been reported by various authors (Oduor and Schagerl, 2007b; Krienitz and Kotut, 2010; Tewodros Kumssa and Afework Bekele, 2014c), affecting higher trophic levels such as zooplankton, benthos vertebrate, population of lesser flamingos (*Phoenicanaias minor*) and potentially also nutrient and energy flows (Burian, 2010; Krienitz and Kotut, 2010; Burian *et al.*, 2014).

Despite the growing interest in soda lakes during the past decades, there have been few attempts studying the dynamics of a biological community, and processes driving community alternations are not yet well understood (Williams, 2002; Oduor and Schagerl, 2007a; Burian, 2010). The difficulties of accessibility and a general lack of familiarity with soda lakes are the probable causes of little exploration by limnological and hydro-biological researchers (Burian, 2010; Tadesse Ogato, 2015; Tenalem Ayenew and GebreEgziabher Merhawi, 2015). Many of the EARV soda lakes are now readily accessible and limnological research has been conducted in the Kenyan lakes Bogoria, Elmentaita, Nakuru and Sonachi. However, Ethiopian saline-alkaline lakes had not received adequate attention from the limnological community (Wood and Talling, 1988; Elizabeth Kebede and Willén, 1996; Tadesse Ogato, 2015).

The major Ethiopian inland soda lakes include Lake Arenguade, Lake Shala, Lake Abijata, Lake Chitu, Lake Beseka, Lake Tillo and Lake Afdera (Matagi, 2004; Schagerl and Renaut, 2016). However, the majority are confined to the central Rift Valley and support economic activity through tourism and soda ash production (Tenalem Ayenew and Dagnachew Legesse, 2007; Tewodros Kumssa and Afework Bekele, 2014a). Particularly, the neighboring Lake Abijata, Shala, and Chitu are unique ecosystems that are important resources for wildlife in providing feeding and breeding grounds for a rich bird fauna of over 453 species of resident and migratory birds with global, regional, national and local importance (Rezenom Almaw, 2012). These lakes are known for supporting a large population of Lesser Flamingo (*Phoeniconaias minor*) (Tewodros Kumssa and Afework Bekele, 2014a). The extraordinary spectacle of ten thousand flocks of this bird on the soda lakes of Abijata-Shala Lakes National Park (ASLNP) has attracted many tourists to Ethiopia.

Even though ASLNP was demarcated as a national park in 1970, the park is increasingly exploited for development activities such as agricultural irrigation and soda ash ($NaCO_3$) extraction. The terminal soda lake, Lake Abijata has undergone significant environmental degradation (Tamiru Alemayehu *et al.*, 2006; Solomon Wagaw *et al.*, 2019). The neighboring Lake Shala is also among the Ethiopian Rift valley lakes currently facing ecological degradation due to diversions of freshwater inflows for irrigation and other human uses from River Adabat and Gidu (Zinabu GebreMariam *et al.*, 2002; Tenalem Ayenew, 2004; Tenalem Ayenew and GebreEgziabher Merhawi, 2015). Determining the dynamic nature of physicochemical and biological variables of Lake Shala is critical to understand this ecologically valuable aquatic environment for sustainable management and utilization of the lake.

Studies on the limnology of Lake Shala are fragmentary when compared to other Ethiopian lakes. Tudorancea and Harrison (1988); Seyoum Mengistou and Fernando (1991); Elizabeth Kebede *et al.* (1994); Zinabu GebreMariam *et al.* (2002) and Tadesse Ogato (2015) summarized ionic composition, physico-chemical, plankton, and macro-invertebrate composition of Lake Shala. Most of these studies described its short time ecology because it was difficult to do long-term dynamics studies due to the remote location of the lake, with some exceptions like Tadesse Ogato (2015) who studied the community structure of phytoplankton and physicochemical features of Lake Shala based on monthly sample collections from one site representing the lake. Considering the importance of Lake Shala regarding ecology, educational, economic, tourism and recreational activities, it is vital to identify the present ecological status of the lake. This study, therefore, updates and compares previous limnological data to complement our knowledge on the relationships between physicochemical features and community structures of phytoplankton, zooplankton and benthic macroinvertebrate of Lake Shala. The present study also aims to investigate aspects of the biology of Nile tilapia, *Oreochromis niloticus* (Pisces: Cichilide). Therefore, this study was conducted on Lake Shala to test the following hypothesis: the physicochemical features and diversity and community structures of phytoplankton, zooplankton and macro-invertebrates in Lake Shala have not been changed over time due to external (human impacts, climate changes) and internal limnological dynamics (atelomixis).

1.2. Statement of the Problem

The Ethiopian Rift Valley Lakes, like other lakes of the world, have been subjected to ecosystem degradation linked to human activities (Zinabu GebreMariam, 2002; Tenalem Ayenew and Dagnachew Legesse, 2007) and, to some extent, climatically driven changes in inflow and evaporation rate (Tamiru Alemayehu *et al.*, 2006). Lake Abijata is being challenged by excessive water withdrawals from its feeder rivers for irrigation and abstracted annually by a soda ash factory (Tenalem Ayenew and Dagnachew Legesse, 2007), which physically damage the lake habitats, and change the water chemistry and biological diversity of the lake's environment (Tadesse Fetahi, 2016; Solomon Wagaw *et al.*, 2019). Plans are also underway to set up a soda ash plant near Lake Shala to replace the existing Lake Abijata based soda ash plant. The company is expected to have a capacity of 200,000 tons per annum of soda ash production during the initial years of operation and that to be expanded to 1,000,000 tons per annum (Abijata-Shalla Soda Ash S.C., 2013). Also, the utilization of water from feeder rivers (Tenalem Ayenew and GebreEgziabher Merhawi, 2015) and large-scale irrigation in the Lake Ziway catchment would cause a reduction in the level of Lake Ziway and ultimately lead to a drastic reduction in the water level of other central Rift Valley lakes due to hydrological inter-connection (Tenalem Ayenew, 2004). This trend will add to the pressures on these saline-alkaline lakes and will trigger conspicuous physical, chemical and biological changes in these inter connected lakes. Therefore, this dissertation will focus on physico-chemical features, plankton composition, macroinvertebrates, and fish biology in Lake Shala by comparing the current limnological data and previous historical data. The study will serve as a baseline information to gauge how the Lake Shala ecosystem will be affected by the new proposed soda ash production project on the lake and its resident biological resources. It also serves as an input for planners and decision-makers to consider future development plans and to mitigate problems that may be encountered. Therefore, this study has tried to fill the above listed research gaps by addressing the following research objectives and questions.

1.3. Objectives of the Study

1.3.1. General Objective

- To understand long-term changes in the ecological condition of the Ethiopian Rift Valley Soda lake, Lake Shala, for better management of the lake and its resources.

1.3.2. Specific Objectives

- To determine the spatial and seasonal variation of some physico-chemical factors of Lake Shala.
- To assess the phytoplankton, zooplankton and macro-invertebrate diversity and abundance among the study sites and seasons in Lake Shala.
- To assess the historical trend in physicochemical parameters, phytoplankton, zooplankton and macro-invertebrate diversity and community structure in Lake Shala.
- To identify the most critical environmental variables that determine the phytoplankton, zooplankton and macro-invertebrate composition, distribution and community structure in Lake Shala.
- To assess the Length-Weight relationship (LWR), Condition Factor (CF), sex ratio, reproductive biology and feeding habit of *O. niloticus* in Lake Shala.

1.4. Research Questions

The main objective of this dissertation was to assess the ecological condition of Lake Shala. Therefore, based on the research gaps and objectives of the study the following research questions were raised and the study tried to address them all separately.

- What does the current physico-chemistry of Lake Shala look like and does this deep lake exhibited internal limnological dynamics associated with atelomixis?
- What do the current composition and community structure of phytoplankton, zooplankton, and macro-invertebrate of Lake Shala look like?
- Has the community structure of all environmental variables exhibited change over time in response to physico-chemical variables and internal limnological dynamics (atelomixis)?
- Which environmental variables are major drivers of the distribution of phytoplankton, zooplankton, and macro-invertebrates in Lake Shala?
- What is the biology of *O. niloticus* in Lake Shala?

1.5. Description of the Study Area

1.5.1. Topography and Morphometric Characteristics of Lake Shala

Lake Shala lies between 7°24’ to 7°33’ N and 38°23’ to 38°39’ E within Abijata-Shala Lakes National Park (ASLNP), some 207 km south of Addis Ababa in the main Ethiopian Rift Valley (Fig. 1.1) (Giday WoldeGabriel *et al.*, 2016). The lake lies at the lowest terminal position at an elevation of 1558 – 1600 m above sea level. Lake Shala is a volcano-tectonic lake (Tenalem Ayenew and GebreEgziabher Merhawi, 2015; Giday WoldeGabriel *et al.*, 2016), found in the hydrologically closed system of the Ziway-Shala basin. Lake Shala is the deepest among the Ethiopian Rift valley lakes. It has approximately a length of 28 km, 12 km width, an average depth of 88 m (maximum 266 m), with a surface area of around 329 km^2 and a vast catchment area (3,920 km^2) (Von Damm and Edmond, 1984; Baxter, 2002). On the western part of the lake are situated eight islands ranging in size from a few hundred square meters to over 0.25 km^2 (Tafesse Kefyalew, 2008). The islands are among the few nesting sites of Pelicans found in Africa (Elizabeth Kebede and Hillman, 1988). Geographical and some basic morphometric characteristics of Lakes Shala are given in Table 1.1.

Table 1.1. Geographical and some basic morphometric characteristics of Lake Shala (Wood and Talling, 1988; Tenalem Ayenew, 2004; Tenalem Ayenew and Dagnachew Legesse, 2007).

Features	Lake Shala
Geographic position	7 °24’-7 °33’N and 38 °23’-38 °39’E
Altitude (m)	1558–1567
Maximum depth (m)	266
Mean depth (m)	88
Surface area (km^2)	329-409
Volume (km^3)	37,000
Catchment area (km^2)	3,920
Basin origin	Volcano-tectonic

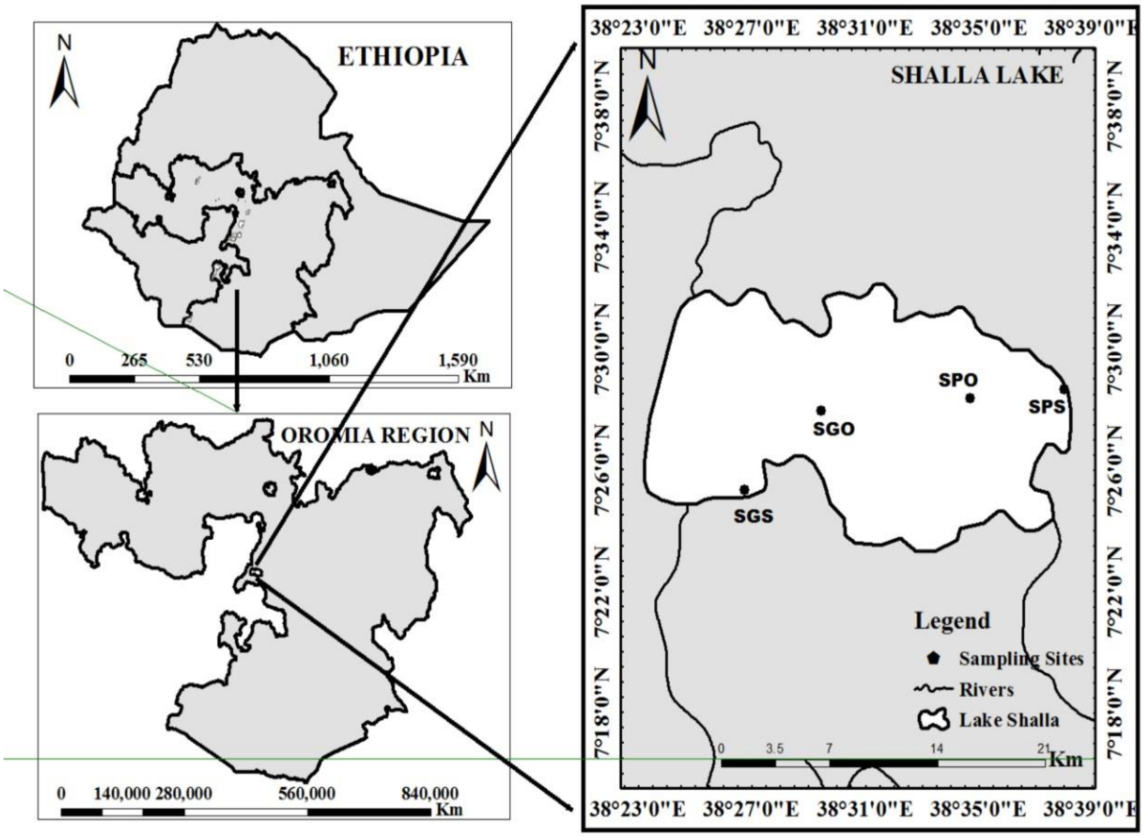


Figure 1.1. Map of Lake Shala showing the study sites/sampling points. (Abbreviation: SPS: Shala Park Shore; SPO: Shala Park Open; SGS: Shala Gike Shore; SGO: Shala Gike Open).

1.5.2. Limnological Characteristics of Lake Shala

Lake Shala is a highly alkaline-saline endorheic lake in the central Ethiopian Rift Valley (Giday WoldeGabriel *et al.*, 2016). The lake is characterized by elevated pH, saline-alkaline conditions, and high phosphate content, but with low nitrogen levels (Zinabu GebreMariam, 2002; Tadesse Ogato *et al.*, 2014). Its water is rich in the dominance of sodium and carbonate-bicarbonate species in the cation and anion dissolved solutes, respectively (Zinabu GebreMariam *et al.*, 2002). The geochemical key to such lakes is a great excess of conservative cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) over conservative anions (Cl,

SO_4^{2-}) (Deocampo and Renaut, 2016). Because charge balance is maintained through the carbonic acid system and gas exchange of CO_2 with the atmosphere, high alkalinity results in high bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) content (Elizabeth Kebede *et al.*, 1994; Zinabu GebreMariam *et al.*, 2002; Deocampo and Renaut, 2016). The high level of salinity of the lakes is related to the presence in large concentrations of the major cations and anions in the trachytic and rhyolitic rocks that formed the Ethiopian rift (Klemperer and Cash, 2007) and the high evaporative concentration of ions in the lake waters (Wood and Talling, 1988; Tenalem Ayenew and Dagnachew Legesse, 2007).

The lake region is characterized by a high evaporation rate that exceeds the mean annual rainfall, causing a water deficit (Tenalem Ayenew and Dagnachew Legesse, 2007) which contributes to the saline-alkaline nature of the lake. Its water salinity and alkalinity are estimated at 18.1 g L^{-1} and 218 meq L^{-1}, respectively (Elizabeth Kebede *et al.*, 1994). The surface water temperatures of Lake Shala range from 22 ℃ to 26 ℃. The lake is experiencing fluctuating electrical conductivity with a mean of approximately 21,940 μS cm^{-1} with a pH fluctuating around 9.65 (Elizabeth Kebede *et al.*, 1994).

Lake Shala receives its water from the River Adabat and Gidu, which originate from the western and eastern highlands (Tenalem Ayenew and GebreEgziabher Merhawi, 2015). Also, hot springs are found along the shorelines of Lake Shala (Baxter, 2002). Collectively these hot springs provide remarkable ecosystems with fascinating gradients of salinity, electrical conductivity, alkalinity, and temperature. The water from inflowing hot springs around Lake Shala is considerably lower in alkalinity (46.3 meq L^{-1}), salinity (4.5 g L^{-1}) and electrical conductivity (8.2 mS cm^{-1}) compared to the lake water (Tadesse Ogato, 2015). The largest and hottest spring (up to 90 ℃) of all springs is on the northeastern shore of Lake Shala. Some limnological features of Lake Shala are presented in Table 1.2.

Table 1.2. Limnological features of Lake Shala (data source: Elizabeth Kebede *et al.* 1994; *Tadesse Ogato, 2015).

Physico-chemical parameters	Values
pH	9.66*
Conductivity (K_{25}, μS cm^{-1})	25,800*
Salinity (g L^{-1})	18.1
Alkalinity (meq L^{-1})	224*
Na^+(meq L^{-1})	272
K^+(meq L^{-1})	4.56
Ca_2^+(meq L^{-1})	0.16
Mg_2^+(meq L^{-1})	0.07
$HCO_3^- + CO_3^{2-}$ (meq L^{-1})	218
Cl^- (meq L^{-1})	54.4
SO_4^{2-} (meq L^{-1})	16.3
SRP (μg L^{-1})	961*
$NO_3^- + NO_2$ (μg L^{-1})	ND
NH_4^+ (μg L^{-1})	42*
SiO_2 (mg L^{-1})	56
Chlorophyll-*a* (*Chl-a*, μg L^{-1})	15.8

1.5.3. Biodiversity of Lake Shala

Lake Shala and the park is world-famous for their exceptionally rich birdlife and is considered as a refuge, feeding and breeding site for over 453 species of resident and seasonal migratory birds, which account for about half of the total recorded for the whole country (Rezenom Almaw, 2012). Because of the high aquatic bird population, lesser flamingos (*Phoeniconaias minor* Geoffroy) inhabiting soda lakes of Shala, Chitu and Abijata the area that has been proposed as a Ramsar site of international importance

(Tewodros Kumssa and Afework Bekele, 2014a). Besides Lesser Flamingos, Lake Shala and its islands support a large population of Greater White Pelican, Cormorants, Storks and *Phalacrocorax carbo* (Stephenson, 1978; Tafesse Kefyalew, 2008; Rezenom Almaw, 2012). Also, volcanically created islands in Lake Shala, serve as the main breeding sites for pelicans without being disturbed by predators and are considered among the most important breeding sites in Africa (Stephenson, 1978; Elizabeth Kebede and Hillman, 1988).

Lake Shala is known for its low phytoplankton productivity and species diversity (Elizabeth Kebede and Willén, 1996). Elizabeth Kebede and Willén (1996) reported high abundances of halophilic diatoms such as *Chaetoceros* and *Thalassiosira* for this lake. However, recently *Cryptomonas* spp. dominated the total phytoplankton abundance of Lake Shala (Tadesse Ogato and Demeke Kifle, 2017). The lake is devoid of *Arthrospira* despite its saline-alkaline water that *Arthrospira* prefers to grow in (Elizabeth Kebede and Ahlgren, 1996; Elizabeth Kebede and Willén, 1996; Tadesse Ogato and Demeke Kifle, 2017). A diversity of non-sulfur purple bacteria from the family *Rhodobaceraceae* (genera *Rhodobaca*, *Rhodobacter*, *Pseudorhodobacter* and *Roseibacter*) and Ammonia-oxidizing archaea (*Thaumarchaeota*) dominated in Lake Shala (Lanzen *et al.*, 2013). Lake Shala also supports a sparse zooplankton community and is dominated by euryhaline salt-tolerant rotifers including *Brachionus dimidiatus* and *B. plicatilis* (Green and Seyoum Mengistou, 1991; Seyoum Mengistou, 2016). Copepods include *Afrocyclop* spp., *Thermocyclops* spp., *Argulus africanus* and *Nitocra lacustris* (Cylopoids and Harpacticoids) also constituting the zooplankton assemblage (Defaye, 1988; Seyoum Mengistou, 2016). Cladocerans are rare in soda lakes, mainly because of the high osmotic pressure, which they cannot withstand. *Moina belli* is the only cladoceran species encountered in Lake Shala (Seyoum Mengistou, 2016).

The benthic macro-invertebrate community of Lake Shala comprises Tubificidae, Ostracoda, Nematoda and Chironomidae (Tudorancea and Harrison, 1988; Seyoum Mengistou, 2016). Lake Shala harbors fish communities of great ecological values. *Aplocheilichthys* spp and *O. niloticus* are described from Lake Shala (Golubtsov *et al.*, 2002; Klemperer and Cash, 2007), which itself supports a population of Pelicans, *Pelecanus onocrotalus*. However, fishing activity is legally controlled in Lake Shala since the lake is enclosed in the national park.

Plate 1.1. Some of the Wetland birds of Lake Shala *Phalacrocorax lucidus* (White-breasted Cormorant), *Pelecanus erythrorhynchos* (white pelican), *Phoenicopterus ruber* (greater flamingo) and *Phoeniconaias minor* (lesser flamingo).

Due to extreme levels of salinity, vegetation in soda lakes is much species-poor and only a few specialist species are able to grow under such conditions. Two species were frequently observed at the shores of Lake Shala, namely *Cyperus laevigatus L.* and *Sporobolus spicatus* (Vahl) Kunth (**Plate 1.2**). The main vegetation community in the catchment is an *Acacia combretum* open woodland (Zerihun Woldu and Mesfin Tadesse, 1990), now extensively deforested whereas deciduous woodlands (*Combretum*, *Oleaeuropaea*, *Celtis*, *Dodonaea viscosa* and *Euclea*) occupy the escarpments (Zerihun Woldu and Mesfin Tadesse, 1990; Mohammed MU and Bonnefille, 1991).

Plate 1.2. Aquatic vegetation (*Cyperus laevigatus L. and Sporobolus spicatus*) in Lake Shala.

1.5.4. Hydrology

Lake Shala receives its groundwater from Langano through faults in the northeastern shore and from the elevated areas in the southeast, south, and probably northwest (Tenalem Ayenew and GebreEgziabher Merhawi, 2015). But rivers and precipitation play significant roles as well (Tenalem Ayenew and Dagnachew Legesse, 2007). Annual input from precipitation is 232 million cubic meters (mcm). The lake receives its water from the River Gidu and Adabat, which originate from the western and eastern highlands, respectively. On average, the annual river inflow contribution in Lake Shala is 245 mcm; 107 mcm from River Gidu and 138 mcm from River Adabat (Tamiru Alemayehu *et al.*, 2006; Tenalem Ayenew and Dagnachew Legesse, 2007; Tenalem Ayenew and GebreEgziabher Merhawi, 2015). However, the recent inflow is low due to upstream diversions for local irrigation (Tenalem Ayenew and GebreEgziabher Merhawi, 2015). Intermittent surface runoff from local drainage channels during the rainy seasons represents another important source of water to Lake Shala and contributed 40 mcm of inflow (Tenalem Ayenew and Dagnachew Legesse, 2007; Tenalem Ayenew and GebreEgziabher Merhawi, 2015). There are also numerous hot springs of varying discharge rates along the shoreline which feed the lake and with an estimated annual inflow of 18 mcm (Tenalem Ayenew and GebreEgziabher Merhawi, 2015). The only loss from the lake is through evaporation, accounting for 781 mcm annually (Tenalem Ayenew, 2004; Tenalem Ayenew and GebreEgziabher Merhawi, 2015).

Table 1.3. Long-term average annual water balance of Lake Shala (10^6 m^3) (Tenalem Ayenew and GebreEgziabher Merhawi, 2015).

Water budget component	**Estimated quantity**
Precipitation onto lake	232
Inflow from rivers	245
Groundwater inflow	18
Inflow from surface runoff	40
Lake evaporation	781
Net flux	**-246**

1.5.5. Climatic and Meteorological Features of Lake Shala Region

Lake Shala region is characterized by hot semi-arid and warm temperatures of the tropical climate. The average annual temperature is 21.7 ℃; with a mean maximum of 31.4 ℃ and a mean minimum of 11.4 ℃ (EWNHS, 2016) (Fig. 1.2). The climate in the Lake Shala region is categorized by rainy (April to September) and dry (October to March) seasons. The rainy months are noted as the minor rainy period extending from April to June and the main rainy season from late June to September. This seasonal pattern generally characterizes the Ethiopian Rift Valley region (Daniel Gamachu, 1977; Tenalem Ayenew and Dagnachew Legesse, 2007). The mean annual rainfall of this area is 1405 mm (ENMSA, 2016). Lake Shala is, therefore, in a region of high rainfall deficit with evaporation exceeding precipitation and the lake depends largely on surface water and groundwater inflows from the adjacent plateaus and escarpments (Tenalem Ayenew and Dagnachew Legesse, 2007).

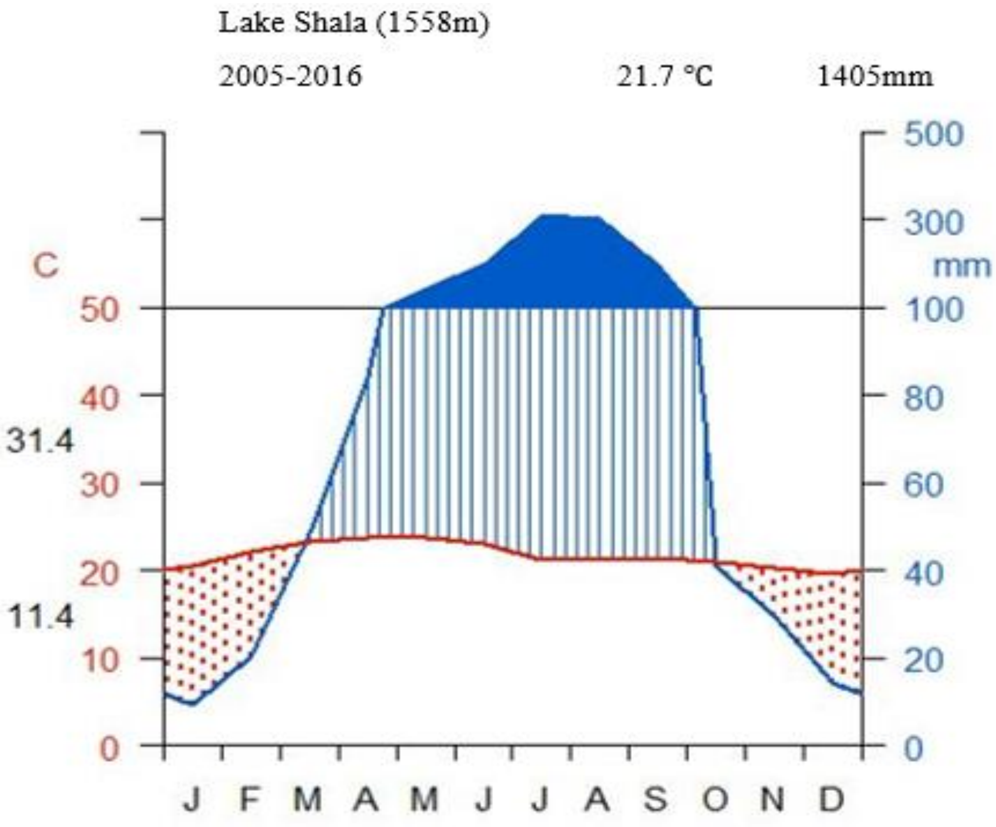


Figure 1.2. Walter and Lieth climate diagram showing a summary of climate conditions around Lake Shala area during the years of 2005 to 2016 (Source: ENMSA, 2016).

1.5.6. Eco-tourism and Socio-economic Importance of the Area

Abijata-Shala Lakes National Park (ASLNP) ranks among the most attractive lakes serving as a recreation site in Ethiopia (Zerubabel Worku and Tsion Mohammed, 2019). Its alkaline edge and the surrounding shallow lake-side are dominated by larvae and pupae Chironomidae midges and provide a plentiful source of high-energy food for wetland birds of Lake Shala (Elizabeth Kebede and Hillman, 1988). The more fish in the lake, the more fish-eating birds can be observed. Such nature of the lake makes it an ideal site for bird watching (Stephenson, 1978; Tafesse Kefyalew, 2008). Also, many hot springs found along the eastern and southern shores of Lake Shala attract tourists and are used by several local people for sanitation, health, recreation and watering livestock (Tafesse Kefyalew, 2008; Zerubabel Worku and Tsion Mohammed, 2019). It has great potential and significant contribution to the tourism development of the country or the national economy and this can create an opportunity/benefit to the local community (Tadesse Fetahi, 2016; Zerubabel Worku and Tsion Mohammed, 2019). Agriculture (crop production and animal husbandry), sand, mineral salts and charcoals are the major means of income generation. However, the agricultural sector dominates all other livelihood activities (Tafesse Kefyalew, 2008; Zerubabel Worku and Tsion Mohammed, 2019).

Plate 1.3. Local people extract the mineral salt for their livestock and for sale at Lake Shala shore.

1.6. Dissertation Structure

The dissertation consists of seven chapters. The first chapter is an introduction part, which presents background information of the study, research gaps, description of general and specific objectives, research questions, and the study area. The second chapter deals with the physico-chemical parameters of the study sites and seasons. Historical trends in the physico-chemical features of the lake are also discussed. The third chapter describes the composition and community structure of phytoplankton in Lake Shala and identifies which environmental factors are key drivers of phytoplankton dynamics. This is followed by research into ecology and zooplankton community structure in relation to abiotic and biotic factors (Chapter 4). The fifth chapter describes the diversity of macro-invertebrates in relation to some physico-chemical factors. Chapter six provides information on the biology of *O. niloticus* in Lake Shala, which was identified in the lake after a long time, and described for the first time. This dissertation ends by concluding the major findings of the study with specific recommendations for further investigation in the study area that may be helpful for designing better lake management.

Chapter Two: Spatial and Seasonal Variations of Abiotic Factors in a Deep Tropical Endorheic Soda Lake Shala, Ethiopia

2.1. Introduction

The alkaline-saline lakes of the East African Rift Valley are among the world's most productive ecosystems (Oduor and Schagerl, 2007a; Krienitz and Kotut, 2010). This high productivity is the cornerstone of the food supply to the hundreds of thousands of lesser flamingos (*Phoeniconaias minor* Geoffroy Saint-Hilaire, 1798) and support associated several avifaunae (Rezenom Almaw, 2012; Kihwele *et al.*, 2014). However, these ecosystems have undergone extreme and erratic fluctuations in both water level and environmental conditions over the last few decades (Zinabu GebreMariam *et al.*, 2002; Tenalem Ayenew and Dagnachew Legesse, 2007). Among several factors, deforestation, expansion of agriculture, livestock, soda ash extraction, and upstream irrigation, soil erosion, and conflict in resource use in the region are the main causes that lead to rapid and unpredictable fluctuations in physicochemical conditions and aquatic biodiversity (Zinabu GebreMariam *et al.*, 2002; Solomon Wagaw *et al.*, 2019). Even relatively small variations in abiotic features can cause irreversible changes in their ecological state (Oduor and Schagerl, 2007b).

Physicochemical parameters play a major role in the distribution and abundance of biological communities in the alkaline saline lake, which can influence food web structure and energy flow in the aquatic ecosystem (Schagerl and Oduor, 2008; Tadesse

Ogato and Demeke Kifle, 2017). East African Rift Valley Soda Lakes are sensitive to changes in seasonality fluctuations in environmental factors, such as nutrients, stratification and mixing patterns, salinity and ionic concentrations, which affect the structure and functioning of biotic communities (Oduor and Schagerl, 2007b; Schagerl and Oduor, 2008; Lanzen *et al.*, 2013). For instance, fluctuations in physical and chemical conditions have been shown to regulate the phytoplankton composition of EARV Soda Lakes (Oduor and Schagerl, 2007a; Schagerl and Oduor, 2008; Okoth *et al.*, 2009; Kihwele *et al.*, 2015; Tadesse Ogato and Demeke Kifle, 2017). Zooplankton distribution, in terms of species abundance, composition and size structure, is also affected by physicochemical and biological processes (Okoth *et al.*, 2011).

Ethiopia is endowed with many soda lakes forming part of the EARV system (Schagerl and Renaut, 2016). Among those, Lake Shala is known for its important natural assets with considerable esthetic, economic, recreational, scientific, conservation, and ecological values (Tafesse Kefyalew, 2008). However, the lake is facing ecological degradation due to rapidly increasing human populations and development activities in the basin during the past few decades (Zinabu GebreMariam *et al.*, 2002; Tenalem Ayenew and Dagnachew Legesse, 2007). Furthermore, there is a plan to expand the Abijata Soda Ash production factory to Lake Shala which may have a profound impact on the integrity of its ecosystem, ultimately hampering all the ecosystem services it renders. Therefore, long-term studies on environmental variable changes can provide scientific information for the sustainable management of the lake.

Limnological researches have been done on temporary and shallow saline lakes (García and Niell, 1993; Melack *et al.*, 2002), but few studies have been carried out on permanent and deep saline lakes (Hammer, 1986; Gülle *et al.*, 2010). Previous studies on the limnological aspect of Lake Shala is well documented, but the overwhelming majority was based on a short time scale and did not address large scale changes (Wood and Talling, 1988; Elizabeth Kebede *et al.*, 1994; Zinabu GebreMariam, 2002; Zinabu GebreMariam *et al.*, 2002). Since the area has witnessed major changes, with increasing anthropogenic activities, very pronounced climate change and the dynamic nature of physicochemical variables, the availability of up-to-date limnological data recorded over the long term is believed essential for sustainable management of the lake. Therefore, this study aims to contribute to the overall understanding of the environmental condition of Lake Shala by evaluating the seasonal and spatial variations of the physicochemical variables over a year. The study also made a comparison on some physicochemical variables starting from 1961 to assess the ecological status of Lake Shala. The study may also serve as a baseline study to gauge future changes because of the new project on the lake and its resident biological resources.

2.2. Materials and Methods

2.2.1. Site Selection

Sites for this study were selected based on their accessibility. Based on this criterion, four sites were selected. These sites are described in table 2.1 and displayed in Figure 1.1 below.

Table 2.1.Description of sampling sites.

Site Name	Abbreviation	Habitat type
Shala Park Shore	SPS	Shore site on the park main office side where there are hot springs and different anthropogenic activities like livestock watering, washing clothes, and bathing
Shala Park Open	SPO	Open water site on the park main office side with a depth of around 70 meters
Shala Gike Shore	SGS	Shore site on the side where Lake Chitu is located. Here also there are hot springs and different anthropogenic activities like livestock watering, washing clothes, and bathing.
Shala Gike Open	SGO	Open water site of Shala Gike site with a depth of around 70 meters

2.2.2. Abiotic Factors Analysis

Four georeferenced sampling sites were identified for studies on spatial and temporal variations of physicochemical parameters (Fig. 1.1). pH, dissolved oxygen, temperature, salinity, and electrical conductivity of the lake water were measured *in situ* using a portable digital multi-parameter probe (Model HQ 9012 HACH) at each sampling station at monthly intervals from January to December 2018. The electrical conductivity measured *in situ* was properly adjusted to conductivity at 25℃ using a temperature coefficient of 2.3% per ℃ (Talling and Talling, 1965).

Composite water samples (by compositing samples from varying depths) were collected from each sampling site to analyze nutrients and the analysis was done monthly using a spectrophotometric method in the limnology laboratory of the Addis Ababa University, following the standard analytical procedures detailed in APHA (1999). After filtration of the water sample through a 45-μm GFF, nitrite-nitrogen (NO_2-N) by sulfanilamide and N-naphthyl-(1)-ethylenediamine-dihydrochloride; nitrate-nitrogen (NO_3-N) by sodium-salicylate method; ammonia-nitrogen (NH_3-N) by Indo-Phenol blue method; Soluble reactive phosphorus (SRP) by the standard ascorbic acid method and dissolved silica (SiO_2) by the ammonium molybdate method, were determined. Total phosphorus (TP) was determined by the ascorbic acid method after digesting the unfiltered sample using potassium persulphate consistent with APHA (1995). Total alkalinity (TA) was determined by titration with 1N HCl to pH 4.5 using a mixed indicator (bromocresol green-methyl red) according to Wetzel and Likens (2000).

2.3. Data Analysis

Logarithmic transformations, Log10(x + 1), of physicochemical variables data were performed before all statistical tests to meet assumptions of normality and to reduce the effect of extreme values. The significant differences in the value of physicochemical variables between the study sites and seasons were compared using one-way ANOVA. Data analyses were done with the R-programming language (R i3.4.2).

2.4. Results

2.4.1. Spatial Variation of Abiotic Factors

The values of abiotic factors recorded among the sampling sites during this study are summarized in Table 2.2. Except for spatial variation in mean dissolved oxygen values, all other abiotic factors demonstrated significant spatial variations ($P < 0.05$). The highest mean pH values were recorded at SGS (10.08±0.15) while SPO had the lowest values (9.94±0.27) with a mean value of 10.01±0.19. A comparison of the mean water temperature values showed that there was a significant difference among sampling stations ($P < 0.05$) (Table 2.2). Mean water temperature values were highest in SPS (25.13±1.19 ℃) and SGO recording the lowest mean temperatures with 24.15±0.82 ℃. Spatial variations in electrical conductivity (EC) and salinity were also significant ($P < 0.05$). The EC (32.89±2.82 mS cm^{-1}) and salinity (20.56±1.96 g L^{-1}) measured at SPO were significantly higher. Alkalinity also showed spatial variations (Table 2.2). The highest concentration of alkalinity (291.1±16.05 meq L^{-1}) was recorded at SGS and was statistically significant compared to other sampling stations.

The nutrient concentrations NO_3-N, NH_3-N, SiO_2, TP and SRP exhibited spatial variations ($P < 0.05$) (Table 2.2). The mean value of NO_3-N was almost undetectable over the study sites (< 0.2 μg L^{-1}) and ranged from 0.14 μg L^{-1} of the SPO to 0.17 μg L^{-1} of the SGS, with a mean value of 0.154±0.04 μg L^{-1} (mean±SD). NH_3-N, SiO_2, TP and SRP records at the shore sites were higher than those recorded at the open sampling stations (Table 2.2).

The mean NH_3-N (µg L^{-1}) recorded were 100.28, 71.37, 108.78, and 74.87 for SPS, SPO, SGS, and SGO, respectively (Table 2.2). The mean concentration of SiO_2 showed significant spatial variations and with a mean record of 0.99 mg L^{-1} (SPS), 0.67 mg L^{-1} (SPO), 1.09 mg L^{-1} (SGS) and 0.72 mg L^{-1} (SGO). The highest mean concentration of TP (2.03 mg L^{-1}) and SRP (1.23 mg L^{-1}) were recorded at SGS and exhibited significant spatial variations compared to other study sites ($P < 0.05$) (Table 2.2).

Table 2.2. Spatial and seasonal variation of physico-chemical variables of the studied stations of Lake Shala (SPS: Shala Park Shore; SPO: Shala Park Open; SGS: Shala Gike Shore; SGO: Shala Gike Open; Temp: Temperature; DO: Dissolved Oxygen; EC: Electrical Conductivity; Alka: Alkalinity, TP: Total Phosphorus; SRP: Soluble Reactive Phosphorus)

	pH	**Temp** ℃	**EC** (mS cm^{-1})	**DO** (mg L^{-1})	**Sal** (g L^{-1})	**Alka** (meq L^{-1})
SPS	9.94±0.27^{a}	25.13±1.19^{b}	31.51±3.51^{a}	7.28±1.13^{a}	19.63±2.43^{a}	275.1±28.27^{a}
SPO	9.96±0.14^{ab}	24.57±1.24^{a}	32.89±2.82^{b}	7.59±0.57^{a}	20.56±1.96^{b}	252.9±10.59^{b}
SGS	10.08±0.15^{c}	24.66±0.79^{ab}	30.40±1.04^{a}	7.37±1.09^{a}	18.71±1.33^{a}	291.1±16.05^{c}
SGO	10.06±0.16^{bc}	24.15±0.82^{a}	31.37±0.98^{a}	7.36±0.97^{a}	19.51±0.67^{a}	268.1±14.2^{a}
Mean	10.01± 0.19	24.63±1.08	31.54±2.55	7.40±0.96	19.60±1.84	271.8±22.9

	NO_3-N (µg L^{-1})	**NH_3-N** (µg L^{-1})	**SiO_2** (mg L^{-1})	**TP** (mg L^{-1})	**SRP** (mg L^{-1})
SPS	0.16±0.04^{ab}	100.28±26.63^{a}	0.99±0.37^{a}	1.79±0.44^{a}	1.16±0.49^{a}
SPO	0.14±0.02^{a}	71.37±14.70^{b}	0.67±0.24^{b}	1.31±0.41^{b}	0.88±0.39^{b}
SGS	0.17±0.05^{b}	108.78±36.90^{a}	1.09±0.39^{a}	2.03±0.44^{c}	1.25±0.47^{a}
SGO	0.15±0.03^{a}	74.87±16.63^{b}	0.72±0.25^{b}	1.52±0.50^{b}	0.80±0.40^{b}
Mean	0.154±0.04	88.82±29.82	0.87±0.36	1.66±0.52	1.02±0.47

Note. Values with different letters (a, b, c) within a column are significantly different at $P < 0.05$ level (Tukey test).

2.4.2. Temporal and Seasonal Variations in Abiotic Factors

The abiotic factor values of Lake Shala showed temporal and seasonal variations (Fig. 2.1 & Fig. 2.2). The mean pH value displayed a significant difference among the sampling months and the values varied from 9.76 in April to 10.17 in August, with a mean of 10.01±0.19 (Fig. 2.1). Alkalinity values ranged from 250.75 meq L^{-1} (April) to 290.88 meq L^{-1} (August) (271.81±22.95 meq L^{-1}; mean±SD) (Fig. 2.1). Their seasonal variations were also significant, pH and alkalinity showed an increasing trend during the rainy season with a mean value of 10.1 and 280.5 meq L^{-1}, respectively (Table 2.3). Water temperature in Lake Shala also showed variations among months and the values varied from 23.7 ℃ in February to 26.09 ℃ in April, with a mean of 24.63±1.08 ℃ (Fig. 2.1). The highest water temperature value was recorded during the pre-rainy season (25.24±1.28 ℃) and statistically significant ($P < 0.05$) compared to other seasons (Table 2.3).

The value of DO; EC and salinity showed some variability among months and showed significant seasonal variation ($P < 0.05$). DO varied from 6.38 mg L^{-1} in June to 8.76 mg L^{-1} in April, with a mean of 7.40±0.96 mg L^{-1} (Fig. 2.1). EC ranged from at least 29.67 mS cm^{-1} in June to a maximum of 35.39 mS cm^{-1} in February, with a mean of 31.54±2.55 mS cm^{-1} (Table 2.3). The value of salinity also varied from 18.08 g L^{-1} in April to 22.31 g L^{-1} in February, with a mean of 19.60±1.84 g L^{-1} (Fig. 2.1). The average level of DO (8.12±0.83 mg L^{-1}), EC (33.99±3.42 mS cm^{-1}) and salinity (21.34±2.37 g L^{-1}) were generally high during the dry season and statistically significant ($P < 0.05$) (Table 2.3). These parameters also increased slightly during the rainy season (Fig.2.1; Table 2.3).

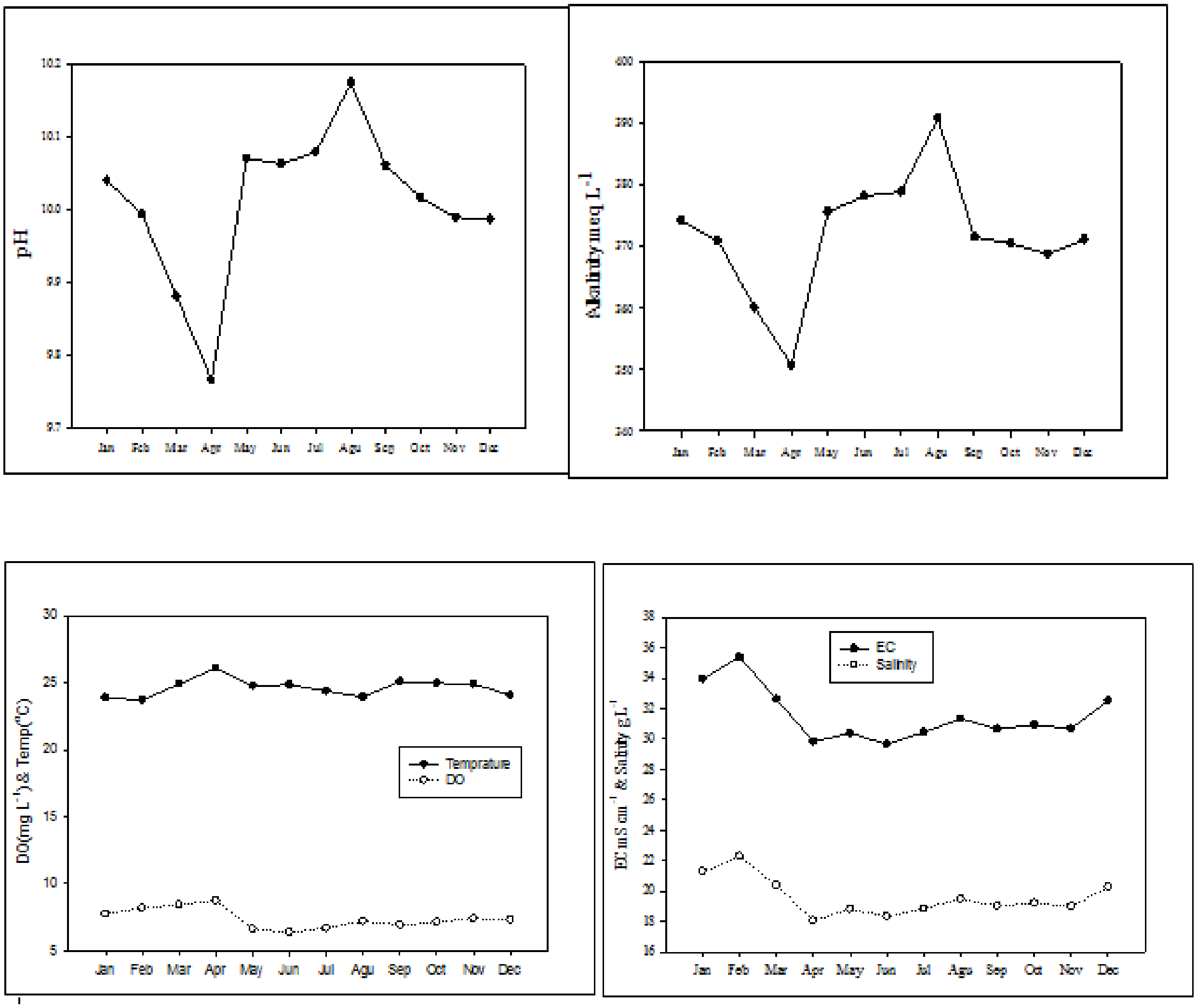


Figure 2.1. Temporal variations of physical environmental variables in Lake Shala from January to December 2018.

Table 2.3. Seasonal variation of physical environmental variables of Lake Shala (Temp: Temperature; DO: Dissolved Oxygen; EC: Electrical Conductivity; Alka: Alkalinity)

	pH	**Temp** °C	**EC** (mS cm^{-1})	**DO** (mg L^{-1})	**Sal** (g L^{-1})	**Alka** (meq L^{-1})
Dry	9.97 ± 0.16^{a}	24.16 ± 0.92^{a}	8.12 ± 0.83^{a}	33.99 ± 3.42^{c}	21.34 ± 2.37^{c}	268.4 ± 20.17^{a}
Pre rainy	9.97 ± 0.16^{a}	25.24 ± 1.28^{b}	7.26 ± 1.27^{b}	29.97 ± 1.97^{a}	18.42 ± 1.6^{a}	268.2 ± 20.71^{a}
Rainy	10.1 ± 0.08^{b}	24.47 ± 1.07^{a}	6.94 ± 0.72^{b}	30.82 ± 0.9^{ab}	19.13 ± 0.61^{ab}	280.5 ± 18.06^{b}
Post rainy	9.99 ± 0.29^{a}	24.65 ± 0.68^{a}	7.29 ± 0.42^{b}	31.39 ± 0.92^{b}	19.51 ± 0.64^{b}	270.2 ± 29.55^{ab}

Note. Values with different letters (a, b, c) within a column are significantly different at $p < 0.05$ level (Tukey test).

Distinct seasonal and temporal variations were observed for all inorganic nutrients (Fig. 2.3; Table 2.4). The long rainy seasons in July to September resulted in increased concentrations of NO$_3$–N, NH$_3$–N, SiO$_2$; TP and SRP in Lake Shala. The concentration of NO$_3$–N and NH$_3$–N ranged from 0.098 µg L^{-1} in March to 0.223 µg L^{-1} in July (0.154±0.04 µg L^{-1}, mean±SD) and from 52.23 µg L^{-1} in March to 122.62 µg L^{-1} in July (88.82±29.82 µg L^{-1}, mean±SD), respectively (Fig.2.3, Table 2.4). The variations in NO$_3$–N and NH$_3$–N concentration among the seasons were significant ($P < 0.05$) and the highest mean values of NO$_3$–N (0.19 µg L^{-1}) and NH$_3$–N (113.69 µg L^{-1}) was recorded during the rainy season (Table 2.4).

SiO$_2$ concentration was variable among the study months and seasons with a general increase in rainy months (Fig. 2.3, Table 2.4). SiO$_2$ ranged from 0.33 to 1.33 mg L^{-1} (0.87±0.36 mg L^{-1}, mean±SD) in March and July, respectively. Like other organic nutrients, the mean concentration of SiO$_2$ among the seasons was statistically significant and the highest value (1.16 mg L^{-1}) was recorded during the rainy season (Table 2.4). The concentrations of TP and SRP varied from 1.14 mg L^{-1} in December to 2.36 mg L^{-1} in July (1.66±0.52, mean ±SD) and from 0.4 mg L^{-1} in March to 1.54 mg L^{-1} in September (1.02±0.47 mg L^{-1}, mean ±SD) respectively (Fig. 2.2, Table 2.4). The concentration of TP and SRP also varied seasonally with an increasing trend during the rainy season, the highest values of TP (2.14 mg L^{-1}) and SRP (1.45 mg L^{-1}) were recorded during the rainy season while shows the lowest concentration during the dry season (Table 2.4).

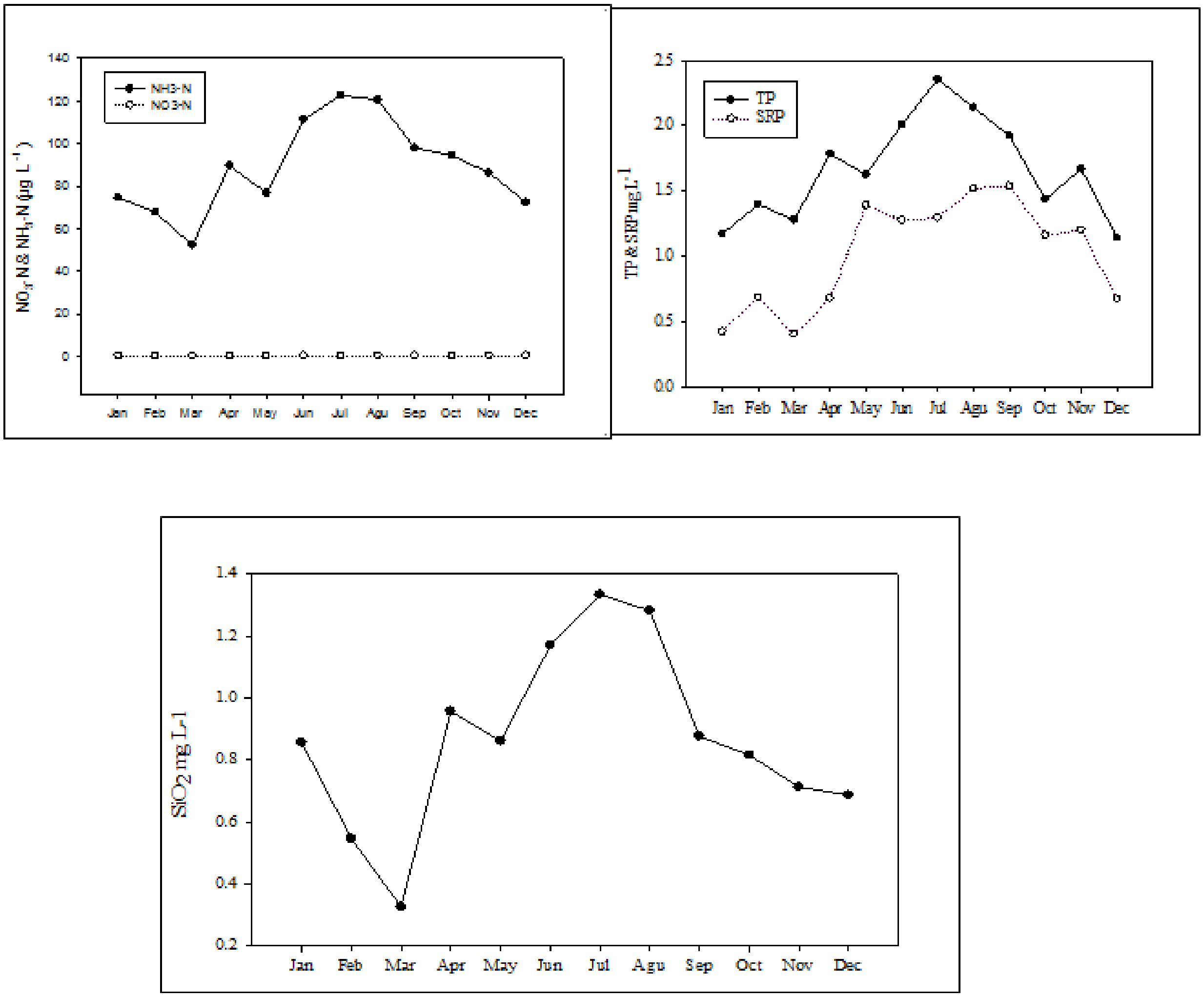


Figure 2.2. Temporal variations of chemical variables in Lake Shala from January to December 2018.

Table 2.4. Seasonal variation of chemical environmental variables of Lake Shala from January to December 2018.

	NO_3-N (μg L^{-1})	**NH_3-N** (μg L^{-1})	**SiO_2** (mg L^{-1})	**TP** (mg L^{-1})	**SRP** (mg L^{-1})
Dry	0.12 ± 0.02^a	64.8 ± 14.8^a	0.58 ± 0.24^a	1.28 ± 0.39^a	0.51 ± 0.19^a
Pre rain	0.15 ± 0.02^b	92.51 ± 31.1^b	0.996 ± 0.36^b	1.81 ± 0.47^b	1.12 ± 0.44^b
Rain	0.19 ± 0.04^c	113.69 ± 31.9^c	1.16 ± 0.34^c	2.14 ± 0.43^c	1.45 ± 0.22^c
Post rain	0.16 ± 0.01^b	84.3 ± 12.4^b	0.74 ± 0.14^b	1.42 ± 0.29^a	1.02 ± 0.39^b

Note: (TP: Total Phosphorus; SRP: Soluble Reactive Phosphorus) (Note. Values with different letters (a, b, c) within a column are significantly different at $P < 0.05$ level (Tukey test).

2.4.3. Trends in Physicochemical Parameters

The chronological outline of previous work on some physicochemical variables of Lake Shala from the period of 1961 to 2018 is presented in Table 2.5 and showed clear variations. Comparing this mean pH value to studies made during 1961 to 2012, the highest mean value of pH was recorded within the present study (Table 2.5). The mean EC was generally higher in the present study compared to data from the 1960s (Table 2.5) and is nearly comparable to the mean value (33,000 μS cm^{-1}) reported by Talling and Talling (1965) (Table 2.5). The current mean value of salinity in Lake Shala (19.6 g L^{-1}) is comparable to the value (19.6 g L^{-1}) reported by Talling and Talling (1965), but higher than that reported by Talling and Talling (1965) (15.7 g L^{-1}), 16.8 g L^{-1} (Baumann *et al.*, 1975); 18.1 g L^{-1} (Elizabeth Kebede *et al.*, 1994).

The concentration of soluble reactive phosphorus (SRP) appears to decrease from 1964 to 2000 in Lake Shala, except in 1991 (809 μg L^{-1}) a record by Elizabeth Kebede *et al.*

(1994). However, the highest values were reported during the recent year sampling period by Tadesse Ogato (2015) (961 μg L^{-1}) and 1,020 μg L^{-1} in the present study. Concentrations of silicate decreased markedly in Lake Shala. Compared to the current data, the high silicate value (130 mg L^{-1}) were recorded in the 1960s by Talling and Talling (1965). Tadesse Ogato (2015) measured the lowest concentration in 2012, which is comparable to the current result (Table 2.5). The mean concentration of NH_3-N increased considerably when compared with some results reported by Elizabeth Kebede *et al*. (1994) (4.3 μg L^{-1}), Zinabu GebreMariam (2002) (4.65 μg L^{-1}), Tadesse Ogato (2015) (42 μg L^{-1}).

Table 2.5. Some previous and current physicochemical values of Lake Shala, and trends over 50 years back from the present study.

References	Sampling time	pH	EC (μS cm^{-1})	Salinity (g L^{-1})	Alkalinity (meq L^{-1})	SRP (μg L^{-1})	SiO_2 **(**mg L^{-1})	NO_3-N (μg L^{-1})	NH_3-N (μg L^{-1})
Talling and Talling (1965)	May 1961		33,000	19.582	200		130		
Wood and Talling (1988)	Jan 1964				210				
Wood and Talling (1988)	Mar 1964	9.9	21,940	21.5	212	760	112		
Wood and Talling (1988)	Oct 1966		24,640		216				
Baumann *et al.* (1975)	May 1971	10		16.8	188				
Von Damm and Edmond (1984)	Jan 1976				218.8				
Elizabeth Kebede *et al.* (1994)	March-May 1991	9.65	21,940	18.1	218	809	56	ND	4.3
Zinabu GebreMariam *et al.* (2002)	1990-2000	9.7	22,863		217.3	727	49.1		
Zinabu GebreMariam (2002)	Wet & dry seasons (1990-2000)	9.72	22,757		216.71	613.85	49.5	0.85	4.65
Tadesse Ogato (2015)	Feb 2012 to Jan 2013	9.96	25,800	15.7	224	961	0.9	ND	42
This study		10.01	31,540	19.6	271.8	1,020	0.87	0.154	88.82

2.5. Discussion

2.5.1. Physicochemical Features of Lake Shala

The physicochemical variables recorded in Lake Shala such as pH, alkalinity, salinity, and electrical conductivity are similar to those observed in most soda lakes of East Africa (Talling and Talling, 1965; Wood and Talling, 1988; Oduor and Schagerl, 2007b; Okoth *et al.*, 2011; Kihwele *et al.*, 2015). The observed high pH, alkalinity, salinity, and electrical conductivity is an indication of the alkaline-saline nature of Lake Shala, this might probably be contributed by high concentrations of carbonate salts (e.g. sodium carbonate), the release of alkalis from soluble solutes by chemical weathering (Deocampo and Renaut, 2016), sodium chloride and other dissolved salts, cause the saline-alkaline characteristics of Lake Shala (Talling and Talling, 1965; Elizabeth Kebede *et al.*, 1994; Deocampo and Renaut, 2016). Also, high surface evaporation rate in the study area and leaching of volcanic rock minerals through weathering and biological activities (Grant *et al.*, 2006; Tenalem Ayenew and Dagnachew Legesse, 2007), low level of divalent cations (Ca^{2+} and Mg^{2+}), enhance alkalinity due to the reduced precipitation of the divalent cations as carbonates and contribute to the lake saline-alkaline properties (Zinabu GebreMariam *et al.*, 2002; Klemperer and Cash, 2007).

Inorganic sources of nitrogen were often suggested to be limiting to algal production in African Soda lakes (Oduor and Schagerl, 2007a; Oduor and Schagerl, 2007b; Okoth *et al.*, 2009; Tadesse Ogato and Demeke Kifle, 2017). In Lake Shala, the concentrations of nitrate-nitrogen and ammonium-nitrogen are low and reflected the characteristic features of most soda lakes of East Africa (Talling and Talling, 1965; Wood and Talling, 1988).

Previous studies also reported similar findings in this and other soda lakes of Ethiopia (Wood and Talling, 1988; Elizabeth Kebede *et al.*, 1994; Zinabu GebreMariam *et al.*, 2002; Tadesse Ogato, 2015). However, Ballot *et al.* (2004) and Schagerl and Oduor (2008) recorded considerably higher values of nitrate in Nakuru, Bogoria, and Elmentaita lakes in Kenya compared to our findings in Lake Shala. The wide distribution of ammonia, nitrate and nitrite-oxidizing organisms within the soda lakes could be accountable for low nitrogen levels in African soda lakes (Jones and Grant, 1999; Grant *et al.*, 2006; Lanzen *et al.*, 2013). High diversity and abundance of ammonia and nitrite-oxidizing organisms (e.g. *Thaumarchaeota* spp.) were recently reported from Lake Shala (Lanzen *et al.*, 2013), which can contribute to the low concentration of nitrogen content within the lake. Also, in the present study and Tadesse Ogato and Demeke Kifle (2017), several cyanobacteria were found in this lake such as *Anabaena* spp. which are nitrogen fixers and can contribute to nitrogen depletion.

Concentrations of TP and SRP in alkaline-saline lakes are generally high in African soda lakes (Ballot *et al.*, 2004; Schagerl and Oduor, 2008). This study recorded higher concentrations of phosphate comparable to the values reported in the same lake and other East African soda lakes (Wood and Talling, 1988; Elizabeth Kebede *et al.*, 1994; Ballot *et al.*, 2004; Oduor and Schagerl, 2007b; Schagerl and Oduor, 2008; Tadesse Ogato, 2015). High phosphorus concentrations in Lake Shala may be coming from the predominance of phosphatic mineral-rich rocks (Talling and Talling, 1965), being anoxic in Lake Shala, as well as the high pH which could be chargeable for the release of much phosphorus from the sediment (Oduor and Schagerl, 2007b).

Dissolved silica can even be a limiting nutrient in soda lakes (Wood and Talling, 1988; Elizabeth Kebede *et al.*, 1994), and this appeared to be the case for Lake Shala in the present study, where silicate had low concentrations in lake water. Bacillariophyta (diatoms) was the foremost abundant population in Lake Shala (94.9% of Lake Shala phytoplankton; **Chapter Three**), expressed a high-affinity to silicate than the other phytoplankton (Hecky, 1993) and thus may be important removers of SiO_2 in the lake (Wood and Talling, 1988; Elizabeth Kebede *et al.*, 1994; Zinabu GebreMariam *et al.*, 2002). Several studies also reported the association of low concentration of SiO_2 with the abundance of diatoms on tropical African lakes (Hecky and Kilham, 1973; Lemoalle, 1981). Dissolved SiO_2 could also be removed from the water column due to the sedimentation of diatom frustules (Milbrink, 1977).

2.5.2. Spatial and Seasonal Variability in Physicochemical Parameters

In the current study, Lake Shala exhibited considerable spatial and seasonal variations in pH. These substantial variations are due to photosynthetic activity, respiration, the vacillation of temperature, seasonality in rainfall, freshwater influx, and decay of organic matter which will shift the pH (Okoth *et al*., 2009; Tadesse Ogato and Demeke Kifle; 2017). Besides, the observed high water temperature during the pre-rainy and rainy seasons might catalyze the ionization of salts (Kihwele *et al.*, 2015), which has the effect of both raising the pH and increasing the alkalinity in African soda lakes (Deocampo and Renaut, 2016). The mean pH (10.08) and alkalinity (291.1 meq L^{-1}) value at the SGS sampling site was significant ($P < 0.05$). The highest phytoplankton abundance (*Chl a*) at SGS could be responsible for CO_2 consumption and leads to higher pH and alkalinity. Tadesse Ogato *et al*. (2016) and Tadesse Ogato and Demeke Kifle (2017) also reported a strong correlation of pH and alkalinity with rainfall, *Chl-a*, and cell densities of phytoplankton in Lake Shala. The finding of the present study also agree with the findings of Okoth *et al.* (2009) in alkaline-saline Lake Nakuru, Kenya.

Seasonal and spatial variations in salinity and EC seems to be related to the seasonal influence of precipitation and evaporation. The highest value of salinity and EC were recorded during the dry season and offshore sampling station. It is associated with a high rate of evaporation in the lake region (Tenalem Ayenew and Dagnachew Legesse, 2007). Similarly, Zinabu GebreMariam *et al.* (2002) and Abnet Woldesenbet (2019) observed an increase in electrical conductivity during the dry season in some Ethiopian Rift Valley lakes (e.g., Lake Hawassa, Langano, and Ziway). The statistical evaluation of salinity and EC from four sample sites of the lake showed a significant difference ($P < 0.05$). The lowest salinity and EC values at the SGS site were probably due to the dilution by less saline (4.5 g L^{-1}) and conductivity (8.2 mS cm^{-1}) of inflowing hot springs water at this site (Tadesse Ogato, 2015). Owen *et al.* (2008) also noted the influence of hot springs which contain less salt than the lake water on the salinity and conductivity of saline-alkaline Lake Bogoria, Kenyan Rift Valley.

Considering all the four sampling stations, the highest (25.13±1.19 ℃) mean temperature value was recorded at the SPS site and is significantly different compared to other study sites. The plausible reason for the observed maximum temperature value might be due to the hot springs (= 97 ℃) that feed the lake throughout the area where SPS sampling station was located. Lugomela *et al.* (2006) and Kihwele *et al.* (2015) also observed the highest water temperature on the shore of Lake Manyara and suggested high water temperature due to the hot springs that feed the lake and the discharge of sodium bicarbonate and silicon dioxide. Also, the difference in sampling time may be attributed to spatial variation in the present study. Remarkable seasonal variations in the water temperature were also noted throughout the study seasons. Water temperature increased slightly during the pre-rainy and rainy seasons but decreased in the dry season. This variation may be due to the influx of warm water from the tributary rivers and the surrounding hotsprings. High water temperatures recorded during the rainy season were also enhanced by the surface water heating through the absorption of infrared radiation because of high concentrations of suspended solids within the water column (Oduor *et al.*, 2003).

Rates of photosynthesis and respiration, oxidation-reduction reactions, and stratification and mixing patterns are considered the most important factors governing the variability of dissolved oxygen in EARV soda lakes (Oduor and Schagerl, 2007a; Schagerl and Oduor, 2008; Okoth *et al.*, 2009; Krienitz and Kotut, 2010). The spatial distribution pattern of DO levels was insignificant among the study stations in Lake Shala. However, there was seasonal variation in DO. The observed highest amount of DO during the dry season and lowest in the rainy season might be related to the activities of photosynthetic organisms and the rate of respiration by decomposers like bacteria and fungi in soda lakes of East Africa (Jones and Grant, 1999; Grant and Sorokin, 2011; Kambura *et al.*, 2016). Extremely high microbial load within the Great East Africa Rift Valley soda lakes is described by Lanzen *et al.* (2013) and Grant and Jones (2016). Wood *et al.* (1984) and Melack (2009) also suggested the depletion of DO in tropical soda lakes by algal biomass decomposition and high microbial activity. According to the above authors, a rise in decomposition rates and oxygen reduction usually occurs during the rainy season, when decomposing organic matter input to the lakes increases. This process rapidly results in a decrease in DO because of microbial respiration during decomposition (Duckworth *et al.*, 1996; Lanzen *et al.*, 2013; Kihwele *et al.*, 2015). The high record of temperature during the rainy season might enhance the decomposition rate by bacterial activity, and reduce DO concentrations (Rocha *et al.*, 2009). Also, depletion in DO during the rainy season might have been caused by changes in the composition and abundances of phytoplankton (Tadesse Ogato, 2015).

Inorganic Nutrients

In the present study, nitrate-nitrogen and ammonium-nitrogen displayed seasonal and spatial variations, the rapid increase in NO_3-N and NH_3-N concentration with the start of rains suggests that the inflowing rivers and runoffs from the catchment might bring nitrogen compounds into the lake. A similar observation was made by Zinabu GebreMariam (2002) and Tadesse Ogato *et al*. (2016) that showed an evident external source of NO_3-N and NH_3-N in Lake Shala related to seasonal hydrological events. The current study findings also correlate with the findings of Oduor and Schagerl (2007b) and Dessie Tibebe *et al*. (2018) which state that maximum nitrogen components during the rainy season due to external nutrients load, phytoplankton excretion, recycling of nitrogen, and bacterial decomposition from planktonic detritus and denitrification. Also, large numbers of domestic and wild animal populations in ASLNP might contribute to the nitrogen through solid wastes during the rains particularly at the shore of the lake.

The highest concentration of nitrogen nutrients was recorded in the SGS site during this study, in which lesser and greater flamingos, white pelicans, cormorants, Egyptian goose, and *O. niloticus* that inhabit the area in substantial numbers can have the potential contribution to increased ammonia and nitrates. A previous study by Baye Sitotaw (2014) reported nitrogen sources from waterbird feather degradation in soda Lake Shala and Chitu by keratin-degrading microbes. Oduor and Schagerl (2007b) and Kihwele *et al.* (2015) also reported faecal droppings from wetland birds and domestic animals as major contributions to escalated nutrient levels in Kenyan Rift Valley saline-alkaline lakes and Lake Manyara, Tanzania.

The concentration of TP, SRP, and SiO_2 exhibited considerable spatial and seasonal variations. These variations are strongly linked to the hydrological cycle (Oduor and Schagerl, 2007b), biogeochemical processes, nutrient input from river flows, and hotsprings (Deocampo and Renaut, 2016), triggering variations in phosphorus and silicate concentration along with the sampling site and season. Oduor and Schagerl (2007b) stated that TP, SRP, and SiO_2 are strongly influenced by the nature of the incoming water and its periodicity. A similar correlation between rainy season and nutrients was observed in Kenyan soda lakes, Lake Nakuru, Baringo, and Naivasha (Oduor *et al*., 2003; Oduor and Schagerl, 2007b) and in Ethiopian soda Lake Chitu (Tadesse Ogato, 2015). Furthermore, at the shore of Lake Shala numerous hot springs and volcanos are active (Tenalem Ayenew and Dagnachew Legesse (2007), and used for the personal hygiene of the local population causing a further input of nutrients into the lake (personal observations) and responsible for phosphorus and silica variations among the studied sites.

Data on the seasonal and spatial physicochemical variations in many deep tropical lakes are rare. However, in the present study, the most driving forces like high air temperature

(Fig.1.2) and water temperature differences (Fig. 2.1 and Table 2.3), combined with the morphological features and also the wind regime of this lake (Tadesse Ogato, 2015), allows the development of atelomix. Partial atelomixis and its key role in the distribution of nutrient concentration has been observed in many tropical lakes (Lopes *et al.*, 2005; Becker *et al.*, 2008; Souza *et al.*, 2008). In the present study, seasonal variations (Prerainy and Postrainy nutrients) initiate more nutrients from atelomictic mixing than influx from the catchment and demonstrated the onset of partial atelomixis.

2.5.3. Trends in Physicochemical Conditions

Some physicochemical parameters examined in this study were considerably higher than values reported on the same lake (Talling and Talling, 1965; Baumann *et al.*, 1975; Elizabeth Kebede *et al.*, 1994; Zinabu GebreMariam *et al.*, 2002; Tadesse Ogato, 2015), indicating that Lake Shala ecosystem has undergone fundamental ecological shifts. Several limnological studies have reported that physicochemical parameter changes over a time scale was associated with the degradation of the lake (Zinabu GebreMariam *et al.*, 2002). Tenalem Ayenew and Dagnachew Legesse (2007) also noted environmental degradation on the neighboring soda lake, Lake Abijata. This environmental degradation is also reflected in variations within the distribution and community structure of biodiversity in this aquatic system (**Chapter 2**, **3**, and **4**).

Comparing with studies made during 1965 to 2015 (Talling and Talling, 1965; Baumann *et al.*, 1975; Elizabeth Kebede *et al.*, 1994; Zinabu GebreMariam *et al.*, 2002; Tadesse Ogato, 2015), the higher mean value of pH (10.01) was recorded in the present study but was found with the same range (Table 2.5). This seems to suggest that the extensive buffering capacity of Lake Shala that causes the change of pH within a narrow limit could be one factor for this insignificant change. A gradual increasing trend in pH value was also reported in earlier investigations made in other similar alkaline–saline water bodies of East Africa (Schagerl and Oduor, 2008; Kihwele *et al.*, 2015).

The mean salinity and EC values measured during this study 19.6 g L^{-1} and 31.54 mS cm^{-1}, respectively, were higher than values of 18.1 g L^{-1} and 21.94 mS cm^{-1} reported by Elizabeth Kebede *et al.* (1994); 15.7 g L^{-1} and 25.8 mS cm^{-1} reported by Tadesse Ogato (2015). The observed somewhat progressive increasing trend of salinity and EC might be related to the buildup of solutes and saline surface runoff from its degraded catchments. Similarly, in recent years, the water environment problems of salinization of the Ziway-Shala basin have become serious accompanied by population growth and rapidly developing industry, catchment degradation, water level reduction, water abstraction for irrigation, soda ash production, and expansion of agriculture (Zinabu GebreMariam *et al.*, 2002; Abnet Woldesenbet, 2019; Solomon Wagaw *et al.*, 2019).

Lake Shala also showed a considerable increasing trend in phosphorus concentrations compared to data from the 1960s to 2015. The mean SRP value found in this study 1,020 μg L^{-1} was higher than values reported by Wood and Talling (1988) (760 μg L^{-1}), Elizabeth Kebede *et al.* (1994) (809 μg L^{-1}), Zinabu GebreMariam *et al.* (2002) (727 μg L^{-1}) and Tadesse Ogato (2015) (961 μg L^{-1}) in the same lake. The higher values of phosphorus content in Lake Shala can be due to human activities within the catchment like deforestation and surface water runoff, organic fertilizers and livestock production. A similar situation was also observed in other central rift valley lakes such as Lake Ziway due to nutrient enrichment of the lake from anthropogenic sources in the catchment area (Dessie Tibebe *et al*., 2018; Abnet Woldesenbet, 2019).

The high silicate values recorded in the 1960s to 2000 in Lake Shala were not measured by Tadesse Ogato (2015) and in the present study. The general decline in silicate concentrations was also observed in some Ethiopian Rift valley lakes like Lakes Abaya and Langano (Zinabu GebreMariam *et al.*, 2002). Hecky and Bugenyi (1992) and Bootsma and Hecky (1993) also reported the same situation in Lake Victoria, where silicon concentrations declined by an order of magnitude between 1961 and 1988. Talling (1966) suggested the decline of silica concentration with an abundance of diatoms and sedimentation, where the accumulated organic matter would impose a slower rate of regeneration in East Africa alkaline lakes (Hecky and Kilham, 1973). Silicate will also be removed from the solution in the reverse weathering process of sediment formation (Wood and Talling, 1988).

This study concludes that the physicochemical feature is an indicator of the ecological status of the lake. A long-term increasing trend in pH, Alkalinity, Salinity, EC, NO3-N, NH3-N, SRP, and TP, and a decreasing trend in SiO2 indicate the presence of considerable anthropogenic pressure and internal limnological dynamics. Moreover, the long-term changes in physicochemical characteristics in Lake Shala directly affect the phytoplankton, zooplankton, and macroinvertebrate diversity and community structure, which was evidenced from the long-term trends of phytoplankton zooplankton and macroinvertebrate changes of the lake **(Chapter Three**, **Four** and **Five**). To solve such pressure on Lake Shala, both the Ziway-Shala basin and effective Lake management measures are recommended to properly maintain the ecosystem sustainably.

Chapter Three: Phytoplankton Community and their Response to Environmental Changes in a Tropical Soda Lake, Lake Shala, Ethiopia

3.1. Introduction

Phytoplankton is the main component of aquatic ecosystems, as they form the vital energy source at the first trophic level (Oduor and Schagerl, 2007a; Krienitz and Kotut, 2010). They are also functionally important in sequestering and transforming many inorganic nutrients into organic forms and act as important bioindicators of environmental conditions and long-term ecological changes of aquatic ecosystems (Morando and Capone, 2018). East African Soda Lakes (EASL) are among the most productive ecosystems because of superabundant populations of phytoplankton (Schagerl *et al.*, 2015; Tadesse Ogato *et al.*, 2016). However, their community structure and abundance have exhibited variations of drastic changes in water chemistry caused by human activities and seasonal alteration of hydrological conditions (Oduor and Schagerl, 2007b; Okoth *et al.*, 2009; Schagerl *et al.*, 2015).

Most phycological researches were conducted on EASL in the Kenyan lakes Bogoria, Elmentaita, Nakuru, and Sonachi (Ballot *et al.*, 2004; Oduor and Schagerl, 2007b; Ballot *et al.*, 2009; Okoth *et al.*, 2009; Schagerl *et al.*, 2015), focusing on the influence of environmental factors on phytoplankton community structure. These authors observed taxa paucity and some periodicity in the temporal occurrence of various algal groups in response to environmental stress expressed as changes in physical and chemical variables. However, limnological studies on community shifts and the spatio-temporal phytoplankton community structure with the environmental variable in the deep soda lake ecosystem are very limited (Melack *et al.*, 2002; Kazanci *et al.*, 2004).

Lake Shala lies within a graben in the Ethiopian Rift Valley and supports large residents of avifauna including the great white pelican (*Pelecanus onocrotalus roseus*) and fesser Flamingos (*Phoeniconaias minor*) (Golubtsov *et al.*, 2002; Tewodros Kumssa and Afework Bekele, 2014a; Tewodros Kumssa and Afework Bekele, 2014b), which constitute one of the main attractions for the tourism industry of the country. However, natural and human-induced ecological disturbances have been reported in ASLNP (Zinabu GebreMariam *et al.*, 2002; Tenalem Ayenew and Dagnachew Legesse, 2007). Neighboring Soda Lake Abijata (Tenalem Ayenew and Dagnachew Legesse, 2007; Solomon Wagaw *et al.*, 2019) and Lake Natron from Tanzania (Kadigi *et al.*, 2014; Oduor and Kotut, 2016), were reported to have been undergoing exceptional loss of habitat. There is also a plan to expand the Abijata Soda Ash production factory to Lake Shala. The Soda Ash production is believed to influence the biodiversity of Lake Shala and the lake may face ecological problems similar to Lake Abijata and Natron.

Studies on the composition and distribution of plankton species in Ethiopian alkaline-saline lakes are very scant compared to freshwater systems (Elizabeth Kebede and Willén, 1996). Meanwhile, a few articles on water chemistry, species composition, and biomass of phytoplankton in Lake Shala were published (Gasse *et al.*, 1983; Elizabeth Kebede and Willén, 1996; Zinabu GebreMariam, 2002; Tadesse Ogato and Demeke Kifle, 2017). However, information on the historical trend of phytoplankton diversity and the community structure of Lake Shala is still lacking. Therefore, this study was conducted in Lake Shala to test the following hypothesis: the diversity and community structure of phytoplankton in Lake Shala has not been changed over time due to human impacts and internal limnological dynamics (atelomixis). The main objective of this study was, therefore, a) to document a checklist of the phytoplankton community which could serve as baseline data against which future changes can be monitored; b) to determine the major variables that significantly affect the phytoplankton communities in these special environments; c) assess long-term trends in phytoplankton composition and community structure in relation to internal limnological dynamics (atelomixis) and external impacts in the lake (catchment impacts).

3.2. Materials and Methods

3.2.1. Identification, Abundance and Biomass of Phytoplankton

Phytoplankton samples were collected from four stations monthly between January and December 2018 (Fig. 1.1). For the taxonomic analysis of phytoplankton, samples were collected with a 15-μm mesh size plankton net, towed vertically from 10 m to the surface and fixed with Lugol's solution. In the laboratory, 1 ml of phytoplankton sub-sample was transferred to a Sedgewick-Rafter counting chamber and allowed to settle before counting (Hötzel and Croome, 1999). Proper identification and enumeration of taxa in Lugol's samples were carried out using a Nikon inverted microscope with identification keys at a magnification of 100X and 400X (Gasse *et al.*, 1983; Komárek and Kling, 1991; Bellinger and Sigee, 2010). For diatoms, each sample was acid cleaned with hydrochloric acid (HCl) and potassium permanganate ($KMnO_4$) to oxidize organics and remove the carbonates (Cvetkoska *et al.*, 2018). For the filamentous algae, the number of cells per filament of 15 filaments was determined and the mean number of cells per filament for the sample was calculated. The average number of cells per filament or colony was multiplied by the number of filaments and colony to estimate the abundance of filamentous taxa. The counting procedure and abundance of phytoplankton were calculated using the equation in Hötzel and Croome (1999).

$$\mathrm{C}\ (\text{cells mL}^{-1}) = \frac{\mathrm{N} * 1000\mathrm{mm}^3}{\mathrm{A} * \mathrm{D} * \mathrm{F} * \text{Concentration factor}}$$

Wher, N = number of cells counted

A = area of the grid (mm^2)

D = depth of a grid (Sedgwick-Rafter chamber depth) (mm)

F = number of grids counted.

$$\text{Concentration factor} = \frac{\text{volume of lake water filtered (mL)}}{\text{volume of concentrate (mL)}}$$

Phytoplanktonic Chlorophyll-*a* (*Chl-a*) concentrations were estimated from water samples collected from the same place where the *in situ* variables were measured. *Chl a* was extracted using 90% acetone after gentle vacuum filtration under dim light through Whatman GF/F filters. The filters were stored at −20 °C for at least 8 hours to aid in the bursting of the cells and then homogenized in a tissue grinder covered with the extraction solvent. After a 12 hour extraction time, the extract was centrifuged and the absorbance of the supernatant was measured spectrophotometrically at a wavelength of 665 nm and 750 nm and its concentration was determined according to the procedure of Talling and Driver (1963).

3.3. Statistical Data Analysis

Mean differences in phytoplankton cell densities and *Chl-a* biomass among sites and seasons, were analyzed using one-way ANOVA followed by Tukey-HSD. All statistical tests were performed on Log10(X+1) transformed data to normalize it. The independent interrelationships between physicochemical parameters and phytoplankton species were evaluated by canonical multivariate analysis using CANOCO for windows 4.5 version software program (Ter Braak and Smilauer, 2002). Detrended Correspondence Analysis (DCA) was employed to check the response of the data, and it was found that the length of the longest gradient was 0.26. Therefore, Redundancy Analysis (RDA) was used to show relations between the phytoplankton species and environmental variables.

3.4. Results

3.4.1. Phytoplankton Composition

Species of phytoplankton encountered in samples collected from the four sampling sites in Lake Shala are listed in Table 3.1. A total of 72 phytoplankton taxa were identified and quantified throughout the sampling period in four stations, belonging to 6 taxonomic groups (Fig. 3.1, Table 3.1). Bacillariophyta dominated the phytoplankton communities in all the sampling sites both in terms of species richness and abundance. The most diverse group of algae was the Bacillariophyta (55 taxa, representing 76.4%), followed by Chlorophyta (7 taxa, representing 9.7%) and Cyanophyta (6 taxa, representing 8.3%) (Fig. 3.1, Table 3.1). The remaining algal divisions, Euglenophyta (2 taxa, representing 2.8%), Dinophyta (1 taxon, representing 1.4%) and Charophyta (1 taxon, representing 1.4%) were also observed during the present study (Fig. 3.1, Table 3.1).

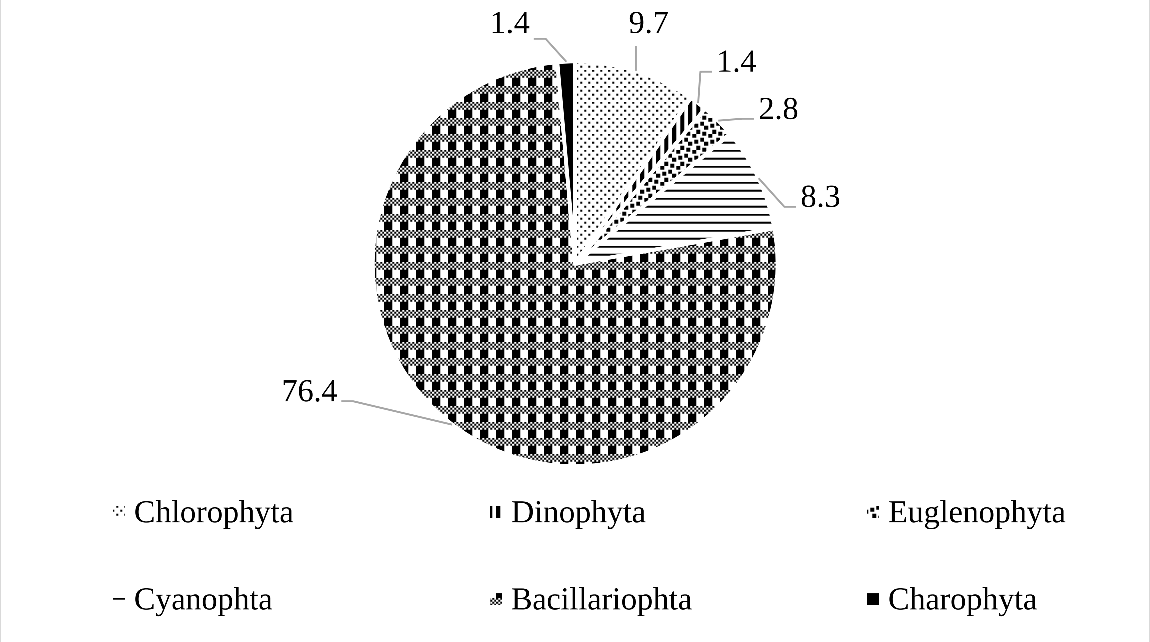


Figure 3.1. Percentage contribution to the total of phytoplankton species in Lake Shala.

Table 3.1. List and taxonomic classification of identified phytoplankton taxa in Lake Shala.

Bacillariophyta
Achnanthes spp.
Amphora spp.
Anomoeoneis sphaerophora
Aulacoseira ambigua
A. distans
A. granulata
Campylodiscus clypeus
Chaetoceros muelleri
Cocconeis spp.
Cyclotella iris
C. meneghiniana
Cyclotella spp.
Cymbella cistula
Cymbella spp.
Denticula spp.
Encyonema cespitosum
Encyonema spp.
Encyonopsis microcephala
Eunotia spp.
Epithemia adnata
E. argus
E. frickei
E. gibba
E. hyndmannii
E. operculata
E. smithii
E. sorex var. *gracilis*
E. turgida
E. vermicularis
Fragilaria spp.
Frustulia rhomboides
Gyrosigma scalproides
Gomphonema affine
Gomphonema parvulum
Hantzschia spp.
Iconella capronii
I. linearis
I. tenera
Navicula spp.
Nitzschia sigma
Nitzschia spp.
Pantocsekiella ocellata
Pinnularia spp.
Pleurosigma salinarum
Rhopalodia acuminata
R. acuminata var. *protracta*
R. gibberula
R. rupestris
Rhopalodia spp.
Sellaphora pupula
Stauroneis spp.
Stephanodiscus spp
Surirella ovalis
Thalassiosira spp.
Ulnaria spp.
Charophyta
Staurastrum spp.
Chlorophyta
Chlorotetraedron incus
Monactinus simplex
Oocystis spp.
Scenedesmus ellipticus
S. quadricauda
Tetradesmus dimorphus
Tetradesmus obliquus
Cyanophyta
Anabaena cylindrica
Anabaena spp.
Arthrospira fusiformis
Kamptonema formosum
Planktolyngbya spp.
Spirulina major
Dinophyta
Glenodinium spp.
Euglenophyta
Euglena spp.
Phacus acuminatus

3.4.2. Phytoplankton Abundance (Cell Densities)

Bacillariophyta was the most dominant group throughout the annual cycle, which accounted for 94.9% of the total phytoplankton cell densities in the samples (Fig. 3.2). The mean abundance contribution of Cyanophyta varied from 1.4% to 4.2% with a mean of 2.9%. While the contribution of Euglenophyta (1.1%) varied from at least 0.14% in January to a maximum of 2.5% in October (Fig. 3.2). Chlorophyta (0.7%), Dinophyta (0.4%), and Charophyta (0.01%) were the least abundant. The dominance of Bacillariophyta was due to *Nitzschia* spp., *Rhopalodia* spp., *R. gibberula*, *Anomoeoneis sphaerophora*.

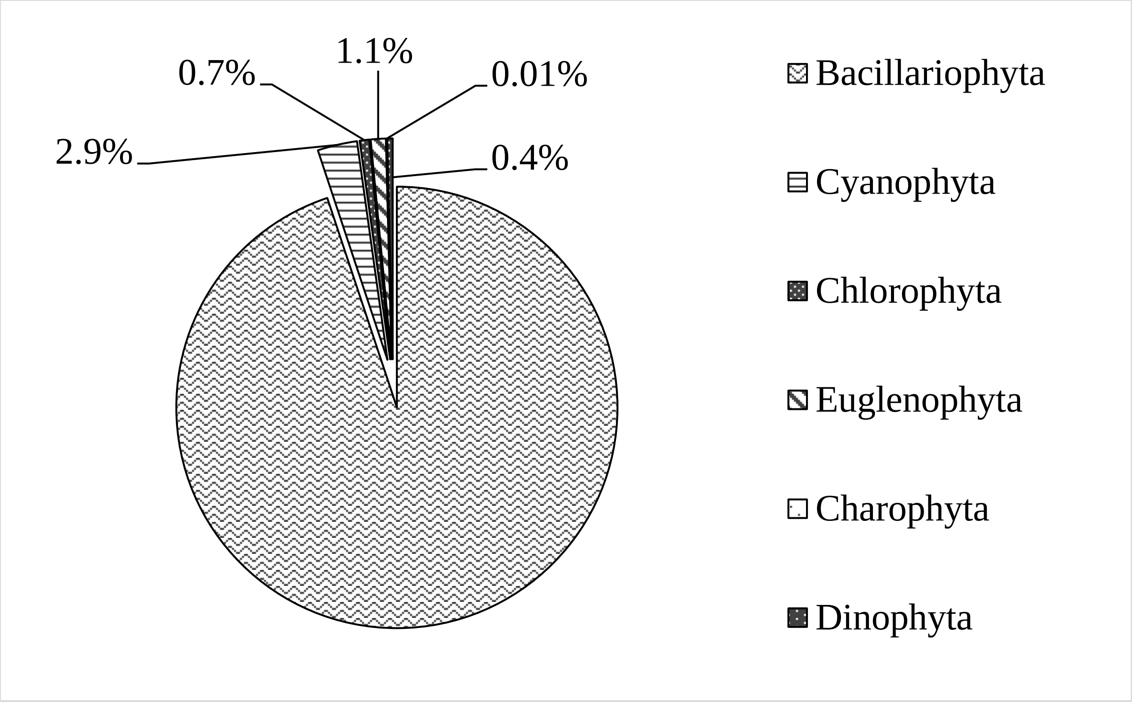


Figure 3.2. Percentage abundance contribution based on cell counts (indi. mL^{-1}) of phytoplankton taxa in Lake Shala.

The relative abundance of algal divisions from January to December 2018 of Lake Shala is shown in Fig. 3.3. Cell densities percentage contribution of Bacillariophyta to the phytoplankton community structure was increased during the dry period, however, their percentage contribution somehow declined during the pre-rainy and rainy months of the study (Fig. 3.3). Whereas the contribution of the Cyanophyta and Chlorophyta group increased during the rainy months from July to the end of September. The peak cell densities of Euglenophyta (*Euglena* spp.) occurred during post rainy periods from October to December and declined during the dry months. The Dinophyta algal class remained constant in their cell densities percentage contribution throughout the study periods (Fig. 3.3).

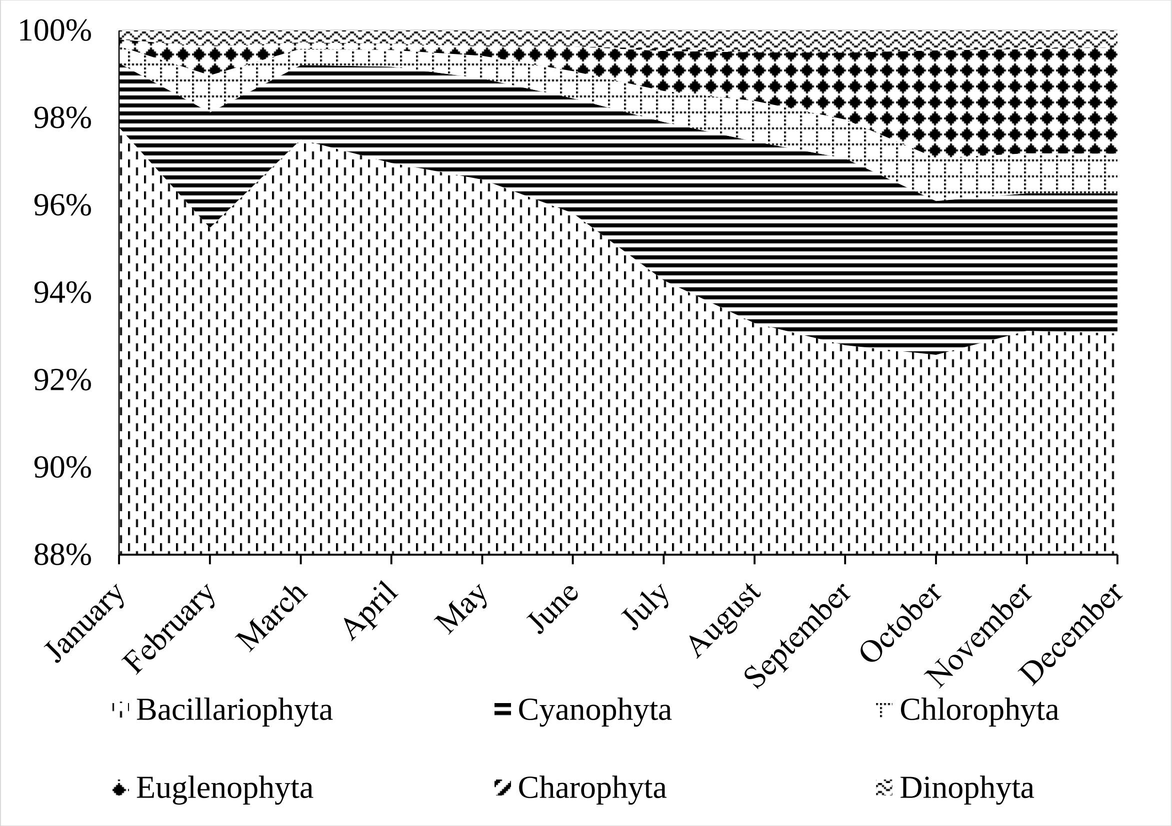


Figure 3.3. Temporal contributions of the algal groups to total phytoplankton abundance (cells mL^{-1}) in Lake Shala from January to December 2018.

Temporal trends in the phytoplankton cell densities for 12 months are shown in Fig. 3.4. In the dry periods between January and March, the phytoplankton densities were low (5,789 cells ml^{-1}, at SPO with a mean of 6,561±836 cells ml^{-1} during February). However, in the rainy period (July to September), the phytoplankton abundance is observed to increase and reached the maximum during this period in July (up to 12,516 cells ml^{-1}, at SGS site), which coincided with increases in algal nutrients. The peak cell densities observed during the rainy period declined steadily following the end of rainfall in the region (Fig 3.4). Common species frequently encountered in the phytoplankton throughout the sampling period included *Nitzschia* spp., *N. sigma*, *Navicula* spp. *F. rhombodies*, *A. sphaerophora*, *Achnanthes* spp., *Rhopalodia* spp., *R. gibberula*, *R. acuminata*, *Glenodinium* spp. and *Thalassiosira* spp.

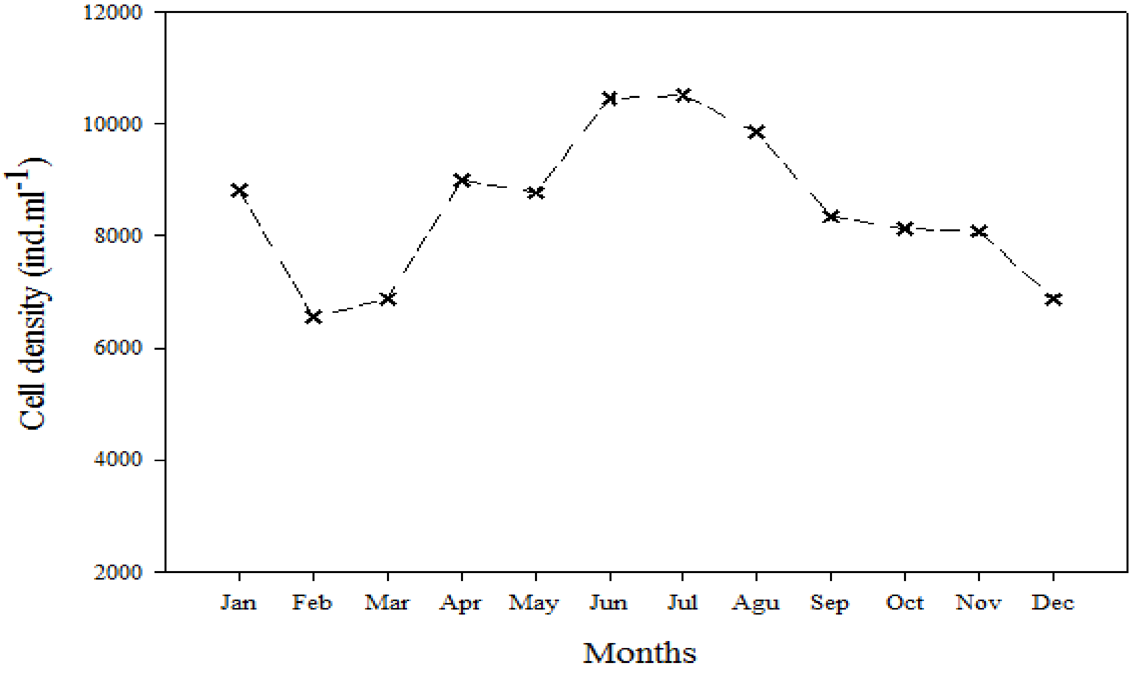


Figure 3.4. Temporal variations in phytoplankton cell densities of Lake Shala from January to December 2018.

3.4.3. Spatial and Seasonal Variations of Phytoplankton Community Structure

3.4.3.1. Phytoplankton Biomass (*Chl-a* (µg L^{-1})) and Cell Densities (cells ml^{-1})

Spatial and seasonal variations in the overall phytoplankton biomass are summarized in Fig. 3.5. Biomass as *Chl-a* of phytoplankton in Lake Shala showed seasonal variation ($P < 0.05$), peaks in biomass were observed from July to September 2018 (Fig. 3.6). The spatial variations in phytoplankton biomass were not significant ($P > 0.05$), however, the inshore sampling sites (SGS) had on average higher phytoplankton biomass than the other stations. *Chl-a* ranged from at least about 9.8 µg L^{-1} in February to a maximum of 25.8 µg L^{-1} in July (Fig. 3.6), with a mean of 17.01 µg L^{-1}. Generally, *Chl-a* biomass exhibited similar trends with the total cell densities or abundance of phytoplankton of the lake and increased during rainy periods (Fig. 3.4 and Fig. 3.6).

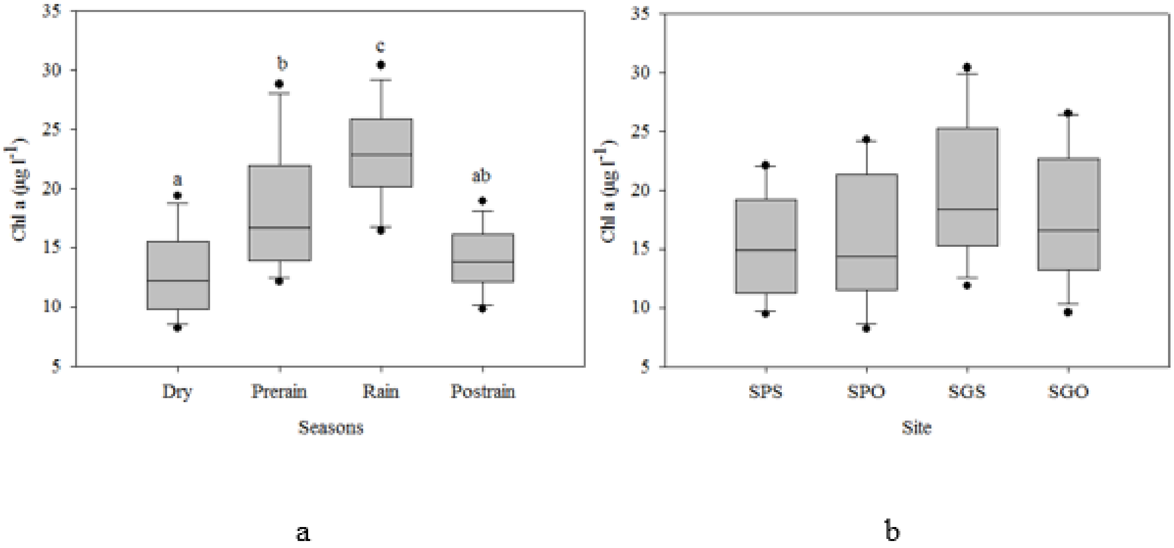


Figure 3.5. Seasonal (a) and spatial (b) variations in biomass (*Chl-a*) of phytoplankton in Lake Shala from January to December 2018.

Seasonally, mean phytoplankton cell densities differ significantly among the seasons (ANOVA, $P < 0.05$), being highest during the rainy season (9,575±1,504.9 cells ml^{-1}) and lowest in the dry period (8240.4±1961 cells ml^{-1}) (Fig. 3.7.a). ANOVA analysis has shown that variation in phytoplankton cell abundance among the sampled sites and was significant at the SGS sampling station ($P < 0.05$) (Fig 3.7.b). The highest phytoplankton cell densities was recorded at the SGS site (10,461.3±1,595.6 cells ml^{-1}), followed by SGO (8,897.4±1,381.4 cells ml^{-1}), SPO (8,110.6±1,476.8 cells ml^{-1}) and lastly SPS (7,558.3±864.5 cells ml^{-1}).

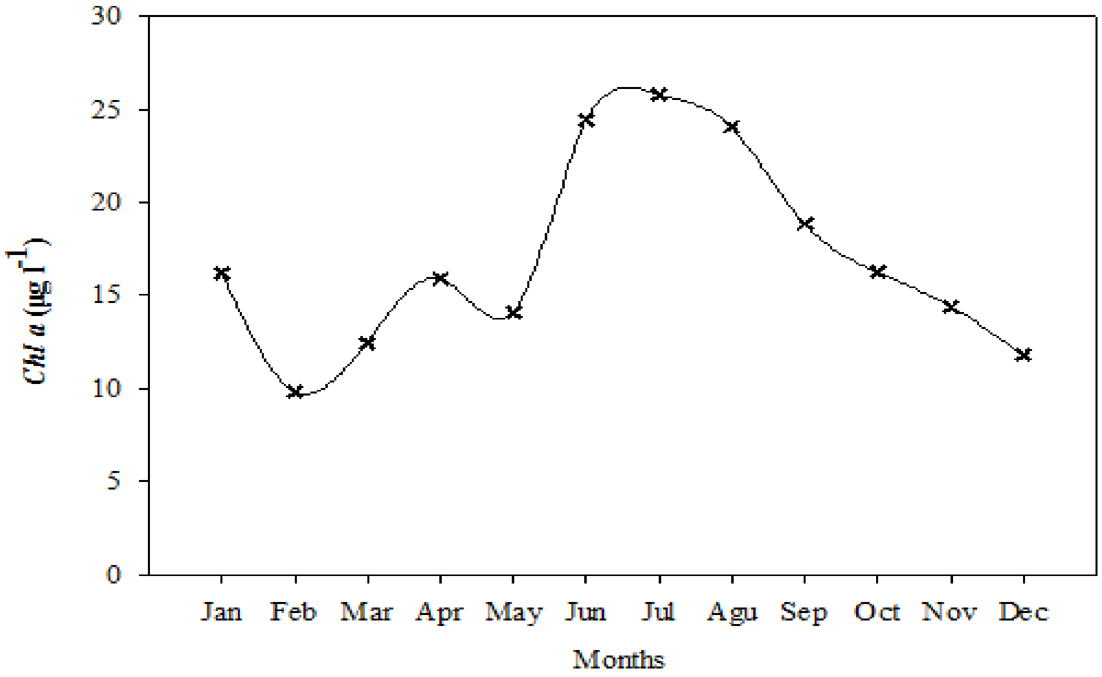


Figure 3.6. Temporal variations in biomass (*Chl*-*a*) of phytoplankton among months in Lake Shala from January to December 2018.

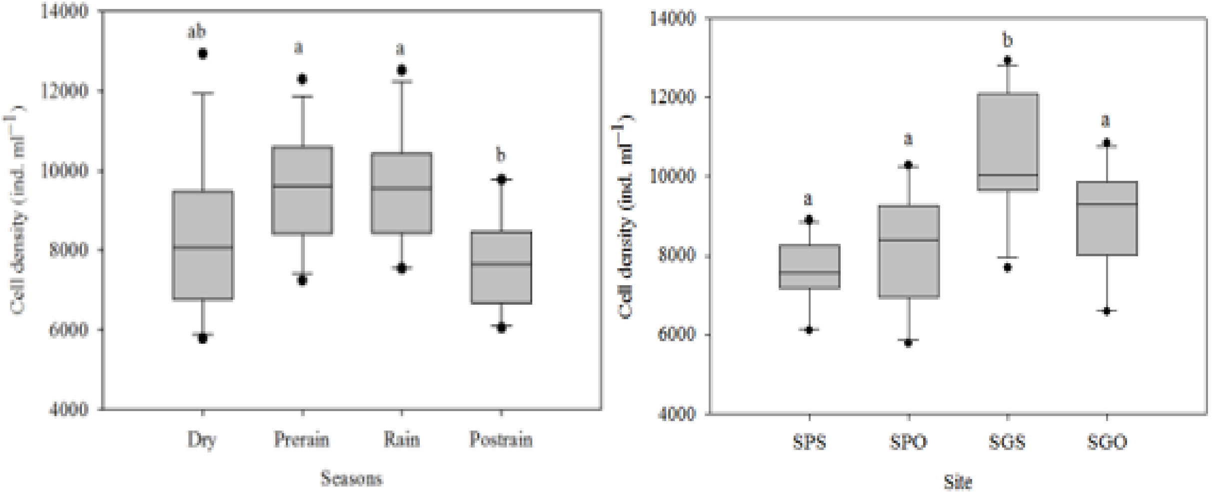


Figure 3.7. Seasonal and spatial variations in cell densities contribution (abundance, cells ml-1) of the phytoplankton community in Lake Shala from January to December 2018.

3.4.4. Phytoplankton Community Structure

The biodiversity indices of phytoplankton are shown in Table 3.2. As recorded in the Table, except for taxa richness, there was no significant variation in all diversity indices across categories of sites ($P > 0.05$). In this study, the minimum value (52 Taxa) was recorded at SGO and the maximum (70 Taxa) was documented at SGS. Shannon-Wiener's diversity index (H') range between 1.87 and 2.03, diversity index of SPS and SGS (2.03) stations was higher than that of SPO (1.9) and SGO (1.87) stations. The Simpson (dominance) index varies between 0.73 and 0.76. The highest value was in SPS (0.76) followed by SGS (0.75), SPO and SGO (0.73). The index ranges from 0 to 1, meaning high dominance since the value was greater than 0.5. Equitability_J was higher and variation ranges between 0.53 and 0.57 in studied stations.

Table 3.2. Biodiversity indices of the phytoplankton community of Lake Shala

	SPS	SPO	SGS	SGO
Taxa_S	59^{ab}	65^{bc}	70^{c}	52^{a}
Simpson_1-D	0.76±0.04	0.73±0.06	0.75±0.03	0.73±0.05
Shannon_H	2.03±0.2	1.9±0.26	2.03±0.22	1.87±0.22
Equitability_J	0.57±0.04	0.53±0.06	0.55±0.04	0.53±0.05

3.4.5. Distribution of Phytoplankton Species in Relation to Environmental Variables

The main environmental variables responsible for the phytoplankton community variability were identified with RDA that simultaneously represented species-environmental variables in a dimensional space. The RDA-triplot of sample sites, phytoplankton species, and environmental variables indicated that the first two axes explained 98.6 % of the variance of phytoplankton distribution (Fig. 3.8). In RDA analysis, the species environmental correlations for all axes are high and most of the phytoplankton appear on the right side of the factorial graph corresponding to the nutrient level of the studied stations (Fig. 3.8; Table 3.3). The RDA ordination of the phytoplankton species association indicated that pH (0.87), Alkalinity (0.79), NO_3-N (0.71), TP (0.7), SiO_2 (0.58), NO_3-N (0.71), NH_3-N (0.57), Fish predation (0.95) and macroinvertebrate abundance (0.69) were positively correlated with the first axis and contributed 74.2% of the variance. These environmental variables determined the distribution of *A. fusiformis, S. major, F. rhomboides, Rhopalodia* spp., *R. gibberula, R. acuminata, R. rupestris, E. operculata, Thalassiosira* spp., *Achnanthes* spp., *Navicula* spp., *Nitzschia* spp., *Kamptonema formosum* and *Planktolyngbya* spp. The first RDA axis was also strongly and negatively correlated with EC (-0.8), salinity (-0.84) and

Zooplankton abundance (-0.42) and determined the distribution of *Euglena* spp. and *A. sphaerophora*. Generally, the species-environment correlation for axes 1 and 2 was high (Table 3.3).

Table 3.3. Results of redundancy analysis (RDA) of phytoplankton species versus physicochemical variables relationship including eigen values and percentage variance explained by the first two axes (**Abbreviations:** DO: Dissolved oxygen; EC: Electrical Conductivity; SRP: Soluble Reactive Phosphate; TP: Total Phosphate; Alka: Alkalinity and Sal: Salinity), (strong correlations are marked bold).

Axes	**1**	**2**
Eigenvalues	0.742	0.244
Cumulative percentage variance of species-environment relation	74.2	98.6
pH	**0.87**	-0.34
Temp	-0.23	**0.91**
EC	**-0.80**	-0.41
DO	-0.19	**-0.68**
Sal	**-0.84**	-0.39
Alka	**0.79**	**0.58**
NO_3-N	**0.71**	**0.68**
NH_3-N	**0.57**	**0.82**
SiO_2	**0.58**	**0.81**
TP	**0.70**	**0.70**
SRP	0.49	**0.83**
Zooplankton abundance	-0.42	**0.87**
Fish predation	**0.95**	0.21
Macroinvertebrate abundance	**0.69**	**0.72**

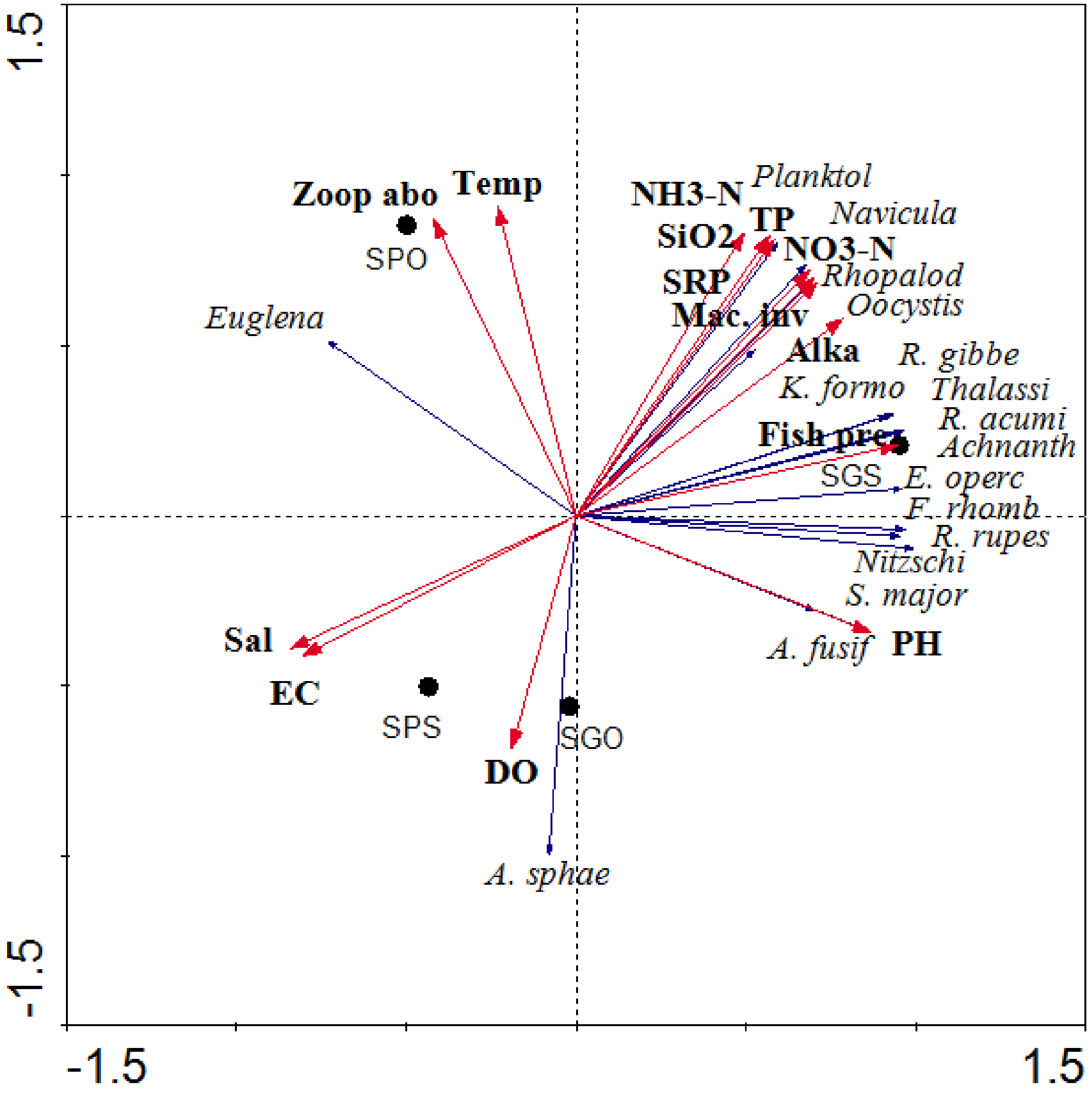


Figure 3.8. RDA-triplot of sites, phytoplankton, and environmental variables based on the first two axes (**Abbreviations:** EC: Electrical Conductivity, TP: Total Phosphorus, SRP: Soluble Reactive Phosphorus, Sal: Salinity, Alka: Alkalinity; DO: Dissolved oxygen; Temp: Temperature; Zoop abu: Zooplankton abundance; Fish pre: Fish predation; Mac. inv: Macroinvertebrate abundance). Sites are shown in a black circle, Species in blue and Environmental variables in Red

3.5. Discussion

3.5.1. Phytoplankton Composition, Abundance, and Biomass (*Chl-a* Concentration)

In the present study, six (6) different phytoplankton groups (Bacillariophyta, Chlorophyta, Cyanophyta, Euglenophyta, Dinophyta, and Charophyta) with 72 phytoplankton taxa were identified. The lake's taxa composition exhibited similarity to other *Arthrospira* dominated saline-alkaline lakes of East Africa including Lake Nakuru, Naivasha, and Bogoria in Kenya (Ballot *et al.*, 2004; Schagerl and Oduor, 2008; Ballot *et al.*, 2009; Okoth *et al.*, 2009; Schagerl *et al.*, 2015) and in Lake Abijata (Tewodros Kumssa and Afework Bekele, 2014c) and Lake Chitu (Tadesse Ogato *et al.*, 2016) in Ethiopia. Although considering the microscopy-based richness estimation of phytoplankton communities of other Ethiopian and Kenyan saline-alkaline lakes, which range between 23 in Lake Abijata (Tewodros Kumssa and Afework Bekele, 2014c), 23 taxa in Lake Nakuru, 18 taxa in Lake Bogoria (Schagerl *et al.*, 2015) and 15 in Lake Chitu (Tadesse Ogato *et al.*, 2016), the richness of phytoplankton community in Lake Shala was higher and it is among the maximum recorded in the saline-alkaline lakes in East Africa. This could be associated with the low level of alkalinity and salinity, and supported by Oduor and Schagerl (2007b), who noted less alkaline-saline environments supported higher species diversity and more.

Bacillariophyta is the most diversified algal group and dominated most stations in the present study. However, the dominance of the Cyanophyta species, *Arthrospira fusiformis*, is a common feature in several African saline lakes (Oduor and Schagerl, 2007b; Krienitz and Kotut, 2010; Krienitz *et al.*, 2013; Kihwele *et al.*, 2015; Schagerl *et* *al.*, 2015). The reason for the dominance of the Bacillariophyta in Lake Shala has been attributed to their tolerance to the low concentration of nitrogen found in the water column of soda lakes (Elizabeth Kebede and Willén, 1996). Unlike Tadesse Ogato and Demeke Kifle (2017), previous studies in Lake Shala have also reported the overall dominance of Bacillariophyta (diatoms) in the phytoplankton community (Gasse *et al.*, 1983; Elizabeth Kebede and Willén, 1996).

Among the Bacillariophyta, the dominance of typically benthic diatom (*Nitzschia* spp., *Anomoeoneis sphaerophora*, *Navicula* spp., *Achnanthes* spp., *Rhopalodia* spp., and *Thalassiosira* spp.) to the phytoplankton community indicating a significant exchange with the benthic communities. Also, the dominance of turbulence-dependent benthic diatoms in the epilimnion explains the partial atelomixis nature of Lake Shala. According to Sui *et al.* (2016), heavier algae occurs in clear epilimnia of atelomictic lakes where daily mixing prevents species from sinking ultimately to the hypolimnion. Overall, diatom assemblages in Lake Shala were very similar to other soda lakes (Hecky and Kilham, 1973; Gasse *et al.*, 1983; Kocer and ŞEN 2012). The dominance of heavy taxa alga (e.g. desmids, diatoms, dinoflagellates) has also been reported in deep tropical lakes due to atelomixis (Souza *et al*., 2008; Assefa Tessema *et al*., 2020).

Also, the roles and relevance of wind-caused current in phytoplankton dynamics have been explored in areas where the day-night air temperature difference is high; typically in the tropical and subtropical regions and/or at high altitudes (Fabbro and Duivenvoorden, 1996; Bouvy *et al*., 2006). This wind-caused current caused complete or partial atelomixis in the lake (Barbosa and Padisa´k, 2002). The consistent daily mixing keeps non-motile diatoms in suspension and avoids ultimate sedimentation to the dark layers (hypolimnion). Padisa´k *et al*. (2009) and Sui *et al.* (2016) also described the remarkable ability of diatoms to tolerate mixing and capacity for buoyancy regulation. Similar findings are also reported in several water bodies with relevant climates, like Lake Zirahue´n, Mexico (Tavera and Martı´nez-Almeida, 2005), Dom Helve´cio and Carioca Lakes, Brazil (Souza *et al*., 2008; Barbosa *et al*., 2011, 2013); Lake Cuicocha, Ecuador (Gunkel and Beulker 2009); Feitsui Reservoir, Taiwan (Wu and Kow, 2010); Lake Hayq (Tadesse Fetahi *et al*., 2010; Assefa Tessema *et al*., 2020) and Lake Wonchi (Fasil Degefu and Schagerl, 2015) in Ethiopia.

Glenodinium spp. and *Euglena* spp. also occurred throughout the study period in Lake Shala but their contributions to total phytoplankton abundance was low. However, Chlorophyta and Charophyta were found during the rainy and post rainy periods. Greater availability of algal nutrients (e.g. nitrates and phosphates) in the rainy season might have supported the growth of Chlorophyta such as *Oocystis* spp., *Chlorotetraedron incus*, *Monactinus simplex*, *Scenedesmus quadricauda* and *Tetradesmus dimorphus*. But their contribution to the phytoplankton abundance was insignificant in Lake Shala.

The phytoplankton biomass (*Chl*-*a*) in Lake Shala was low and contributed by only a very few phytoplankton species. Compared to earlier studies by Elizabeth Kebede and Willén (1996) (16 µg L^{-1}) and Tadesse Ogato and Demeke Kifle (2017) (16.6 µg L^{-1}), Lake Shala exhibits slightly higher biomass in the present study (17.01 µg L^{-1}). On the other hand, the phytoplankton biomass values in other saline-alkaline lakes of Kenya like Lake Nakuru (646±34 µg L^{-1}), Lake Bogoria (388±26 µg L^{-1}), and Elmentaita (267±29 µg L^{-1}) had high *Chl*-*a* biomass (Oduor and Schagerl, 2007a). The *Chl*-*a* biomass of Lake Shala is less than other Ethiopian alkaline-saline lakes, which recorded about 224 µg L^{-1}

in Lake Chitu (Elizabeth Kebede and Willén, 1996), 422 µg L^{-1} and 29 µg L^{-1} in Lake Arenguade and Metehara, respectively (Zinabu GebreMariam and Taylor, 1997). The main reason for Lake Shala's low biomass is supposed to be its differences in the predominant algal groups and their average cell size, which accounts for the variation in the *Chl-a* biomass (Schagerl *et al.*, 2015).

3.5.2. Seasonal and Spatial Variations of Phytoplankton

Phytoplankton composition in EARV saline-alkaline lakes is influenced mainly by the dry and wet seasons, which influence the chemical dynamics of the water column and ultimately their biota (Ballot *et al.*, 2009; Kihwele *et al.*, 2015; Tadesse Ogato *et al.*, 2016). In the present study, the distinct variations of the four seasons based on biomass (*Chl-a*) and cell densities (abundance) reflect community response to the change in environmental variables for hydrological change and nutrient concentration. This observation is supported by Schagerl and Oduor (2008) and Kihwele *et al.* (2015), who reported great changes in the phytoplankton abundance and biomass because of changes in water budget in EARV saline-alkaline lakes.

In the present study, the mean phytoplankton biomass and cell densities differ significantly among the seasons (**Fig. 3.5 a. & Fig. 3.7 a**), being highest during the rainy season (22.9 µg L^{-1}, 9,575 cells ml^{-1}) and lowest in the dry period (12.8 µg L^{-1}, 8,240.4 cells ml^{-1}). The peak cell densities and biomass records during the rainy periods are in line with the finding of Zinabu GebreMariam (2002) and Okoth *et al.* (2009). However, this observation is contrary to those of Nweze (2006) and Girma Tilahun and Ahlgren (2010), who reported increased phytoplankton cell densities and biomass during the dry season. Thus, increases in phytoplankton cell densities and biomass during the rainy periods appear to be directly related to increased nutrients which stimulate the growth of phytoplankton populations (**Chapter two**). Kalff (2002) also reported a critical role of precipitation in phytoplankton cell densities and biomass due to the flushing of a considerable quantity of allochthonous materials and nutrients from the catchments into water bodies.

In the present study, the phytoplankton cell abundance and *Chl-a* biomass among the sampled stations were similar, except at the SGS inshore sites. This relatively high phytoplankton cell densities at the SGS site could be because of the shallow sampling depth which causes decomposed matter formed at the bottom water column to frequently stirred and backed into the lake's photic zone and being utilized by the existing phytoplankton to produce more organic matter for their growth. This is also supported by Kocer and ŞEN (2014), who reported dominant phytoplankton taxa and *Chl-a* in the lake shore side in well-mixed saline-alkaline environments.

In the current study, a high percentage contribution of Euglenophyta to the cell densities in the post-rainy season was prominent (**Fig. 3.3**). Euglenophyta is usually abundant in shallow eutrophic lakes and thrives in waters enriched with organic matter (Nassar and Gharib, 2014), but contribute to the phytoplankton biomass of deep lakes (Jensen *et al.*, 1994). Genera like *Euglena* and *Phacus* indicate organic pollution by higher anthropogenic activities (Noel and Rajan, 2015). Also in Lake Shala, this observation seems to suggest that the population pressures in the catchment could alter the quality of the water draining into the lake from Rivers Gidu and Adabat with subsequent impacts on the phytoplankton community structure of the lake.

In addition, Cyanophyta and Chlorophyta groups had higher cell densities and increased during the rainy months from July to the end of September (**Fig. 3.3**). This observation is in line with Okoth *et al.* (2009), who reported increased Cyanophyta and Chlorophyta cell densities during the rainy season, rather than during the dry season. Whereas, cell density percentage contribution of Bacillariophyta to the phytoplankton community structure was increased during the dry period (**Fig. 3.3**), which corresponded with high salinity and electric conductivity. This might be due to their stability to tolerate a wide range of salinity and conductivity, which is due to their osmoregulatory response-ability to salinity (Clavero *et al.*, 2000; Potapova, 2011).

3.5.3. Distribution of Phytoplankton in Relation to Environmental Variables

Numerous studies conducted on the influence of environmental factors on phytoplankton communities have shown the importance of water pH and related variables (e.g., salinity, alkalinity, electrical conductivity) as the main drivers structuring phytoplankton communities (Okoth *et al.*, 2009; Schagerl *et al.*, 2015; Tadesse Ogato and Demeke Kifle, 2017). In the present study, RDA analysis demonstrated that the phytoplankton community structure of Lake Shala was highly influenced by environmental variables, which explained 98.6 % of the total variance. The species environmental correlations for all axes were high (**Table 3.3**). So according to their position in the RDA diagram, an increase in Bacillariophyta and Cyanophyta taxa was associated with an increase in alkalinity, pH, NO_3-N, NH_3-N, SiO_2 and TP (**Fig. 3.9**). The first axis of the RDA triplot explained that alkalinity, pH, NO_3-N, NH_4-N, SiO_2 and TP are closely related with *A. fusiformis*, *S. major*, *Planktolyngbya* spp, *K. formosum*, *F. rhomboides*, *Rhopalodia* spp., *R. gibberula*, *R. acuminata*, *Thalassiosira* spp., *Achnanthes* spp., *Navicula* spp. and

Nitzschia spp. than other variables at SGS stations, as opposed to salinity and electrical conductivity. Similar observations were made by Kocer and ŞEN (2012) and Bernard *et al.* (2019), who reported salinity and EC as the main environmental factors that explained variation in distributing phytoplankton composition and the dominance of the assemblage by cosmopolitan species with high salinity tolerances.

The association of *Euglena* spp. with zooplankton abundance, temperature, salinity, EC, and DO were positive. Noel and Rajan (2015) reported that a temperature above 25 ℃ is good for the growth of Euglenophyta. The high temperature and DO in Lake Shala might have played an important role in the growth and development of Euglenophyta. In the present study, *A. sphaerophora* had also a strong positive correlation with DO, salinity, and EC. Stenger-Kovács *et al.* (2014) also reported that DO, salinity, and EC are positively correlated with *A. sphaerophora* and other diatom community structures in saline-alkaline lakes in Central Europe. The RDA analyses indicated strong spatial variability, highlighting the importance of the different physicochemical factors in structuring the phytoplankton community, which could largely be attributed to variations in physicochemical features and can be used as an indicator of lake development, erosion, alkalinization, salinization and climate change.

3.5.4. Long-term Trends of Phytoplankton Changes in Deep Tropical Lake Shala

A comparison with previous works revealed a more or less similar phytoplanktonic group composition, but a remarkable increase in taxa richness. Studies made by Gasse *et al.* (1983), Elizabeth Kebede and Willén (1996), and Tadesse Ogato and Demeke Kifle (2017) on the same lake have recorded 11, 16, and 23 phytoplankton taxa, respectively

(**Table 3.4**). Among 72 identified phytoplankton taxa in the current study, some were mentioned in previous studies: 3 species in the study of Gasse *et al.* (1983); 8 species in the study of Elizabeth Kebede and Willén (1996), and 17 species in the study of Tadesse Ogato and Demeke Kifle (2017). About 76.4% of the phytoplankton taxa identified in the present study are new records for Lake Shala. This might be due to extensive spatial and temporal sampling.

The present study showed almost 3-4 folds in the species composition of phytoplankton compared to the previous works. Some of the very common species, which were recorded in this study, were not observed by Elizabeth Kebede and Willén (1996) and Tadesse Ogato and Demeke Kifle (2017). One reason for the variation in the number of species between the present and previous studies is an increase in the number of diatom species. Gasse *et al.* (1983), Elizabeth Kebede and Willén (1996), and Tadesse Ogato and Demeke Kifle (2017) reported 11, 14, and 13 diatom species, respectively, whereas 55 diatom taxa were recorded in the present study. A large variation in the species composition could be due to a large number of surveyed stations, more sampling seasons, the current water physico-chemical variables, and the intensive method used for sample collection and analysis. Several recent studies also reported higher taxa richness of planktonic community in saline-alkaline lakes from Ethiopia (Lanzen *et al.*, 2013) and Kenya (Luo *et al.*, 2013; 2017) than previously estimated.

Previous studies in Lake Shala have reported the dominance of Cryptophyta by Tadesse Ogato and Demeke Kifle (2017), which was not found in the phytoplankton community during the present study. This may be due to the current physico-chemical characteristics of Lake Shala which differs from that of Tadesse Ogato and Demeke Kifle (2017), the slight increase in salinity, EC, and alkalinity of Lake Shala water may inhibit cryptophytes growth. Sampling material and method (15 µm mesh size plankton net in the present study and bottle sampler by Tadesse Ogato and Demeke Kifle (2017)), might also be responsible for the absence of small cryptophyte algae in the 2018 phytoplankton samples. Another possible explanation for the complete absence of cryptophytes in the phytoplankton population might be due to the dense growth of ciliates in Soda lakes (Okoth *et al.*, 2011), which mainly feed on cryptophytes (Tirok and Gaedke, 2007). This is probably signifying that the phytoplankton composition of Lake Shala is shifting from Cryptophyta to Bacillariophyta dominated community and such quantitative and qualitative changes in the composition of the phytoplankton communities may suggest changes in ecosystem conditions. Phytoplankton community shift was also observed in Lake Naivasha from cyanobacteria towards dominance of Chlorophyta, in Lake Oloidien from Chlorophyta towards dominance of cyanobacteria (Ballot *et al*., 2004; 2009) and in Nakuru, Bogoria, and Oloidien lakes, cyanobacterium *Arthrospira fusiformis* replaced partly by *Anabaenopsis* or by chlorophyte *Picocystis salinarum* (Krienitz and Kotut, 2010). This is probably due to the increasing degradation of the water chemistry, caused by salinization, which leads to significant changes in the phytoplankton composition and community structure in the lake.

Arthrospira fusiformis dominates in EARV saline-alkaline lakes characterized by high carbonate-bicarbonate, alkalinity, and pH (Oduor and Schagerl, 2007a; Schagerl and Oduor, 2008; Kihwele *et al.*, 2015; Tadesse Ogato *et al.*, 2016). Even though Lake Shala is a saline-alkaline lake, previously it lacked cyanobacterium *A. fusiformis* and *Spirulina major* (Elizabeth Kebede and Willén, 1996; Tadesse Ogato and Demeke Kifle, 2017).

However, during the present study, *A. fusiformis* and *S. major* were present in the phytoplankton population with a sparse distribution. This is highly likely due to a consequence of the high salinity and pH values, which is suggestive for the growth of *A. fusiformis* and *S. major* (Tadesse Ogato, 2015). Lake Shala is also in an area with high temperature and irradiance and nearly constant photoperiod (Tadesse Ogato and Demeke Kifle, 2017), which seem to favor *A. fusiformis* and *S. major* (Elizabeth Kebede and Ahlgren, 1996; Tadesse Ogato *et al.*, 2014).

Table 3.4. Number of algal species and intra-specific taxa reported from Lake Shala

Gasse *et al.* (1983)	Elizabeth Kebede and Willén (1996)	Tadesse Ogato and Demeke Kifle (2017)	
Bacillariophyta	**Bacillariophyta**	**Bacillariophyta**	**Chlorophyta**
Melosira	*Anomoeoneis sphaerophora*	*Anomoeoneis sphaerophora*	*Oocystis* spp.
moniliformis	*Aulacoseira granulata var. valida*	*Cyclotella iris*	**Cryptophyceae**
Nitzschia elliptica	*Chaetoceros muelleri*	*C. meneghiniana*	*Cryptomonas*
N. palea var. debilis	*C. cf. ceratosporum*	*Cyclotella* spp.	*marssonii*
N. pusilla	*Chaetoceros* spp.	*Navicula* spp.	*C. obovata*
N. latens	*C. meneghiniana*	*Nitzschia* spp.	*C. ovata*
N. frustulum	*C. cf. muelleri*	*Rhopalodia gibba*	*C. reflexa*
N. subrostrata	*C. prostrata*	*R. gibberula*	*Cryptomonas* spp.
N. etoshensis	*Cymbella* spp.	*R. musculus*	**Dinophyeae**
Thalassiosira rudolfii	*Navicula radiosa*	*R. vermicularis*	*Glenodinium* spp.
Navicula elkab	*Nitzschia frustulum*	*Rhopalodia* spp.	
N. vixvisibilis	*N. subacicularis*	*Stephanodiscus* spp.	
	Surirella brebissonii var. punctata	*Thalassiosira* spp.	
	Thalassiosira rudolfii	**Cyanophyta**	
	Chlorophyta	*Anabaena cylindrica*	
	Oocystis spp.	*Phormidium formosum*	
	Green coccoid coenobia	*Pseudanabaena* spp.	
N = 11	**N = 16**	**N = 23**	

Chapter Four: Zooplankton Community Structure in Relation to Environmental Variables in Tropical Soda Lake: Lake Shala, Ethiopia

4.1. Introduction

Zooplankton communities play an important ecological role in aquatic ecosystems (Fernandes and Ramaiah, 2019), being a critical link between phytoplankton and higher consumers and they contribute to element recycling and energy transfers (Burian, 2010; Helenius, 2015). The diversity and abundance of zooplankton are greatly influenced by different biotic and abiotic factors like physicochemical parameters of water, availability of phytoplankton, lake morphology, and anthropogenic changes in lakes and watersheds (Okoth *et al.*, 2011; Waya *et al.*, 2014; Diego *et al.*, 2015; Khitam *et al.*, 2017), which alters characteristics and ecology of the lake (Fernández-Álamo and Färber-Lorda, 2006; Helenius, 2015). Therefore, understanding their dynamics and the factors that affect their community, and their critical linkages with other ecosystem elements, are important aspects in aquatic ecology for optimizing resource use and enhancing sustainable lake ecosystem management (Joseph and Yamakanamardi, 2011; Savitha and Yamakanamardi, 2012).

Soda lakes are variable in their physicochemical features and prone to hydrological influences since they are often in semi-arid regions (Oduor and Schagerl, 2007b; Schagerl *et al.*, 2015; Oduor and Kotut, 2016) and in closed basins. These factors control the zooplankton diversity and community structure (Burian, 2010; Okoth *et al.*, 2011).

The zooplankton community structure of saline-alkaline lakes is related to the salinity gradient (Gülle *et al.*, 2010; Anton-Pardo *et al.*, 2012; Diego *et al.*, 2015). Also, saline-alkaline lake zooplankton are strongly influenced by hydro-dynamics, while seasonality impacts community composition (Isumbisho *et al.*, 2006; Okoth *et al.*, 2011) or other factors, mainly nutrients, water depth, temperature, dissolved oxygen, and food availability can be reasons for vertical and horizontal variations in species composition (Waya *et al.*, 2014; Voutilainen *et al.*, 2016).

Despite the importance of zooplankton in aquatic ecosystems, understanding their dynamics and the factors that affect their community structure have not been well explained in alkaline–saline lakes, especially Ethiopian saline-alkaline lakes have received less attention than other kinds of water systems. The only published sets of data on zooplankton of Lake Shala are those of Defaye (1988), Green and Seyoum Mengistou (1991), and Seyoum Mengistou (2016), whose reports involved the analysis of single occasion sampling. Lake Shala offers a good model to investigate the role of partial atelomxis in driving plankton dynamics in the surface mixing layers of deep tropical lakes, such as Lake Zirahue´n, Mexico (Tavera and Martı´nez-Almeida, 2005), Dom Helve´cio and Carioca lakes, Brazil (Souza *et al*., 2008; Barbosa *et al*., 2011, 2013). However, few observations have been done on zooplankton dynamics in deep highland lakes in Ethiopia, especially in relation to seasonal mixing patterns (Tadesse Fetahi *et al*., 2011; Fasil Degefu and Schagerl, 2015).

Lake Shala has been facing ecological degradation due to rapidly increasing human populations and development activities in the basin during the past few decades (Zinabu GebreMariam *et al*., 2002; Tenalem Ayenew and Dagnachew Legesse, 2007).

Furthermore, there is a plan to expand the Abijata Soda Ash production factory to Lake Shalla which may impact the structure of biological communities. Therefore, the present study had 3 major objectives: a) prepare a checklist of the zooplankton community which could serve as baseline data to monitor future changes in the lake; b) determine the major drivers of zooplankton dynamics in the lake; c) assess long-term trends in zooplankton composition and biomass in relation to internal and external impacts in the lake (atelomixis or catchment impacts). The study may also contribute data towards a better understanding of how climate change and human impacts affect zooplankton dynamics in deep tropical lakes.

4.2. Materials and Methods

4.2.1. Sampling and Analysis

Zooplankton and physicochemical parameter sampling were carried out at monthly intervals during the period from January to December 2018. Zooplankton sampling was done with a plankton net of 30 µm mesh size from four horizontal sampling sites (Fig. 1.1) and vertically hauled from 30 m to the surface from two open water stations and 10 m from two shore sites. A vertical bottle sampler (van Dorn, 2 L capacity) was also used for the determination of vertical distribution and abundance of zooplankton at the water surface (0 m), 5, 10, 15, 20, and 30 m depth of open water sampling station and water temperature and dissolved oxygen were measured at each depth simultaneously with zooplankton sampling. Zooplankton samples were preserved in 4% formalin and brought to Addis Ababa University, Limnology Laboratory. Zooplankton were identified to the lowest taxonomic unit according to these taxonomic keys: Rotifers (Fernando, 2002), Copepods (Defaye, 1988), and Cladocerans (Korinek, 1999). Counting was carried out using a plankton counting chamber under an inverted microscope. Total counts were made and individual densities were expressed as numbers per liter.

Zooplankton biomass was determined based on measurements of each species and from all stages, made with a micrometric Nikon microscope equipped with a digital photographic camera. Biovolume calculation for rotifers was determined from individual size measurements using geometric approximations as described by Ruttner-Kolisko (1977). These biovolume values were used to estimate fresh weights if 10^6 μm^3 volume corresponds to 1 µg of fresh weight (Bottrell *et al.*, 1976). A fresh-dry mass conversion factor of 0.1 was used for all genera (Dumont *et al.*, 1975). The cladoceran and copepods biomass were estimated through calculated Length-Weight relationships (McCauley and Kalff, 1981; Wetzel and Likens, 2000).

4.3. Data Analyses

The zooplankton data were quantitatively analyzed for percentage contribution in the study by using Excel spreadsheet Microsoft 2007. Spatial and temporal variability of zooplankton community between sites, and among seasons, were analyzed by non-parametric Kruskall–Wallis ANOVA (Kruskal and Wallis, 1952). The association between the distribution of zooplankton species, abiotic and biotic factors and sampling stations was evaluated with canonical multivariate analysis using CANOCO windows 4.5 version Software (Ter Braak and Smilauer, 2002). Detrended correspondence analysis (DCA) was employed to check the response of the data, and the length gradient was 0.195. Therefore, redundancy analysis (RDA) was used to determine the relationship between zooplankton species distribution and environmental parameters.

4.4. Results

4.4.1. Zooplankton Community

A list of zooplankton species and their percentage composition in Lake Shala is presented in Table 4.1 and Figure 4.1. Analysis of the zooplankton community of Lake Shala revealed that the maximum contribution was made by Rotifera (71.9%) followed by Copepoda (18.8%) and Cladocera (9.4%) (Fig 4.1). During the study, 32 zooplankton species were identified from four sampling stations (Table 4.1), which comprised 23 rotifers, 6 copepods, and 3 cladocerans (Table 4.1). Of the 23 rotifers identified, 10 species belonged to the genus *Brachionus* including *B. budapestinesis*, *B. calyciflorus*, *B. dimidiatus*, *B. dimidiatus inermis*, *B. falcatus*, *B. plicatilis*, *B. quadridentatus*, *B. rubens* and *B. urceolaris* (Table 4.1). *Argulus africanus* and *Nitocra lacustris* both of which occurred as the sole species representatives of the Arguloida and Harpacticoida group and showed irregular occurrence in the community.

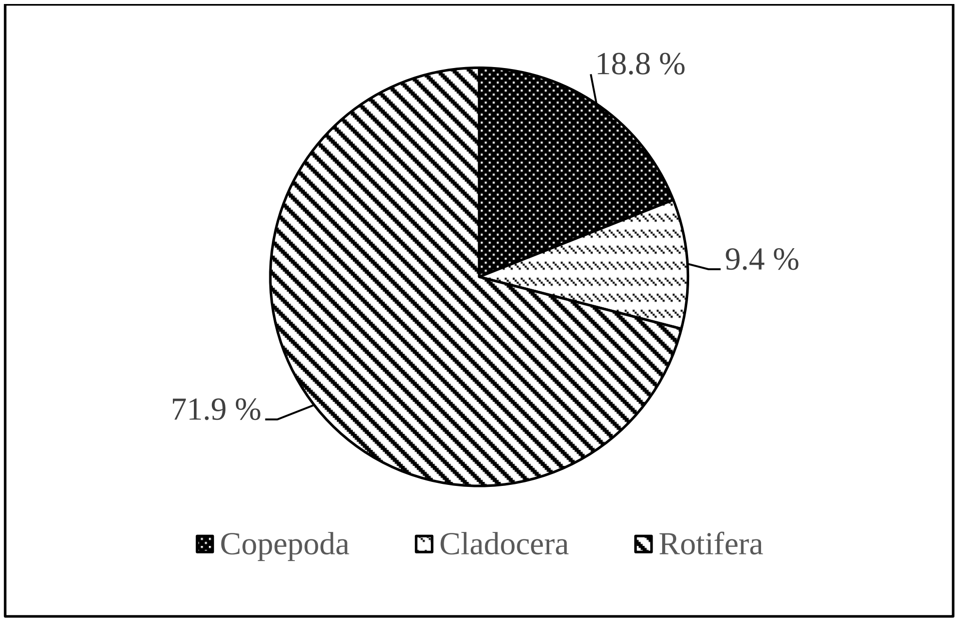


Figure 4.1. Percent composition of three zooplankton groups in Lake Shala.

Table 4.1. Zooplankton taxa recorded in Lake Shala from January to December 2018.

Arguloida (Copepoda)	**Cyclopoida (Copepoda)**	**Harpacticoida (Copepoda)**	**Cladocera**	**Rotifera**
Argulus africanus	*Afrocyclops gibsoni*	*Nitocra lacustris*	*Diaphanosoma excisum*	*Anuraeopsis fissa*
	Eucyclops serrulatus		*Moina belli*	A. *navicula*
	Thermocyclops ethiopiensis		*M. micrura*	*Brachionus angularis*
	T. oblongatus			*B. budapestinesis*
				B. calyciflorus
				B. dimidiatus
				B. dimidiatus inermis
				B. falcatus
				B. plicatilis
				B. quadridentatus
				B. rubens
				B. urceolaris
				Filinia pejleri
				Hexarthra jenkina
				Keratella tropica
				Lecane hastate
				L. bulla
				L. luna
				Polyarthra spp.
				Trichocerca tetractis
				Trichocerca spp.
				Testudinella patina trilobata

Rotifera was the dominant group in terms of quantity, and its species richness and abundance were higher when compared to copepods and cladocerans ($P < 0.05$). The highest values of Shannon-Wiener Index H’ were recorded for rotifer (1.76) while cladoceran had the lowest species diversity (1.01) (Table 4.2). Maximum evenness values were recorded for cladoceran (0.91) (Table 4.2), being high species taxa, evenly distributed, and minimum for rotifer (0.26). The present results indicate a consistently higher copepod and cladoceran evenness (Table 4.2). This reflects the equitable abundance of various species throughout the study period. The highest value for species dominance was recorded for rotifer (0.77) and lowest for cladoceran (0.61) (Table 4.2).

Table 4.2. Variation of diversity indices of different groups of zooplankton in Lake Shala from January to December 2018.

	Rotifera	**Copepoda**	**Cladocera**
Taxa_S	23^{a}	6^{b}	3^{c}
Simpson_1-D	0.77^{a}	0.72^{b}	0.61^{c}
Shannon_H	1.76^{a}	1.44^{b}	1.01^{c}
Evenness_e^H/S	0.26^{a}	0.70^{b}	0.91^{c}
Equitability_J	0.57^{a}	0.80^{b}	0.92^{c}

Note. Values with different letters (a, b, c) within a column are significantly different at $P < 0.05$ level (Tukey test).

4.4.2. Patterns in Zooplankton Community Abundance and Biomass

The mean integrated values of the zooplankton community in the overall water of Lake Shala ranged from 830.37 to 1,538.64 ind. L^{-1}, with the maximum values in August and the minimum in January (Fig. 4.2). Rotifera was the dominant group in terms of abundance and higher when compared to copepods and cladocerans ($P < 0.05$). The rotifers contributed 86.3% on average to monthly total zooplankton abundance throughout the sampling period (Fig.4.3), whilst the remaining 13.7% was shared by the nauplii (10.9%), copepods (2.4%), and cladoceran (0.4%).

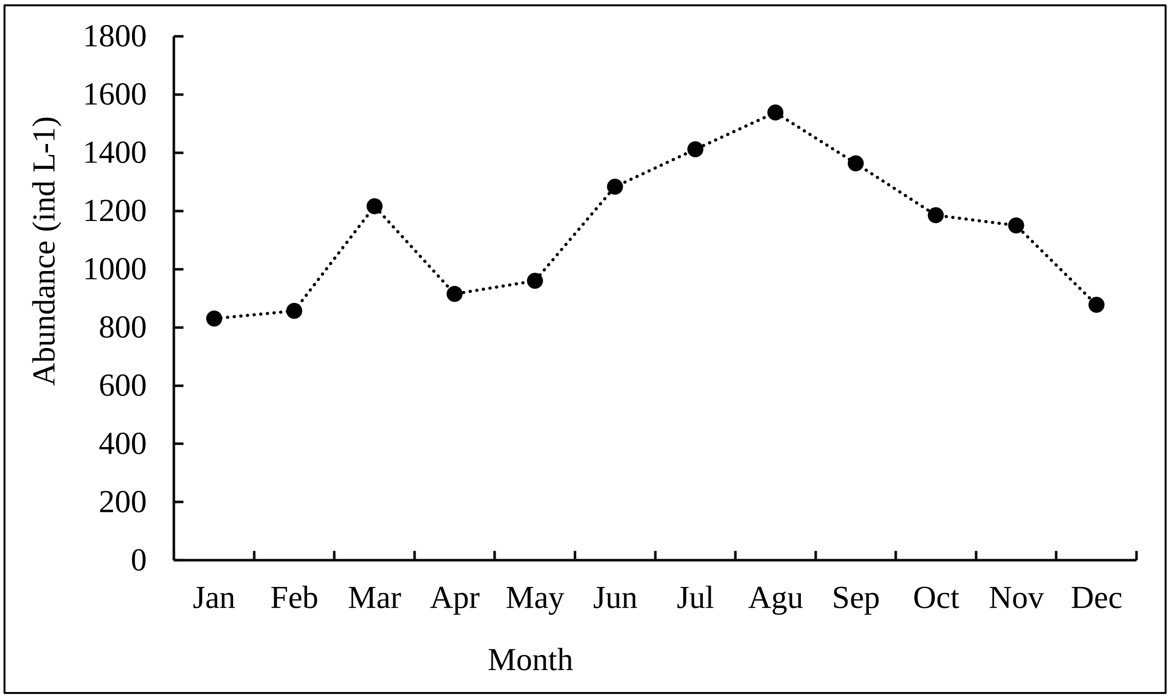


Figure 4.2. Monthly pattern of total zooplankton abundance (ind. L^{-1}) in Lake Shala from January to December 2018.

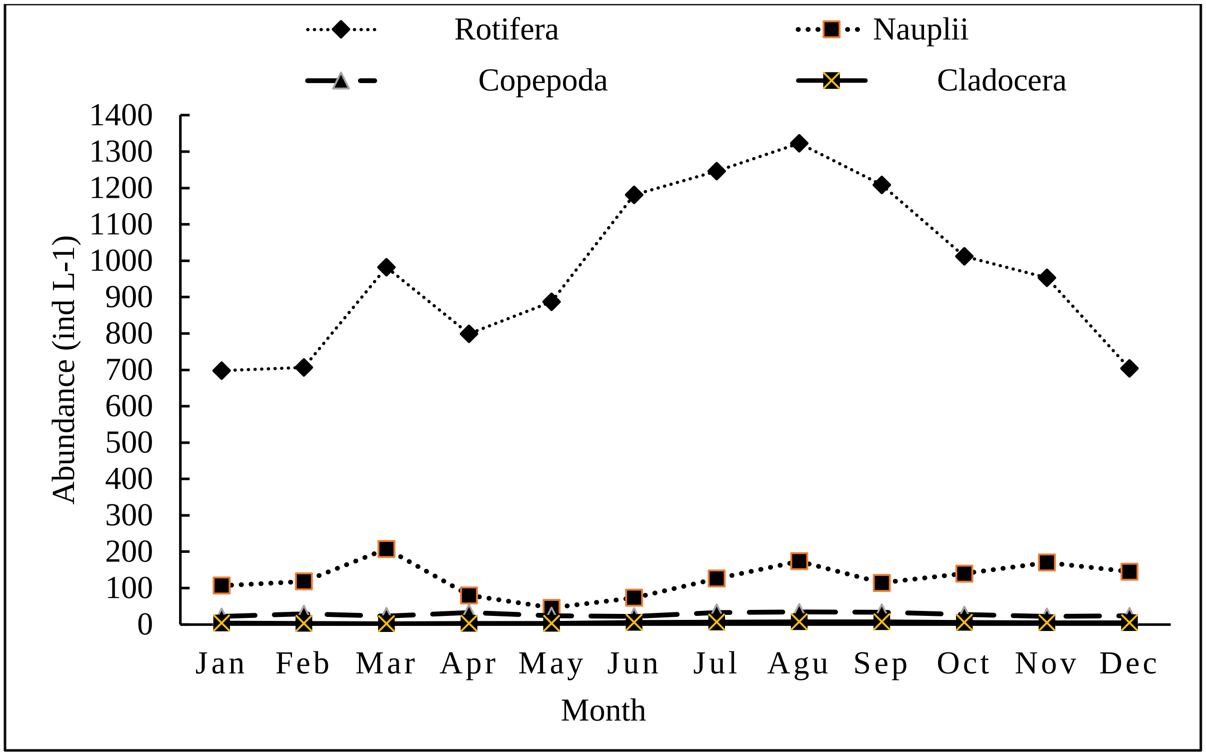


Figure 4.3. Monthly distribution of zooplankton groups abundance (ind. L^{-1}) in Lake Shala from January to December 2018.

The zooplankton densities were dominated by *Brachionus dimidiatus*, *B. dimidiatus inermis*, *B. plicatilis* and *B. calyciflorus* during all sampling periods. The temporal variations in the four most dominant individual zooplankton abundance (ind. L^{-1}) during the study period are summarized in Fig. 4.4. The highest densities of *B. dimidiatus* occurred during the dry (January - March) and post rainy months (September - December). The densities of *B. dimidiatus inermis*, however, increased during the pre-rainy months (April - May). Similar patterns of *B. plicatilis* and *B. calyciflorus* were observed, with increasing abundance during the rainy months (July - September) (Fig. 4.4).

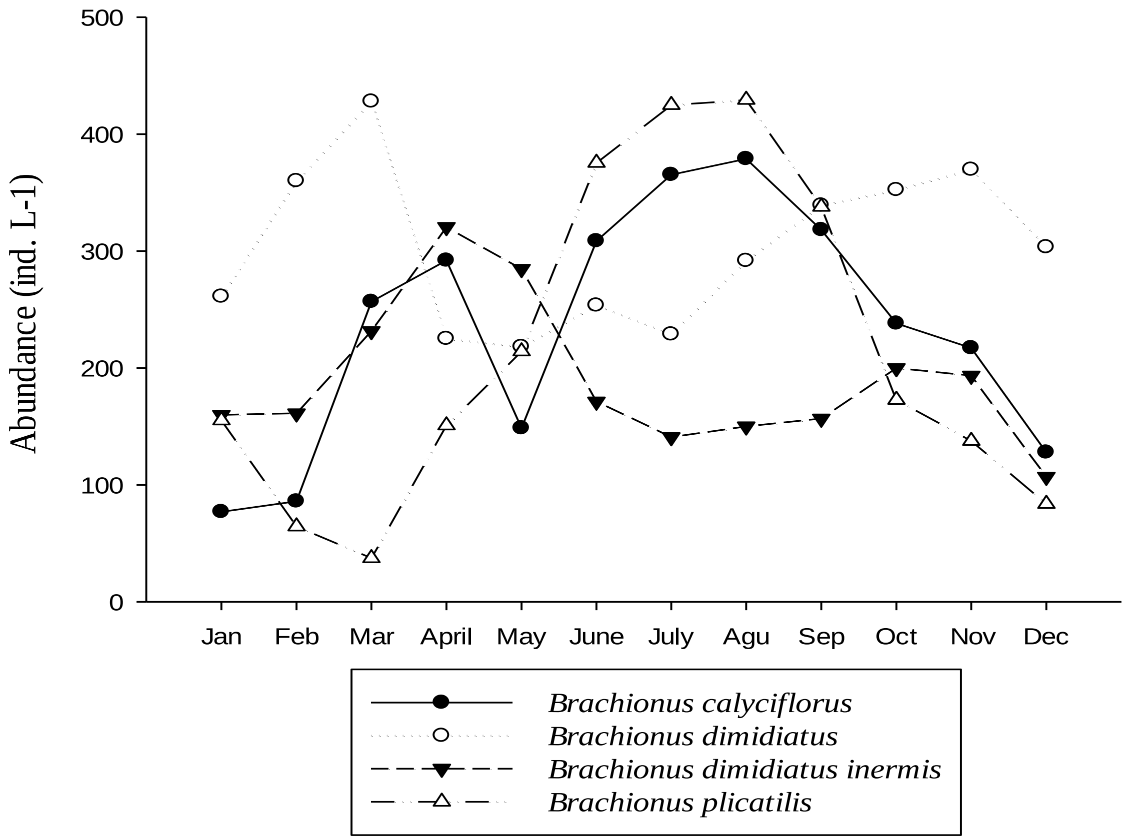


Figure 4.4. Temporal variation of the four dominant rotifer species in Lake Shala from January to December 2018.

For most of the study period, rotifers accounted for the largest fraction of zooplankton densities (86.3%) and contributed 36.8% (DW) of the total zooplankton biomass (Table 4.3). The mean total biomass of rotifers for the investigation period was 71.05 µg L^{-1} dry weight. Remarkably, *B. plicatilis*, *B. dimidiatus*, and *B. calyciflorus* accounted for the largest fraction of the rotifer biomass in the lake (Table 4.3). The mean total biomass of copepods and cladocerans was 88.36 µg L^{-1} and 7.5 µg L^{-1} dry weight which contributed 45.7% and 3.9% to the total zooplankton biomass, respectively (Table 4.3). The mean total biomass of nauplii was 26.29 µg L^{-1} and accounted for 13.6% (DW) of the total biomass (Table 4.3).

Table 4.3. Geometric mean biomass (µg L^{-1}) and abundance (ind. L^{-1}) of zooplankton in Lake Shala.

	Mean length (µm)	**Mean abundance (ind. L^{-1})**	**FW (µg ind^{-1})**	**DW (µg ind^{-1})**	**Mean DW (µg L^{-1})**
Rotifera					
Anuraeopsis fissa	74.58	0.6	0.0033	0.033	0.00198
Anuraeopsis navicula	78.61	0.9	0.0038	0.038	0.00342
Brachionus angularis	88.27	12.2	0.0122	0.122	0.14884
Brachionus budapestinesis	95.8	3.8	0.017	0.1662	0.0646
Brachionus calyciflorus	172.6	234.5	0.065	0.653	15.2425
Brachionus caudatus	154.7	0.13	0.048	0.478	0.00624
Brachionus dimidiatus	168.7	302.7	0.061	0.61	18.4647
Brachionus dimidiatus inermis	125.88	189.7	0.017	0.168	3.2249
Brachionus falcatus	127.94	0.01	0.037	0.371	0.00037
Brachionus plicatilis	196.48	214.3	0.134	1.34	28.7162
Brachionus quadridentatus	194.8	6.6	0.3	3.001	1.98
Brachionus rubens	175.9	11.3	0.103	1.029	1.1639
Brachionus urceolaris	201.47	7.5	0.21	2.07	1.575
Filinia pejleri	138.52	0.1	0.028	0.279	0.0028
Hexarthra spp	138.9	0.3	0.037	0.37	0.0111
Keratella tropica	120.01	0.5	0.041	0.4045	0.0205
Lecane hastate	89.24	0.1	0.017	0.17	0.0017
Lecane bulla	136.5	0.07	0.056	0.56	0.00392
Lecane luna	116.8	0.07	0.046	0.46	0.00322
Polyarthra spp	127.35	0.1	0.037	0.37	0.0037
Trichotria tetractis	154.82	1.4	0.061	0.605	0.0854
Trichocerca sp.	186.4	3.2	0.102	1.02	0.3264
Testudinella patina trilobata	94.2	0.5	0.006	0.06	0.003
		990.9			**71.05**
Copepoda					
Afrocyclops gibsoni	949.57	9.2	1.46	14.6	13.432
Argulus africanus		0.2			
Eucyclops serrulatus	1054.72	5.6	6.8	68	38.08
Nitocra lacustris	475.28	1.02	0.45	4.5	0.459
Thermocyclops ethiopiensis	928.63	5.8	2.72	27.2	15.776
Thermocyclops oblongatus	1054.76	5.3	3.89	38.9	20.617
		125.2			**88.36**
Cladocera					
Diaphanosoma excisum	666.77	1.7	1.79	17.9	3.043
Moina belli	185	0.8	0.65	6.5	0.52
Moina micrura	627.3	2.4	1.64	16.4	3.936
		4.9			**7.5**
Nauplii	205.66	**125.2**	0.21	2.1	**26.29**
Total Mean		**1148.2**			**193.2**

4.4.3. Spatial and Seasonal Distribution of Zooplankton

The spatial and seasonal variations in the abundance of zooplankton were computed for all the sampling sites and seasons (Tables 4.4 and Tables 4.5). On average SPS site had the highest zooplankton mean abundance of 1,198.5±296.3 ind. L^{-1} followed by SPO (1,145.0±214.8 ind. L^{-1}), SGO (1,109.6±257.4 ind. L^{-1}) and SGS (1,076.6±360.2 ind. L^{-1}) (Table 4.4). However, there was no significant difference in spatial zooplankton abundance among the four stations (**F = 0.395**, $P = 0.757$).

Table 4.4. Spatial variations in zooplankton community abundance (ind. L^{-1}) in Lake Shala.

	Rotifer	**Nauplii**	**Copepoda**	**Cladocera**	**Total Abundance**
SPS	1,020.9±242.9	145.8±84.4	26.4±4.8	5.3±2.0	1,198.5±296.3
SPO	964.6±185.9	148.4±99.4	27.2±5.5	4.8±1.7	1,145.0±214.8
SGS	1,019.7±224.7	87.5±33.4	27.6±5.7	4.8±1.7	1,139.7±222.8
SGO	958.4±249.4	119.0±77.8	27.6±5.7	4.6±1.5	1,109.6±257.4
Mean	990.9±221.7	125.2±79.2	27.2±5.1	4.9±1.7	1,148.2±243.9

The seasonal maximal abundance of zooplankton was observed during the rainy season as 1,438.1±159.5 ind. L^{-1}, and minimum abundance during the dry season as 967.8±209.0 ind. L^{-1}, thus seasonal fluctuation in the zooplankton community was evident ($P < 0.05$) (Table 4.5). Rotifer, naupliar, copepod and cladoceran abundance (ind. L^{-1}) exhibited a significant seasonal pattern, showing a maximum value during the rainy season for rotifers, copepods and cladocerans while nauplii had the highest abundance during post rainy season (Table 4.5; Fig. 4.3).

Table 4.5. Seasonal variations in the abundance (ind. L^{-1}) of zooplankton group.

	Rotifer	**Nauplii**	**Copepoda**	**Cladocera**	**Total Abundance**
Dry	795.5±161.6^{a}	144.3±96.1^{a}	24.8±4.1^{a}	3.1±0.5^{a}	967.8±209.0^{a}
Pre rain	1,021.7±128.1^{b}	66.4±36.3^{b}	26.2±4.7^{a}	4.1±1.0^{b}	1,118..4±142.7^{a}
Rain	1,256.8±97.4^{c}	138.2±85.5^{a}	33.5±1.1^{b}	7.1±0.7^{c}	1,435.5±159.5^{b}
Post rain	889.8±164.5^{ab}	151.8±61.9^{a}	24.2±3.5^{a}	5.3±0.8^{d}	1,071.1±178.2^{a}
Mean	990.9±221.7	125.2±79.2	27.2±5.1	4.9±1.7	1,132.4±281.6

4.4.4. Vertical Distribution of Zooplankton

The vertical distribution and percentage contribution of the zooplankton group in Lake Shala are shown in Figure 4.5. The vertical distribution of zooplankton demonstrated a significant correlation between zooplankton groups and water depth. Overall, zooplankton abundance was highest in the top 10 m of the water column, having its maximum in the surface (1,357. 7 ind. L^{-1}). The average densities of rotifers and nauplii decreased with increasing depth. It attained the highest averages of 712.7 ind. L^{-1} and 504.1 ind. L^{-1} at the surface and it decreased to 1.6 ind. L^{-1} and 39.6 ind. L^{-1} at 15 – 20 m, respectively (Fig. 4.5). The greatest contrast in the distribution and percentage contribution was observed for the copepods and cladocerans, which were concentrated in the mid and deeper layer of the water, respectively (Fig. 4.5). Vertical dissolved oxygen and temperature profile of the lake were determined in the same period (Fig. 4.6). The vertical distribution patterns of zooplankton followed a remarkably similar pattern to that of dissolved oxygen and temperature curves (Fig. 4.5; 4.6).

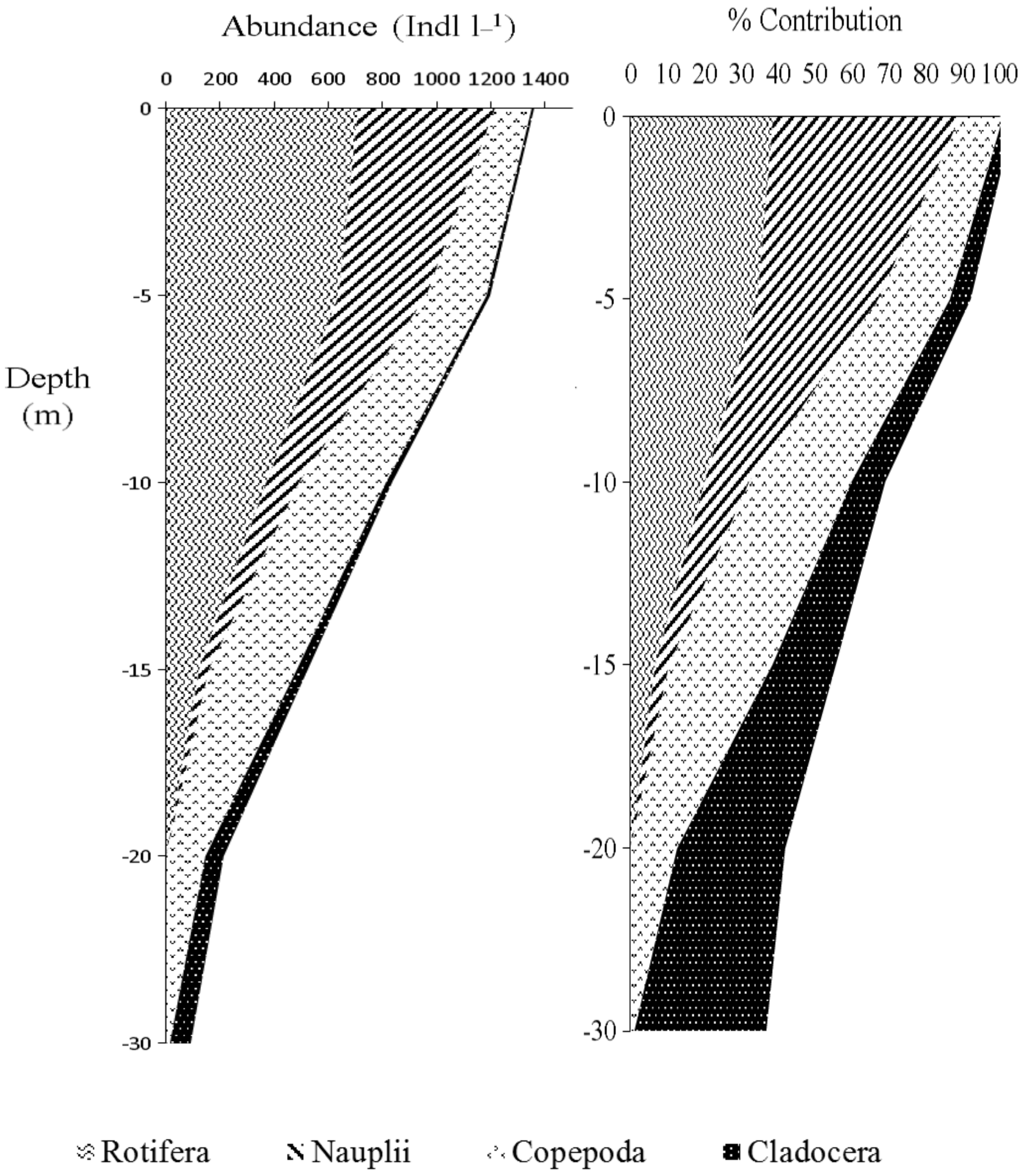


Figure 4.5. Mean vertical distributions of zooplankton in Lake Shala from January to December 2018.

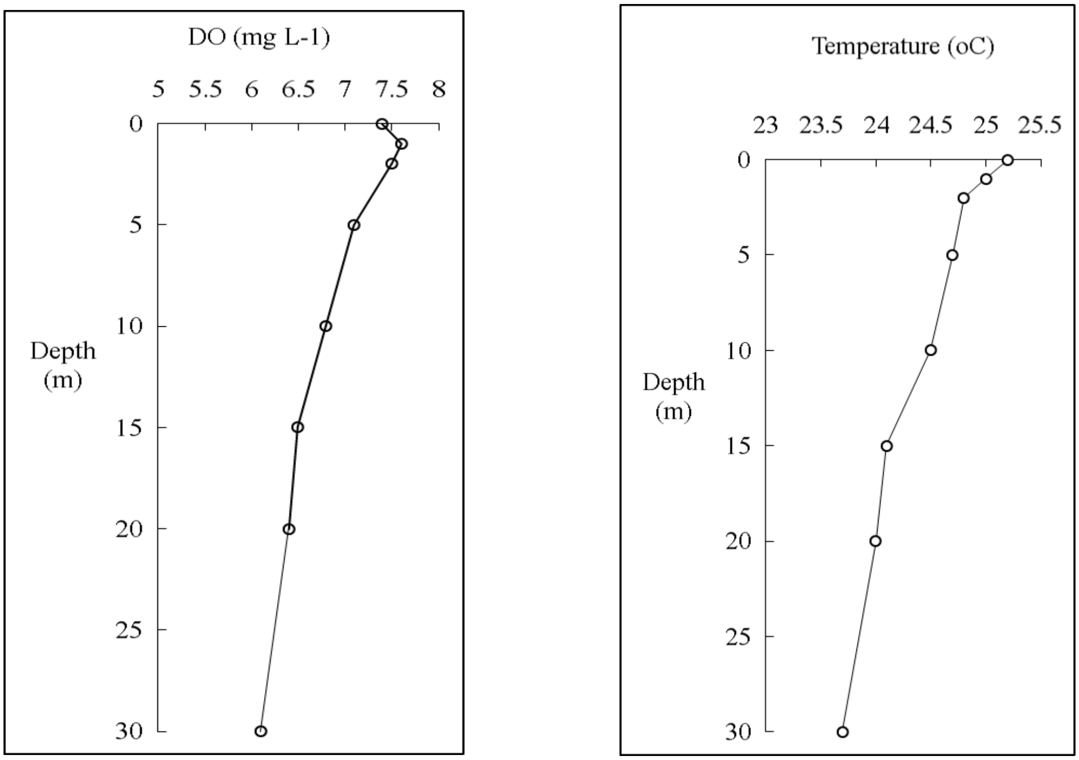


Figure 4.6. Dissolved oxygen (DO) and Water temperature depth profile of Lake Shala from January to December 2018.

4.4.5. Zooplankton Species and Environmental Variables

The Redundancy Analysis (RDA) indicated that the first two axis contributed 94.5% of the total variance in species data (axis-1, 73.5%; axis-2, 20.9%). Some zooplankton species were associated with environmental variables: (i) *Brachionus angularis, B. urceolaris, B. plicatilis, Thermocyclops ethiopiensis*, and *Diaphanosoma excisum*, highlighted on the right-hand side were associated with high levels of SRP (0.51), NH_3-N (0.61), NO_3-N (0.76), TP (0.75) and macro-invertebrate, and negatively correlated with salinity (-0.89) and electrical conductivity (-0.86) (Fig. 4.7, Table 4.6); (ii) *Brachionus dimidiatus, B. rubens, B. quadridentatus* and *Thermocyclops oblongatus* were positively correlated with alkalinity (0.83), *Chl-a* (0.98), phytoplankton abundance (0.97), pH

(0.88) and fish pressure (0.93) (Fig. 4.7, Table 4.6); (iii) *Moina belli*, *M. micrura*, *Afrocyclops gibsoni*, *Eucyclops serrulatus* and nauplii shown on the left-hand side were associated with salinity, electrical conductivity and dissolved oxygen (Fig. 4.7); (iv) *Brachionus dimidiatus inermis* and *B. calyciflorus* were positively correlated with temperature (Fig. 4.7). In addition, most species shown in the upper half of the tri-plot were negatively correlated with salinity and EC (Fig. 4.7).

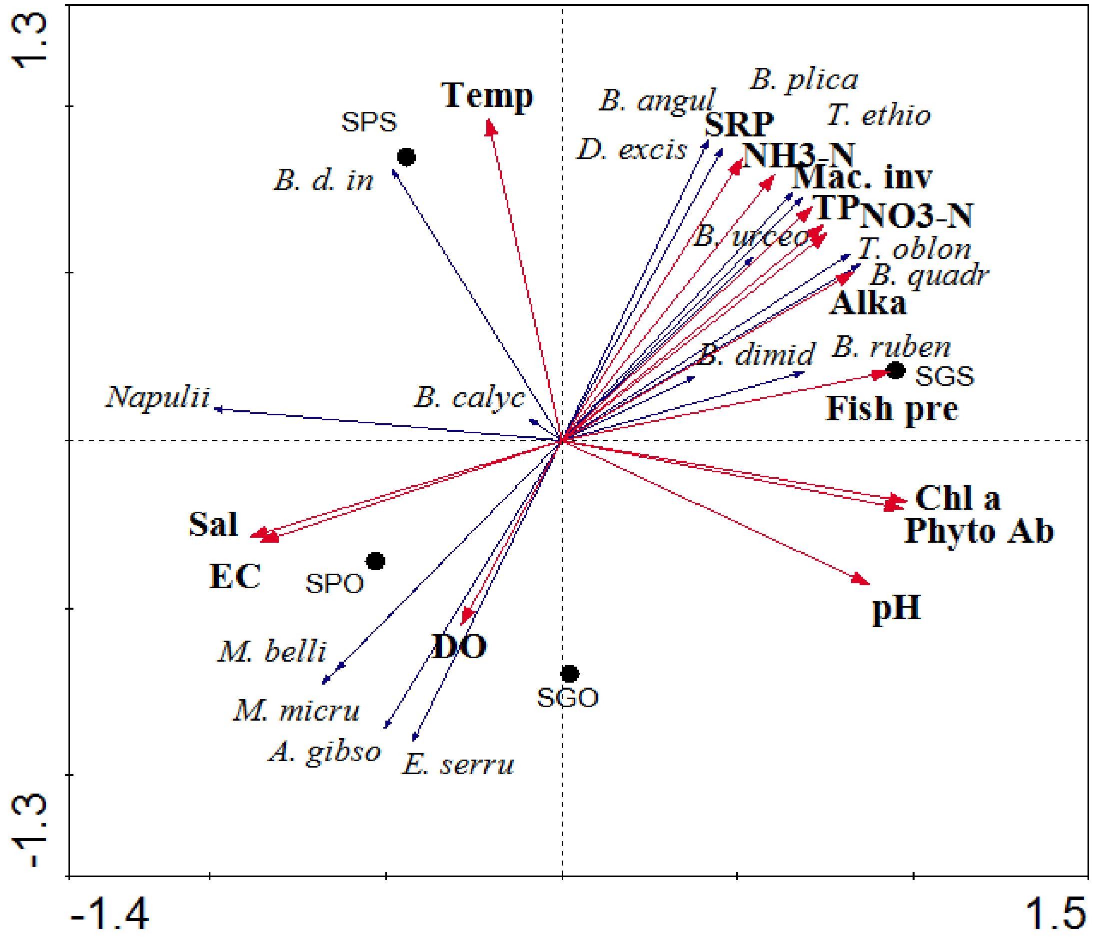


Figure 4. 7. Redundancy analysis (RDA) triplot of zooplankton species in relation to environmental variables and sites *(E. serru. - Eucyclops serrulatus, A. gibso. - Afrocyclops gibsoni, M. micru. - Moina micrura, M. belli. - Moina belli, B. calyc. -*

Brachionus calyciflorus, B.d. in. - Brachionus dimidiatus inermis, D. excis.- Diaphanosoma excisum, B. angul.- Brachionus angularis, T. ethio. - Thermocyclops ethiopiensis, B. plica. - Brachionus plicatilis, B. urceol. - Brachionus urceolaris, T. oblong. - Thermocyclops oblongatus, B. quadr.- Brachionus quadridentatus, B. dimid. - Brachionus dimidiatus, B. ruben. - Brachionus rubens, SPS-Shala Park Shore; SPO-Shala Park Open; SGS-Shala Gike Shore; SGO-Shala Gike Open; Alka-Alkalinity; *Chl-a* - Chlorophyll; Phyto Ab - Phytoplankton Abundance)

Table 4.6. Correlation table of environmental variables with the first two axis (strong correlations are marked bold).

Axes	**1**	**2**
Eigenvalues	0.74	0.21
Cumulative percentage variance of species- environment relation	73.7	94.5
pH	**0.88**	-0.43
Temp	-0.21	**0.96**
EC	**-0.86**	-0.30
Sal	**-0.89**	-0.29
DO	-0.29	-0.56
Alka	**0.83**	0.50
NO_3-N	**0.76**	0.62
NH_3-N	0.61	**0.79**
TP	**0.75**	0.64
SRP	0.51	**0.84**
Chl a	**0.98**	-0.18
Phyto Ab	**0.97**	-0.20
Fish predation	**0.93**	0.21
Macroinvertebrate abundance	**0.71**	0.70

4.5. Discussion

4.5.1. Zooplankton Species Composition, Abundance and Biomass

Species in endorheic saline-alkaline lakes are adapted to considerable variability of water chemistry, particularly salinity, temperature, and conductivity (Burian, 2010; Gülle *et al.*, 2010). In Lake Shala, thirty-two species of zooplankton were recorded and exhibited typically tropical saline inland water euryhaline biotic forms (Derry *et al.*, 2003; Burian, 2010; Okoth *et al.*, 2011; Geoffrey *et al.*, 2013). In the present study, euryhaline rotifers and crustaceans such as *Brachionus dimidiates, B. plicatilis, B. calyciflorus, Afrocyclops gibsoni, Eucyclops serrulatus, Thermocyclops oblongata*, and *T. ethiopiensis* inhabited the lake. These rotifers and crustacean species are cosmopolitan and broadly distributed given their broad tolerance to salinity (Derry *et al.*, 2003; Echaniz *et al.*, 2006; Okoth *et al.*, 2011).

During the study period, rotifers comprised 71.9% of the total zooplankton composition, while copepods and cladocerans contributed 18.8% and 9.4% of the composition, respectively. Among the rotifers, the family Brachionidae contributed the most significant percentage to the total zooplankton composition. This observation agrees with the finding of Kassahun Wodajo and Amha Belay (1984) in Lake Abijata and Burian *et al.* (2014) in Lake Nakuru. On the other hand, the species richness of cladocerans was low, according to Afonina and Tashlykova (2018) this group is typical of freshwater, and most species do not tolerate high salinity and electrical conductivity. In EARV Soda Lakes, species richness and composition are correlated positively with salinity (Seyoum Mengistou, 2016). The species richness of cladocerans decreases with increasing levels of salinity and electrical conductivity of the water body (Diego *et al.*, 2015). High salinity and EC in Lake Shala also restricted the diversity of cladocerans species. This agrees with the observations of Kassahun Wodajo and Amha Belay (1984) and Geoffrey *et al.* (2013), who reported low or no record of cladoceran diversities in soda lakes due to high electrical conductivity and salinity, which limits osmoregulation capacity, reduce reproductive and survival rates of cladocerans (Tavsanoglu *et al.*, 2015; Afonina and Tashlykova, 2018).

The zooplankton species diversity index indicated that rotifers ranked first in terms of Shannon Weiner diversity index (H') and species richness (Taxa_S) of Lake Shala. The significant diversity of rotifers represents a characteristic of tropical lakes (Waya *et al.*, 2014; Umi *et al.*, 2018). The high diversity of rotifers is related to their ability to survive in harsh environments (Burian, 2010). Okogwu *et al.* (2010) noted that rotifers are more tolerant of adverse environmental conditions, which enabled them to flourish in tropical lakes than cladocerans and copepods (Okogwu *et al.*, 2010; Okoth *et al.*, 2011; Umi *et al.*, 2018). Their unspecialized feeding (Joseph and Yamakanamardi, 2011) also enables them to ingest microscopic particles like bacteria often abundant in saline-alkaline environments (Lanzen *et al.*, 2013; Geoffrey *et al.*, 2013).

Despite the low phytoplankton biomass of Lake Shala (**Chapter three**), high zooplankton species diversity was recorded compared to Kenyan and Ethiopian saline-alkaline lakes (**Table 4.7**). Zooplankton diversity in saline Rift valley lakes such as Lake Abijata (17 species) (Kassahun Wodajo and Amha Belay, 1984), Lake Nakuru (9 species) (Okoth *et al.*, 2011), and Lake Chitu (5 species) (Seyoum Mengistou, 2016) were recorded. However, the number of zooplankton taxa recorded in Lake Shala in the present study was lower than reported in Lake Old Fort (Arora and Mehra, 2009) (**Table 4.8**). These variations might be due to the trophic status and ecological structures of the aquatic systems, level of nutrients, variations in electrical conductivity, development in the growth and biomass of phytoplankton, climate zones, and the mixing nature of the lake water (Bozkurt and Akın, 2012; Tavsanoglu *et al.*, 2015).

Table 4.7. Zooplankton species composition of Lake Shala and other saline-alkaline aquatic ecosystems.

Lake	Copepod	Cladoceran	Rotifers and Ciliate	Total	Source
Abijata	4		13	17	Kassahun Wodajo and Amha Belay (1984)
Chitu			5	5	Seyoum Mengistou (2016)
Nakuru			9	9	Okoth *et al.* (2011)
Burdur	3		3	6	Gülle *et al*. (2010)
Ojo de Agua Uriburu	1	2	3	6	Vignatti *et al.* (2017)
Meke	2	4	11	17	Tavsanoglu *et al.* (2015)
Acı	2	2	9	13	Tavsanoglu *et al.* (2015)
Old Fort	1	5	46	52	Arora and Mehra (2009)
Shala	**6**	**3**	**23**	**32**	Present study

Zooplankton abundance estimated in Lake Shala was similar to findings reported in Lake Ziway (Adamneh Dagne, 2008) and Lake Tinishu Abaya (Yirga Enawgaw and Brook Lemma, 2018) in Ethiopian Rift valley lakes. However, zooplankton abundance in the present study was lower (with the average abundance of 1,148.2±243.9 ind. L^{-1}) compared to values commonly found in certain saline-alkaline lakes such as Lake Kivu in Great Rift lakes of Eastern Africa (Isumbisho *et al.*, 2006), Lake Burdur in Turkey (Gülle *et al.*, 2010) and Lake Nakuru and Bogoria in Kenya (Burian, 2010; Okoth *et al.*, 2011). These differences in zooplankton abundance among lakes are attributed to patchiness in resource distribution within the lake and the effects of other factors such as physico-chemical parameters (Yongo and Outa, 2017).

In the present study, small-sized rotifers were numerically dominant in the zooplankton population with a significant difference. Similarly, comprehensive studies on the distribution of zooplankton size groups in saline lakes were done, and some studies reported the dominance of small-sized zooplankton taxa (Echaniz *et al.*, 2006; Burian, 2010; Gülle *et al.*, 2010; Okoth *et al.*, 2011; Geoffrey *et al.*, 2013; Seyoum Mengistou, 2016). The dominance of rotifers in Lake Shala is comparable to observations in many saline-alkaline lakes such as Lake Abijata (Kassahun Wodajo and Amha Belay, 1984; Green and Seyoum Mengistou, 1991), Lake Bogoria (Burian, 2010) and Lake Nakuru (Burian, 2010; Okoth *et al.*, 2011). The leading factors to explain this dominance by rotifers are attributed to fast reproductive rates and developmental stages (Nandini *et al.*, 2007; Yin *et al.*, 2016). Further, small-sized rotifers tolerated a wide range of salinity and electrical conductivity (Echaniz *et al.*, 2006; Okoth *et al.*, 2011). Anton-Pardo *et al.* (2012), also suggested that the low abundance and diversity of cladocerans in saline lakes promotes the development of rotifers.

Among the rotifers, *B. dimidiatus*, *B. dimidiatus inermis, B. plicatilis* and *B. calyciflorus* are dominant (**Fig 4.4**. **Table 4.3**). Similar observations have also been made from the other saline lakes (Kassahun Wodajo and Amha Belay, 1984; Green and Seyoum Mengistou, 1991; Burian, 2010; Okoth *et al.*, 2011). However, the relative contribution of cladocerans, *M. micrura* (2.4 ind. L^{-1}) and *D. excisum* (1.7 ind. L^{-1}) to the zooplankton were low compared to the densities of *M. micrura* (30 ind. L^{-1}) in Lake Ziway (Adamneh Dagne *et al.*, 2008) and 18 ind. L^{-1} in Lake Awassa (Seyoum Mengistou and Fernando, 1991) and 13 ind. L^{-1} in Lake Ziway (Adamneh Dagne *et al.*, 2008) for *D. excisum*. This variation might be caused by salinity differences among the lakes. It is well known that salinity has a negative influence on the diversity and abundance of zooplankton due to their limited osmoregulation capacity (Derry *et al.*, 2003; An *et al.*, 2012; Tavsanoglu *et al.*, 2015). Particularly, cladocerans are sensitive to salinity changes for salinities above 3.5‰ restricted the survival of most large-bodied cladocerans (Gülle *et al.*, 2010; Afonina and Tashlykova, 2018).

In the present study, the mean biomass of zooplankton was 193.2 μg.dw.L^{-1} (= 193.2 mg.dw.m^{-3}). This is low compared to the result obtained from Lake Nakuru (64,384 mg.dw.m^{-3}) (Vareschi and Jacobs, 1984), Northern Gulf of Aqaba (213.05 mg.dw.m^{-3}) (Al-Najjar and Mohsen M., 2008), Lake Capivara (265,740 μg.dw.m^{-3}) and Lake Osmar (252,993 μg.dw.m^{-3}) (Bonecker *et al.*, 2011) and Lake Hayq (236.4 mg.dw.m^{-3}) (Tadesse Fetahi *et al.*, 2011). While this value was more significant than the mean biomass reported by Seyoum Mengistou and Fernando (1991) from Lake Awassa (44.85 mg.dw.m^{-3}) and Lake Ziway (133.5 mg.dw.m^{-3}) (Adamneh Dagne *et al.*, 2008). These variations in zooplankton biomass among the lakes might be due to differences in food quality and quantity, predation pressure, phytoplankton diversity, pollution status of the lake (Bonecker *et al.*, 2011; Voutilainen *et al.*, 2016). Zakaria *et al.* (2018) also reported that temperature and salinity are the essential factors affecting the size and biomass of zooplankton in different water systems.

4.5.2. Spatial and Seasonal Patterns in the Zooplankton Community

Even though significant differences in environmental factors such as physicochemical parameters and phytoplankton densities (**Chapter Two and Three**) were recorded in four sampling stations, zooplankton abundance did not show significant difference among sampling stations. The relative zooplankton abundance homogeneity among sites of Lake Shala follows the findings of Nandini *et al.* (2008) in the Valle de Bravo reservoir, Brazil. However, Adamneh Dagne *et al.* (2008) and Yongo and Outa (2017) found the strongest horizontal gradients in large-bodied zooplankton. In the present study, the observed lack of horizontal or spatial distribution is not a surprise since the lake is dominated by small-bodied taxa and juvenile ontogenetic stages which have low susceptibility to predation and coupled with the low locomotory ability explains a lack of spatial variations in distribution. The physical structure of Lake Shala is also distinguished by high wind mixing in the afternoon, which could have a significant contribution to the lack of horizontal variations in zooplankton distribution by ensuring horizontal food availability throughout the mixolimnion.

Several studies on other saline-alkaline lakes documented seasonal variations in zooplankton abundance (Kassahun Wodajo and Amha Belay, 1984; Derry *et al.*, 2003; Gülle *et al.*, 2010; Okoth *et al.*, 2011; Afonina and Tashlykova, 2018). These studies were on deep, oligotrophic lakes such as Lake Burdur (Gülle *et al.*, 2010), and shallow alkaline–saline lakes of Ethiopia (Lake Abijata) (Kassahun Wodajo and Amha Belay, 1984) and Kenya (Lake Nakuru and Bogoria) (Burian, 2010; Okoth *et al.*, 2011). The above mentioned authors observed a clear seasonality pattern in the abundance of different zooplankton taxa. The present study also exhibited seasonal variations with the increasing trend during the rainy season, similar to the observed rise of phytoplankton densities and biomass (**Chapter Three**), which resulted in greater abundance and possibly quality of edible resources (Nandini *et al.*, 2008; Arora and Mehra, 2009; Joseph and Yamakanamardi, 2011). Okoth *et al.* (2011) and Gülle *et al.* (2010) also observed the highest zooplankton abundance during periods of long rains in saline-alkaline lakes of Nakuru and Burdur.

4.5.3. Vertical Distribution of Zooplankton

Vertical distribution of zooplankton has been studied in various deep lakes (e.g. Gülle *et al.*, 2010). Usually, zooplankton shows distinct vertical distribution rather than being homogeneously distributed through the water column. During the present study, the vertical distribution of different zooplankton taxa was concentrated in various zones (0-5 m; 5-10 m; 10-20 m and 20-30 m), nevertheless, the most concentrated region was between 0-15 m ($P < 0.05$). Most zooplankton densities that exist in the upper 15 meters (euphotic layer) of Lake Shala may be due to the abundance of phytoplankton. Gutkowsk *et al.* (2018), discussed and indicated a strong positive correlation between phytoplankton and zooplankton population densities in Vistula Lagoon and Lake Łebsko. According to the above author, the phytoplankton abundance and biomass showed a pronounced high occurrence in the euphotic zone than in the non-euphotic layer, which resulted in a dense zooplankton population. Moreover, surface water temperatures in Lake Shala are tropical, whereas the minima remain high enough to allow zooplankton production to proceed (Burian, 2010; Okoth *et al.*, 2011).

Conversely, during the persistent mixing due to partial atelomixis, zooplankton prefers the mixing epilimnion (mixolinion) and this indicates that food conditions are optimal in this water column, apparently due to frequent diurnal partial atelomictic mixing, which suspends food particles like phytoplankton, protozoans, and bacteria freely in the upper zone of the water column and allows a rapidly growing zooplankton population in Lake Shala, as occurs in other deep tropical lakes after atelomixis (Ciros-Pérez *et al*., 2001; Fasil Degefu and Schagerl, 2015). Rotifers and nauplii in particular may experience rapid population peaks if food resources increase due to frequent mixing and contributing to the unpredictable rises in population abundance (Ciros-Pérez *et al*., 2001; 2015). Ortega-Mayagoitia *et al*. (2011) also verified that opportunistic genera of rotifers especially *Brachionus* are able to take advantage over increasing food availability for their growth. Other important factors that explain variations in zooplankton abundance could be light-related tolerance factors, oxygen saturation, competition, and predation (Williamson *et al*. 2020). According to Ciros-Pérez *et al*. (2015), copepods and cladocerans migrated to the zone with very low levels of visible light in a deep tropical oligotrophic lake.

The most notable occurrence of rotifers and nauplius was detected as the most dominant species in 0 - 10 m depth throughout the year and their densities decreased with increasing depth (**Fig. 4.5**). These differences were significant for rotifers (**F = 17.65, *P* = 0.00, ANOVA**) and nauplius (**F = 28.898, *P* = 0.00, ANOVA**) between the various sampling depth. Rotifers attained their highest densities year-round due to the flourishing of *Brachionus* species which can tolerate high temperature, salinity, and electrical conductivity. In addition, low phytoplankton biovolume and species composition and anoxic conditions due to a decrease in temperature with depth attributed to the reduced densities of rotifers and nauplii with an increase in depth (Gülle *et al.*, 2010). In this study, the phytoplankton composition and *Chl-a* biomass in relation to the depth was not assessed but a reduction and variance distribution of phytoplankton and *Chl-a* biomass occur in relation to depth (Nandini *et al.*, 2008; Voutilainen *et al.*, 2016). This finding is concordant with Isumbisho *et al.* (2006) in Lake Kivu and Gülle *et al.* (2010) in Lake Burdur, which reported that rotifers and nauplii larvae inhabited the surface layer (1-10) and the lower depth by copepods and cladoceran.

In this study, the vertical distribution patterns of zooplankton were similar to that of dissolved oxygen and temperature depth profiles (**Fig. 4.5 & Fig. 4.6**). copepods and cladocerans are known to migrate vertically even in the lower oxygen zone (Dimante-Deimantovicaa *et al.*, 2012; Voutilainen *et al.*, 2016). In this study, the abundance of copepods (**F = 19.899, *P* = 0.00, ANOVA**) and cladocerans (**F = 11.908, *P* = 0.00, ANOVA)** were different among the sampling depth and the deepest region had the highest densities. This might be attributed to the variations in dissolved oxygen and temperature with depth. This is supported by findings from various authors (Isumbisho *et al.*, 2006; Gülle *et al.*, 2010) who reported depth, dissolved oxygen, temperature and their feed-feeding relations as a key factor governing changes in zooplankton abundance. Also, copepods and cladocerans were found in deeper water column because of their inability to tolerate the light intensity on the surface compared to the depths (Gülle *et al.*, 2010; Khitam *et al.*, 2017) and this can also explain the increase in the total densities in the depths compared to the surface.

4.5.4. Driving Factors of Zooplankton Abundance and Distribution

By comparing the zooplankton community structure with environmental factors, the zooplankton community varied significantly as biotic and abiotic factors changed between different sampling stations. *Chl-a*, phytoplankton abundance, pH, alkalinity, and TP, reached the highest values at Shala Gike Station (SGS), where we find abundant *B. dimidiatus*, *B. rubens*, *B. quadridentatus*, and *Thermocyclops oblongatus* species. Temperature, NH_3–N and SRP were also positively correlated with zooplankton abundance, which contributes to the high abundance of *D. excisum*, *Thermocyclops ethiopiensis*, *B. urceolaris*, *B. budapestinesis*, and *B. plicatilis*. Several earlier studies have also confirmed that abiotic and biotic factors such as temperature, nutrients (N and P), SiO_2, pH, ionic concentrations, and predation influence, directly or indirectly, the distribution and abundance of zooplankton species (Derry *et al.*, 2003; Waya *et al.*, 2014; Tavsanoglu *et al.*, 2015).

The present study showed that the zooplankton community structure is generally influenced by EC and most of the zooplankton species were found against electrical conductivity. Gülle *et al.* (2010) and Afonina and Tashlykova (2018), also pointed electrical conductivity (salinity) as one of the several factors responsible for the structure of zooplankton communities in saline-alkaline lakes. Its impact can be strongly modified by other factors, and there are also indirect mechanisms by which it may exert its effects e.g., by imposing osmoregulatory stress, influence the availability of feed, or inducing migrations of organisms trying to evade high or low salinity and impact on the abundance of the zooplankton population (Perumal *et al.*, 2009.; Afonina and Tashlykova, 2018; Gutkowsk *et al.*, 2018).

4.5.5. Long-term Trends of Zooplankton Changes in Deep Tropical Lake Shala

A few studies have been carried out on the zooplankton of Lake Shala (Defaye, 1988; Green and Seyoum Mengistou, 1991; Seyoum Mengistou, 2016). A comparative checklist of species recorded during the present and previous studies in Lake Shala is presented in **Table 4.8.** The total zooplankton taxa reported by Defaye (1988), Green and Seyoum Mengistou (1991), and Seyoum Mengistou (2016) were 1, 4, and 9, respectively and while compared with the present study most species are still present. The number of rotifer species (23) is greater than that of the previous reports (3 or 7) by Green and Seyoum Mengistou (1991) and Seyoum Mengistou (2016). Simultaneously, previous researchers collected samples irregularly and used different mesh size net (64 and 55µm), since rotifer species have a short life span, longer sampling intervals might have caused such rotifer species to be missed. But still, there are some species (*B. dimidiatus, B. plicatilis, B. urceolaris, B. angularis, L. bulla*, and *L. luna*) that were recorded by all the authors. Further, Cladocerans (*D. excisum* and *M. micrura*) were unrecorded in earlier studies but recorded recently which may be due to differences in methodology, large number of samples collected, and inclusion of open water system and deep species.

The zooplankton community structure of Lake Shala has also changed over time. Tudorancea and Taylor (2002) and Seyoum Mengistou (2016) reported benthic harpacticoids (*Nitocra lacustris*) as dominant species from Lakes Shala. However, in the current study, *Nitocra lacustris* were replaced by small-bodied and generalist-feeders rotifers (genus *Brachionus*) as the dominant taxa within all sampling sites and seasons. The notable absence of dominance of the benthic harpacticoids in Lake Shala might indicate the presence of ecological or major habitat shifts in the lake over the years. Also, the shift might be due to several reasons including the changes in the water chemistry of the lake (**Chapter Two**). Various studies in East African soda lakes revealed that plankton community structure changes in relation to water chemistry (Schagerl and Oduor, 2008; Tadesse Ogato and Demeke Kifle, 2017). Also, sampling material difference (plankton nets in the present study and only Ekman grab by Tudorancea and Taylor (2002)), may responsible for this phenomenon. Zooplankton community shift may also be associated with 'atelomixis' changes brought about by unusual mixing behavior in deep, tropical lakes (Tadesse Fetahi *et al*., 2011; Fasil Degefu and Schagerl, 2015).

Table 4.8. List and number of zooplankton taxa reported from Lake Shala.

Taxon	Defaye (1988)	Green & Seyoum Mengistou (1991)	Seyoum Mengistou (2016)
Cyclopoida (Copepoda)	*Thermocyclops ethiopiensis*		
Harpacticoida (Copepoda)			*Nitocra lacustris*
Cladocera			*Moina belli*
Rotifera		*Brachionus dimidiatus* *B. plicatilis* *Hexarthra jenkinae* *Lacinularia elliptica*	*B. dimidiatus* *B. plicatilis* *B. urceolaris* *B. angularis* *Lecane luna* *L. bulla* *Trichocerca tetractis*
	N = 1	**N = 4**	**N = 9**

Chapter Five: Macro-invertebrate Diversity and Abundance in Lake Shala, a Tropical Soda-lake, Ethiopia

5.1. Introduction

5.1.1. Background

Benthic macro-invertebrates are the most diverse and abundant organisms in aquatic ecosystems (Kratzer, 2002) and are key components for various reasons. First, they play a key role in understanding the structure and functioning of aquatic ecosystems as they have a wide distribution and limited migration ability (Barbour *et al.*, 1999). Also, they are a primary food source for many fish species, amphibians, and birds forming an important trophic link (Voshell, 2002) in the aquatic ecosystem. Due to the several attributes that make them particularly preferable (Marzin, 2013), benthic macroinvertebrates have been also widely used in biomonitoring programs. They are indicators of the status of water quality in their environment and have been used in many parts of the world to access and monitor water quality (Tarekegn Wondmagegn and Seyoum Mengistou, 2020).

Because of the significant role they play and the increasing anthropogenic effect of the aquatic ecosystems, understanding macro-invertebrate community structure and their relation to environmental factors are crucial for integrated management practices. Their use in biomonitoring indicates the fact that abundance and diversity of macro-invertebrates are affected by myriads of local environmental conditions like habitat structural complexity and physicochemical characteristics of water (Muli, 2005; Elias *et al.*, 2014). For instance, in soda lakes, where most of the physicochemical characteristics are hostile i.e. high pH, high salinity, and high alkalinity (Matagi, 2004), very few organisms that have evolved mechanisms to tolerate the extreme conditions would be expected to survive (Mutanga *et al.*, 2000). Hence, it becomes evident that any ecological change in the internal and external lake conditions will lead to drastic changes in the specialized biota of such ecosystems, especially to loss and decimation.

In Ethiopia, nowadays, limnological studies are getting attention particularly from higher education institutions and scientific communities in the field. But mostly, attention has focused on documenting the changes in the diversity of plankton (Mesfin Gebrehiwot *et al.*, 2017), fish (Mulugeta Wakjira, 2016) and the physicochemical properties (Berhan Teklu *et al.*, 2018) of freshwater ecosystems. So far, as compared to the other aquatic organisms, few studies have been conducted on macro-invertebrate ecology including their role in biomonitoring (Aschalew Lakew and Moog, 2015), their ecology in association with macrophytes (Wondie Zelalem *et al.*, 2017) and their abundance and distribution (Tilahun Kibret and Harrison, 1989).

In comparison with the freshwater bodies, soda lakes of Ethiopia have been given less attention regarding their macro-invertebrate ecology and hence there is a paucity of quantitative data on the abundance and diversity of benthos for the soda lakes. This might be due to their hostile nature, and so they are often remote from the main centers of human activity (Seyoum Mengistou, 2016). But recently, development activities are threatening these lakes and one simple example is Lake Abijata on the verge of total drying mainly due to soda ash production and drying of the inflowing Bulbula River due to irrigation schemes (Brook Lemma and Hayal Desta, 2016). There is also a plan to establish a soda ash production plant on nearby Lake Shala which may end with the same fate as that of Lake Abijata. But, for Lake Shala, historical documentation of benthic diversity is not comprehensive enough to demonstrate changes and trends of benthic diversity. Only one study was conducted by Tudorancea and Harrison (1988) in 1985 based on a one-time sampling and there is a need to update the information through intensive all-year-round sampling. Therefore, this study was conducted on Lake Shala to test the following hypothesis: the diversity of macro-invertebrate in Lake Shala has not changed over time, mainly because of minimal human impacts in the lake catchment. The spatial and seasonal variation in diversity of the macroinvertebrate taxa was also used to discuss possible ecological stressors around the lake-shore. Therefore, the present study had objectives to prepare a checklist of macroinvertebrates and to assess long-term trends in composition in relation to physicochemical and depth gradient. This baseline data will also be useful for further studies in water quality and biodiversity monitoring.

5.2. Materials and Methods

5.2.1. Site Selection and Macro-invertebrate Sampling

5.2.1.1. Site Selection

Sites for this study were selected based on their accessibility. Based on this criterion, four sites were selected. These sites are described in table 5.1 and displayed in Figure 5.1 below.

Table 5.1. Description of sampling sites.

Site Name	Abbreviation	Habitat type
Shala Park Shore	SPS	Shore site on the park main office side where there are hot springs and different anthropogenic activities like livestock watering, washing clothes, and bathing
Shala Park Open	SPO	Open water site on the park main office side with a depth of around 10 meters
Shala Gike Shore	SGS	Shore site on the side where Lake Chitu is located. Here also there are hot springs and different anthropogenic activities like livestock watering, washing clothes, and bathing.
Shala Gike Open	SGO	Open water site of Shala Gike site with a depth of around 10 meters

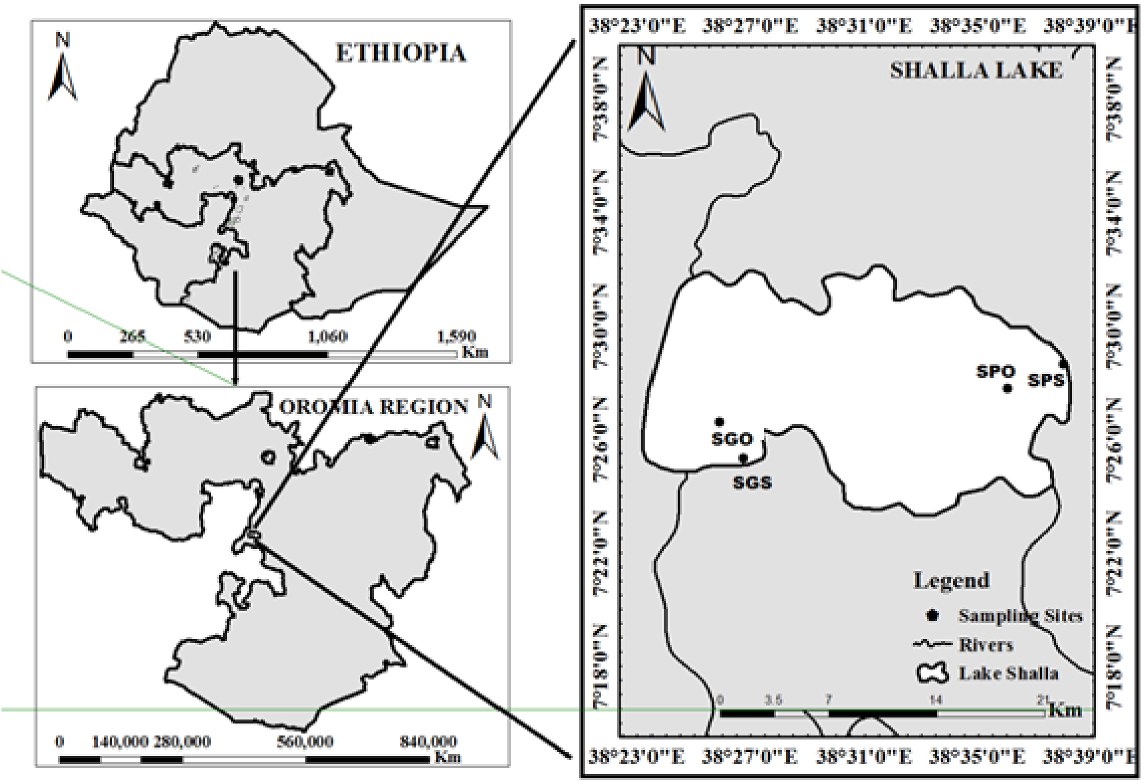


Figure 5.1. Location of sampling sites on Lake Shala (Abbreviation: SPS = Shala Park Shore, SPO = Shala Park Open, SGS = Shala Gike Shore, and SGO = Shala Gike Open)

5.2.1.2. Macro-invertebrate Sampling

Macro-invertebrate sampling was carried out monthly from January to December 2018. From the shore sites, benthic macroinvertebrates were collected based on the method outlined in Ontario Benthos Biomonitoring Network Protocol Manual (Jones *et al.*, 2007). Three transects were established from the water's edge to 1-meter depth (nearly 3 m distance). Then macro-invertebrates were collected along the transects using a 500 μm mesh D-frame (30 cm x 28 cm in diameter) traveling kick net and sampling was actively carried out until at least 100 animals were collected. The three net samples collected at a site were combined to form one composite sample. From the open water sites, triplicate quantitative macro-invertebrate samples were collected (from approximately 10 m depth) using an Ekman Grab with a sampling area of 225 cm^2. Similarly, the three grab samples collected at a site were pooled to form one composite sample. Organisms were separated from sediment and debris using sieves of progressively finer mesh size (20, 2, 1, and 0.5 mm) and a white plastic tray. In the field, specimens were fixed using formalin (10%) and in the Limnology Laboratory of Addis Ababa University, the preservative was replaced by 70% ethanol to prevent hard body parts from dissolving as per the recommendation of Barbour *et al.* (1999). Then before identification, samples were washed through a 500 μm sieve again and were rinsed well with water to remove the preservative, to make the samples suitable for examination.

Plate 5.1. Macro-invertebrate sampling from shore site

As problems of taxonomy should not be a deterrent in biodiversity assessment and biomonitoring studies using diversity indices and biotic indices based on invertebrates, identification to family/genus level is sufficient (Mason, 1991). Therefore, for this study, all the macro-invertebrates were identified and enumerated to the family level using a dissecting microscope and important keys (Clifford, 1991; Jessup *et al.*, 1999; Gooderham and Tsyrlin, 2002; Bouchard, 2004). Then diversity metrics representing richness, composition, diversity, and abundance measures were considered using PAST software.

5.3. Data Analysis

Descriptive statistics were used to analyze physicochemical data. The densities of macroinvertebrates (numbers m^{-2}) per station and month were estimated following the equation (1):

$$D = \frac{\text{ind}}{\text{m}^2} = \frac{\text{Total number of individuals}}{\text{Area of sampling units}} \text{ -------------- } (1)$$

The mean annual densities were calculated from the monthly densities over the whole sampling period. Different aspects of the diversity indices were calculated including taxa richness simply a number of taxa (S), Pielou evenness index: which is expressed following the equation (2):

$$J = H'/H'\max \text{ -------------------------------------- } (2)$$

where H' is the number derived from the Shannon diversity index and H'max is the maximum value of H' and Shannon heterogeneity index calculated using equation (3):

$$H' = -\Sigma pi \ln pi \text{ -------------------------------------- } (3)$$

where pi is the proportion of individuals found in the ith taxon and Equitability expressed following equation (4):

$$\text{Equitability } (E) = H/\ln S \text{ ------------ } (4)$$

Where H was the Shannon-Wiener index, S was the number of species in samples.

Variation in physicochemical parameters and macro-invertebrate diversity measures among sampling sites and seasons were analyzed using one-way Analysis of Variance (ANOVA) and then means were separated using the Tukey-HSD test. Two-way ANOVA was used to test the impact of locality and season interaction on macro-invertebrate assemblages. All statistical tests were performed on Log10(X+1)-transformed data to normalize it. The relationship of macroinvertebrates diversity measures with physicochemical variables was evaluated by redundancy analysis (RDA) using CANOCO for windows 4.5 version Software (Ter Braak and Smilauer, 2002). RDA was used because the species data showed a linear response to the environmental variables and the longest gradient length (1.41) was less than 3 (Detrended correspondence analysis (DCA). To reduce the effect of a rarity on RDA analysis, families that comprised <1% of the organisms at sampling sites were excluded (Kuchapski and Rasmussen, 2015). The statistical analysis was conducted using the R programming language 3.4.2.

5.4. Results

5.4.1. Macro-invertebrate Community

The present study attempted to determine the abundance and diversity of macro-invertebrates in Lake Shala in samples taken from shore sites and sediment in open water stations.

5.4.1.1. Species Composition and Abundance

21 macro-invertebrate taxa belonging to 8 orders were identified. The complete catalogue of the macro-invertebrates found in the lake is displayed in **Table 5.2**. The highest families (7) were recorded in the Order Diptera followed by Gastropoda (4) and Hemiptera (3). The number of taxa at the sites ranged from 18 at Shala Gike Shore to 3 at the Shala Park Open site. Most families were absent from the open water stations and when present, these sites were represented by Diptera (Ceratopogonidae and Chironomidae) and Oligochaeta (Tubificidae and Naididae).

Plate 5.2. Macro-invertebrates sampled from Lake Shala

Table 5.2. Macroinvertebrates collected from the study sites from January to December 2018 (SPS = Shala Park Shore, SPO = Shala Park Open, SGS = Shala Gike Shore, and SGO = Shala Gike Open, "+" = present," –" = absent).

	Study sites			
Taxon Order/Family	**SPS**	**SPO**	**SGS**	**SGO**
Hemiptera (Water or true bugs)				
Corixidae	+	-	+	-
Mesoveliidae	-	-	+	-
Naucoridae	+	-	+	-
Diptera (Two winged / True flies)				
Ceratopogonidae	+	-	+	+
Chironomidae	+	+	+	+
Culicidae	-	-	+	-
Dolichopodidae	-	-	+	-
Ephydridae	-	-	+	-
Syrphidae	-	-	+	-
Tabanidae	-	-	+	-
Coleoptera (Aquatic Beetles)				
Dytiscidae	-	-	+	-
Hydrophilidae	+	-	+	-
Gastropods				
Glacidorbidae	+	-	+	-
Planorbidae	-	-	+	-
Physidae	+	-	+	-
Thiaridae	+	-	-	-
Fish louse (Argulidae**)**	+	-	-	-
Aquatic spider (Arachnida**)**	+	-	+	-
Oligochaeta				
Tubificidae	+	+	+	+
Naididae	-	+	-	+
Megaloptera				
Corydalidae	+	-	+	-
Total taxon per site	12	3	18	4

5.4.1.2. Site-specific Diversity Measures

Site-specific diversity were calculated and ranged from 3 taxa (SPO) to 18 taxa (SGS) (**Table 5.3**). Taxa richness significantly varied among the sampling sites ($P < 0.05$), with the two shore sites having significantly higher taxa richness than the open sites. The abundance of macro-invertebrates among sampling sites ranged from 380 ind./m^2 at SGS to 13,609 ind./m^2 at SPO and significantly varied among sampling sites ($P < 0.05$), the open water sites having value significantly higher than the shore sites. Similarly, the Shannon diversity index ranged from 0.31 at SGO to 0.92 at SGS and significantly varied among sampling sites ($P < 0.05$), the value at the shore sites being significantly higher than the open stations. But equitability and evenness values did not show significant variation among the sampling sites ($P = 0.13$ and $P = 0.06$, respectively) (**Table 5.3**).

Table 5.3. Site-specific macro-invertebrate diversity measures from January to December 2018 (values are mean from 12 months).

Diversity Measures	**Sites**			
	SPS	**SPO**	**SGS**	**SGO**
Abundance/m^2	630^a	13,609^b	380^a	11,783^b
Taxa richness	12^b	3^a	18^b	4^a
Shannon (H’)	0.77^b	0.43^a	0.92^b	0.31^a
Evenness	0.57^a	0.74^a	0.56^a	0.66^a
Equitability (J)	0.59^a	0.55^a	0.61^a	0.39^a

NB: Means within a row followed by the same letter are not significantly different (Abbreviations: SPS = Shala Park Shore, SPO = Shala Park Open, SGS = Shala Gike Shore and SGO = Shala Gike Open)

5.4.1.3. Seasonal Variation

Effect of season and its interaction with locality on macro-invertebrates distribution

Variability in all indices value among sampling sites is stated above in section 5.4.1.2. The mean seasonal abundance of macro-invertebrates in Lake Shala ranged from 5,230 ind/m^2 in the rainy season to 7,553 ind./m^2 in the post-rainy season, but there was no significant variation in the seasonal macro-invertebrate abundance ($P = 0.50$). The mean Shannon diversity index value of the lake was 0.50 in the dry season, increased to 0.76 in the rainy season and had fallen to 0.57 in the post-rainy season. The value showed significant variation among the seasons ($P = 0.03$); the value in the dry season is significantly lower than the rainy season (**Table 5.4**). For the interaction, the lowest Shannon mean value (0.13) was recorded at SGO during the dry season while the highest value (1.13) was recorded at SGS during the rainy season (**Fig. 5.2**). However, the interaction between sampling sites and seasons had no significant effect on the Shannon diversity index value of Lake Shala ($P = 0.19$).

Table 5.4. Seasonal variation in macro-invertebrate diversity measures of Lake Shala from January to December 2018.

Season	**Abundance/m^2**	**Taxa richness**	**Shannon**	**Evenness**	**Equitability**
Dry	6910^{a}	7^{a}	0.50^{a}	0.70^{a}	0.51^{a}
Pre-rainy	6709^{a}	13b^{c}	0.60^{ab}	0.53^{a}	0.44^{a}
Rainy	5230^{a}	16^{b}	0.76^{bc}	0.69^{a}	0.68^{a}
Post-rainy	7553^{a}	8^{ac}	0.57^{ab}	0.61^{a}	0.51^{a}

NB: Means within a column followed by the same letter are not significantly different.

The average seasonal value of macro-invertebrate evenness in Lake Shala fluctuated between 0.53 (pre-rainy season) and 0.70 (dry season). The evenness value was not significantly affected by season (*P* = 0.07) (**Table 5.4**). Even though the interaction between site and season had no significant effect on the macro-invertebrate evenness of Lake Shala (*P* = 0.77), its value ranged from 0.43 at SPS during the pre-rainy season to 0.86 at SPO during the rainy season (**Fig. 5.2**). The average seasonal equitability value was 0.51 in the dry season, decreased to 0.44 in the pre-rainy season and then increased to 0.68 in the rainy season (**Table 5.4**). Equitability was not significantly affected by season (*P* = 0.09) (**Table 5.4**) and also the interaction between season and sites did not affect equitability value (*P* = 0.34). But values for the interaction case ranged from 0.18 at SGO during the dry season to 0.81 at SPO during the rainy season (**Fig. 5.2**).

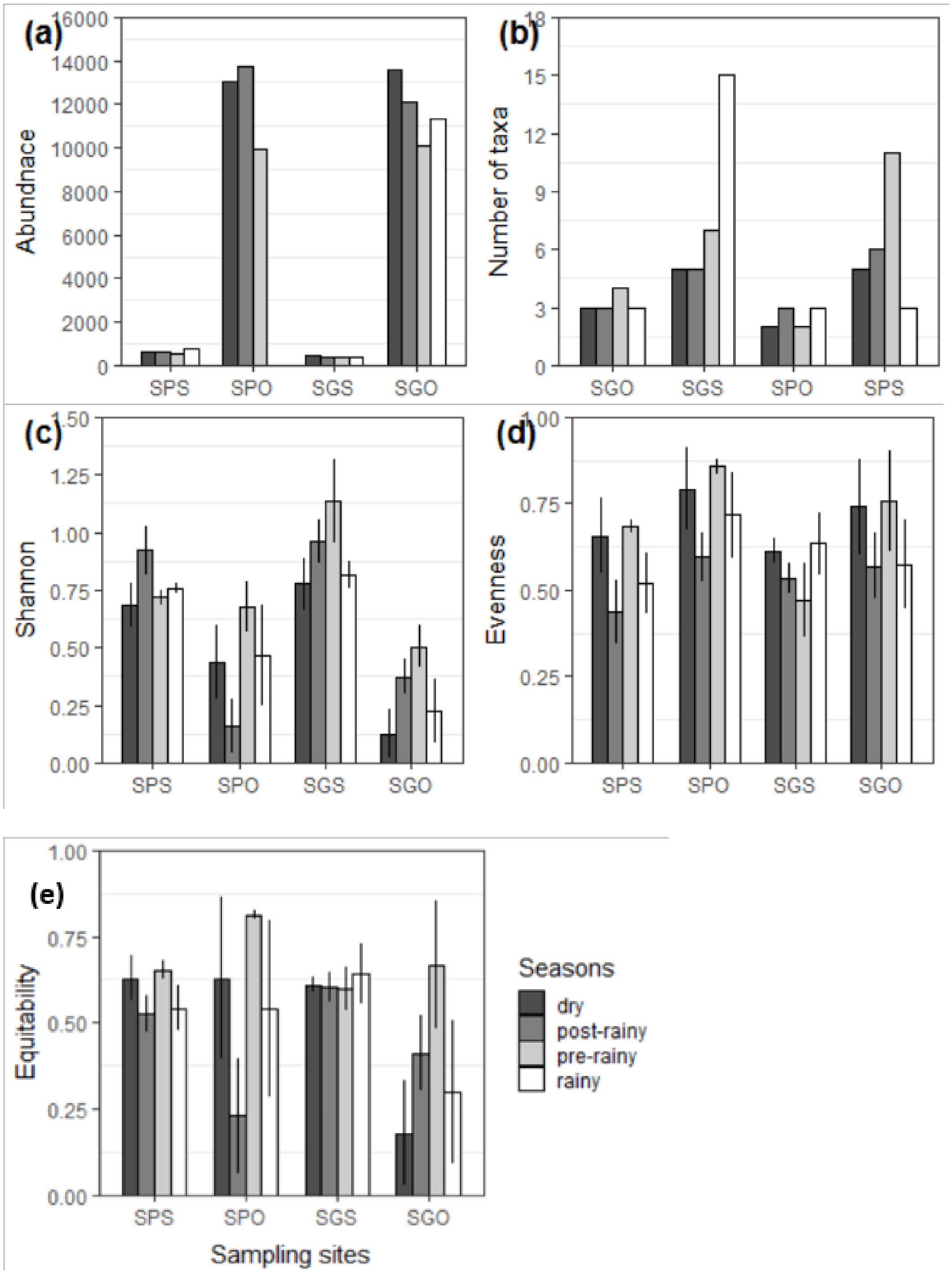


Figure 5.2. Seasonal variation in macro-invertebrate community assemblages among sampling sites in Lake Shala from January to December 2018 (Sites abbreviations: SPS = Shala Park Shore, SPO = Shala Park Open, SGS = Shala Gike Shore and SGO = Shala Gike Open).

5.4.1.4. Correlations of Macro-invertebrates with Environmental Variables

Results of RDA showed that eight of the environmental factors (pH, temperature, electrical conductivity, dissolved oxygen, nitrate, soluble reactive phosphorous, alkalinity, and salinity) were the main determining factors that governed the distribution of macro-invertebrates in Lake Shala. The first two axes explained 83.7% of the species-environment relation while axis 1 explained only 61.2%. Electrical conductivity (0.59), dissolved oxygen (0.57) and salinity (0.56) had a significant positive correlation with axis 1 and determined the distribution of the Oligochaeta (*Tubificidae and Naididae*) and Dipterans (*Chironomidae* and *Ceratopogonidae*). But temperature (-0.63), nitrate (-0.79), soluble reactive phosphate (-0.81) and alkalinity (-0.72) were strongly and negatively correlated with axis 1 and determined the distribution of the aquatic bugs (*Naucoridae* and *Corixidae*). Electrical conductivity, dissolved oxygen and salinity were also strongly and negatively correlated with axis II (**Table 5.5 and Fig. 5.3**).

Table 5.5. Correlation table of physicochemical parameters with the first two axis (strong

Environmental Variables	**Axis 1**	**Axis 2**
Eigenvalues	0.61	0.39
Cumulative percentage variance of species-environment relation	61.2	83.7
pH	0.04	**0.54**
Temperature	**-0.63**	-0.46
Electrical Conductivity	**0.59**	**-0. 51**
Dissolved Oxygen	**0.57**	**-0.54**
Salinity	**0.56**	**-0.50**
Nitrate (NO_3-N)	**-0.79**	0.16
Soluble Reactive Phosphate (PO_4-P)	**-0.81**	-0.18
Alkalinity	**-0.72**	0.32

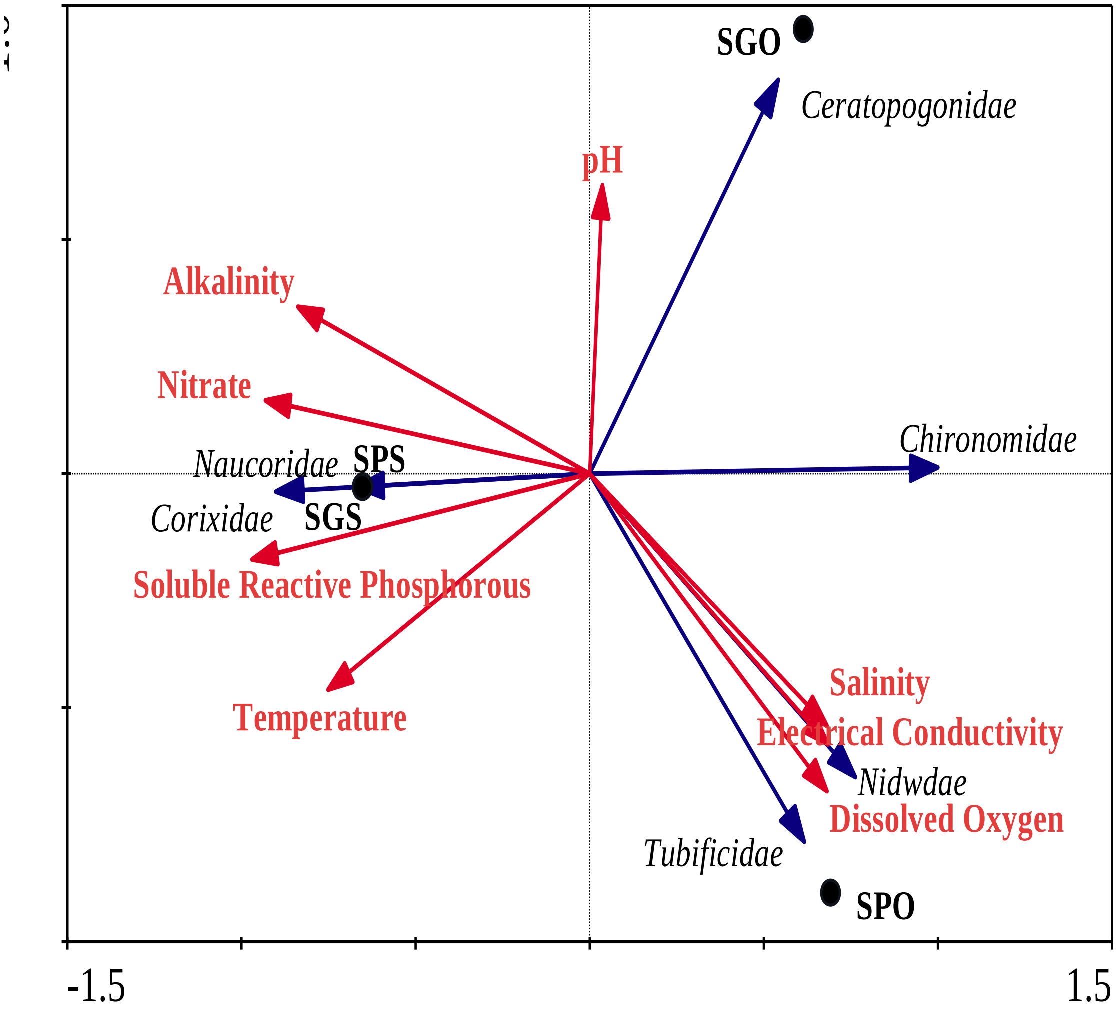


Figure 5.3. Redundancy analysis (RDA) diagram of macroinvertebrates in relation to water physicochemical properties and sites (Sites Abbreviations: SPS = Shala Park Shore, SPO = Shala Park Open, SGS = Shala Gike Shore and SGO = Shala Gike Open)

5.5. Discussion

5.5.1. Macro-invertebrate Composition

Owing to the hostile nature of soda lakes (high pH, high salinity, and high alkalinity), only a few specialized groups of macroinvertebrates can typically survive (Mutanga *et al.*, 2000). In this study, 21 macro-invertebrate taxa were identified. In line with this, Seyoum Mengistou (2016) in his review on invertebrates of EARV soda lakes indicated a maximum of 20 taxa, and restricted to a few specialized taxa that have evolved mechanisms to tolerate the extreme alkalinity and salinity. The number of taxa from this study was higher than other soda lakes of Ethiopia, Kenya, and Tanzania (**Table 5.6**). This might be due to the variation in sampling frequency and effort and the geographical location of the lakes. Unlike the results from this study, Tudorancea and Harrison (1988) surveyed benthos of Lake Shala in 1985 and reported only 8 taxa. This considerable variation might be due to variation in sampling frequency (12 times for the present study and only two samples for 1985), sampling material (a combination of net and Ekman grab in the present study and only Ekman grab in 1985), and several sampling stations and locations and sampling depth for open sites (approximately 10 m for the present study but 15.5 m for the 1985 study). Nearly all the benthic species found in the Lake Shala have also been found in nearby freshwater Lakes Ziway and Hawassa but many benthic forms common in these freshwater lakes are absent from the saline Lake Shala (Abnet Woldesenbet, 2019; Tarekegn Wondmagegn and Seyoum Mengistou, 2020).

Table 5.6. Checklist of invertebrates in East African soda lakes ((1) Arenguade, (2) Abijata, (3) Shala, (4) Chitu, (5) Elmentaita, (6) Nakuru, (7) Bogoria, (8) Sonachi, (9) Natron, (10) Eyasi, (11) Manyara).

Group/Family	Lake Code	Reference
Corixidae	1, 2, 5, 6	b, d
Notonectidae	1, 2, 4, 6	b
Dytiscidae	8	b
Anostraca	5	b, d
Ostracoda	1, 2, 3	a, b
Chironomidae	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11	a, b, d
Ceratopogonidae	2	a
Chelicerata	2, 3	b
Nematoda	2, 3	a, b, c
Oligochaeta	2, 3, 6	a, b, d

[a] Tudorancea and Harrison (1988); [b] Seyoum Mengistou (2016); [c] Abebe Eyualem (2002); [d] Matagi (2004).

5.5.2. Site-specific Macro-invertebrate Community Assemblages and their Historical Trend

In Ethiopia, attention has focused on documenting the changes in the diversity of plankton, fish and the physical and chemical properties of the lake water, ignoring the soda lakes and their benthos. Due to the above-mentioned bias, historical documentation of benthic diversity is not comprehensive enough to demonstrate trends of benthic diversity. A study conducted on Lakes Abijata and Shala (Tudorancea and Harrison, 1988) reported only a few (8) taxa in Lake Shala far below the 21 taxa in the present study. Different factors might contribute to the variation for which intensive 12 months sampling in the present study might be one. The other possible reason might be a shift in community structure over the years. Tudorancea and Harrison (1988) reported Ephemeroptera and Trichoptera families at a depth of 0.3 m. But in the present study, even though intensive 12 months sampling was conducted from multiple sites, these families were not recorded at the shore sites. This might be an indication of the presence of a shift/change in the benthos community of the lake over the years. In the present study, *Chironomidae* were equally abundant at the open and shore sites, and the *Corixidae* were more abundant at the shore sites while no single *Ostracoda* was recorded both from the shore and open stations (Appendix 3). Contrary to this, Tudorancea and Harrison (1988) indicated that *Ostracoda* and *Tubifex* were abundant down to 15.5 m but *Chironomidae* were more abundant in shallower water. This might indicate the presence of community shifts in the lake over the years. The shift might be due to several reasons including the changes in the water chemistry of the lake and food resources (**Chapter two**). Also, a major change has taken place in the main lake's ecology since these studies and the most notable one is the recession of the lake shore from its original site (Personal Communication with Local Park Scout).

Seyoum Mengistou (2016) noted that few studies had been conducted on the invertebrate composition and distribution of soda lakes and the dominant forms were from the Hemiptera (families *Corixidae* and *Notonectidae*), Nematoda (roundworms), Oligochaeta (aquatic earthworms), Chelicerata and Diptera (highly represented by the family *Chironomidae*). In this study, too, even though all the above taxa were not recorded, Diptera (family *Chironomidae*) and *Tubificidae* at both open and shore sites, Hemiptera (family *Corixidae*) at the shore sites were dominant. Estimation of benthic diversity using diversity indices has not been documented and it is difficult to track historical trends in this aspect.

The macro-invertebrate community structure is determined by the spatial difference between the complexities of habitats (Abnet Woldesenbet, 2019; Tarekegn Wondmagegn and Seyoum Mengistou, 2020). In this study, the macro-invertebrate abundance and taxa richness in different sites of Lake Shala showed spatial heterogeneity ($P < 0.05$). The abundance of the macro-invertebrates, *Chironomidae* and *Tubificidae*, in the open lake area of Shala Lake were significantly higher than those in other shore site habitats. These may be due to its tolerance to extreme environmental situations like the hypoxia state of deep lake habitat. Also, many studies have shown the diversity of macro-invertebrate in the lakeshore is significantly higher than that in open lake habitats (Waters and San Giovanni, 2002; Tolonen, 2004; Hartman *et al.*, 2019). In the present study, the diversity of macro-invertebrate in the Shala Gike Shore (SGS) and Shala Park Shore (SPS) was significantly higher than that in other open site habitats, as benthic macro-invertebrates were more likely to live in a habitat with sufficient dissolved oxygen, sandy transitional zone, and quality food. This follows Li *et al.* (2019) who suggested that type and availability of food, water transparency, depth, organic matter contents, dissolved oxygen concentration, and the ability of resident genera to tolerate the physicochemical environment as the leading factors controlling their spatial distribution.

5.5.3. Seasonal Variation in Macro-invertebrate Community Assemblages

Seasonal variability in macro-invertebrate composition and community structure is strongly influenced by differences in the environmental variables, as has been noted in other studies in the different aquatic ecosystems (Kibichii *et al.*, 2007; Rasoloariniaina, 2017; Adadu *et al.*, 2019; Wang *et al.*, 2020). In the present study, seasonal changes in macro-invertebrate species composition were observed. The highest taxonomic richness was recorded during the rainy season (16) compared to 7 in the dry season. This significant variability in the seasonal taxonomic richness of macro-invertebrate might be more associated with environmentally triggered (i.e., food availability, water quality change, water level fluctuation) key events in the life-cycles of the species (i.e., pupation and emergence periods). This result in line with the findings of Li *et al.* (2019), in that the difference in the availability of food remains the key determinant factor for macro-invertebrate species composition fluctuations among the seasons. Other investigators have also reported water-level fluctuations (Baumgärtner *et al.*, 2008), microclimate and land-use change (Mantyka Pringle *et al.*, 2014); water chemistry changes (Abnet Woldesenbet, 2019; Tarekegn Wondmagegn and Seyoum Mengistou, 2020), as probable causes for fluctuation in macro-invertebrate composition.

The present study indicated low diversity of Shannon, Equitability, and Evenness. According to several authors, low values of diversity index reflect poorly diversified communities with a low organization and an unbalanced ecosystem (Marini *et al.*, 2013; Ghosh and Biswas, 2015). Also, the low diversity index values in all seasons of the year might be due to the relatively even distribution and higher abundance of the predominant taxa in Lake Shala, such as *Chironomidae*. In this study, the mean abundance of macro-invertebrate and the indices Evenness and Equitability values did not show significant variation among the sampling seasons. But there was a significant variation in the mean Shannon diversity index value (P = 0.03) and the value in the dry season (0.50) being significantly lower than the rainy season (0.76). These differences in the Shannon diversity index provide further evidence on seasonal changes in community assembly processes due to possible variations in physicochemical and ecological heterogeneity across the studied seasons (**Chapter Two**). Li *et al.* (2019) in their study of benthic invertebrates from Poyang Lake Basin in China, also observed significant seasonal variation in diversity metrics, suggesting seasonality as the main driving factor of macroinvertebrate community variation in the aquatic ecosystem.

5.5.4. Factors Affecting Macro-invertebrate Assemblages in Lake Shala

The macro-invertebrate communities of soda lakes are regulated by a variety of environmental factors, among which alkalinity, salinity and electrical conductivity comprise critical factors for their distribution (Mutanga *et al.*, 2000; Matagi, 2004). Other key factors may include nutrient or food availability, temporal variation in dissolved oxygen, water column transparency and the stability of various substrata available to benthic organisms (Seyoum Mengistou, 2016). In the present study, RDA analysis authentically suggested that several ecological factors play a role in distributing the macro-invertebrate in Lake Shala. In the ordination diagram, macro-invertebrate and environmental variables indicated that axis 1 and axis 2 make 83.7% of the cumulative percentage of variance in a species-environmental relationship, whereas the remaining 17.3% of variance might be due to biotic and abiotic factors not considered in this study such as BOD, COD, water level fluctuation, sediment structure, food availability, organic matter in silt, etc.

In this study, electrical conductivity, dissolved oxygen and salinity had a significant positive correlation and determined the distribution of aquatic worms and dipterans. The importance of conductivity and salinity was not surprising given that soda lakes had high electrical conductivity and salinity which are known determinants of macroinvertebrate assemblages (Velasco *et al.*, 2006; Herbst *et al.*, 2013; Seyoum Mengistou, 2016). From the present study, *Tubificidae*, *Naididae*, *Chironomidae* and *Ceratopogonidae* were positively correlated with electrical conductivity and salinity, which might be due to their adaptive tolerance to high electrical conductivity and salinity. This is most likely because of the high resistance to a wide range of ecological conditions (Butakka *et al.*, 2016). But temperature, nitrate, soluble reactive phosphate and alkalinity determined the distribution of aquatic bugs community (*Naucoridae* and *Corixidae*). Studies also have shown that environmental factors such as water temperature, nitrate, soluble reactive phosphate and alkalinity typically affect the macro-invertebrate community structure (Çamur-Elipek *et al.*, 2010; Rasoloariniaina, 2017; Tarekegn Wondmagegn and Seyoum Mengistou, 2020).

Chapter Six: Some Aspects of the Biology of *Oreochromis niloticus* (Pisces: Cichlidae) in Lake Shala, Ethiopia

6.1. Introduction

East African Saline lakes harbor several unique and endemic fish communities of great economic, aesthetic, ecological, and biological value (Kavembe *et al.*, 2016). Unlike their counterparts in freshwater lakes, fish communities in saline lakes remain largely unaltered by species introductions, overstocking, and overexploitation (Melack, 1996). But, some economically driven developments in and around the lakes continue to exert considerable pressure on saline lake fish populations (Kathleen, 2011; Kavembe *et al.*, 2016). The best example of this is Lake Abijata, in which the lake was populated with *Oreochromis niloticus* (Kathleen, 2011). However, Mohammed Abdi (1993) noted the disappearance of *O. niloticus* from Lake Abijata after the establishment of the soda ash factory. At the same time, it was noted that several piscivorous birds such as the Great White Pelican (*Pelecanus onocrotalus*) and Cormorant were migrating to nearby lakes.

Fish in EASL have attracted limited attention from scientists relative to freshwater fishes (Musˇka *et al.*, 2012; Kavembe *et al.*, 2016). However, there is growing interest among biologists, ecologists, fisheries, and conservation managers, resulting in an enhanced understanding of saline lake fish populations. Several studies on saline lake fish have been undertaken in recent years (Po¨rtner *et al.*, 2010; Musˇka *et al.*, 2012; Zaccara *et al.*, 2014; Kavembe *et al.*, 2016). Although little is known about the fish communities in

Ethiopian saline lakes (Abebe Getahun, 2001), Lake Shala is known by its indigenous *O. niloticus* (Golubtsov *et al.*, 2002) and *Aplocheilichthys antinori* populations as reported in Klemperer and Cash (2007).

Fish require quality foods for growth, reproduction, and other normal physiological functions (Wakil *et al.*, 2014; Cuevas-Rodríguez *et al.*, 2017). Fish exploit food items in nature according to the possessed adaptations such as their mouth, gill rakers, dentition and gut system related to feeding (Bwanika *et al.*, 2004). In the aquatic environment, the availability of food determines the general well-being, growth pattern, and reproductive potential of fish (Bwanika *et al.*, 2004; Lemma Abera, 2012; Mathewos Temesgen *et al.*, 2018). Studying food and feeding habits of fish enable the identification of the trophic relationships, identifying feeding composition, structure, and stability of food webs in the ecosystem (Adeyemi *et al.*, 2009; Hussian *et al.*, 2019). Without knowledge of the feeding behavior pattern, it is impossible to understand the predicted changes that might result from any natural or anthropogenic intervention (Njiru *et al.*, 2004; Kavembe *et al.*, 2016). Therefore, examining fish feeding habit in natural waters are among the important aspects of fish biology (Abdulhakim *et al.*, 2015; Kuebutornye *et al.*, 2019).

Oreochromis niloticus breeds continuously throughout the year, but the breeding activity is intensive during rainy periods (Zenebe Tadesse, 1997; Lemma Abera, 2013; Workiyie Worie and Abebe Getahun, 2014; Mathewos Temesgen *et al.*, 2018; Tsegay Teame *et al.*, 2018; Assefa Tessema *et al.*, 2019). However, all fish species have different intensities of breeding time in the year, which mainly depends on the availability and quality of food and seasonal fluctuations in water temperature (Peña-Mendoza *et al.*, 2005; Mathewos Temesgen *et al.*, 2018; Tsegay Teame *et al.*, 2018). Therefore, information on the reproductive biology of *O. niloticus* can provide basic knowledge for the proper management and conservation of the fish in the ecosystems.

Knowledge of the Length-Weight relationship (LWR) and Condition Factor (CF) of fish is important in studying fish biology (Gashaw Tesfaye and Zenebe Tadesse, 2008). The Length-Weight relationship gives information on the growth patterns of the fish and is used to predict weight from length measurements made in the yield assessment (Bagenal and Tesch, 1978). Length-Weight relationship is further used in the estimation of fish Condition Factor (CF) and providing information on growth type (Froese, 2006). On the other hand, the CF serves as an indicator of the physiological state of the fish based on the assumption that a heavier fish of a length is in a better condition (Gashaw Tesfaye and Zenebe Tadesse, 2008; Mondal and Chakravartty, 2016). Information on the LWR and CF of *O. niloticus* has been reported by several authors such as Lemma Abera (2012) for Lake Beseka, Ethiopia, Mortuza and Al-Misned (2013) for Wadi Hanifah, Riyadh, Saudi Arabia, and Assefa Tessema *et al*. (2019) for Lake Hayq, Ethiopia. According to these studies, LWR and CF are affected by age, season, sexual maturity and gender. Nowadays, the study of LWR, CF, and associated environmental factors of fish species are the most important biological factors for the management and conservation of natural populations (Gashaw Tesfaye and Zenebe Tadesse, 2008; Dan-Kishiya, 2013; Mondal and Chakravartty, 2016).

The ecological value of *O. niloticus* is highly significant and constitutes an irreplaceable component of the saline lake food chain in Lake Shala. *O. niloticus* support significant populations of fish-eating birds (Kavembe *et al.*, 2016). Even though there is considerable information on the ecology and biology of *O. niloticus* in most of the

Ethiopian water bodies (Gashaw Tesfaye and Zenebe Tadesse, 2008; Lemma Abera, 2013; Workiyie Worie and Abebe Getahun, 2015; Tsegay Teame *et al.*, 2018; Assefa Tessema *et al.*, 2019), there is no available information on the feeding habits and reproductive biology of the Lake Shala fish species, and it was presumed that tilapia had disappeared from a neighboring soda lake, Lake Abijata due to osmotic stress and other factors from the lake (Mohammed Abdi, 1993). It was a new finding for this study to 'locate' a tilapia stock from the southern lake shore hotsprings. Therefore, the present study generates baseline information on the Length-Weight relationship, condition factor, sex ratio, fecundity and breeding season through the relationships among fecundity-length, fecundity-weight, and gonadosomatic index analyses, food and feeding habit of *O. niloticus* in Lake Shala for management and conservation of the species.

6.2. Materials and Methods

6.2.1. Field Fish Sampling and Morphometric Measurements

Samples of *O. niloticus* were collected monthly between January and December 2018 using a gill net at a fixed site (Shala Gike Shore) (Fig. 6.1) throughout the study. Site for this study was selected based on their accessibility and using fishing birds such as the Great White Pelican and Cormorant as indicators for the presence of the fish. Gillnets with stretched mesh sizes of 4-14 cm, a panel length of 50 m and a width of 1.5-2.0 m per mesh size were used for capturing fishes. The nets were set parallel to the shoreline in the evening (about 17:00) and lifted in the following morning (around 7:00). Immediately after capture, Total Length (TL) and Total Weight (TW) of each specimens were measured to the nearest 0.1 cm and 1.0 g, respectively. Each specimen was dissected to determine sex and the gonad maturity stage was recorded following Holden and Raitt (1974) procedures. Stomach containing food and ovaries of the mature fishes were preserved in 5 % and 10% formaldehyde, respectively and transported to Addis Ababa University for further Laboratory analysis.

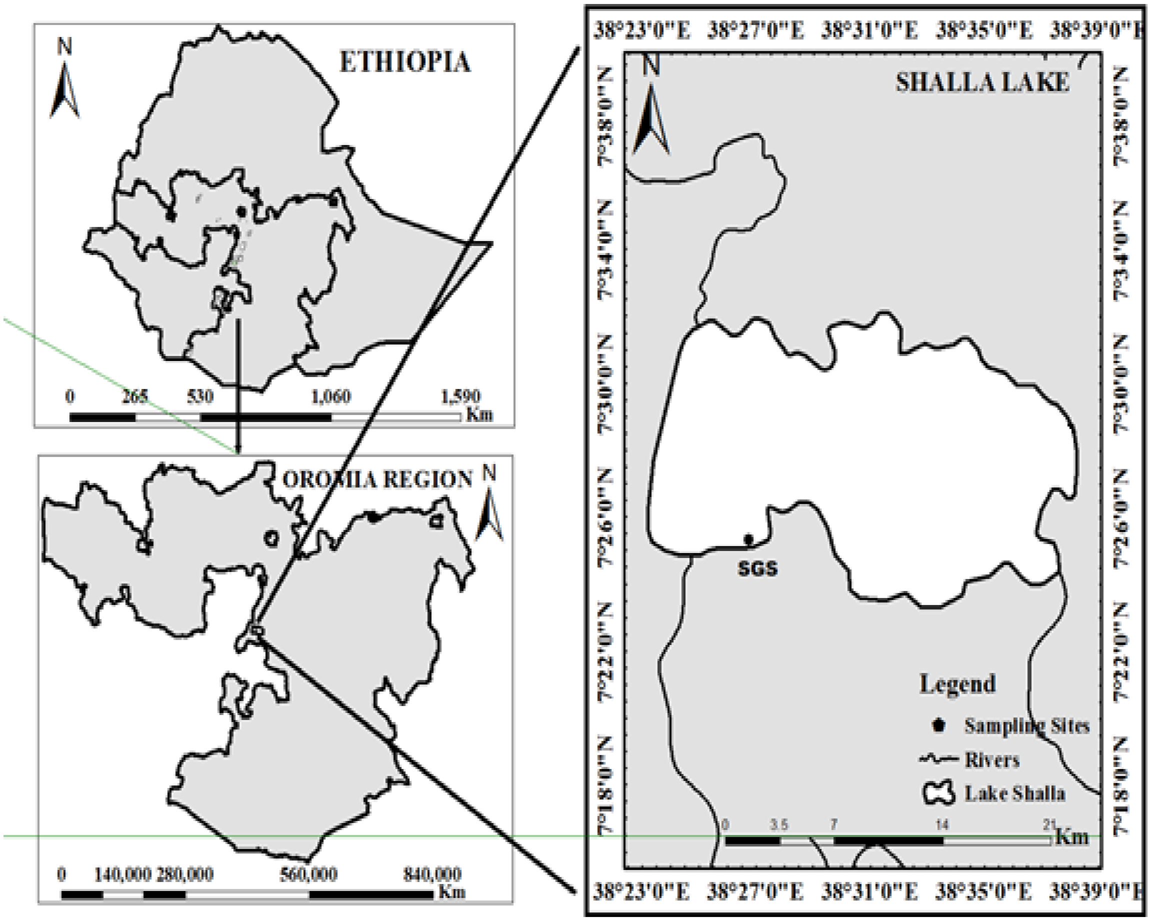


Figure 6.1. Location of Lake Shala in Ethiopia, showing the study site/sampling point. (Abbreviation: SGS: Shala Gike Shore).

6.2.2. Estimation of Length-Weight Relationship

The Length-Weight relationship was estimated using the formula:

$$\mathrm{TW} = aTL^{b}$$

Where, TW = Total Weight of fish (g), TL = Total Length of fish (cm), a (intercept) and b (slope) are constants of Regression Equation.

6.2.3. Estimation of Condition Factor (CF)

The value of 'b' from the Length-Weight relationship (Gashaw Tesfaye and Zenebe Tadesse, 2008) was used to compute the relative Condition Factor. Individual values of the CF were obtained through the formula $\mathbf{CF} = \frac{TW}{TL^b} * \mathbf{100}$ (Bagenal and Tesch, 1978; Nehemia *et al.*, 2012). Where, CF = Condition Factor; TW = Total Weight of the fish in gram (g); TL = Total Length of the fish in centimeters (cm) and 'b' = the value obtained from the Length-Weight equation.

6.2.4. Reproductive Biology

6.2.4.1. Estimation of Sex-ratio and Gonado-Somatic Index (GSI)

Individual fish samples were dissected to determine sex and gonad maturity status by examination of gonads. The maturity status of each fish was determined and assigned as stages I, II, III, IV, V and VI following Armstrong *et al.* (2004). Ovaries of the mature fishes were removed and preserved in 10% formalin immediately. The preserved ovaries were transported to Addis Ababa University, Fishery Laboratory for further analysis.

Sex ratio (Female: Male) was also calculated for each species and the total samples. The Gonado Somatic Index (GSI) for each fish was calculated as the weight of the gonads relative to the total body weight, expressed as a percentage (Peña-Mendoza *et al.*, 2005). Gonado Somatic Index (GSI) was computed for each fish species to determine the breeding season of fishes in the lake (Armstrong *et al.*, 2004; Peña-Mendoza *et al.*, 2005).

$$GSI = \frac{GW * 100}{TW}$$

Where, GSI = Gonado somatic index; GW = Gonad Weight in g; TW = Total Weight in g where the weight of the gonad is the weight of the fresh gonad, blotted on absorbing paper.

6.2.4.2. Fecundity

The actual number of mature eggs in the ovaries was physically counted to determine the fecundity of *O. niloticus*. Fecundity was estimated from total counts of eggs in the ovaries of fish in the most advanced state of development (Peña-Mendoza *et al.*, 2005; Shoko *et al.*, 2015). Ripe females of stage IV and V were used for the fecundity estimation. A mean fecundity for all the samples was then determined. The relationship of fecundity with total length (TL) and total body weight (TW) of fish were analyzed by regression analysis and expressed by the following equation:

$\boldsymbol{F = mTL^{n}}$ and $\boldsymbol{F = aTW^{b}}$, where F = Fecundity; TL = Total Length of individual fish; TW = Total Weight of individual fish, m, n, a, and b are constants.

6.2.5. Food and Feeding Habits

6.2.5.1. Stomach Content Analysis

The preserved stomach content of *O. niloticus* was transferred into a petri dish and analyzed using a modified point method according to Hyslop (1980). Food items were examined under a dissecting LEICA S8 APO and a compound LEICA DME microscope (100X to 400X). The food items were identified to the lowest possible taxonomic level by using description, illustrations and keys in the literature (Gasse *et al.*, 1983; Defaye, 1988; Bellinger and Sigee, 2010). Each category was assigned points proportional to the estimated contribution.

The contribution of each prey functional category to the overall stomach contents was assessed using two indices: percent frequency of occurrence (%Q) and percent composition by volume (%V) (Hyslop, 1980). In the frequency of occurrence method, food items were expressed as the percentage of the total of stomachs. %Q provides information on the proportion of fish stomachs containing a particular prey item despite the amount (Hyslop, 1980). The percentage volume contribution of each food item is visually assessed relative to the food items present in the gut. Volumetric contribution (ml) and frequency of occurrence were also used to compute the index of food preponderance (IOPa) and geometric importance of index (GIIi).

For the assessment of the importance of each prey category, the index of preponderance (IOPa) (Sreeraj *et al.*, 2006; Daiki Tomojiri *et al.*, 2019) was calculated as:

$$\boldsymbol{IOPa\,(I)} = \frac{\boldsymbol{Qi} * \%\boldsymbol{Vi}}{\sum_{\boldsymbol{i=1}}^{\boldsymbol{S}}(\boldsymbol{Qi} + \%\boldsymbol{Vi})}$$

Where S is the number of prey types, Qi is the frequency of occurrence of species i and %Vi is the percent composition by volume of species i. To facilitate comparisons among species, IOPa was converted into percent IOPa (%IOPa).

To evaluate the relative importance of food items and species-level dietary variations, the Geometric Index of Importance (GIIi) (Assis, 1996) was computed as:

$$\boldsymbol{GIIi} = \frac{(\sum \boldsymbol{RMPQi}}{(\sqrt{\boldsymbol{n}})}$$

Where, RMPQi = percentage of volume and frequency of occurrence (as a percentage of total occurrences) and n= total number of RMPQ parameters used to generate GIIi. GIIi index treats each dietary metric equally and some prey items were better represented by %Q (e.g., smaller but countable prey) whereas others were better represented by %V (e.g., fish and other larger prey).

Phytoplankton Preference Index (PPI) was determined using the percentage frequency of occurrence through the following equation described by Chrisafi *et al.* (2007) and Hussian *et al.* (2019).

$$\boldsymbol{PPI = \frac{QPhi}{QEPi} * 100}$$

Where: **PPI**= Phytoplankton Preference Index

QPhi = number of stomachs with a specific phytoplankton species

QEPi = the number of non-empty stomachs with phytoplankton

The different values of this index, allow the separation of phytoplankton preference into three categories as the main diet, secondary and accidentally eaten phytoplankton species (Hussian *et al.*, 2019).

6.2.5.2. Estimation of Size and Seasonal Based Food Habit Relationship

Size and seasonal based dietary variations of *O. niloticus* in Lake Shala were studied based on the percent volumetric contribution, frequency of each food item, IOPa and GIIi indices within each length group and seasons. For studying size and seasonal based diet variation, fish were classified into five size classes and two seasons (dry and wet seasons).

6.3. Statistical Analysis

Descriptive statistics was employed to ascertain the percentage in volume and frequency of each prey item. The relationship between total length and total weight, fecundity and the total length, fecundity, and the total weight of fishes were computed by Linear Regression. One-way Analysis of Variance (ANOVA) was used to check the statistical variation of the regression analysis, GSI, CF, FCF, and diet among size classes diet of *O. niloticus*. Chi-square goodness of fit test was used to test for a difference in the sex ratio of *O. niloticus* population from a 1:1 ratio. The Student’s t-test was employed to test the significance of differences between the ideal ‘b’ values (3.0) and seasonal diet variations.

6.4. Results

6.4.1. Length-Weight Relationship

A total of 343 fish specimens ranging in size from 7.70 cm to 33 cm in TL and 7.80 g to 708.21 g in TW were used to determine Length-Weight relationships. The regression coefficient (b) of *O. niloticus* (3.19) were significantly different from an ideal fish growth (b =3) (*t-test*, $P < 0.05$) and indicating positive allometric growth of *O. niloticus* in Lake Shala. An exponential relationship was obtained between the Total Length (TL) and Total Weight (TW) of *O. niloticus*, and the equation results of these relationships are given in Table 6.1 and Figure 6.2.

Table 6.1. Length–Weight relationship of *Oreochromis niloticus* sampled between January and December 2018 from Lake Shala, Ethiopia. 'a' = intercept of the regression line, 'b' = slope of the regression line, R^2 = Regression Coefficient.

Sex	N	Regression Equations	a	b	R^2
Combined	343	$TW = 0.0104TL^{3.19}$	0.0104	3.19	0.98

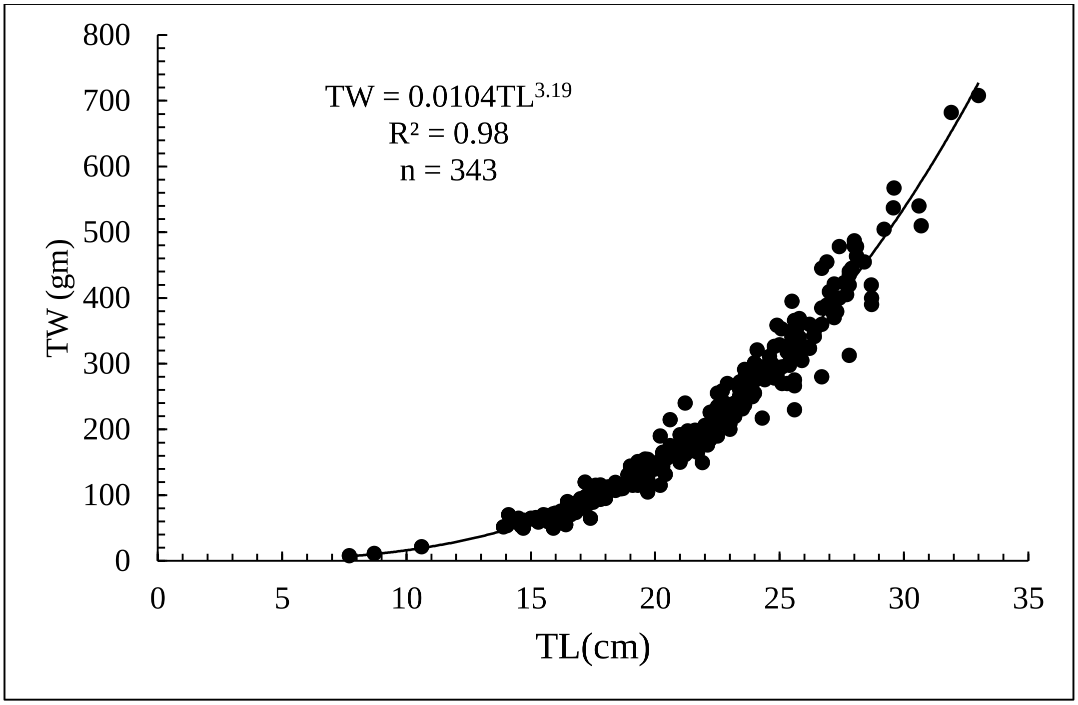


Figure 6.2. Length-Weight relationship of *Oreochromis niloticus* in Lake Shala from January to December 2018.

6.4.2. Condition Factor (CF)

The Condition Factor (CF) of *O. niloticus* ranged from 0.72 to 1.51 with a mean of 1.05. The Condition Factor for males and females ranged from 0.72 to 1.41 and 0.83 to 1.51, respectively (Table 6.2). Generally, the observed CF value of *O. niloticus* was slightly higher in females (1.06) as compared to males (1.04), but was not significantly different (ANOVA, $P > 0.05$).

Table 6.2. The mean Condition Factor (CF) of *Oreochromis niloticus* in Lake Shala (monthly from January to December 2018).

	Sex	Number	Mean ± SD	Minimum	Maximum
Condition Factor (CF)	Male	165	1.04±0.11	0.72	1.41
	Female	178	1.06±0.09	0.83	1.51
	Combined	343	1.05±0.10	0.72	1.51

6.4.3. Sex Ratio

The sex ratio of *O. niloticus* collected from Lake Shala (expressed as percentage frequency of males versus females) is presented in Table 6.3. 343 fish specimens were examined with 178 females (51.9%) and 165 males (48.1%). The ratio was not significantly different from 1:1 for all sampling months, except in September, November, and December (Table 6.3). The overall sex ratio (Females: Males) was 1:0.93 and did not differ significantly from the hypothetical sex ratio 1:1 (**$\chi 2 = 0.47$,** $P > 0.05$).

Table 6.3. Monthly number of males and females and sex ratio (Females: Males) of *Oreochromis niloticus* in Lake Shala from January to December 2018 (* means significant at 5% level).

Month	Females No	Males No.	Sex ratio	χ2
January	9	13	1:1.45	0.89
February	14	11	1:0.79	0.32
March	12	19	1:1.58	2.04
April	20	12	1:0.60	1.6
May	13	16	1:1.23	0.35
June	27	14	1:0.52	3.13
July	21	14	1:0.67	1.17
August	21	9	1:0.43	3.43
September	13	3	1:0.23	3.85*
October	10	19	1:1.90	4.05*
November	11	16	1:1.45	1.14
December	7	19	1:2.7	10.29*
Total	**178**	**165**	**1:0.93**	**0.47**

6.4.4. Monthly Variation of Gonado-Somatic Indexes (GSI)

Gonado Somatic Index (GSI) monthly mean values of females ranged from 1.92 to 4.33 with a mean of 3.23±1.53 whereas, GSI of males ranged from 0.69 to 1.3 with a mean of 0.99±0.55 (Fig. 6.3). The GSI values of female *O. niloticus* varied significantly among months (ANOVA, $P < 0.05$). However, the GSI mean values of male *O. niloticus* did not vary significantly among months (ANOVA, $P > 0.05$). A similar pattern of mean GSI value for female and male *O. niloticus* was detected (Fig. 6.3). The maximum values of the GSI for females were obtained during February and July while the value was generally low in September and November. For males, maximum mean GSI values were recorded during February and August. However, the mean GSI of male *O. niloticus* slightly decreased in January, March and May.

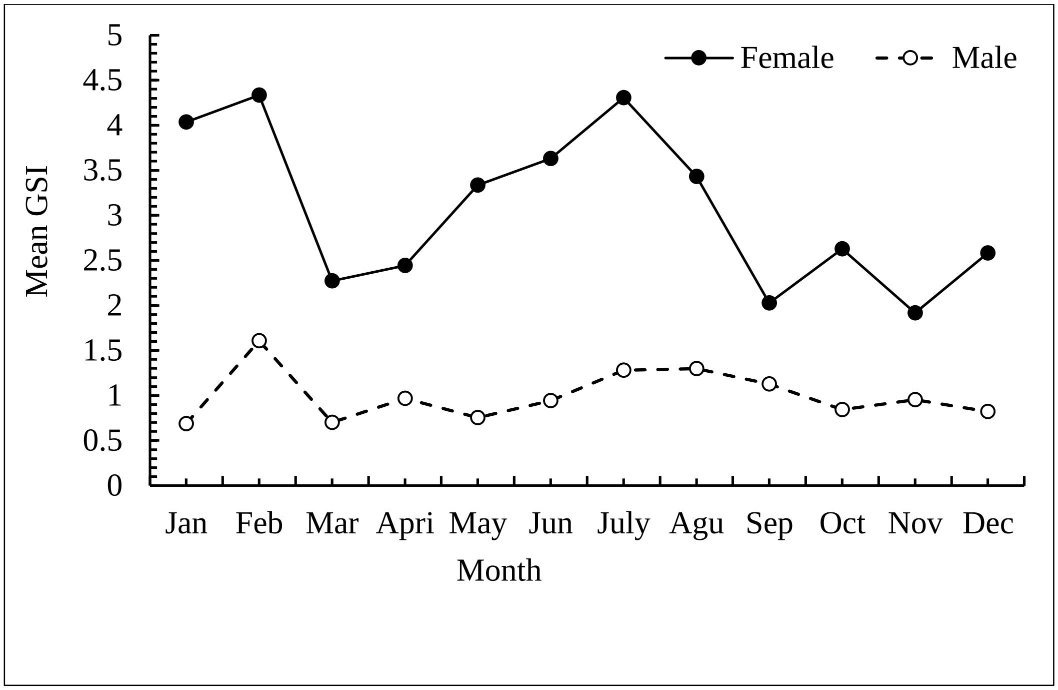
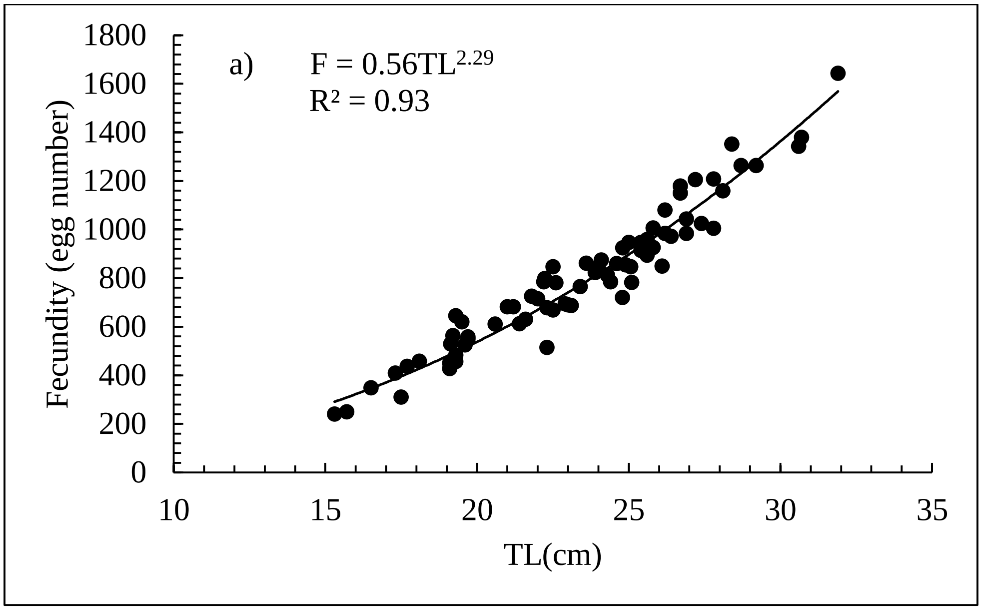


Figure 6.3. Monthly variation of Gonado-Somatic Indexes (GSI) for females and males of *Oreochromis niloticus* in Lake Shala from January to December 2018.

6.4.5. Fecundity

Fecundity was estimated for 79 ripe females *O. niloticus* that ranged from 15.3 cm to 31.9 cm TL and 63.7 g to 682.1 g TW (Fig. 6.4 a & b). The number of eggs for all the examined *O. niloticus* varied between 240 and 1,642 per fish. The overall mean fecundity of *O. niloticus* was 806 eggs per fish. Fecundity was positively correlated and increasing with increasing fish length and body weight (Fig. 6.4). The relationship of fecundity and total length were described by $\mathbf{F = 0.56TL^{2.29}}$ where F = Fecundity; TL = Total Length of individual fish (cm) and the correlation was very significant ($R^2 = 0.93$, $P < 0.05$). The relationship of fecundity with body weight was expressed by the equation; $\mathbf{F = 18.83TW^{0.67}}$ where F = Fecundity; TW= Total Weight and the correlation was significant ($R^2 = 0.90$, $P < 0.05$) (Fig. 6.4 a & b).



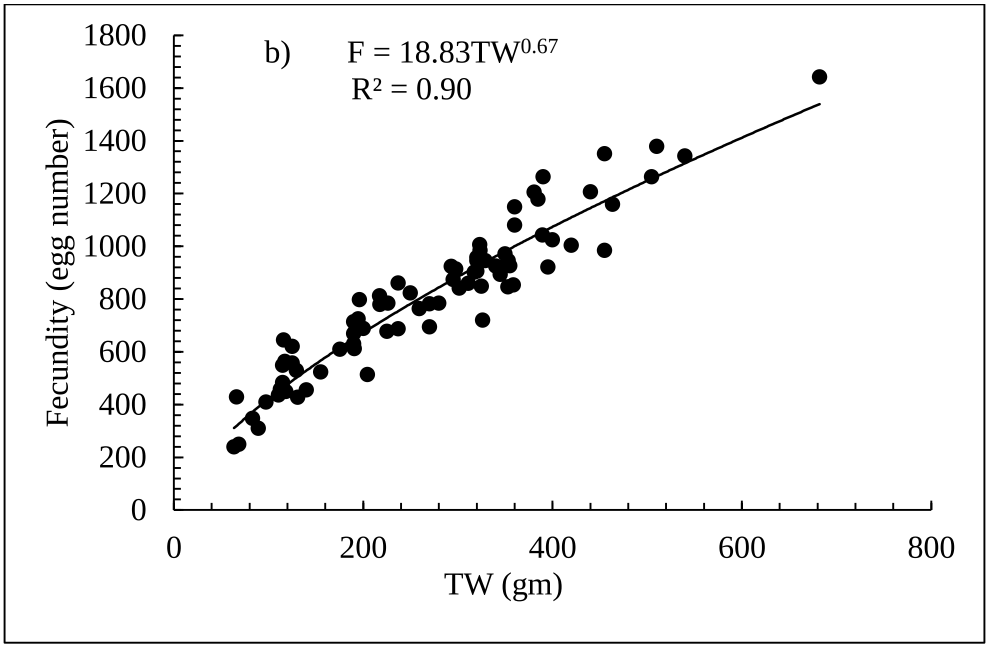


Figure 6.4. The relationship between (a) fecundity and total length (b) fecundity and total weight of *Oreochromis niloticus* in Lake Shala from January to December 2018.

6.4.6. Diet Composition of *O. niloticus* in Lake Shala

A total of 343 *O. niloticus* specimens were caught during the period of this study. Out of the total collected 117 (34.1%) had empty stomachs, while 226 (65.9%) fish specimens contained different food items in their stomach contents. The food of *O. niloticus* in Lake Shala consisted of different food items including phytoplankton, zooplankton, insect, detritus, nematodes, and fish scales (Table 6.4). Out of these food items, phytoplankton constituted the bulk of the foods consumed while zooplankton were the intermediately consumed prey types (Table 6.4 & Table 6.5). The remaining food items such as an insect, detritus, nematodes, and fish scales were rarely consumed food items (Table 6.4 & Table 6.5). The percentage of Geometric Importance Index value (%GIIi) also showed that phytoplankton was the primarily consumed prey type (Fig. 6.5). According to this index, zooplankton constituted the next important prey in the diet of *O. niloticus*, whereas insect, detritus, nematodes, and fish scales were occasionally consumed (Fig. 6.5).

Table 6.4. Frequency of occurrence (Qi), Volumetric contribution (Vi), and Index of Preponderance (IOP) of functional prey categories in the diet of *Oreochromis niloticus* (n = 226) in Lake Shalla from January to December 2018.

Food type	**Qi**	**%Qi**	**Vi**	**%Vi**	**IOP**	**%IOP**
Phytoplankton	204	**90.3**	221.3	**75.5**	31.4	**91.0**
Zooplankton	87	**38.5**	42.5	**14.5**	2.6	**7.5**
Insects	27	11.9	14.9	5.1	0.3	0.8
Nematodes	24	10.6	2.4	0.8	0.04	0.1
Fish scales	18	8.0	4.6	1.6	0.06	0.2
Detritus	31	13.7	7.25	2.5	0.2	0.5

Phytoplankton occurred in 90.3% and constituted 75.5% of the total volume of food items (Table 6.4). Based on the %IOP index, phytoplankton also contributed about 91.0% of the diet. Among the phytoplanktons, Bacillariophyta (Diatoms) such as *Nitzschia*, *Anomoeoneis*, *Navicula*, and *Aulacosira* largely contributed to the highest preponderance index value (91.3%) which occurred in 88.9% and accounted for 72.3% of the total volume of food items (Table 6.5). The food selectivity index for phytoplankton species also indicated that *O. niloticus* in Lake Shala is more selective to *Nitzschia*, *Anomoeoneis*, *Navicula*, and *Aulacosira* from Bacillariophyta (Fig. 6.6). While Cyanophyta (blue-green algae) such as *Anabaena*, *Planktolyngbya*, *Kamptonema*, and *Spirulina* were observed in 28.3% of the stomachs and constituted 3.2% of the total volume (Table 6.5).

Zooplankton (Rotifers, Cyclopoids, and Cladoceran) were the second important food items in the diet of *O. niloticus* that occurred in 38.5% of the stomachs examined and constituted 14.5% of the total volume of the food items consumed (Table 6.4). The percentage index of preponderance (%IOP = 7.5%) and Geometric Importance Index value (%GIIi = 19.4%) also showed that zooplankton were the second most preferred food types (Table 6.4, Fig. 6.5). In the zooplankton food items, rotifers were the dominant group observed in 31.4% of the stomachs and accounted for 8.5% of the total food (Table 6.5). The frequency of insect occurrence was 11.9% and their volumetric contribution was 5.1% of the total volume of food items. Other food items identified were: nematode, detritus, and fish scale which occurred in 10.6%, 13.7%, and 8.0% and accounted for 0.8%, 2.5%, and 1.6%, respectively of the total volume of food items (Table 6.4).

Table 6.5. Frequency of occurrence (Qi), Volumetric contribution (Vi), Index of preponderance (IOP), and percentage contribution of various food items of *Oreochromis niloticus* (n = 226) in Lake Shala from January to December 2018.

Food items		**Qi**	**%Qi**	**Vi**	**%Vi**	**IOPa**	**IOP%**
Phytoplankton	**Bacillariophyta**	**201**	**88.9**	**211.9**	**72.3**	**24.9**	**91.3**
	Nitzschia	198	87.6	89.04	**30.4**	4.7	**17.8**
	Navicula	176	77.9	27.1	**9.3**	1.3	**14.4**
	Aulacoosira	121	53.5	15.4	**5.3**	0.5	**9.8**
	Achnanthes	36	15.9	2.6	0.9	0.02	2.9
	Anomoeoneis	181	80.1	36.7	**12.5**	1.8	**15.1**
	Cyclotella	52	23.0	7.1	2.4	0.1	4.2
	Epithemia	43	19.0	4.8	1.6	0.05	3.5
	Rhopalodia	71	31.4	13.4	4.6	0.3	6.0
	Frustulia	86	38.1	7.9	2.7	0.18	6.9
	Campylodiscus	41	18.1	1.91	0.7	0.02	3.2
	Amphora	36	15.9	1.4	0.5	0.01	2.8
	Surullia	28	12.4	0.81	0.3	0.006	2.2
	Flagillaria	31	13.7	0.94	0.3	0.008	2.4
	Cymbella	48	21.2	1.1	0.4	0.014	3.8
	Gomphonema	25	11.1	1.7	0.6	0.011	2.0
	Cyanophyta	**64**	**28.3**	**9.4**	**3.2**	**0.4**	**1.3**
	Anabaena	35	15.5	1.8	0.6	0.02	2.8
	Planktolyngbya	51	22.6	3.8	1.3	0.05	4.1
	Kamptonema	46	20.4	3.1	1.1	0.04	3.7
	Spirulina	29	12.8	0.7	0.2	0.01	2.3
Zooplankton	Rotifera	71	31.4	24.8	8.5	0.5	6.2
	Copepoda	48	21.2	13.6	4.6	0.2	4.1
	Cladocera	24	10.6	4.1	1.4	0.03	2.0

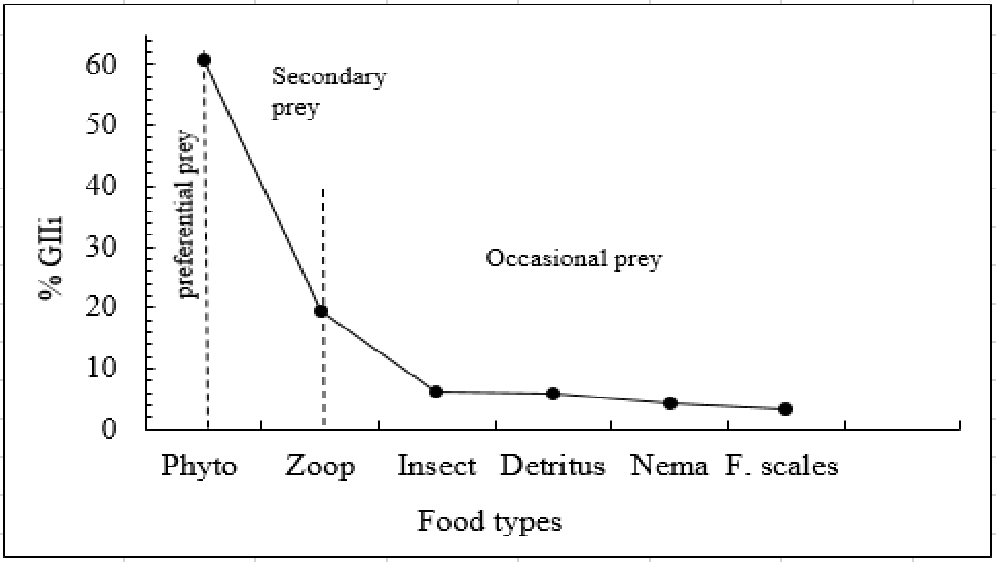


Figure 6.5. Graphical presentation of percentage Geometric Index of Importance (% GIIi) for food types of *O. niloticus* (n = 226) in Lake Shala from January to December 2018. Phyto – Phytoplankton; Zoop –Zooplankton; Nema – Nematodes and F. scale – Fish scales; vertical lines separate the different degrees of preference of the food items.

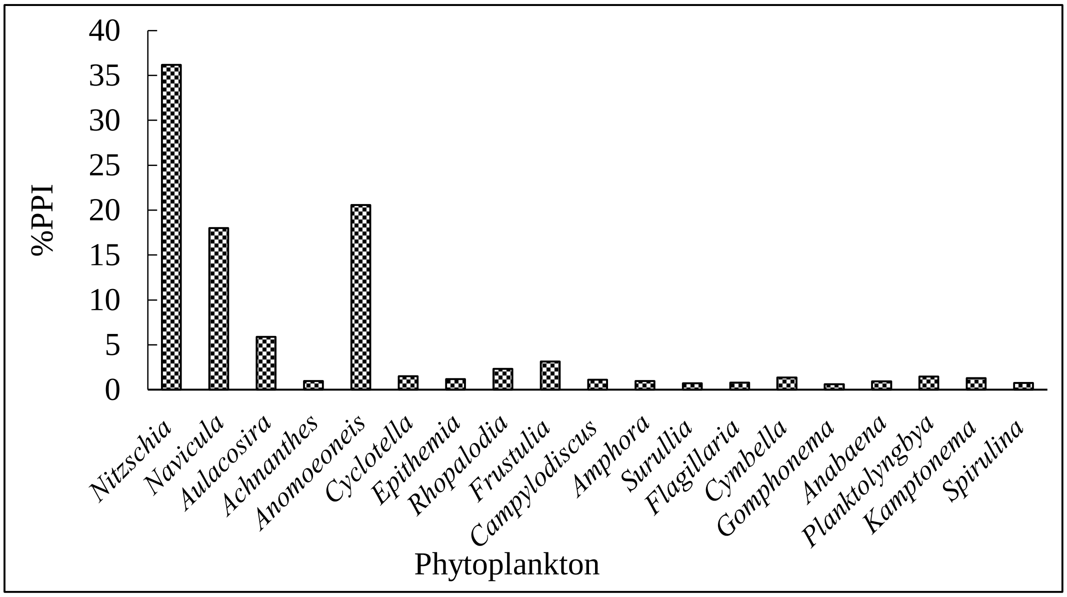


Figure 6.6. Phytoplankton preference index of *Oreochromis niloticus* in Lake Shalla from January to December 2018.

6.4.7. Variation in Food Composition and Feeding Habits with Fish Size

In O. *niloticus* there were significant differences in diet among size classes (ANOVA, $P < 0.05$). The most important food source was zooplankton over the fish below 15 cm size classes (Fig. 6.7). Their volumetric contribution was 48.9% of the total food items. Besides zooplankton as the main prey item, other important food resources for smaller-sized fish (<15 cm) were phytoplankton and accounted for 24.6% of the total volume of food items (Fig. 6.7). Insect (Chironomidae) was another food source of animal origin relatively important in the diet. Their volumetric contribution was 18.9% of the food items in this specific size class. However, the volumetric contribution of zooplankton, insect, and detritus decreased considerably as the fish size increased (Fig. 6.7).

The volumetric contribution of phytoplankton showed significant variation among the different size classes (ANOVA, $P < 0.05$). The volumetric contribution of phytoplankton showed an increasing trend with fish size. In the intermediate and largest size classes of 15-20 cm, 20-25 cm, 25-30 cm, and >30 cm TL, the contribution of phytoplankton was 64.8%, 85.9%, 98.9%, and 100 % of the total volume of food items, respectively (Fig. 6.7). While the contributions of other foods of animal origin such as zooplankton and insects were insignificant.

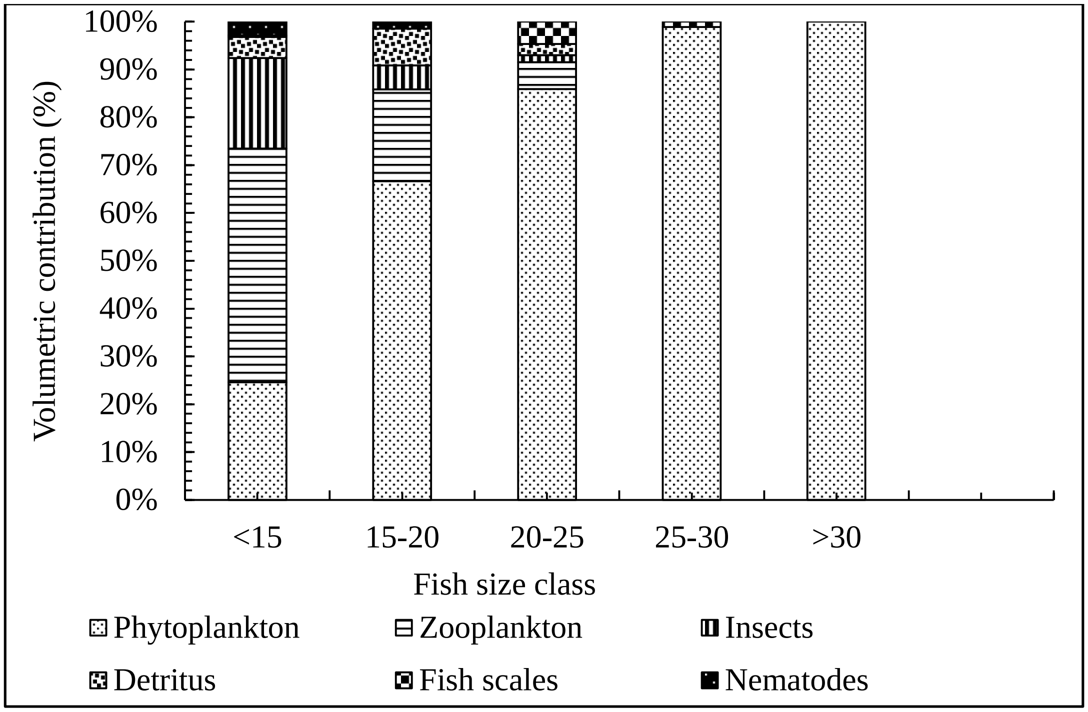


Figure 6.7. Volumetric contributions of different food items in the diet of different size classes of *Oreochromis niloticus* in Lake Shala from January to December 2018.

6.4.8. Seasonal Variation in the Diet of *O. niloticus* in Lake Shala

The seasonal contribution of different food items in the stomach of *O. niloticus* is shown in Table 6.6. The result exhibits seasonal variations in the diet composition of the fish in Lake Shala. Phytoplankton was the most important food item during both the dry and wet seasons. However, phytoplankton showed a significant variation in the dietary contribution of *O. niloticus* (t-test, $P < 0.05$) and significant during the dry months (Table 6.6). During the dry season, phytoplanktons occurred in 94.7% of the stomachs and comprising 84.9% of the total volume of food items. However, its contribution decreased to 60.3% of the total volume during the wet season.

Zooplankton also showed a seasonal variation in the diet composition of *O. niloticus* and significant during the wet season (Table 6.6). Zooplankton was observed in 54.3% of the stomach contents and comprised 21.4% of the total volume of the food during the wet season. But their contribution declined during the dry season (27.3%) and accounted for 10.3% of the total volume of food items (Table 6.6). Insects (Chironomids), nematodes, fish scales, and detritus also demonstrated significant seasonal variations in the diet of *O. niloticus* and it was important during the wet season (Table 6.6).

Table 6.6. Relative contribution of different food items in the diet of *Oreochromis niloticus* in Lake Shala during the dry and wet seasons.

Food type	**%Qi**		**%Vi**		**IOP%**		**(% GIIi)**	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Phytoplankton	**94.7**	84.0	**84.9**	60.3	**96.2**	77.4	**65.8**	47.4
Zooplankton	27.3	**54.3**	10.3	**21.4**	3.4	**17.7**	13.8	**24.9**
Insects	9.1	**16.0**	3.0	**8.5**	0.3	**2.1**	4.4	**8.0**
Nematodes	7.6	**14.9**	0.4	**1.4**	0.04	**0.3**	2.9	**5.4**
Fish scales	5.3	**11.7**	0.9	**2.6**	0.06	**0.5**	2.3	**4.7**
Detritus	6.8	**23.4**	0.4	**5.8**	0.04	**2.1**	2.7	**9.6**

6.5. Discussion

6.5.1. Length-Weight Relationship (LWR)

The regression equations and values of the correlation coefficient ‘r’ of *O. niloticus* are suggestive of a close relationship between total length (TL) and total weight (TW) of *O. niloticus* in Lake Shala, Ethiopia (Fig. 6.2 & Table 6.1). For an ideal fish that shows isometric growth, the regression coefficient (b) is 3.0, and populations in which the exponent differs from 3.0 exhibit allometric growths (Allen, 1966). In the present study, the regression coefficient has significantly varied from an ideal fish growth pattern (b = 3) with combined sex (3.19), indicating positive allometric growth of *O. niloticus* in Lake Shala. The result from this study was closely similar to the findings in Lake Turkana (b = 3.17) (Stewart, 1988) and in Lake Victoria (b = 3.20) (Njiru *et al.*, 2006). However, this value is slightly higher than for the same species in Lake Beseka (b = 2.69) (Lemma Abera, 2013), Lake Hayq (b = 2.95) (Workiyie Worie and Abebe Getahun, 2014), and Lake Langano (b = 2.88) (Mathewos Temesgen *et al.*, 2018). This variation can be attributed to the fact that within the same species, variation in ‘b’ values could be due to difference in sex predominance, health and fish condition factor, habitat type, feeding habits, different stages in the ontogenetic development, spawning period, preservation techniques and differences in a geographical location with the associated environmental conditions (Froese, 2006; Elliot *et al.*, 2015). In the present study, the higher values of ‘b’ also indicated a stress-free environment (Lorenz *et al.*, 2014; Omotayo *et al.*, 2019).

6.5.2. Condition Factor (CF)

In the present study, the mean Condition Factor (CF) for *O. niloticus* ranged between 0.72 and 1.51 with a total mean of 1.05 (Table 6.2). This finding agrees with Ighwela *et al.* (2011), who indicated that the fish were above average in terms of condition. The Condition Factors were close to those reported by Olurin and Aderibigbe (2006), where the CF of *O. niloticus* was 1.14 in males and 1.08 in females in Sanni Luba Fish Farm Ijebu-Ode, Ogun State. In this study, female *O. niloticus* (1.06) was slightly heavier than males (1.04). However, the difference between them was not significant (ANOVA, $P > 0.05$). The higher CF of female *O. niloticus* in Lake Shala may be attributed to the higher fat accumulation (Mortuza and Al-Misned, 2013) and gonad weight (Mondal and Chakravartty, 2016). In general, the study showed the mean CF of *O. niloticus* is slightly greater than 1 and indicated that *O. niloticus* in Lake Shala has a good growth condition.

6.5.3. Sex Ratio

In the present study, the overall sex ratio of *O. niloticus* (1:0.93) was not significantly different from the hypothetical distribution of 1:1 which indicates that males and females are distributed equally in Lake Shala. This was also observed for the same species in Lake Nyamusingiri and Kyasanduka, Uganda (Bwanika *et al.*, 2004), and in Itapaji Dam, Nigeria (Omotayo *et al.*, 2019). However, the predominance of female *O. niloticus* has been reported in some Ethiopian inland water bodies such as in Lake Beseka (Lemma Abera, 2013), Lake Hayq (Workiyie Worie and Abebe Getahun, 2014) and Tekeze Reservoir (Tsegay Teame *et al.*, 2018). In contrast, the dominance of the male *O. niloticus* population was reported in Lake Victoria (Njiru *et al.*, 2006), Lake Babogaya

(Lemma Abera, 2012) and Wadi Hanifah (Mortuza and Al-Misned, 2013). Possible reasons for this variation in the predominance of sex could be behavioral difference between sexes, which renders one sex to be more vulnerable to the fishing gear than the others, or the difference in refuge preference due to deviation in sexual maturity stages during the spawning season (Mathewos Temesgen *et al.*, 2018).

6.5.4. Gonado-Somatic Index (GSI) and Fecundity

Studies on breeding season, fecundity, and their associated factors are usually used to protect the recruits (Nyakuni, 2009) and predict recruitment variability (Shoko *et al.*, 2015). Fish life history parameters, such as spawning time, gonadal stage, and fecundity rate considerably vary between fish species (Peña-Mendoza *et al.*, 2005). In this study, GSI values for female *O. niloticus* showed significant temporal variations, with a biannual cycle observed during January - February and June - September (Fig. 6.3). Similar studies conducted on *O. niloticus* in Lakes Ziway (Zenebe Tadesse, 1988), Lake Awassa (Demeke Admassu, 1996), and Tekeze Reservoir (Tsegay Teame *et al.*, 2018) indicated a bi-modal breeding pattern of *O. niloticus*. However, mature ovaries were observed all year round, which is an indication that *O. niloticus* breeds throughout the year. Njiru *et al.* (2006) and Tsegay Teame *et al.* (2018) also reported that most *O. niloticus* breed continuously throughout the year with increased breeding during periods of intense rainfall. In Lake Shala, the peak spawning season of *O. niloticus* is not limited to the rainy period (July - September), but some of it also spawns during the dry season (January - February). High phytoplankton abundance and biomass (*Chl-a*) during these two periods (**Chapter Three**) may be an explanation for the intensification of sexual activity. However, other studies such as Lemma Abera (2012; 2013) cconducted on *O.*

niloticus found that fish breed intensively during the rainy season. During the rainy season flooding from the catchment results in increased nutrient concentrations which result in improved food quantity and quality (Zenebe Tadesse, 1988), so offsprings are produced at times of better growth and survival (Demeke Admassu, 1996). Several studies also explained rainfall, subtle change in water temperature and changing of water level as essential environmental factors associated with the intensive spawning activities of *O. niloticus* in different Ethiopian water bodies (Workiyie Worie and Abebe Getahun, 2014; Mathewos Temesgen *et al.*, 2018) and elsewhere (Peña-Mendoza *et al.*, 2005; Nyakuni, 2009).

In the current study, the observed number of eggs per female ranged from 240 to 1,642 eggs with an overall mean fecundity of 806 eggs. This result is lower than that observed by others on the same species elsewhere. For instance, Nyakuni (2009) obtained a fecundity of 412 to 2,380 eggs (mean of 854 eggs) from female *O. niloticus* in Albert Nile, in Lake Victoria (mean = 2,715 eggs) (Njiru *et al.*, 2006) and Tsegay Teame *et al.* (2018) reported 399 – 2,129 eggs per fish in Tekeze Reservoir, Ethiopia. However, the mean fecundity of *O. niloticus* in Lake Shala was higher than Lake Beseka (261 eggs) (Lemma Abera, 2013), Lake Langano (464 eggs per fish) (Mathewos Temesgen *et al.*, 2018) and Lake Hayq (217 eggs) (Assefa Tessema *et al.*, 2019). This variation in fecundity among the water bodies may be attributed to a combination of different factors such as fishing pressure, abundance, and the quality of food within the population (Peña-Mendoza *et al.*, 2005). In addition, the variation in fecundity may be attributed to the body condition and growth of the fish within the lakes. Fish in poor body condition are reported to have less fecundity than those in better condition (Lowe-McConnell, 1975;

Cuevas-Rodríguez *et al.*, 2017). The fecundity of the same fish species may also vary from one water body to another water body due to the body size of the fish procured for analysis. Tsegay Teame *et al.* (2018) obtained a maximum fecundity of 2,129 eggs from females of size 37 cm TL in Tekeze Reservoir, while Nyakuni (2009) reported a fecundity of 2,380 eggs per female at a size of 42 cm TL in Albert Nile. In the present study, the maximum fecundity (1,642 eggs) was recorded at 31.9 cm TL. These findings, therefore, confirm that fecundity in *O. niloticus* is variable and correlates with body total length. This is quite similar to the findings of other investigators in the Ethiopian rift valley lakes (Lemma Abera, 2012; Lemma Abera, 2013; Workiyie Worie and Abebe Getahun, 2014; Mathewos Temesgen *et al.*, 2018; Assefa Tessema *et al.*, 2019).

6.5.5. Food and Feeding Habits of *O. niloticus*

The food composition of *O. niloticus* can be highly variable within a water body, depending on the size and age of the fish, the habitat occupied and the time of the year (Daiki Tomojiri *et al.*, 2019). The present study found a variety of food items of phytoplankton, zooplankton, insect, nematodes, fish scales, and detritus in the stomachs of *O. niloticus*. This did not differ from the findings of Adeyemi *et al.* (2009) and Kuebutornye *et al.* (2019) which reported *O. niloticus* to have varying food including plant and animal origin in its gut. Many authors have also reported in different Ethiopian water bodies that *O. niloticus* feeds on a variety of food items (Yirgaw Teferi *et al.*, 2000; Filipos Engdaw *et al.*, 2013; Mulugeta Wakjira, 2013; Workiyie Worie and Abebe Getahun, 2015; Mathewos Temesgen, 2018).

Phytoplankton was the most important food item in all stomachs of *O. niloticus* in Lake Shala. This indicated that the fish was a phytoplanktivorous or herbivorous feeder. These findings are supported well by earlier findings that have classified *O. niloticus* as herbivorous that favor phytoplankton species (Abdulhakim *et al.*, 2015; Hussian *et al.*, 2019). Phytoplanktivorous or herbivorous feeding habits of *O. niloticus* have also been reported in Ethiopian water bodies such as Lake Chamo (Yirgaw Teferi *et al.*, 2000), Koka Reservoir (Filipos Engdaw *et al.*, 2013) and Lake Hayq (Workiyie Worie and Abebe Getahun, 2015). However, this result is in disagreement with Oso *et al.* (2006), who suggested that *O. niloticus* has omnivorous feeding habits. The contrasting feeding habits of the fish may be due to the differences in the abundance of food items in different locations.

In the present study, *O. niloticus* preferred Bacillariophyta (diatoms) to the phytoplankton groups. These findings were supported by the work of Abdulhakim *et al.* (2015), Mathewos Temesgen (2018), and Hussian *et al.* (2019) who mentioned that Bacillariophyta was the most predominant food items and highly desired by *O. niloticus*. The study of Shalloof and Khalifa (2009) also pointed out that the diatoms are the most important food items than any food items and represented about 68.0% of the total gut content of *O. niloticus* in Abu-Zabal Lake, Egypt. However, the dominance of green algae in Lake Hawassa (Tudorancea *et al.*, 1988), blue-green algae in Lake Zeway (Zenebe Tadesse, 1988), Koka Reservoir (Filipos Engdaw *et al.*, 2013) and Lake Hayq (Workiyie Worie and Abebe Getahun, 2015) were reported in the food composition of the same fish. These differences could be related to variations in environmental and biological factors among the lakes which influence the food items ingested by the fish

(Bwanika *et al.*, 2004; Mathewos Temesgen, 2018). According to Elizabeth Kebede and Willén (1996) and the present study (**Chapter Three**), the diatoms had a higher percentage abundance than the blue-green algae in Lake Shala. Besides, these diatoms are highly digestible because the holes in the frustules permit the entry of enzymes into the cytoplasm to enhance digestion (Yirgaw Teferi *et al.*, 2000). Although fish find easily food of heavy algae in atelomictic lakes like Lake Shala. This means that *O. niloticus* in Lake Shala was selecting diatoms more than other groups of algae.

Besides the major food items, they also picked a variety of other food items including rotifers, copepods, and Chironomidae, which contributed an appreciable amount to the food composition of *O. niloticus* in Lake Shala due to some nutritional benefits. Several authors have provided similar interpretations about the importance of zooplankton and insects in the diet of *O. niloticus* in different lakes and reservoirs (Yirgaw Teferi *et al.*, 2000; Adeyemi *et al.*, 2009; Filipos Engdaw *et al.*, 2013; Abdulhakim *et al.*, 2015; Workiyie Worie and Abebe Getahun, 2015; Mathewos Temesgen, 2018).

6.5.6. Diet Composition in Relation to Fish Size

Oreochromis niloticus fed on a wide variety of items such as phytoplankton, detritus, plant material, chironomids and zooplankton (Oso *et al.*, 2006; Daiki Tomojiri *et al.*, 2019; Kuebutornye *et al.*, 2019). Its feeding habits may be varying according to size (Mathewos Temesgen, 2018; Daiki Tomojiri *et al.*, 2019). In the present study, *O. niloticus* showed size-based differences in their feeding habit. The main prey items were phytoplankton in the larger-size class, but smaller-size fish consumed various aquatic animals and planktons, such as zooplankton, insects and phytoplankton. This showed that juveniles of *O. niloticus* are generally omnivorous in their feeding style. This did not differ markedly from Mathewos Temesgen (2018), who suggested *O. niloticus* as omnivorous feeding on both animal and plant origin at juvenile size class. However, this was in contrast with Yirgaw Teferi *et al.* (2000) and Filipos Engdaw *et al.* (2013), who reported that *O. niloticus* had a preference for food items of animal origin (zooplankton and insects) at juvenile stages.

The study showed that adult *O. niloticus* fed more on phytoplankton than other food items. This suggested that *O. niloticus* in Lake Shala switched their primary food resource in favor of phytoplankton. This finding agreed with Filipos Engdaw *et al.* (2013) and Hussian *et al.* (2019), who reported *O. niloticus* was phytoplanktivore in its feeding habit at a larger size. Similarly, the findings from the current study also agreed with the work of Yirgaw Teferi *et al.* (2000), who reported phytoplankton as a major item in the diet of adult *O. niloticus* in Lake Chamo. This size-based difference in feeding habits of *O. niloticus* may be due to energy demands, development of the fish's morphological and physiological features as it grows (Njiru *et al.*, 2004; Abdulhakim *et al.*, 2015). Also, the life history of *O. niloticus* is diverse (Bwanika *et al.*, 2004; Nyakuni, 2009), depending on the habitat they used, and its food habits can vary widely (Zenebe Tadesse, 1988; Yirgaw Teferi *et al.*, 2000; Filipos Engdaw *et al.*, 2013; Workiyie Worie and Abebe Getahun, 2015).

6.5.7. Seasonal Variation in the Diet of *O. niloticus* in Lake Shala

During the studies of fish feeding, the effect of seasonality should always be considered, because the seasonal changes of biotic and abiotic factors alter the structure of the food web along the year and, so the fish often shows seasonal diet shifts (Kariman *et al.*, 2009). In the current study, the food items of *O. niloticus* in Lake Shala showed a significant seasonal variation. Some previous studies also found a seasonal variation of food types in the diet composition of *O. niloticus* in the Ethiopian water bodies (Yirgaw Teferi *et al.*, 2000; Filipos Engdaw *et al.*, 2013; Workiyie Worie and Abebe Getahun, 2015; Mathewos Temesgen, 2018). The volumetric contribution of phytoplankton was higher during the dry than in a wet season and follows the study of Mathewos Temesgen (2018) and Workiyie Worie and Abebe Getahun (2015) who indicated that phytoplankton is the most important food item consumed during the dry season. However, this finding contrasted with that recorded by Mulugeta Wakjira (2013), who found a higher contribution of phytoplankton in the diet of *O. niloticus* during the wet season in Gilgel Gibe I Reservoir, Ethiopia.

The results from this study showed that the contribution of zooplankton, insect, detritus, nematodes, and fish scales was higher during the wet season. This was similar to earlier reports for these fish species in some other water bodies (Filipos Engdaw *et al.*, 2013; Mulugeta Wakjira, 2013; Workiyie Worie and Abebe Getahun, 2015; Mathewos Temesgen, 2018). The proportion of zooplankton in the diet of *O. niloticus* was higher during the wet season, which might have attributed to a high abundance of zooplankton during rainy seasons in the lake (**Chapter Four**). Furthermore, a low water temperature record during the rainy period in this study (**Chapter Two**) might contribute to the high abundance of the zooplankton population. Mergeay *et al.* (2006) also noted low water temperature as an essential factor for the hatching of zooplankton in natural water bodies. Seasonal flooding can also contribute to the high zooplankton population by bringing nutrients from the catchments which support the growth of phytoplankton and zooplankton productivity (Okogwu, 2010). This corroborates the reports of Workiyie Worie and Abebe Getahun (2015) and Filipos Engdaw *et al.* (2013) in Lake Hayq and Koka Reservoir, respectively.

The contribution of detritus was higher in the diet of *O. niloticus* during the wet season. This may be due to flooding which brings dead plant and animal parts into the lake and undergo partial decomposition. The dominance of detritus in the diet during the rainy season followed the study by Filipos Engdaw *et al.* (2013) in Koka Reservoir and Mathewos Temesgen (2018) in Lake Langano. Similarly, the high contribution of insects in the diet composition of *O. niloticus* during the wet season may be associated with the reproductive biology of the fish (Mathewos Temesgen *et al.*, 2018). Fish activities to shallow parts of the lake and staying there for reproduction could be an explanation for the increase in ingested insects in the wet season (Mulugeta Wakjira, 2013; Workiyie Worie and Abebe Getahun, 2015; Mathewos Temesgen *et al.*, 2018). This is similar to the findings of other investigators in the Ethiopian rift valley lakes (Zenebe Tadesse, 1988; Yirgaw Teferi *et al.*, 2000; Filipos Engdaw *et al.*, 2013; Mathewos Temesgen, 2018).

Chapter Seven: Conclusion and Recommendations

This work has assessed the physicochemical characteristics, plankton and macroinvertebrate community structure, and some aspects of the biology of *O. niloticus* and discussed the ecological status of the soda Lake Shala by comparing with previous works. The results have contributed to improved understanding of the limnology of Lake Shala. In this chapter, the main findings of the study are summarized and some recommendations are forwarded.

7.1. Conclusion

- Lake Shala's ecosystem has undergone fundamental ecological changes in terms of some physicochemical factors. EC, salinity, alkalinity, pH, SRP, NO_3-N and NH_3-N levels of the lake have increased in recent years, while SiO_2 decreased markedly in Lake Shala compared to reports of previous works. Possible causes which need to be investigated in the future include the biogeochemical process in the lake, agricultural expansion, human and livestock population within the catchment, deforestation and upstream diversions of River Adabat and Gidu for local irrigation. Also, the physicochemical parameters measured for Lake Shala showed seasonal and spatial variations, which might be associated with both in lake and external stressors, including biological (algal photosynthetic activity, microbial activity), biogeochemical and hydrological changes.
- The second component of the study investigated the dynamics and ecology of phytoplankton in Lake Shala in relation to environmental factors. The phytoplankton community of Lake Shala was dominated by diatoms throughout

the annual cycle. The result has shown that the composition and biomass of phytoplankton of the lake exhibited variations among sampling sites and season, probably because of the frequent mixing in the mixolimnion of such atelomictic lakes. Long-term change in some physicochemical variables may also have contributed to a change in phytoplankton composition and even to the demise of some taxa. The phytoplankton community has switched from Cryptophyta to Bacillariophyta dominated one, and dominance of dense taxa may have been favored by atelomixis in such a deep, soda lake. The establishment of *Arthrospira fusiformis* may have been favored in recent years by the high salinity, pH temperature, irradiance and nearly constant photoperiod.

- The zooplankton community of Lake Shala was dominated by rotifers (*Brachionus* species) which may have been enabled by their tolerance to environmental variables, unspecialized feeding, high reproductive rates and developmental stage. Zooplankton abundance and composition showed significant seasonal and vertical variations due to variability in phytoplankton abundance, *Chl a*, EC, and depth. However, Zooplankton abundance did not show a significant difference among sampling stations since the lake is dominated by small-bodied taxa. These observations support the ‘atelomixis’ hypothesis that frequent and irregular mixing in the mixolimnion of such deep lakes provides continuous food supply to zooplankton. The present study also showed that zooplankton community structure was generally influenced by EC.
- Lake Shala is characterized by a higher number of macro-invertebrate taxa than saline lakes of East African. The result also showed that macro-invertebrate taxa

in the lake are significantly reduced from the 1983/85 result which might indicate a shift in their assemblages. Site-specific comparisons showed that macro-invertebrate densities at open-water stations were significantly higher than the shore sites while the opposite is true for taxa richness and Shannon diversity. But evenness and equitability were not affected by locality. The environmental factors pH, conductivity, dissolved oxygen, nitrate, soluble reactive phosphorous, alkalinity, and salinity were the main driving factors that governed the distribution of macro-invertebrates in Lake Shala.

- The length-weight relationships of *O. niloticus* had a positive allometric growth pattern and the condition factor showed that *O. niloticus* were in a good physiological state of wellbeing in the lake. The overall sex ratio of *O. niloticus* was not significantly different from the hypothetical distribution of 1:1. *O. niloticus* breed throughout the year, however, their peak breeding time was from January to February, and June to September. The peek breeding time was strongly associated with phytoplankton abundance, rainfall, water temperature change and water level fluctuation. The mean fecundity was also high as compared to the fecundity of the same species in other lakes and strongly associated with their total weight and length.
- *O. niloticus* had a phytoplanktivorous feeding habits with a great selection for Bacillariophyta (Diatom) in Lake Shala. Phytoplankton was the dominant food type in the dry season, whereas the volume and percentage contribution of insects, zooplankton and detritus were increased during the wet season. The food items also varied with the increase in fish total length. Smaller fish mainly consumed

insects, zooplankton and phytoplankton, whereas larger fish fed on phytoplankton.

7.2. Recommendations

The following recommendations should be part of the conservation and management effort of Lake Shala.

- This study has better defined the current ecological status of Lake Shala ecosystem. Its physicochemical features, biological community structure (phytoplankton, zooplankton and macro-invertebrate) have changed over time, so there is a critical need for reconsidering the upcoming Soda Ash production and any future developments at Lake Shala. Also, population pressure, agricultural expansion and overgrazing of livestock are among the most degrading activities in the ASLNP. So lake and catchment management plans for lakes of ASLNP should be developed.
- Increasing of water diversion from river inflows into saline lakes and water abstraction for soda ash mining will shrink them and alter water quality. For example, Soda Lake Abijata has shrunk by 60 % since the 1980s because of Soda ash production and irrigated agriculture in upstream rivers and Lake Ziway (Solomon Wagaw *et al.*, 2019). Agricultural irrigation on the River Adabat and Gidu, tributaries of Lake Shala and future planned Lake Shala soda ash plant, will affect the lake water level. Therefore, this Lake Shala-based soda ash factory should not be established before conducting serious environmental impact assessment studies. If the project goes ahead, it should be carefully managed and

should consider the water balance of Lake Shala and the entire Ziway-Shala Lake basin.

- Documentation of aquatic biodiversity assemblages for all Ethiopian Soda lakes should be conducted and this can solve the problem of data shortage to show the historical trends.
- The future of soda lakes and their fish populations in Ethiopian soda lakes remain uncertain (E.g. *O. niloticus* in Lake Abijata). Sometimes, prompt interventions may have to be made to save the remaining local populations from extinction. This would require extensive surveys to collect data on species composition, distribution, life-history traits and other aspects of individual fish populations.

7.3. Research Gaps and Needs

- Continuous assessment of biodiversity and information on the ecological dynamics of Lake Shala should be considered to understand ecosystem functioning. Results can also show trends, the “cause-effect” and then after conservation and management plans will be developed.
- Baseline taxonomic inventory should be conducted for other biodiversity elements such as viruses, bacteria, water birds, mammals, macrophytes and vegetation of Lake Shala and their surrounding catchment.
- Paleontological studies are essential to explain changes over time and will assist in measuring the impact of climate and anthropogenic activities on the lakes. Results from these studies can then assist in designing catchment plans and restoration programs on the ASLNP.

8. References

Abdulhakim, A., Addo, S., Lawan, Z. A., and Ebenezer, A. (2015). Feeding habits and condition factor of *Oreochromis niloticus* in Lake Alau, Northeastern Nigeria. *Algae*. **32:** 23-36.

Abebe Eyualem (2002). Free-living aquatic nematodes of the Ethiopian Rift Valley. *Ethiopian Rift valley lakes. Backhuys Publishers, Leiden*, pp.143-156.

Abebe Getahun (2001). Lake Afdera: A threatened saline lake in Ethiopia. *SINET: Ethiopian Journal of Science* **24**(1)**:** 127–131.

Abijata-Shalla Soda Ash S.c. (2013). *Bid document for consultancy services for carrying out an environmental and social impact assessment (ESIA) study for a soda ash plant to be established at Abijata, Ethiopia*.

Abnet Woldesenbet (2019). *Assessment of the biotic integrity and water quality of Lake Ziway using benthic macroinvertebrate and diatom based multimetric index*. Ph.D. Thesis. Addis Ababa University, Addis Ababa, Ethiopia, 196pp.

Adadu, M., Garba, A., and Yusufu, I. (2019). Seasonal variation in macroinvertebrate community of river Okpokwu. *International Journal of Fisheries Aquatic Studies.* **7**(5)**:** 182-189.

Adamneh Dagne, Herzig, A., Jersabek, C. D., and Zenebe Tadesse (2008). Abundance, species composition and spatial distribution of planktonic rotifers and crustaceans in Lake Ziway (Rift Valley, Ethiopia). *International review of hydrobiology.* **93**(2)**:** 210-226.

Adeyemi, S. O., Akombu, P. M., and Toluhi, O. O. (2009). Food and feeding habits of *Oreochromis niloticus* in Lake Gbedikere, Bassa, Kogi state. *Continental Journal of Animal and Veterinary Research*. **1:** 25 - 30.

Afonina, E. Y., and Tashlykova, N. A. (2018). Plankton community and the relationship with the environment in saline lakes of Onon-Torey plain, Northeastern Mongolia. *Saudi journal of biological sciences.* **25**(2)**:** 399-408.

Al-Najjar, T. H., and Mohsen M., E.-S. (2008). Spatial and Seasonal Variations in Biomass and Size Structure of Zooplankton in Coastal Waters of the Gulf of Aqaba. *Jordan Journal of Biological Sciences.* **1**(2)**:** 55-59.

An, X., Du, Z., Zhang, J., Li, Y., and Qi, J. (2012). Structure of the zooplankton community in Hulun Lake, China. *Procedia Environmental Sciences.* **13:** 1099-1109.

Anton-Pardo, M., Armengol, X. J. E., Coastal, and Science, S. (2012). Effects of salinity and water temporality on zooplankton community in coastal Mediterranean ponds. *Estuarine, Coastal and Shelf Science*. **114:** 93-99.

APHA, Ed. (1995). Standard methods for the examination of water and wastewater. 19th Edition ed. Washington DC, USA.: American Public Health Association.

APHA, Ed. (1999). Standard methods for the examination of water and wastewater. . 19th Edition ed. Washington DC, USA.: American Public Health Association.

Armstrong, M. J., Gerritsen, H. D., Allen, M., McCurdy, W. J., and Peel, J. A. D. (2004). Variability in maturity and growth in a heavily exploited stock: Cod (*Gadus morhua* L.) in the Irish Sea. *ICES Journal of Marine Science.* **61:** 98-112.

Allen, K. R. (1966). A method of fitting growth curves of the von Bertalanffy type to observed data. J*ournal of the Fisheries Board of Canada*. **23**(2): 163-179.

Arora, J., and Mehra, N. (2009). Seasonal dynamics of zooplankton in a shallow eutrophic, man-made hyposaline lake in Delhi (India): role of environmental factors. *Hydrobiologia.* **626**(1)**:** 27-40.

Aschalew Lakew, and Moog, O. (2015). Benthic macroinvertebrates based new biotic score “ETHbios” for assessing ecological conditions of highland streams and rivers in Ethiopia. *Limnologica.* **52:** 11-19.

Asfaw Alemayehu (2011). *Effect of feed quality on growth performance and water quality in cage culture system for production of Nile Tilapia (Oreochromis niloticus, (Linnaeus, 1758)) in Lake Hora-Arsedi, Ethiopia.* Addis Ababa University.

Assefa Tessema, Abebe Getahun, Seyoum Mengistou, Tadesse Fetahi, and Eshete Dejen (2019). Length-weight relationship, condition factor and some reproductive aspects of Nile tilapia (*Oreochromis niloticus*) in Lake Hayq, Ethiopia. *International Journal of Fisheries and Aquatic Studies* **7**(5)**:** 555-561.

Assefa Tessema, Abebe Getahun, Seyoum Mengistou, Tadesse Fetahi, and Eshete Dejen (2020). Trend of Phytoplankton Composition and Physicochemical Water Quality Parameters of Lake Hayq, Ethiopia. *International Journal of Ecology and Environmental Sciences*. **46**(2): 155-165.

Assis, C. (1996). A generalized index for stomach contents analysis in fish. *Scienta Marina.* **60**(2–3)**:** 385–389.

Bagenal, T. B., and Tesch, F. W. (1978). Age and Growth. **In**: *Methods for Assessment of Fish Production in Fresh Waters* (T. B. Bagenal, Ed.), pp. 101-136. Blackwell Scientific Publications, Oxford, London.

Ballot, A., Kotut, K., Novelo, E., and Krienitz, L. (2009). Changes of phytoplankton communities in Lakes Naivasha and Oloidien, examples of degradation and salinization of lakes in the Kenyan Rift Valley. *Hydrobiologia.* **632**(1)**:** 359-363.

Ballot, A., Krienitz, L., Kotut, K., Wiegand, C., Metcalf, J. S., Codd, G. A., and Pflugmacher, S. (2004). Cyanobacteria and cyanobacterial toxins in three alkaline Rift Valley lakes of Kenya—Lakes Bogoria, Nakuru and Elmenteita. *Journal of Plankton Research.* **26**(8)**:** 925-935.

Barbosa, F. A., and Padisák, J. (2002). The forgotten lake stratification pattern: atelomixis, and its ecological importance. *Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen*. **28**(3): 1385-1395.

Barbosa, L. G., Barbosa, P. M. M., and Barbosa, F. A. R. (2011). Vertical distribution of phytoplankton functional groups in a tropical shallow lake: driving forces on a diel scale. *Acta Limnologica Brasiliensia*. **23**(1): 63-73.

Barbosa, L. G., Barbosa, F. A. R., and Bicudo, C. E. M. (2013). Adaptive strategies of desmids in two tropical monomictic lakes in southeast Brazil: do morphometric differences promote life strategies selection?. *Hydrobiologia*. **710**(1): 157-171.

Barbour, M. T., Gerritsen, J., Snyder, B. D., and Stribling, J. B. (1999). *Rapid bioassessment protocols for use in streams and wadeable rivers: periphyton, benthic macroinvertebrates and fish.* 339 Second Edition. EPA 841-B-99-002. US Environmental Protection Agency, Office of Water, Washington DC

Baumann, A., Förstner, U., and Rohde, R. (1975). Lake Shala: water chemistry, mineralogy and geochemistry of sediments in an Ethiopian rift lake. *Geologische Rundschau.* **64**(1)**:** 593-609.

Baumgärtner, D., Mörtl, M., and Rothhaupt, K.-O. (2008). Effects of water-depth and water-level fluctuations on the macroinvertebrate community structure in the littoral zone of Lake Constance. **In**: *Ecological Effects of Water-Level Fluctuations in Lakes*, pp. 97-107. Springer.

Baxter, R. M. (2002). *Lake morphology and chemistry.* Ethiopian Rift Valley Lakes. Backhuys, Leiden.

Baye Sitotaw (2014). *Microbial diversity of two Ethiopian soda lakes having contrasting physicochemical features*. Ph.D. Addis Ababa University, Addis Ababa.

Becker, V., Cardoso, L. S., and Huszar, V. L. M. (2008). Diel variation of phytoplankton functional groups in a subtropical reservoir in southern Brazil during an autumnal stratification period. *Aquatic Ecology*. **43**(2), 285-293.

Bellinger, E., and Sigee, D. (2010). Introduction to freshwater algae. *Freshwater algae: Identification and use as bioindicators.* 1-40.

Berhan Teklu, Amare Hailu, Wiegant, D. A., Scholten, B. S., and Van den Brink, P. (2018). Impacts of nutrients and pesticides from small-and large-scale agriculture on the water quality of Lake Ziway, Ethiopia. *Environmental Science and Pollution Research.* **25**(14)**:** 13207-13216.

Bernard, C., Escalas, A., Villeriot, N., Agogué, H., Hugoni, M., Duval, C., Carré, C., Got, P., Sarazin, G., and Jézéquel, D. (2019). Very Low Phytoplankton Diversity in a Tropical Saline-Alkaline Lake, with Co-dominance of *Arthrospira fusiformis* (Cyanobacteria) and *Picocystis salinarum* (Chlorophyta). *Microbial ecology.* 1-15.

Bonecker, C. C., Azevedo, F. d., and Simões, N. R. (2011). Zooplankton body-size structure and biomass in tropical floodplain lakes: relationship with planktivorous fishes. *Acta Limnologica Brasiliensia.* **23**(3): 217-228.

Bootsma, H. A., and Hecky, R. E. (1993). Conservation of the African Great Lakes: a limnological perspective. *Conservation Biology*. **7**(3): 644-656.

Bottrell, H., Duncan A, Gliwicz ZM, Grygierek E, Herzig A, Hillbricht-Ilkowska A, Kurasawa H, Larsson P, and T, W. (1976). A review of some problems in zooplankton production studies. *Norwegian Journal of Zoology.* **24:** 419-456.

Bouchard, R. W. (2004). *Guide to aquatic invertebrates of the Upper Midwest: identification manual for students, citizen monitors, and aquatic resource professionals*. University of Minnesota, Water Resources Research Center, USA.

Bozkurt, A., and Akın, Ş. (2012). Zooplankton fauna of Yeşilırmak (between Tokat and Blacksea), Hasan Uğurlu and Suat Uğurlu Dam Lakes. *Turkish Journal of Fish and Aquatic Science.* **12:** 777–786.

Bouvy, M., Ba, N., Ka, S., Sane, S., Pagano, M., and Arfi, R. (2006). Phytoplankton community structure and species assemblage succession in a shallow tropical lake (Lake Guiers, Senegal). *Aquatic Microbial Ecology*, **45**(2), 147-161.

Brook Lemma, and Hayal Desta (2016). Review of the natural conditions and anthropogenic threats to the Ethiopian Rift Valley rivers and lakes. *Lakes & Reservoirs: Research & Management.* **21**(2): 133-151.

Burian, A. (2010). *Zooplankton dynamics of two alkaline-saline lakes in the Keyan Rift Valley*. P.hD dissertation. Uniwien University.

Burian, A., Schagerl, M., Kainz, M., and Yasindi, A. (2014). Species-specific separation of lake plankton reveals divergent food assimilation patterns in rotifers. *Freshwater Biology*. **59**(6): 1257-1265.

Butakka, C., Ragonha, F., Train, S., Pinha, G., and Takeda, A. (2016). Chironomidae feeding habits in different habitats from a Neotropical floodplain: exploring patterns in aquatic food webs. *Brazilian Journal of Biology*. (ahead)**:** 0-0.

Bwanika, G., Makanga, B., Kizito, Y., Chapman, L., and Balirwa, J. (2004). Observations on the biology of Nile tilapia, *Oreochromis niloticus* L., in two Ugandan crater lakes. *African Journal of Ecology*. **42**: 93-101.

Çamur-Elipek, B., Arslan, N., Kirgiz, T., Öterler, B., Güher, H., and Özkan, N. (2010). Analysis of benthic macroinvertebrates in relation to environmental variables of Lake Gala, a National Park of Turkey. *Turkish Journal of Fisheries and Aquatic Sciences*. **10**(2): 235-243.

Chrisafi, E., Kaspiris, P., and Katselis, G. (2007). Feeding habits of sand smelt (*Atherina boyeri*, Risso 1810) in Trichonis Lake (western Greece). *Journal of Applied Ichthyology*. **23**(3): 209-214.

Ciros-Pérez, J., Carmona, M. J., and Serra, M. (2001). Resource competition between sympatric sibling rotifer species. *Limnology and Oceanography*. **46**(6): 1511-1523.

Ciros-Pérez, J., Ortega-Mayagoitia, E., and Alcocer, J. (2015). The role of ecophysiological and behavioral traits in structuring the zooplankton assemblage in a deep, oligotrophic, tropical lake. *Limnology and Oceanography*. **60**(6): 2158-2172.

Clavero, E., Hernández-Mariné, M., Grimalt, J. O., and Garcia-Pichel, F. (2000). Salinity tolerance of diatoms from thalassic hypersaline environments. *Journal of Phycology*. **36**(6): 1021-1034.

Clifford, H. F. (1991). *Aquatic invertebrates of Alberta: An illustrated guide*. The University of Alberta Press, Edmonton, Alberta, Canada.

Cuevas-Rodríguez, B. L., García-Ulloa, M., Hernández-Llamas, A., Racotta, I., Valdez-González, F. J., Polanco-Torres, A., and Rodríguez-González, H. (2017). Evaluating quality of Nile tilapia (*Oreochromis niloticus*) eggs and juveniles from different commercial hatcheries. *Latin american journal of aquatic research*. **45**(1)**:** 213-217.

Cvetkoska, A., Pavlov, A., Jovanovska, E., Tofilovska, S., Blanco, S., Ector, L., Wagner-Cremer, F., and Levkov, Z. (2018). Spatial patterns of diatom diversity and community structure in ancient Lake Ohrid. *Hydrobiologia*. **819**(1): 197-215.

Daiki Tomojiri, Prachya Musikasinthorn, and Akihisa Iwata (2019). Food habits of three non-native cichlid fishes in the lowermost Chao Phraya River basin, Thailand. *Journal of Freshwater Ecology*. **34**(1): 419-432.

Daniel Gamachu (1977). *Aspects of climate and water budget in Ethiopia*. Addis Ababa University Press, Addis Ababa. 71 pp.

Dan-Kishiya, A. (2013). Length-weight relationship and condition factor of five fish species from a tropical water supply reservoir in Abuja, Nigeria. *American Journal of Research Communication*. **1**(9): 175-187.

Defaye, D. (1988). Contribution a la connaissance des Crustaces Copepodes d’Ethiopie. *Hyrobiologia*. **164**: 103-147.

Demeke Admassu (1996). The breeding season of tilapia, Oreochromis niloticus L. in Lake Hawassa (Ethiopian rift valley). *Hydrobiologia.* **337**: 77-83.

Demeke Admasu (1990). Some Morphometric relationships and Condition Factor of *Oreochromis niloticus* (Pisces: Cichlidae) in Lake Awassa, Ethiopia. *SINET Ethiopian Journal of Science.* **17:** 53-69.

Deocampo, D. M., and Renaut, R. W. (2016). Geochemistry of African soda lakes. **In**: *Soda Lakes of East Africa*, pp. 77-93. Springer.

Derry, A., Prepas, E., and Hebert, P. (2003). A comparison of zooplankton communities in saline lake water with variable anion composition. *Hydrobiologia.* **505** (1-3): 199-215.

Dessie Tibebe, Feleke Zewge, Brook Lemma, Yezbie Kassa, and Ashok N. Bhaskarwar. (2018). External Nutrient Load and Determination of the Trophic Status of Lake Ziway. *CSVTU International Journal of Biotechnology, Bioinformatics and Biomedical*. **3**(2): 01–16.

Diego, F., Yamila, B., Gisela, M., and Patricia, M. (2015). Controlling factors in planktonic communities over a salinity gradient in high-altitude lakes. **In** *Annales de Limnologie-International Journal of Limnology* (Vol. 51, No. 3, pp. 261-272). EDP Sciences.

Dimante-Deimantovica, I., Skute, A., and Skute, R. (2012). Vertical variability of pelagic zooplankton fauna in deep Latvian lakes, with some notes on changes in ecological conditions. *Estonian Journal of Ecology*. **61**(4): 247.

Dodds, W., and Whiles, M. (2010). *Freshwater ecology: concepts and environmental applications of limnology*. 2nd ed. Academic Press, San Diego, CA.

Duckworth, A., Grant, W., Jones, B., and Van Steenbergen, R. (1996). Phylogenetic diversity of soda lake alkaliphiles. *FEMS Microbiology Ecology.* **19**(3): 181-191.

Dumont, H. J., Velde, I. V. D., and S. Dumont (1975). The dry weight estimate of biomass in a selection of Cladocera, Copepoda and Rotifera from the plankton, periphyton and benthos of continental waters. *Oecologia* **19**: 75–97.

Echaniz, S. A., Vignatti, A. M., De Paggi, S. J., Paggi, J. C., and Pilati, A. (2006). Zooplankton Seasonal Abundance of South AmericanSaline Shallow Lakes. *International Review of Hydrobiology.* **91**(1): 86-100.

Elias, J. D., Ijumba, J. N., Mgaya, Y. D., and Mamboya, F. A. (2014). Study on freshwater macroinvertebrates of some Tanzanian rivers as a basis for developing biomonitoring index for assessing pollution in tropical African regions. *Journal of Ecosystems.* **2014. DOI, http://dx.doi.org/10.1155/2014/985389**.

Elizabeth Kebede, and Ahlgren, G. (1996). Optimum growth conditions and light utilization efficiency of *Spirulina platensis* (= *Arthrospira fusiformis* (Cyanophyta) from Lake Chitu, Ethiopia. *Hydrobiologia.* **332**(2): 99-109.

Elizabeth Kebede, and Hillman, J. C. (1988). The conservation status of birds at lakes Abijata and Shalla. *In* "Paper presented at the 7th Pan-African Ornithological Congress (PAOC)", Nairobi, Kenya.

Elizabeth Kebede, and Willén, E. (1996). *Phytoplankton in a salinity-alkalinity series of lakes in the Ethiopian Rift Valley*. Acta Universitatis Upsaliensis.

Elizabeth Kebede, Zinabu Gebre-Mariam, and Ahlgren, I. (1994). The Ethiopian Rift Valley lakes: chemical characteristics of a salinity–alkalinity series. *Hydrobiologia.* **288**: 1–12.

Elliot, H. A., Daniel, N. A., and Francis, A. (2015). Determination of Morphometric Relationship and Condition Factors of Four Cichlids from Golinga Reservoir in Northern Region of Ghana. *OnLine Journal of Biological Sciences* **15**(3): 201-206.

Fasil Degefu, and Schagerl, M. (2015). Zooplankton abundance, species composition and ecology of tropical high-mountain crater Lake Wonchi, Ethiopia. *Journal of Limnology*. **74**(2).

Fabbro, L. D., and Duivenvoorden, L. J. (1996). Profile of a bloom of the cyanobacterium *Cylindrospermopsis raciborskii* (Woloszynska) Seenaya and Subba Raju in the Fitzroy River in tropical central Queensland. *Marine* & *Freshwater Research*. **47**(5): 685-694.

Fernandes, V., and Ramaiah, N. (2019). Spatial structuring of zooplankton communities through partitioning of habitat and resources in the Bay of Bengal during spring intermonsoon. *Turkish Journal of Zoology*. **43**(1): 68-93.

Fernández-Álamo, M. A., and Färber-Lorda, J. (2006). Zooplankton and the oceanography of the eastern tropical Pacific: a review. *Progress in Oceanography*. **69**(2-4): 318-359.

Fernando, C. H. (2002). *A Guide to Tropical Freshwater Zooplankton. Identification, Ecology, and Impact on Fisheries*. Backhuys Publishers, Leiden, The Netherlands.

Filipos Engdaw, Elias Dadebo, and Nagappan, R. (2013). Morphometric relationships and feeding habits of Nile tilapia *Oreochromis niloticus* (L.) (Pisces: Cichlidae) from Lake Koka, Ethiopia. *International Journal of Fisheries and Aquatic Sciences*. **2**(4): 56-71.

Froese, R. (2006). Cube law, condition factor and weight–length relationships: history, meta-analysis and recommendations *Journal of Applied Ichthyology*. **22**: 241–253.

García, C. M., and Niell, F. (1993). Seasonal change in a saline temporary lake (Fuente de Piedra, southern Spain). *Hydrobiologia*. **267**(1-3): 211-223.

Gashaw Tesfaye, and Zenebe Tadesse (2008). Length-weight relationship, Fulton's condition factor and size at first maturity of Tilapia, Oreochromis niloticus in Lakes Koka, Zeway and Langano (Ethiopian rift valley). *Ethiopian Journal of Biological Sciences*. **2**: 139-157.

Gasse, F., Talling, J., and Kilham, P. (1983). Diatom assemblages in East Africa: classification, distribution and ecology (lakes, water chemistry). *Revue d'Hydrobiologie Tropicale (France).*

Geoffrey, O. O., Andrew, W. Y., Steve, O. o., Steffen, J., Michael, S., Bettina, S., and Jens, B. (2013). Ecology and community structure of ciliated protists in two alkaline–saline Rift Valley lakes in Kenya with special emphasis on *Frontonia*. *Journal of Plankton Research*. **35**(4): 759-771.

Ghosh, D., and Biswas, J. K. (2015). Macroinvertebrate diversity indices: A quantitative bioassessment of ecological health status of an oxbow lake in Eastern India. *Journal of Advances in Environmental Health Research*. **3**(2): 78-90.

Giday WoldeGabriel, Daniel Olago., Edwin Dindi., and Owor., M. (2016). Genesis of the East African Rift System. **In**: *Soda Lakes of East Africa* (M. Schagerl., Ed.), pp. 25-59. Springer, Switzerland.

Girma Tilahun, and Ahlgren, G. (2010). Seasonal variations in phytoplankton biomass and primary production in the Ethiopian Rift Valley lakes Ziway, Awassa and Chamo–The basis for fish production. *Limnologica-Ecology and Management of Inland Waters.* **40**(4): 330-342.

Golubtsov, A. S., Dgebuadze, Y. Y., and Mina, M. (2002). Fishes of the Ethiopian rift valley. *Ethiopian rift valley lakes.* **167**: 258.

Gooderham, J., and Tsyrlin, E. (2002). *The waterbug book: a guide to the freshwater macroinvertebrates of temperate Australia*. Csiro publishing. guidance manual. Wisconsin department of natural resources. Madison, WI 53707.

Grant, W. (2004). Half a lifetime in soda lakes. **In**: *Halophilic microorganisms.* (Ventosa A, Ed.), pp. 17–31. Springer, Berlin.

Grant, W., Gerday, C., and Glansdorff, N. (2006). *Alkaline environments and biodiversity*. Eolss Publishers Oxford, UK.

Grant, W. D., and Jones, B. E. (2016). Bacteria, Archaea and Viruses of Soda Lakes. **In**: *Soda Lakes of East Africa* (M. Schagerl, Ed.), pp. 96-147. Springer, Switzerland.

Grant, W. D., and Sorokin, D. Y. (2011). Distribution and diversity of soda lake alkaliphiles. *Extremophiles handbook.* 27-54.

Green, J., and Seyoum Mengistou (1991). Specific diversity and community structure of Rotifera in a salinity series of Ethiopian inland waters. *Hydrobiologia*. **209**: 203-214.

Gülle, I., Turna, I. I., Güçlü, S. S., Gülle, P., and Güçlü, Z. (2010). Zooplankton seasonal abundance and vertical distribution of highly alkaline Lake Burdur, Turkey. *Turkish Journal of Fisheries and Aquatic Sciences.* **10**(2): 245-254.

Gunkel, G., and Beulker, C. (2009). Limnology of the Crater Lake Cuicocha, Ecuador, a cold water tropical lake. *International Review of Hydrobiology*. **94**(1): 103-125.

Gutkowsk, A., Paturej, E., and Koszalka, J. (2018). Does the location of coastal brackish waters determine diversity and abundance of zooplankton assemblages? *Turkish Journal of Zoology*. **42**: 230-244.

Hammer, U. T. (1986). *Saline lake ecosystems of the world*. 59 Springer Science & Business Media.

Hartman, R., Sherman, S., Contreras, D., Furler, A., and Kok, R. (2019). Characterizing macroinvertebrate community composition and abundance in freshwater tidal wetlands of the Sacramento-San Joaquin Delta. *PLoS ONE 14.* **14**(11): e0215421.

Hecky, R. E., and Kilham, P. (1973). Diatoms in Alkaline, Saline Lakes: Ecology and Geochemical Implications. *Limnology and Oceanography.* **18**(1): 53-71.

Hecky, R. E., and Bugenyi, F. W. B. (1992). Hydrology and chemistry of the African Great Lakes and water quality issues: Problems and solutions. *Internationale Vereinigung für Theoretische und Angewandte Limnologie: Mitteilungen*. **23**(1): 45-54.

Helenius, L. (2015). The role of zooplankton in littoral communities: Diversity and food web interactions in the Baltic Sea.

Herbst, D. B., Roberts, S. W., and Medhurst, R. B. (2013). Defining salinity limits on the survival and growth of benthic insects for the conservation management of saline Walker Lake, Nevada, USA. *Journal of insect conservation.* **17**(5): 877-883.

Holden, M. J., and Raitt, D. F. S. (1974). Manual of fisheries science. **In**: *Methods of resource investigation and their application*. FAO. Fish tech.

Hötzel, G., and Croome, R. (1999). *A phytoplankton methods manual for Australian freshwaters*.Land and Water Resources Research and Development Corporation Occasional papers 22/99.

Hussian, A.-E. M., Walid Aly, and Morsi, H. H. (2019). Feeding on phytoplankton profile of two African Cichlids in large reservoir, Lake Nasser, Egypt. *Egyptian Journal of Aquatic Biology and Fisheries.* **23**(4): 451– 464.

Hyslop, E. J. (1980). Stomach contents analysis - a review of methods and their application. *Journal of Fish Biology.* **17**: 411-429.

Ighwela, K. A., Ahmed, A. B., and Abol-Munafi, A. B. (2011). Condition factor as an indicator of growth and feeding intensity of Nile tilapia fingerlings (*Oriochromis niloticus*) feed on different levels of Maltose. *American-Eurasian Journal of Agriculture and Environmental Science.* **11**(4): 559-563.

Isumbisho, M., Sarmento, H., Kaningini, B., Micha, J.-C., and Descy, J.-P. (2006). Zooplankton of Lake Kivu, East Africa, half a century after the Tanganyika sardine introduction. *Journal of Plankton Research.* **28**(11): 971-989.

Jensen, J., Jeppesen, E., Olrik, K., and Kristensen, P. (1994). Impact of nutrients and physical factors on the shift from cyanobacterial to chlorophyte dominance in shallow Danish lakes. *Canadian Journal of fisheries and aquatic sciences.* **51**(8): 1692-1699.

Jessup, B. K., Markowitz, A., Stribling, J. B., Friedman, E., Labelle, K., and Dziepak, N. (1999). *Family-level key to the stream invertebrates of Maryland and surrounding areas*. Maryland department of natural resources Chesapeake Bay and watershed program resource assessment service monitoring and non-tidal assessment division, CBWP-MANTA-EA-99-2.

Jones, B., and Grant, W. (1999). *Microbial Biosystems: New Frontiers: Proceedings of the 8th International Symposium for Microbial Ecology (2000). Atlantic Canada Society for Microbial Ecology, Halifax, Canada*.

Jones, C., Somers, K., Craig, B., and Reynoldson, T. (2007). Ontario Benthos Biomonitoring Network: Protocol Manual. Ontario Ministry of Environmental Biomonitoring Section, Queen's Printer for Ontario.

Joseph, B., and Yamakanamardi, S. (2011). Monthly changes in the abundance and biomass of zooplankton and water quality parameters in Kukkarahalli Lake of Mysore, India. *Journal of Environmental Biology*. **32**(5): p.551.

Kadigi, R. M., Mwathe, K., Dutton, A., Kashaigili, J., and Kilima, F. (2014). Soda ash mining in lake Natron: a reap or ruin for Tanzania?

Kaggwa, M. N., Gruber, M., Oduor, S. O., and Schagerl, M. (2013). A detailed time series assessment of the diet of Lesser Flamingos: further explanation for their itinerant behaviour. *Hydrobiologia.* **710**(1): 83-93.

Kalff, J. (2002). *Limnology: inland water ecosystems*.

Kambura, A. K., Mwirichia, R. K., Kasili, R. W., Karanja, E. N., Makonde, H. M., and Boga, H. I. (2016). Diversity of fungi in sediments and water sampled from the hot springs of Lake Magadi and Little Magadi in Kenya. *African Journal of Microbiology Research.* **10**(10): 330-338.

Kariman, A., Shalloof, S., and Nehad, K. (2009). Stomach Contents and Feeding Habits of *Oreochromis niloticus* (L.) From Abu-Zabal Lakes, Egypt. *World Applied Sciences.* **6**(1): 01-05.

Kassahun Wodajo, and Amha Belay (1984). Species composition and seasonal abundance of zooplankton in two Ethiopian Rift Valley Lakes Abijata and Langano. *Hydrobiologia*. **113**: 136-140.

Kathleen, R.-F. (2011). Abijata-Shalla Lakes National Park: Assessment of Factors Driving Environmental Change for Management Decision-Making. (E. W. C. Authority, Ed.), Addis Ababa, Ethiopia.

Kavembe, G. D., Axel, M., and Chris, M. W. (2016). Fish Populations in East African Saline Lakes. **In**: *Soda Lakes of East Africa* (Michael Schagerl, Ed.), pp. 227-257. Springer, Switzerland.

Kazanci, N., Girgin, S., and Dügel, M. (2004). On the limnology of Salda Lake, a large and deep soda lake in southwestern Turkey: future management proposals. *Aquatic Conservation: Marine and Freshwater Ecosystems.* **14**(2): 151-162.

Khitam, A. M., Nashaat, M. R., and Alkam, F. M. (2017). Environmental and vertical distribution study of zooplankton in Al-Diwaniyah River, Iraq. *Journal of Biodiversity and Environmental Sciences.* **10**(6): 217-228.

Kibichii, S., Shivoga, W. A., Muchiri, M., Miller, S. N. J. L., Research, R., and Management (2007). Macroinvertebrate assemblages along a land-use gradient in the upper River Njoro watershed of Lake Nakuru drainage basin, Kenya. *Lakes & Reservoirs*: *Research & Management*. **12**(2): 107-117.

Kihwele, E., Lugomela, C., Howell, K., and Nonga, H. (2015). Spatial and temporal variations in the abundance and diversity of phytoplankton in Lake Manyara, Tanzania. *International Journal of Innovative Studies in Aquatic Biology and Fisheries*. **1**(1): 1-14

Kihwele, E. S., Lugomela, C., and Howell, K. M. (2014). Temporal changes in the Lesser Flamingos population (Phoenicopterus minor) in relation to phytoplankton abundance in Lake Manyara, Tanzania. *Open Journal of Ecology*. **4**(03): 145.

Klemperer, S. L., and Cash, M. D. (2007). Temporal geochemical variation in Ethiopian Lakes Shala, Arenguade, Awasa, and Beseka: possible environmental impacts from underwater and borehole detonations. *Journal of African Earth Sciences.* **48**(2-3): 174-198.

Kocer, M. A. T., and ŞEN, B. (2012). The seasonal succession of diatoms in phytoplankton of a soda lake (Lake Hazar, Turkey). *Turkish Journal of Botany.* **36**(6): 738-746.

Kocer, M. A. T., and ŞEN, B. (2014). Some factors affecting the abundance of phytoplankton in an unproductive alkaline lake (Lake Hazar, Turkey). *Turkish Journal of Botany.* **38**(4): 790-799.

Komárek, J., and Kling, H. (1991). Variation in six planktonic cyanophyte genera in Lake Victoria (East Africa). *Algological Studies/Archiv für Hydrobiologie, Supplement Volumes.* 21-45.

Korinek, V. (1999). *A guide to limnetic species of Cladocera of African inland Waters (Crustacea, Brachiopoda)(Using the morphology of parthenogenetic females).* Volta Basin Research Project, Accra on behalf of International Association of Theoretical and Applied Limnology c/ o Department of Biological Sciences, University of Alabama.

Kratzer, E. B. (2002). *Temporal and spatial variation of wetland macroinvertebrates of the Okefenokee swamp*. P.hD thesis. University of Georgia, Athens.

Krienitz, L., Dadheech, P. K., and Kotut, K. (2013). Mass developments of the cyanobacteria Anabaenopsis and Cyanospira (Nostocales) in the soda lakes of Kenya: ecological and systematic implications. *Hydrobiologia.* **703**(1): 79-93.

Krienitz, L., and Kotut, K. (2010). Fluctuating algal food populations and the occurrence of Lesser flamingos (Phoeniconaias minor) in three Kenyan rift valley lakes. . *Journal of Phycology*. **46**(6): 1088-1096.

Krienitz, L., Ma¨hnert, B., and Schagerl, M. (2016). Lesser Flamingo as a Central Element of the East African Avifauna. **In**: *Soda Lakes of East Africa* (Schagerl M., Ed.), pp. 259-284. Springer, Switzerland.

Kuchapski, K. A., and Rasmussen, J. B. (2015). Surface coal mining influences on macroinvertebrate assemblages in streams of the Canadian Rocky Mountains. *Environmental toxicology chemistry and Ecology.* **34**(9): 2138-2148.

Kuebutornye, F., Akongyuure, D., and Alhassan, E. (2019). Morphometric Characteristics and Feeding Habits of Five Commercial Fish Species of the Libga Reservoir in the Northern Region of Ghana. *International Journal of Oceanography & Aquaculture.* **3**(2): 000164.

Lanzen, A., Simachew, A., Gessesse, A., Chmolowska, D., Jonassen, I., and Øvreås, L. (2013). Surprising prokaryotic and eukaryotic diversity, community structure and biogeography of Ethiopian soda lakes. *PLoS One.* **8**(8): e72577.

Lemma Abera (2012). The breeding saeason and condition factor of *Oreochromis niloticus* (pisces: cichlidae) in lake babogaya, ethiopia. *Pastoral Livestock Systems: Opportunities and Challenges as a Livelihood Strategy.* 119.

Lemma Abera (2013). Reproductive biology of *Oreochromis niloticus* in Lake Beseka, Ethiopia. *Journal of Cell and Animal Biology.* **7**(9): 116-120.

Li, K., Liu, X., Zhou, Y., Xu, Y., Lv, Q., Ouyang, S., and Wu, X. (2019). Temporal and spatial changes in macrozoobenthos diversity in Poyang Lake Basin, China. *Ecology Evolution.* **9**(11): 6353-6365.

Lopes, M. R. M., Bicudo, C. E. M., and Ferragut, M. C. (2005). Short term spatial and temporal variation of phytoplankton in a shallow tropical oligotrophic reservoir, southeast Brazil. *Hydrobiologia.* **542**: 235–247.

Lorenz, O., Smith, P., and Coghill, L. (2014). Condition and morphometric changes in tilapia (*Oreochromis* sp.) after an eradication attempt in Southern Louisiana. *NeoBiota.* **20**: 49.

Lowe-McConnell, R. H. (1975). *Fish Communities in Tropical Freshwaters: Their Distribution, Ecology, and Evolution*. Longman, London.

Lugomela, C., Pratap, H. B., and Mgaya, Y. D. (2006). Cyanobacteria blooms—a possible cause of mass mortality of Lesser Flamingos in Lake Manyara and Lake Big Momela, Tanzania. *Harmful Algae.* **5**(5): 534-541.

Luo, W., Kotut, K., and Krienitz, L. (2013). Hidden diversity of eukaryotic plankton in the soda lake Nakuru, Kenya, during a phase of low salinity revealed by a SSU rRNA gene clone library. *Hydrobiologia.* **702**(1): 95-103.

Luo, W., Li, H., Kotut, K., and Krienitz, L. (2017). Molecular diversity of plankton in a tropical crater lake switching from hyposaline to subsaline conditions: Lake Oloidien, Kenya. *Hydrobiologia.* **788**(1): 205-229.

Mantyka Pringle, C. S., Martin, T. G., Moffatt, D. B., Linke, S., and Rhodes, J. R. (2014). Understanding and predicting the combined effects of climate change and land use change on freshwater macroinvertebrates and fish. *Journal of Applied Ecology*. **51**(3): 572-581.

Marini, G., Pinna, M., Basset, A., and Mancinelli, G. (2013). Estimation of benthic macroinvertebrates taxonomic diversity: testing the role of sampling effort in a Mediterranean transitional water ecosystem. *Transitional Waters Bulletin.* **7**(2): 28-40.

Marzin, A. (2013). *Ecological assessment of running waters using bio-indicators: associated variability and uncertainty*. Doctorate thesis. Agros Paris Tech, Paris, p. 202.

Mason, C. (1991). *Biology of Freshwater Pollution*. 2nd ed. Longman Scientific and Technical, Essex, England.

Matagi, S. V. (2004). A biodiversity assessment of the Flamingo Lakes of eastern Africa. *Biodiversity*. **5**: 13-26.

Mathewos Temesgen (2018). *Status and trends of fish and fisheries in Lake Langano, Ethiopia*. Ph.D. dissertation submitted to Department of Zoological Sciences. Addis Ababa University, Addis Ababa, Ethiopia.

Mathewos Temesgen, Abebe Getahun, and Brook Lemma (2018). Reproductive Biology of Commercially Important Fish Species in Lake Langano, Ethiopia. *Asian Fisheries Science.* **31**: 319-339.

McCauley, E., and Kalff, J. (1981). Empirical relationships between phytoplankton and zooplankton biomass in lakes. *Canadian Journal of Fisheries and Aquatic Sciences.* **38**: 458–463.

Melack, J. M. (1996). Recent development in tropical limnology. *Verh Internat Verein Theor Angew Limnol.* **26**: 211–217.

Melack, J. M. (2009). Diel variability and community metabolism in African soda lakes. *Natural Resources and Environmental Issues.* **15**(1): 28.

Melack, J. M., Jellison, R., and Herbst, D. B. (2002). *Saline lakes*. 162 Springer Science & Business Media.

Melack, J. M., and MacIntyre, S. (2016). Morphometry and Physical Processes of East African Soda Lakes. **In**: *Soda Lakes of East Africa* (M. Schagerl, Ed.), pp. 61-76. Springer International Publishing, Switzerland.

Mergeay, J., Verschuren, D., and Meester, L. D. (2006). Invasion of an asexual American water flea clone throughout Africa and rapid displacement of a native sibling species. *Procedural Biological Sciences.* **273**: 2839–2844.

Mesfin Gebrehiwot, Demeke Kifle, Stiers, I., and Triest, L. (2017). Phytoplankton functional dynamics in a shallow polymictic tropical lake: the influence of emergent macrophytes. *Hydrobiologia.* **797**(1): 69-86.

Milbrink, G. (1977). On the limnology of two alkaline lakes (Nakuru and Naivasha) in the East Rift Valley System in Kenya. *Internationale Revue der gesamten Hydrobiologie und Hydrographie.* **62**(1): 1-17.

Mohammed Abdi (1993). *Impact of Human Activity on Abijata-Shala Lakes National Park*. M.Sc. Thesis. Agricultural University of Norway.

Mohammed MU, and Bonnefille, R. (1991). The recent history of vegetation and climate around Lake Langano. *Palaeoecology of Africa*. **22**: 275–286.

Mondal, A., and Chakravartty, D. (2016). Grow-out performance, length-weight relationship and variation in condition of all male Nile tilapia (*Oreochromis* *niloticus* Linnaeus 1758) from low saline fertilize earthen ponds of Indian Sundarbans. *Int J Biol Res.* **1**(5): 28-33.

Morando, M., and Capone, D. G. (2018). Direct utilization of organic nitrogen by phytoplankton and its role in nitrogen cycling within the Southern California Bight. *Frontiers in microbiology*. **9**: 2118.

Mortuza, M. G., and Al-Misned, F. A. (2013). Length-weight relationships, condition factor and sex-ratio of Nile tilapia, *Oreochromis niloticus* in Wadi Hanifah, Riyadh, Saudi Arabia. *World Journal of Zoology*. **8**(1): 106-109.

Muli, J. R. (2005). Spatial variation of benthic macroinvertebrates and the environmental factors influencing their distribution in Lake Victoria, Kenya. *Aquatic Ecosystem Health & Management.* **8**(2): 147-157.

Mulugeta Wakjira (2013). Feeding habits and some biological aspects of fish species in Gilgel Gibe Reservoir, Ethiopia. *International Journal of Current Research.* **5**(12): 4124-4132.

Mulugeta Wakjira (2016). *Fish Diversity, Community Structure, Feeding Ecology, and Fisheries of Lower Omo River and the Ethiopian Part of Lake Turkana, East Africa*. Ph.D. Dissertation, Addis Ababa University, Addis Ababa, Ethiopia, 234pp.

Musˇka, M., Vasˇek M, Modry´ D, Jirku° M, Ojwang WO, Malala JO, and Kubecˇka J (2012). The last snapshot of natural pelagic fish assemblage in Lake Turkana, Kenya: a hydroacoustic study. *Journal of Great Lakes Research*. **38**: 98–106.

Mutanga, J., Mwatha, W., Nasirwa, O., and Gichuru, N. (2000). Status and trends in the biodiversity of Eastern Rift Valley lakes in Kenya **In**: *Conservation and sustainable use of biodiversity in Eastern Rift Valley lakes, Kenya* (Bennun LA, Ndede H, and G. NN, Eds.), pp. 6-34. GEF/UNDP Consultancy Report. National Museums of Kenya, Nairobi.

Nandini, S., Merino-Ibarra, M., Sarma, S. J. L., and Management, R. (2008). Seasonal changes in the zooplankton abundances of the reservoir Valle de Bravo (State of Mexico, Mexico). *Lake and Reservoir Management*. **24**(4): 321-330.

Nandini, S., Sarma, S., Amador-López, R. J., and Bolaños-Muñioz, S. (2007). Population growth and body size in five rotifer species in response to variable food concentration. *Journal of Freshwater Ecology*. **22**(1): 1-10.

Nassar, M. Z. A., and Gharib, S. M. (2014). Spatial and temporal patterns of phytoplankton composition in Burullus Lagoon, Southern Mediterranean Coast, Egypt. *The Egyptian Journal of Aquatic Research*. **40**(2): 133-142.

Nehemia, A., Maganira, J. D., and Rumisha, C. (2012). Length-weight relationship and condition factor of tilapia species grown in marine and fresh water ponds. *Agriculture and Biology Journal of North America.* **3**(3): 117-124.

Njiru, M., Ojuok, J. E., Okeyo-Owuor, J. B., Muchiri, M., Ntiba, M. J., and Cowx, I. G. (2006). Some biological aspects and life history strategies of Nile tilapia *Oreochromis niloticus* (L.) in Lake Victoria, Kenya. *African Journal of Ecology.* **44:** 30–37.

Njiru, M., Okeyo-Owuor, J. B., Muchiri, M., and Cowx, I. G., . (2004). Shifts in the food of Nile tilapia, *Oreochromis niloticus* (L.) in Lake Victoria, Kenya. *African Journal of Ecology*. **42**: 163-170.

Noel, S. D., and Rajan, M. (2015). Evaluation of Organic Pollution by Palmer's Algal Genus Index and Physico-chemical Analysis of Vaigai River at Madurai, India. *Natural Resources and Conservation.* **3**(1): 7-10.

Nweze, N. O. (2006). Seasonal variations in phytoplankton populations in Ogelube Lake, a small natural West African Lake. *Lakes & Reservoirs: Research & Management.* **11**(2): 63-72.

Nyakuni, L. (2009). *Habitat utilization and Reproductive Biology of Nile Tilapia (Oreochromis Niloticus) in Albert Nile, Nebbi District*. Makerere University.

Oduor, S., and Schagerl, M. (2007a). Phytoplankton primary productivity characteristics in response to photosynthetically active radiation in three Kenyan Rift Valley saline–alkaline lakes. *Journal of Plankton Research.* **29**(12): 1041-1050.

Oduor, S., and Schagerl, M. (2007b). Temporal trends of ion contents and nutrients in three Kenyan Rift Valley saline-alkaline lakes and their influence on phytoplankton biomass. **In**: *Shallow Lakes in a Changing World*, pp. 59-68. Springer.

Oduor, S., Schagerl, M., and Mathooko, J. (2003). On the limnology of Lake Baringo (Kenya): I. temporal physico-chemical dynamics. *Hydrobiologia.* **506**(1-3): 121-127.

Oduor, S. O., and Kotut, K. (2016). Soda lakes of the East African Rift System: the past, the present and the future. **In**: *Soda Lakes of East Africa* (Schagerl M., Ed.), pp. 365-374. Springer, Swizerland

Okogwu, O. I., Nwani, C. D., and Okoh, F. A. (2010). Seasonal variation and diversity of rotifers in Ehoma lake, Nigeria **31**(4): 533-537.

Okoth, O. E., Mucai, M., Shivoga, W. A., Miller, S. N., Rasowo, J., and Ngugi, C. C. (2009). Spatial and seasonal variations in phytoplankton community structure in alkaline–saline Lake Nakuru, Kenya. *Lakes & Reservoirs: Research & Management.* **14**(1): 57-69.

Okoth, O. E., Muchiri, M., Ngugi, C. C., Njenga, E. W., Ngure, V., Orina, P. S., Chemoiwa, E. C., and Wanjohi, B. K. (2011). Zooplankton partitioning in a tropical alkaline–saline endorheic Lake Nakuru, Kenya: Spatial and temporal trends in relation to the environment. *Lakes & Reservoirs: Research & Management.* **16**(1): 35-47.

Olurin, K. B., and Aderibigbe, O. A. (2006). Length-weight relationship and condition factor of pond reared juvenile *Oreochromis niloticus*. *World Journal of Zoology.* **1**(2): 82-85.

Omotayo, F., Folasade A.O-O., Olugbemi V. E., and Oluwadare A. (2019). Length-Weight Relationship and Condition Factor of Two Species of Tilapia and One Species of Mormyrops from a Tropical Dam in a Southwestern State, Nigeria. *Journal of Zoological Research.* **3**(1): 1-5.

Ortega-Mayagoitia, E., Ciros-Pérez, J., and Sánchez-Martínez, M. (2011). A story of famine in the pelagic realm: temporal and spatial patterns of food limitation in rotifers from an oligotrophic tropical lake. *Journal of Plankton Research*. **33**(10): 1574-1585.

Oso, J. A., Ayodele, I. A., and Fagbuaro, O. (2006). Food and Feeding Habits of *Oreochromis niloticus* (L.) and *Sarotherodon galilaeus* (L.) in a Tropical Reservoir. *World Journal of Zoology.* **1**(2): 118-121.

Owen, R. A., Owen, R. B., Renaut, R. W., Scott, J. J., Jones, B., and Ashley, G. M. (2008). Mineralogy and origin of rhizoliths on the margins of saline, alkaline Lake Bogoria, Kenya Rift Valley. *Sedimentary Geology*. **203**(1-2): 143-163.

Padisák, J., Crossetti, L. O., and Naselli-Flores, L. (2009). Use and misuse in the application of the phytoplankton functional classification: a critical review with pdates. *Hydrobiologia*. **621**(1): 1-19.

Pecoraino, G., D'Alessandro W., and Inguaggiato S. (2015). The other side of the coin: geochemistry of alkaline lakes in volcanic areas. **In**: *Volcanic lakes, Advances in volcanology* (Rouwet D et al, Ed.), pp. 219–237. Springer, Berlin.

Peña-Mendoza, B., Gómez-Márquez, J. L., Salgado-Ugarte, I., and Ramírez-Noguera, D. (2005). Reproductive biology of *Oreochromis niloticus* (Perciformes: Cichlidae) at Emiliano Zapata dam, Morelos, Mexico. *Revista de biologia tropical*. **53**(3-4): 515-522.

Perumal, N. V., Rajkumar, M., Perumal, P., and Rajasekar, K. T. (2009.). Seasonal variations of plankton diversity in the Kaduviyar estuary, Nagapattinam, southeast coast of India. *Journal of Environmental Biology*. **30**: 1035– 1046.

Po¨rtner, H., Schulte PM, Wood CM, and Schiemer F (2010). Niche dimensions in fishes: an integrative view. *Physiol Biochem Zool*. **83**: 808–826.

Potapova, M. (2011). Patterns of diatom distribution in relation to salinity. **In**: *The diatom world*, pp. 313-332. Springer.

Rasoloariniaina, J. R. (2017). Physico-chemical water characteristics and aquatic macroinvertebrates of Lake Tsimanampesotse, south-western Madagascar. *African Journal of Aquatic Science*. **42**(2): 191-199.

Rezenom Almaw (2012). *A Checklist of the Birds of the Abijata-Shalla Lakes National Park (Central Rift-Valley, Ethiopia)*. Ethiopian Wildlife Conservation Authority.

Rocha, R., Thomaz, S., Carvalho, P., and Gomes, L. (2009). Modeling chlorophyll-a and dissolved oxygen concentration in tropical floodplain lakes (Paraná River, Brazil). *Brazilian Journal of Biology*. **69**(2): 491-500.

Ruttner-Kolisko, A. (1977). Suggestions for biomass calculations of plankton rotifers. *Archive of Hydrobiology*. **8**: 71-76.

Savitha, N., and Yamakanamardi, S. M. (2012). Studies on abundance of zooplanktons in lakes of Mysore, India. *Journal of environmental biology*. **33**(6): 1079.

Schagerl, M., Burian, A., Gruber-Dorninger, M., Oduor, S. O., and Kaggwa, M. N. (2015). Algal communities of Kenyan soda lakes with a special focus on *Arthrospira fusiformis*. *Fottea*. **15**(2): 245-257.

Schagerl, M., and Oduor, S. (2008). Phytoplankton community relationship to environmental variables in three Kenyan Rift Valley saline-alkaline lakes. *Marine and Freshwater Research*. **59**(2): 125-136.

Schagerl, M., and Renaut, R. W. (2016). Dipping into the Soda Lakes of East Africa. **In**: *Soda Lakes of East Africa* (M. Schagerl, Ed.), pp. 3-24. Springer, Switzerland.

Seyoum Mengistou (2016). Invertebrates of East African soda lakes. **In**: *Soda Lakes of East Africa*, pp. 205-226. Springer.

Seyoum Mengistou, and Fernando, C. H. (1991). Biomass and production of major dominant crustacean zooplankton in a tropical rift valley lake, Awasa, Ethiopia. *Journal of Plankton Research*. **13**: 831–852.

Shalloof, K. A. S., and Khalifa, N. (2009). Stomach contents and feeding habits of *Oreochromis niloticus* (L.) from Abu-Zabal lakes, Egypt. *World Applied Sciences Journal*. **6**(1): 1-5.

Shoko, A., Limbu, S., Mrosso, H., and Mgaya, Y. (2015). Reproductive biology of female Nile tilapia *Oreochromis niloticus* (Linnaeus) reared in monoculture and polyculture with African sharptooth catfish *Clarias gariepinus* (Burchell). *SpringerPlus*. **4**(1): 275.

Solomon Wagaw, Seyoum Mengistou, and Abebe Getahun (2019). Review of anthropogenic threats and biodiversity assessment of an Ethiopian soda lake, Lake Abijata. *African Journal of Aquatic Science*. **44**(2): 103-111.

Souza, M. B. n. G., Barros, C. F. A., Barbosa, F., Hajnal, E. v., and Padisa´k, J. (2008). Role of atelomixis in replacement of phytoplankton assemblages in Dom Helve´cio Lake, South-East Brazil. *Hydrobiologia*. **607**: 211–224.

Sreeraj, N., Raghavan R., and Prasad G. (2006). The diet of *Horabagrus brachysoma* (G€unther), an endangered bagrid catfish from Lake Vembanad (South India). *Journal of Fish Biology*. **69**(2): 637–642.

Stenger-Kovács, C., Lengye, E., Buczkó, K., Tóth, F. M., Crossetti, L. O., Pellinger, A., Doma, Z. Z., and Padisák, J. (2014). Vanishing world: alkaline, saline lakes in Central Europe and their diatom assemblages. *Inland Waters*. **4**(4): 383-396.

Stephenson, J. G. (1978). *An appraisal of the conservation of nature in the Lakes Abijata and Shala locality with recommendations*. Ethiopian Wildlife Conservation Organization (EWCO) Addis Ababa.

Stewart, K. M. (1988). Changes in condition and maturation of *Oreochromis niloticus* L. Population of Ferguson's Gulf, Lake Turkana, Kenya. *Journal of Fish Biology*. **33**: 181-188.

Sui, F., Zang, S., Fan, Y., and Ye, H. (2016). Effects of Different Saline-Alkaline Conditions on the Characteristics of Phytoplankton Communities in the Lakes of Songnen Plain, China. *PloS one*. **11**(10): e0164734.

Tadesse Fetahi, Seyoum Mengistou, and Schagerl, M. (2011). Zooplankton community structure and ecology of the tropical-highland Lake Hayq, Ethiopia. *Limnologica*. **41**(4): 389-397.

Tadesse Fetahi, Schagerl, M., and Seyoum Mengistou (2014). Key drivers for phytoplankton composition and biomass in an Ethiopian highland lake. *Limnologica*. **46**: 77-83.

Tadesse Fetahi (2016). Greening a Tropical Abijata-Shala Lakes National Park, Ethiopia - A Review. *Journal of Ecosystem and Ecography*. **6**(1): 1-9.

Tadesse Ogato (2015). *Dynamics of phytoplankton and physicochemical features of the Ethiopian soda lakes Chitu and Shala, and evaluation of the potential of their waters for the production of Arthrospira (Spirulina) fusiformis (Cyanophyta) in laboratory cultures*. Ph.D. Addis Ababa University, Addis Ababa.

Tadesse Ogato, and Demeke Kifle (2017). Phytoplankton composition and biomass in tropical soda Lake Shala: seasonal changes in response to environmental drivers. *Lakes & Reservoirs: Research & Management*. **22**(2): 168-178.

Tadesse Ogato, Demeke Kifle, and Brook Lemma (2016). Algal composition and biomass in the tropical soda lake Chitu with focus on seasonal variability of

Arthrospira fusiformis (Cyanophyta). *Marine and Freshwater Research.* **67**(4): 483-491.

Tadesse Ogato, Demeke Kifle, Tadesse Fetahi, and Baye Sitotaw (2014). Evaluation of growth and biomass production of Arthrospira (Spirulina) fusiformis in laboratory cultures using waters from the Ethiopian soda lakes Chitu and Shala. *Journal of applied phycology*. **26**(6): 2273-2282.

Tafesse Kefyalew (2008). *Integrated Assessment of ecosystem services and stakeholder analysis of Abijata-Shalla Lakes National Park, Ethiopia*. M Sc. Thesis in Environmental Sciences, Washington University.

Talling, J. F., and Driver, D. (1963). *Some problems in the estimation of chlorophyll-a in phytoplankton*.

Talling, J., and Talling, I. B. (1965). The chemical composition of African lake waters. *Internationale Revue der gesamten Hydrobiologie und Hydrographie.* **50**(3): 421-463.

Talling, J. F. (1966). Photosynthetic behaviour in stratified and unstratified lake populations of a planktonic diatom. *The Journal of Ecology*. p. 99-127.

Tamiru Alemayehu , Tenalem Ayenew, and Seifu Kebede (2006). Hydrogeochemical and lake level changes in the Ethiopian Rift. *Journal of hydrology*. **316**(1-4): 290-300.

Tarekegn Wondmagegn, and Seyoum Mengistou (2020). Effects of anthropogenic activities on macroinvertebrate assemblages in the littoral zone of Lake Hawassa, a tropical Rift Valley Lake in Ethiopia. *Lakes Reservoirs: Research Management.* **25**(1): 61-71.

Tavera, R. and Martínez-Almeida, V. (2005). Atelomixis as a possible driving force in the phytoplankton composition of Zirahue´n, a warm-monomictic tropical lake. *Hydrobiologia*. **533**(1): 199–208.

Tavsanoglu, U. N., Maleki, R., and Akbulut, N. (2015). Effects of Salinity on the Zooplankton Community Structure in Two Maar Lakes and One Freshwater Lake in the Konya Closed Basin, Turkey. *Ekoloji Dergisi.* **24**(94): 25-32.

Tenalem Ayenew (2004). Environmental implications of changes in the levels of lakes in the Ethiopian Rift since 1970. *Regional Environ Chang.* **4**: 192–204.

Tenalem Ayenew, and Dagnachew Legesse (2007). The changing face of the Ethiopian rift lakes and their environs: call of the time. *Lakes & Reservoirs: Research & Management.* **12**(3): 149-165.

Tenalem Ayenew and GebreEgziabher Merhawi (2015). Morphometric characteristics and hydrology of selected Ethiopian Rift lakes. **In**: *Landscapes and Landforms of Ethiopia*, Springer, Dordrecht. pp. 275-287.

Ter Braak, C. J., and Smilauer, P. (2002). *CANOCO reference manual and CanoDraw for Windows user's guide: software for canonical community ordination (version 4.5).*www. canoco. com.

Tewodros Kumssa, and Afework Bekele (2014a). Current population status and activity pattern of lesser flamingos (*Phoeniconaias minor*) and greater flamingo (Phoenicopterus roseus) in Abijata-Shalla Lakes National Park (ASLNP), Ethiopia. *International Journal of Biodiversity.* p.8.

Tewodros Kumssa, and Afework Bekele (2014b). Feeding ecology of Lesser Flamingos (*Phoeniconaias minor*) in Abijata-Shalla Lakes National Park (ASLNP) with special reference to lakes Abijata and Chitu, Ethiopia. *Asian Journal of Biological Sciences.* **7**(2): 57-65.

Tewodros Kumssa, and Afework Bekele (2014c). Phytoplankton Composition and Physico-Chemical Parameters Study in Water Bodies of Abijata-Shalla Lakes National Park (ASLNP), Ethiopia. *Greener Journal of Biological Sciences* **4**(2): 069-076.

Tilahun Kibret, and Harrison, A. D. (1989). The benthic and weed-bed faunas of Lake Awasa (Rift Valley, Ethiopia). *Hydrobiologia.* **174**(1): 1-15.

Tirok, K., and Gaedke, U. (2007). Regulation of planktonic ciliate dynamics and functional composition during spring in Lake Constance. *Aquatic Microbial Ecology*. **49**(1): 87-100.

Tolonen, K. T. (2004). *Patterns in diversity and assemblages of lake littoral macroinvertebrates in relation to abiotic and biotic factors.* Ph.D. University of Joensuu.

Tsegay Teame, Haftom Zebib, and Tesfay Meresa (2018). Observations on the biology of Nile tilapia, *Oreochromis niloticus* L., in Tekeze Reservoir, Northern Ethiopia. *International Journal of Fisheries and Aquaculture.* **10**(7): 86-94.

Tudorancea, C., Fernando, and Paggi, J. (1988). Food and feeding of *Oreochromis niloticus* L. juveniles in Lake Hawassa, Ethiopia. *Arch Hydrobiology Supply*. **79**: 267-289.

Tudorancea, C., and Harrison, A. D. (1988). The benthic communities of the saline lakes Abijata and Shala (Ethiopia). **In**: *Saline Lakes*, pp. 117-123. Springer.

Tudorancea, C., and Taylor, W. (2002). *Ethiopian Rift Valley Lakes*. Backhuys Publishers, Leiden.

Umi, W., Yusoff, F., Aris, A., and Sharip, Z. (2018). Rotifer community structure in tropical lakes with different environmental characteristics related to ecosystem health. *Journal of Environmental Biology*. **39**(5): 795-807.

Vareschi, E., and Jacobs, J. (1984). The ecology of Lake Nakuru (Kenya) V. Production and consumption of consumer organisms. *Oecologia* **61**: 83–98.

Velasco, J., Millán, A., Hernández, J., Gutiérrez, C., Abellán, P., Sánchez, D., and Ruiz, M. (2006). Response of biotic communities to salinity changes in a Mediterranean hypersaline stream. *Saline systems.* **2**(1)**:** 12.

Vignatti, A. M., Cabrera, G. C., Echaniz, S. A., and Canosa, M. (2017). Environmental and zooplankton parameter changes during the drying of a saline shallow temporary lake in central Argentina. *Universitas Scientiarum.* **22**(3): 177-200.

Von Damm, K., and Edmond, J. (1984). Reverse weathering in the closed-basin lakes of the Ethiopian Rift. *American Journal of Science.* **284**(7): 835-862.

Voshell, J. (2002). *A guide to common freshwater invertebrates of North America* McDonald and Woodward Publishing Company, Blacksburg, Virginia.

Voutilainen, A., Jurvelius, J., Lilja, J., Viljanen, M., and Rahkola-Sorsa, M. (2016). Associating spatial patterns of zooplankton abundance with water temperature, depth, planktivorous fish and chlorophyll. *Boreal Environment Research*. **21**: 101–114

Wakil, U., Haruna, A., Mohammed, G., Ndirmbita, W., Yachilla, B., and Kumai, M. (2014). Examinations of the stomach contents of two fish species (*Clarias* *gariepinus* and *Oreochromis niloticus*) in Lake Alau, North-Eastern Nigeria. *Agriculture, Forestry and Fisheries.* **3**(5): 405-409.

Wang, J., Hu, J., Tang, T., Heino, J., Jiang, X., Li, Z., and Xie, Z. (2020). Seasonal shifts in the assembly dynamics of benthic macroinvertebrate and diatom communities in a subtropical river. *Ecology evolution.* **10**(2): 692-704.

Waters, N. M., and San Giovanni, C. R. (2002). Distribution and diversity of benthic macroinvertebrates associated with aquatic macrophytes. *Journal of freshwater ecology.* **17**(2): 223-232.

Waya, R. K., Limbu, S. M., Ngupula, G. W., Mwita, C. J., and Mgaya, Y. D. (2014). Spatial patterns of zooplankton distribution and abundance in relation to phytoplankton, fish catch and some water quality parameters at Shirati Bay, Lake Victoria-Tanzania. *Tanzania Journal of Science.* **40**(1): 21-33.

Wetzel, R. G., and Likens, G. E. (2000). *Limnological analyses*. 3rd ed. ed. Springer New York.

Williams, W. D. (2002). Environmental threats to salt lakes and the likely status of inland saline ecosystems in 2025. *Environmental conservation.* **29**(2): 154-167.

Williamson, C. E., Overholt, E. P., Pilla, R. M., and Wilkins, K. W. (2020). Habitat-mediated responses of zooplankton to decreasing light in two temperate lakes undergoing long-term browning. *Frontiers in Environmental Science*.

Wondie Zelalem, Demeke Kifle, Seyoum Mengistu, and Ayalew Wondie (2017). Weed-bed Macro-invertebrate Composition and Abundance in Relation to Water Hyacinth (*Eichhornia crassipes* (Mart) Solms) in the North-Eastern Lake Tana, Ethiopia. *Journal of Agriculture and Environmental Sciences.* **2**(1): 52-66.

Wood, R., Baxter, R., and Prosser, M. (1984). Seasonal and comparative aspects of chemical stratification in some tropical crater lakes, Ethiopia. *Freshwater Biology.* **14**(6): 551-573.

Wood, R., and Talling, J. (1988). Chemical and algal relationships in a salinity series of Ethiopian inland waters. **In**: *Saline Lakes*, pp. 29-67. Springer.

Workiyie Worie, and Abebe Getahun (2014). Length-weight relationship, condition factor and some reproductive aspects of Nile Tilapia, *Oreochromis niloticus*, in Lake Hayq, Ethiopia. *International Journal of Zoology and Research*. **5**(4): 47-60.

Workiyie Worie, and Abebe Getahun (2015). The food and feeding ecology of Nile tilapia, *Oreochromis niloticus*, in Lake Hayq, Ethiopia. *Journal of Fisheries and Aquatic Studies.* **2**(3): 176-185.

Wu, J. T., and Kow, L. C. (2010). Alteration of phytoplankton assemblages caused by changes in water hardness in Feitsui Reservoir, Taiwan. *Botanical Studies*. **51**(4).

Yin, X.-W., Tan, B.-B., Zhou, Y.-C., Li, X.-C., and Liu, W. J. H. (2016). Development time of male and female rotifers with sexual size dimorphism. *Hydrobiologia*. **767**(1): 27-35.

Yirga Enawgaw, and Brook Lemma (2018). Zooplankton communities as an indicator of ecosystem productivity in Lake Tinishu Abaya, Rift Valley, Ethiopia. *International Journal of Fisheries and Aquaculture.* **10**(5): 53-70.

Yirgaw Teferi, Demeke Admassu, and Seyoum Mengistu (2000). The food and feeding habit of *Oreochromis niloticus* L. (Pisces: Cichlidae) in Lake Chamo, Ethiopia. *SINET: Ethiopian Journal of Science.* **23**(1): 1-12.

Yirgaw Teferi, and Demeke Admasu (2002). The length-weight relationship, body condition and sex ratio of tilapia (*Oreochromis niloticus*) in Lake Chamo, Ethiopia. *SINET: Ethiopian Journal of Science.* **25**(1): 19-26.

Yongo, E., and Outa, N. (2017). Spatial distribution and abundance of zooplankton communities in Lake Victoria, Kenya. *International Journal of Fisheries and Aquatic Research.* **2**(1): 33-35.

Zaccara, S., Crosa G, Vanetti I, Binelli G, Harper DM, Mavuti KM, Balarin JD, and Britton JR (2014). Genetic and morphological analyses indicate high population mixing in the endangered cichlid *Alcolapia* flock of East Africa. *Conserv Genet.* **15**: 429–440.

Zakaria, H. Y., Hassan, A.-K. M., El-Naggar, H. A., and Fekry M. Abo-Senna (2018). Biomass determination based on the individual volume of the dominant copepod species in the Western Egyptian Mediterranean Coast. *Egyptian Journal of Aquatic Research.* **44**: 89-99.

Zenebe Tadesse (1988). *Studies on some aspects of the biology of Oreochromis niloticus Linn, (Pisces: Cichilidae) in Lake Ziway Ethiopia.* M.Sc. Addis Ababa University, Addis Ababa.

Zenebe Tadesse (1997). Breeding season, fecundity, length-weight relationship and condition factor of *Oreochromis niloticus* L.(Pisces: Cichlidae) in Lake Tana, Ethiopia. *SINET: Ethiopian Journal of Science.* **20**(1): 31-47.

Zerihun Woldu, and Mesfin Tadesse (1990). The status of the vegetation in the Lakes Region of the Rift Valley of Ethiopia and the possibilities of its recovery. *SINET, Ethiopian Journal of Science.* **13**(2): 97-120.

Zerubabel Worku, and Tsion Mohammed (2019). Eco-Lodges and Tourist Infrastructure Development in and Around Abijata Shalla Lakes National Park; From the Perspective of Evaluating their Sustainability. *Journal of Tourism, Hospitality and Sports* **45**.

Zinabu GebreMariam (2002). The effects of wet and dry seasons on concentrations of solutes and phytoplankton biomass in seven Ethiopian rift-valley lakes. *Limnologica.* **32**(2)**:** 169-179.

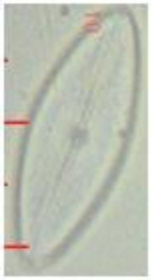
Zinabu GebreMariam, Elizabeth Kebede, and Zerihun Desta (2002). Long-term changes in chemical features of waters of seven Ethiopian rift-valley lakes. *Hydrobiologia.* **477**(1-3): 81-91.

Zinabu GebreMariam, and Taylor, W. (1997). Bacteria—chlorophyll relationships in Ethiopian lakes of varying salinity: are soda lakes different? *Journal of Plankton Research.* **19**(5): 647-654.

Zinabu GebreMariam (2002). The Ethiopia rift valley lakes: major threats and strategies for conservation. **In**: *Ethiopia rift valley lakes* (Tudorancea C, and T. WD, Eds.), pp. 259–270. vols. Backhages, Leiden.

Appendex

Apendex 1. Some phytoplankton species identified from Lake Shala.



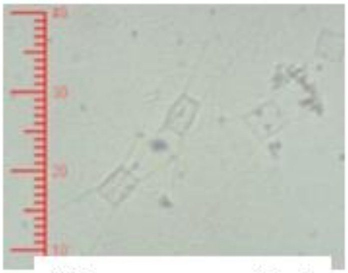
Achnanthes spp.

Anomoeoneis sphaerophora

Aulacoseira distant

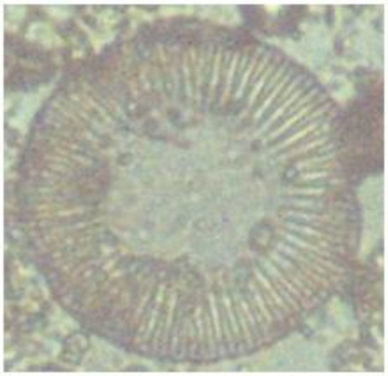
A granulata

Campylodiscus clpeus

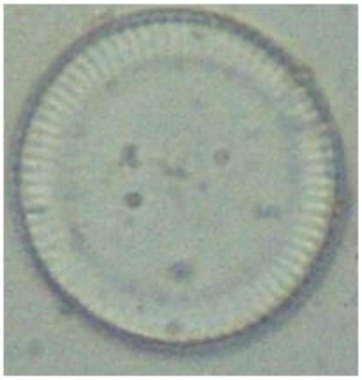


Chaetoceros mulleri

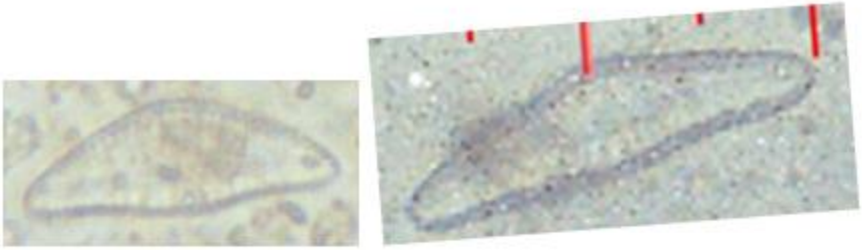
Cocconeis spp.



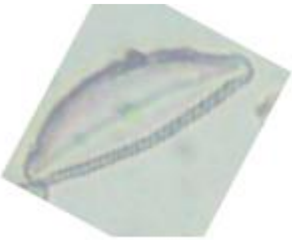
Cyclotella iris



C. ocellata



Cymbella spp.



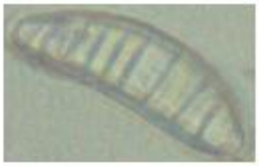
Cymbella cistula

Denticula spp.

Encynonema spp.

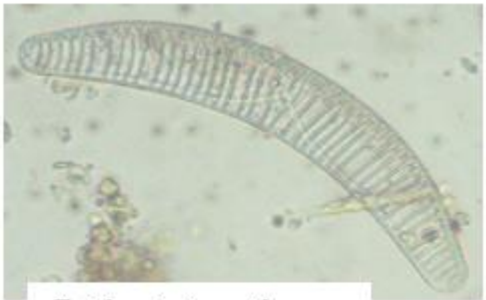
Epithemia adnata

Epithemia argus

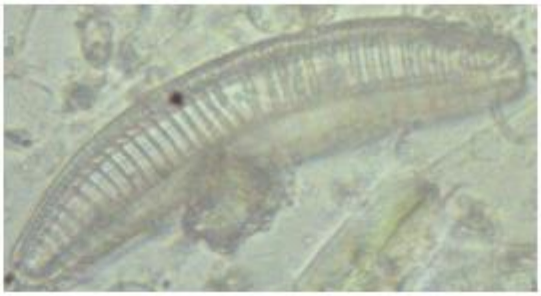


E. frickei

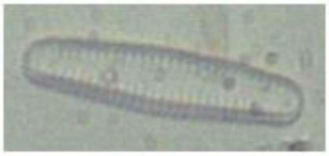
E. gibba



Epithemia turgida



E. hyndmanii

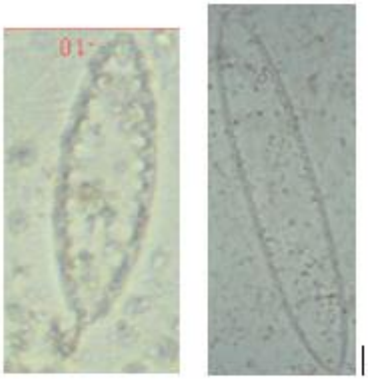


Fragillaria spp.

Gyrosigma scalproides

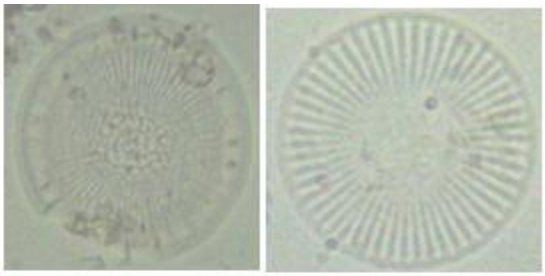
Gomphonema affine

Gomphonema parvulum

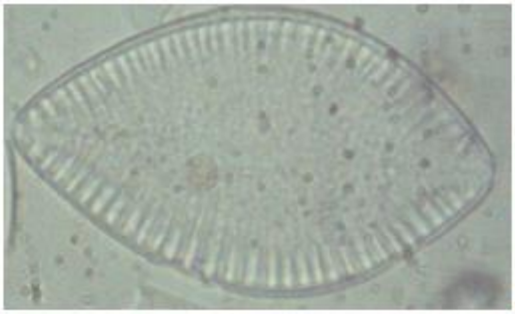


Iconella linearis

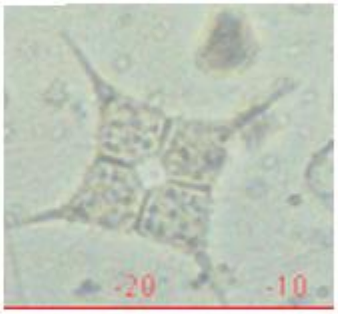
Pleurosigma salinarum



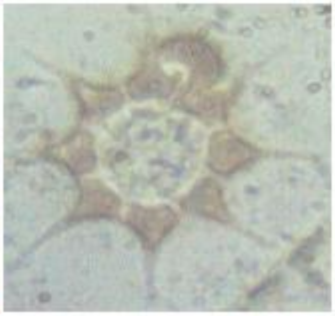
Stephanodiscus spp.



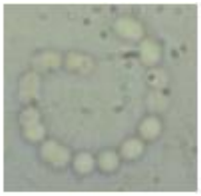
Surirella ovalis



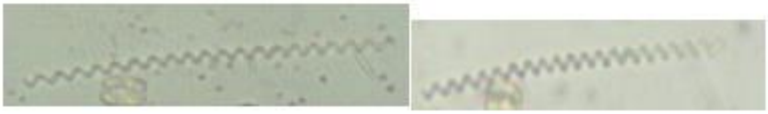
Chlorotetraedron incus



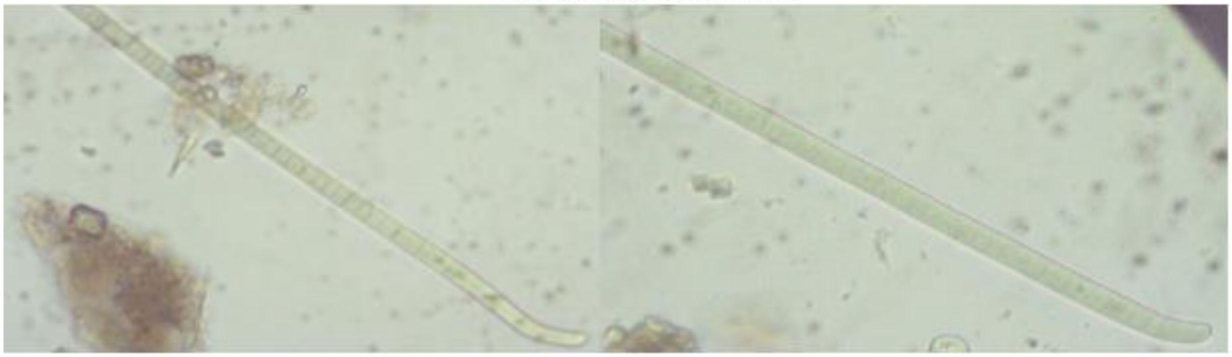
Monactinus simplex



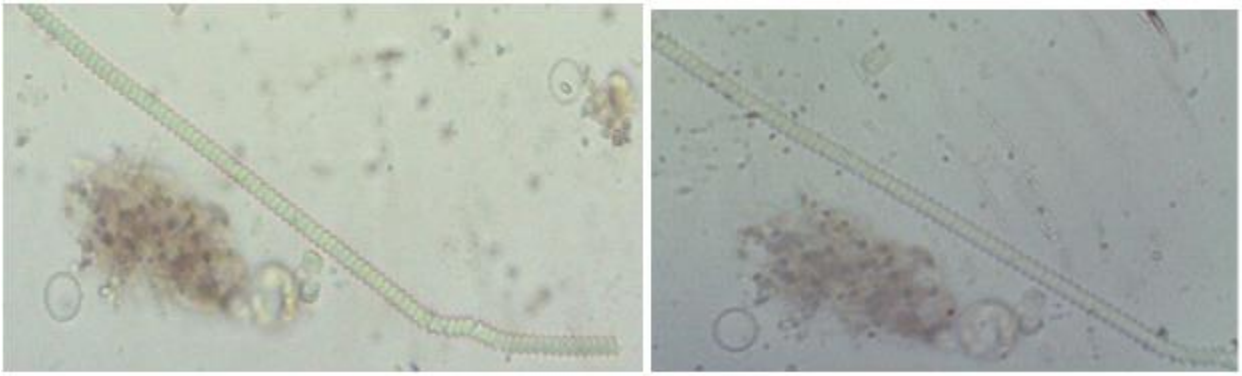
Anabaena cylindrica



Arthrospira fusiformis



Kamptonema formosum



Spirulina major

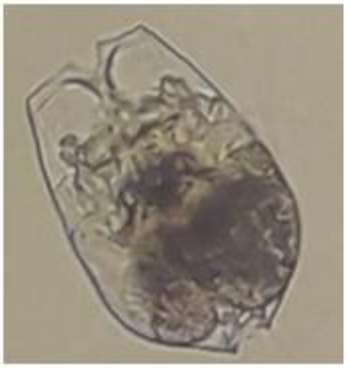
Phacus acuminatus

Euglena spp.

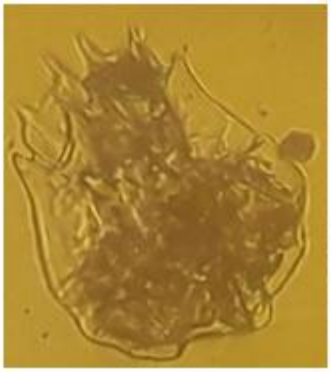
Appendix 2: Some zooplankton species identified from Lake Shala

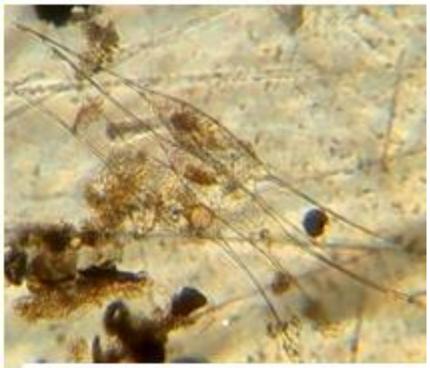

Anuraeopsis fissa


Brachionus dimidiatus


B. dimidiatus inermis


Brachionus falcatus


Brachionus urceolaris

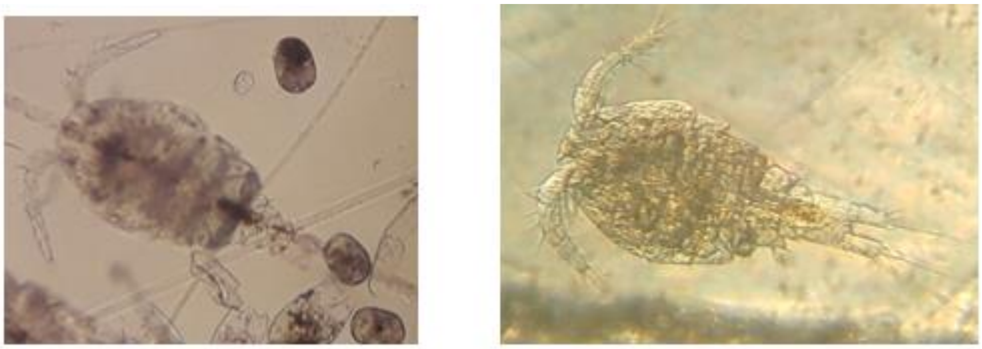

Filinia pejleri


Hexarthra jenkina

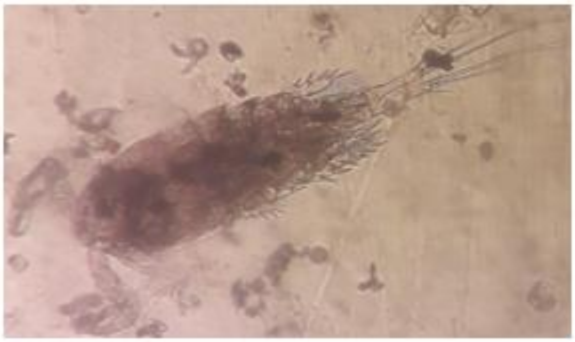

Keratella tropica


Lecane hastate


Testudinella patina

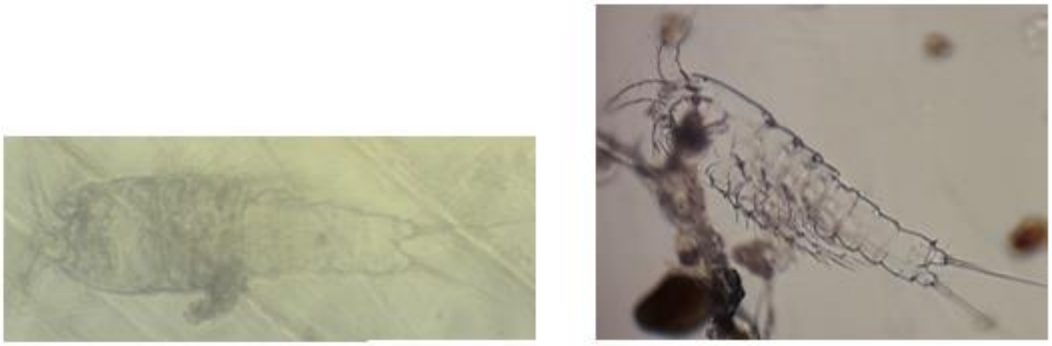


Eucyclops serrulatus



Thermocyclops ethiopiensis

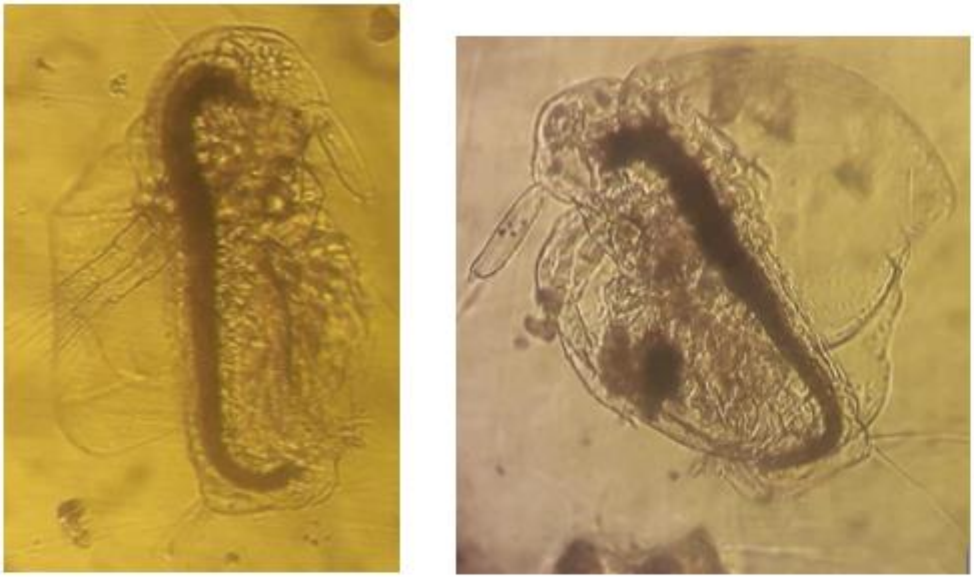
Thermocyclops oblongatus



Nitocra lacustris

Diaphanosoma excisum

Moina belli



Moina micrura

Appendix 3. Densities (ind./m^2) of macro-invertebrates at the different sampling sites

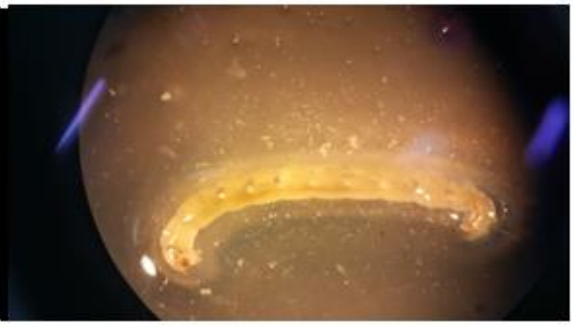
Taxa	Study sites			
	SPS	**SPO**	**SGS**	**SGO**
Diptera (Two winged / True flies)				
Chironomidae	2195	134272	1706	128806
Clucidae	0	0	14	0
Ceratopogonidae	132	0	173	11961
Syrphidae	0	0	5	0
Dolichopodidae	0	0	6	0
Tabanidae	0	0	2	0
Ephydridae	0	0	3	0
Hemiptera (Water or true bugs)				
Corixidae	5060	0	2506	0
Mesoveliidae	0	0	8	0
Naucoridae	81	0	10	0
Coleoptera (Aquatic Beetles)				
Hydrophildae	12	0	3	0
Dytisidae	0	0	2	0
Gastropods				
Physidae	3	0	2	0
Glacidorbidae	2	0	2	0
Planorbidae	0	0	2	0
Thiaredae	5	0	0	0
Aquatic spider (Arachnida)	4	0	6	0
Fish louse (Argulidae)	4	0	0	0
Megaloptera (Corydalidae)	2	0	10	0
Aquatic worm(Oligochaeta)				
Tubificidae	55	27117	95	224
Naididae	0	1912	0	401

Abbreviations: SPS = Shalla Park Shore, SPO = Shalla Park Opent, SGS = Shalla Gike Shore, and SGO = Shalla Gike Open

Appendix 4. Pictutres showing major groups of identified macro-invertebrates

Diptera (Two winged /True flies)

Ceratopogonidae



Chironomidae

Syrphidae (Rat-tailed maggot)

Coleoptera (Aquatic Beetles)

Dytiscidae

Hydrophilidae

Hemiptera (Water or true bugs)

Naucoridae