The Nile tilapia (*Oreochromis niloticus* L. 1758) of three Ethiopian Rift Valley lakes: Physico-chemical conditions, phenotypic and reproductive characters, and response to elevated fry rearing temperature

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Addis Ababa University
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A Dissertation submitted to the Department of Zoological Sciences, Addis Ababa University, in partial fulfillment of the requirements for the Degree of Doctor of Philosophy in Zoological Sciences (Aquatic Sciences, Fisheries and Aquaculture)

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ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE PROGRAMMES

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By

Megerssa Endebu

A Thesis Presented to the School of Graduate Programmes of the Addis Ababa University in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Zoological Sciences (Aquatic Sciences, Fisheries and Aquaculture)

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Abstract

Fishery and aquaculture development along with sustainable use of natural resources play significant role in alleviating the problems of nutritional insecurity and environmental degradation in Ethiopia. The ecological status of Ethiopian Rift Valley lakes; which provide substantial economic, environmental and social benefits across diverse ecological settings; and the potential of the Nile tilapia, *Oreochromis niloticus* (L. 1758) populations in aquaculture development were not comprehensively studied. This study was thus undertaken to assess the current and past physico-chemical conditions of Lakes Chamo, Koka and Ziway, phenotypic and reproductive characters of *O. niloticus* populations of the lakes, and potential of the fish populations for aquaculture development. Field, laboratory and experimental data were obtained using standard methods over a period of three years, and analyzed using various computations, and compared against previous records and standards. The study demonstrated that water physico-chemical parameters varied significantly between seasons, and within and between the lakes. The findings have shown that some of the parameters were higher than previously reported levels. Anthropogenic associated factors including water turbidity, soluble reactive phosphorus, and nitrate-N concentrations varied among the lakes and across seasons. Invasion of water hyacinth and wetland vegetation cover also varied considerably across the lakes. Phenotypic and reproductive characters, and response to elevated fry rearing temperature of the three *O. niloticus* populations from the three lakes were also investigated. There were significant differences ($p \leq 0.05$) in most of the morphometric character indices, meristic counts, mean length and weight, Fulton's condition factor, length at first sexual maturity (L_{50}), absolute fecundity, peak breeding seasons and response to heat treatment among the three *O. niloticus* populations. The current values of some of the parameters, like L_{50}, decreased from previous reports, indicating urgent need for implementation of proper fishery management. Possessing desired phenotypic and reproductive qualities in aquaculture, populations of Chamo followed by Koka appear to be potentials for further genetic improvement. Further research is required to investigate whether the fish populations could maintain those characters in pond cultures. To improve sex reversal efficiency by heat treatment, sensitive individuals can be selected and their degree of sensitivity can be improved through continuous selection of progenies from temperature sensitive parents. Generally, there is an urgent need for proper agricultural practices, proper municipal and industrial waste management practices, protection of wetland vegetation and delimitation of the lakes' buffer zones to sustain the services of the lakes.

Key words: Aquaculture, heat treatment, Lake Chamo, meristic, sex reversal, water hyacinth.

Dedication

This dissertation is dedicated to my parents, my father Endebu Angessa and my mother Mergitu Yadessa (both of whom passed away during this PhD study in February, 2017 and April, 2021, respectively; RIP), who have inspired and helped me learn without attending formal education themselves. It is also dedicated to my beloved wife Shewaye Kumessa who encouraged me to advance in my career and took full responsibility of caring for our children while I was doing my PhD research.

Acknowledgements

I am very much grateful to my advisors, Prof. Abebe Getahun of Addis Ababa University and Dr. Misikire Tessema of Ethiopian Biodiversity Institute, for their unreserved advices, guidance and encouragements in the process of this PhD research work. I really appreciate the fatherly advice and support of Prof. Abebe to start my PhD study and to proceed with the study without interruption while I was seeking withdrawal on those sorrow and challenging hospital days. I also thank Water Thematic Research (Aquatic production and productivity in the Rift Valley and Awash Basins, Ethiopia) of Addis Ababa University and Agricultural Growth Program (AGP-II) of Oromia Agricultural Research Institute for the financial support that covered costs of field data collection and expenses in experimental processes of this research. I would like to thank Dr. Dagnachew Lule, the coordinator of AGP-II program and Dr. Tesfaye Alemu, the director of livestock research directorate of Oromia Agricultural Research Institute (IQQO) who accepted this PhD dissertation work for financial support under AGP-II research activities, without which this activity would not have been completed with the limited fund from Addis Ababa University only. My heartfelt thanks go to the staff of Batu Fishery and other Aquatic Life Research Center for their support in assigning technical assistants, arranging logistics, laboratory setups and experimental ponds for this research. Dr. Lemma Abera, center director at Batu; Mr. Mathewos Hailu, fishery research director; Mr. Kemal Ketebo, the laboratory technician; Mr. Kufa Urgessa, the finance and procurement head at the center and all their staff members deserve special gratitude for their limitless official and friendly support during the entire research period. I appreciate the strength of the field crew: the boat operators on Chamo, Koka and Ziway lakes, Kassim Indris (Kereyu), Bune Uki (Tewerwari), Bedane Dalu (Aba Geda), Ashu Bantashe, Feyiso Ittiso (nurse) and Nanecha Bajiga and the car drivers, Lissan Hussein (Sancho), Dawit Hirpho and Tadele Kufa in the quarterly travel between the lakes for two years. I am also thankful to Gamo Zone Administration, Gamo Zone Livestock and Fishery Development Office, Arbaminch Zurea Livestock and Fishery Development Office, Fishery Cooperatives at Chamo, especially Mr. Haymanot of Leto, Mr. Wondu Tesfaye of Elgo and Mr. Zemenu as well as chairperson of Koka fishery cooperative, Mr. Kurjisa Gudeta, for their assistance and collaboration in data collection. I would also thank Mrs. Aynalem Birhane, Mr. Habib Negesso, Mr. Bune Uki, Mr. Dawit Emiru and Mr. Teshale Takele who were my guarantors at my employer office to leave for my PhD study. I am also grateful to my cousin Dr. Tefera Tolera who has been with me from my early elementary school days up to now, supporting me morally and financially through all my study period. My beloved family, my wife Mrs. Shewaye Kumessa and our children, Merob, Wakgari, Eba, Robera and Olani Megerssa, and Derartu Guteta are all my supporters at home and in field works, who helped me morally, during my data collection in recording, data entry to computer, and also assisted me in fish feeding and monitoring in lab and pond experiments. Finally, I thank the Almighty God who gave me the endurance and patience to pass the challenging days and complete this PhD study.

Megerssa Endebu Angessa

December 2021

Addis Ababa, Ethiopia

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Chapter One

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1. Background

1.1 Fisheries and Aquaculture in Ethiopia

1.1.1 Fisheries development in Ethiopia

Ethiopia being one of the fastest growing economies, is a large country in East Africa with about 120 million people, where food insecurity continued to be a problem for the population (Haan *et al.*, 2006; Addisu Awoke *et al.*, 2019; Teshager Assefa, 2020). Though agriculture is a backbone of the country's economy with about 80% of the population involved in the business, productivity of the traditional farming is poor at farmers' levels leading to food self-insufficiency. Productivity and sustainability of traditional rain fed agriculture at small scale farmers level has been challenged by recurrent drought in some parts of Ethiopia, affecting the food and nutritional security goal of the country. Currently, nutritional insecurity of the population has become a concern in many regions of the country. Therefore, increasing productivity of the farms, sustaining the natural resources and diversifying farm products are better approaches to alleviate the nutritional insecurity problems. Accordingly, development of fishery and aquaculture, especially fish culture, are among the potential and applicable approaches to achieve the nutritional security at household level in potential areas of the country.

Fish are highly diversified aquatic species that provide food to the world population in the first rank with total annual production of 171 million metric tonnes in 2016; 88% of which were utilized for direct human consumption. The average annual increase in global apparent food fish consumption was 3.2%, outpaced population growth (1.6%) and exceeded consumption of meat from all terrestrial animals except 4.9% record for the poultry (FAO, 2018). Fish has been leading in the production of all animal protein sources followed by pig meat (112.3 million MT), poultry (109.0 million MT), beef & buffalo (68.0 million Mt) and Sheep & goat (14.1 million MT) in 2013 (Ritchie and Roser, 2018). However, the contribution of fish as food in Ethiopia remained insignificant.

On the other hand, the demand for fish and its price at the local market is dramatically increasing in the country, following the increase in beef price and the rise in fish eating culture of the society. The per capita fish consumption of Ethiopia increased slowly from about 200 g (Gordon *et al.*, 2007) to about

250 g as estimated from a report of the Ministry of Agriculture (2012/13). Fish usually comes from capture fisheries while aquaculture is an alternative way of quality fish supply to fill a demand-supply gap and substitute the stagnating or declining fish supply from the wild. The fish production in Ethiopia was still below 0.5 kg fish production per person per year in 2015 while the world's per capita fish consumption was about 20.2 kg in 2015 at an average increasing rate of 1.5 percent per year (FAO, 2018).

According to several sources, the current fish catch compares with the previous fish potential estimate of the country, which is in the order of 45,000–51,500 tonnes per year. This exploitation rate is nearly the country's potential mainly from the natural lakes and major reservoirs whereby some of the lakes are showing signs of over exploitation (Vijverberg *et al*., 2012). However, the construction of new reservoirs, under-exploited riverine fisheries and aquaculture are some of the development prospects of fish production in the country and the recent fish potential estimate from empirical models is about 94,500 tonnes per year (Gashaw Tesfaye and Wolff, 2014); which's contribution is still insignificant (below 1 kg percapita fish production) for the over 120 million Ethiopian population. The water bodies supporting fish production in the country also support the existence of aquatic and terrestrial animals and plants, balancing the ecosystem functions. However, the quality and quantity of the water and their functions are declining because of the increased human pressure related to improper land use system, improper waste disposal, uneconomical water use for municipal and irrigation, climate change and other industrial activities in the catchment (Brook Lemma and Hayal Desta, 2016). Some of the Rift Valley lakes such as Koka and Hawassa have been contaminated with effluents from their catchments and heavy metals found in water and in tissues of fishes (Dsikowitzky *et al*., 2012). Proper management plans are required to sustain/restore the environments of the water bodies in general and the fishery sector in particular. On the other hand, development of aquaculture in the country potentially reduces the pressure on capture fisheries and also fulfils the fish demand supply gap.

1.1.2 Aquaculture development in Ethiopia

Aquaculture is the farming of aquatic organisms including finfish, mollusks, crustaceans and aquatic plants in a controlled environment. Global aquaculture production was 110.2 million tonnes in 2016, of which food fish constituted 80.0 million ($231.6 billion USD), aquatic plants 30.1 million tonnes (USD $11.7 billion) and non food products 37,900 tonnes ($214.6 million USD) (FAO, 2018). Aquaculture has grown at annual growth rate of 5.8 percent during 2001 to 2016 which was faster than other food production sectors (FAO, 2018).

Aquaculture is a new technique in Ethiopia that started a few decades ago. Its expansion in a given area is determined by a large number of factors. Considering fish culture in land based ponds, these factors include water availability and quality, topography and soil texture, land use and cover, temperature and economic parameters. According to the study by FAO sub-regional Office for Eastern Africa (FAO SFE) (Rothuis *et al.*, 2012), based on GIS assisted modeling, about 15,158 km^2 is highly suitable while 871,731 km^2 land area of Ethiopia is moderately suitable for *O. niloticus* pond culture. However, the aquaculture activities haven't yet developed in Ethiopia as intended because of several reasons. Lack of awareness, knowledge and skill among aquaculture farmers and fish users, lack of fish seed sources and fish feeds, and shortage of skilled manpower in the extension services are among the major bottlenecks in aquaculture development. Bureaucratic procedure for investment permission was also a bottleneck for the development of aquaculture investment in the region.

1.1.3 Importance of *O. niloticus* in fisheries and aquaculture of Ethiopia

Among the freshwater fish in Ethiopia, *O. niloticus* is indigenous and popular in the country's fishery production. The fish is cultured worldwide and currently ranked second only to carps in global farmed food fish (Ridha, 2006). The appropriateness of *O. niloticus* in aquaculture is attributed to its adaptation to wide range of environmental conditions, rapid growth rate, easy and rapid propagation, and tolerance to stress in handling (Getinet Gebretsadik and Bart, 2007). However, the efficiency of reproduction in *O. niloticus* has paradoxical consequences. It allows easy and rapid propagation of the fish in various environmental conditions. In contrary, within a limited environment, uncontrolled multiplication of the fish not only reduces the faunal diversity of the system but also produces stunted fish population of poor market value (Hepher and Pruginin, 1981; Coleman, 2001). Moreover, in mixed sex culture, growth rate of female *O. niloticus* are slower than their male counterpart whereby the weight of male *O. niloticus* at harvest is twice as big as its female batches in mixed sex population grown in pond culture (Megerssa Endebu *et al.,* 2016).

The aquaculture activity in Ethiopia mainly involves pond culture of *O. niloticus* which has been challenged by poor fish growth performance. Productivity of the *O. niloticus* in pond culture was limited because of a number of problems among which over population and undersized fish in the ponds as a result of unwanted reproduction which causes competition for space, food and oxygen is well noted. In order to alleviate the overpopulation problem of *O. niloticus* in pond culture, predatory control of the unwanted recruitment by introducing predatory fish such as *Clarias gariepinus* has been practiced in Ethiopia (Megerssa Endebu *et al*., 2016). However, the efficiency of predatory control, the availability of predator fish and the slower growth rate of female *O. niloticus* are some of the problems related to predatory control of unwanted population in mixed sex culture. Use of male mono-sex is practiced in commercial production of *O. niloticus* worldwide.

1.2 Biology of *O. niloticus*

In taxonomy, *O. niloticus* is one of the hundred species of cichlid fishes under the former genus Tilapia. Recently some of the tilapia was moved into a few other genera, notably *Oreochromis, Sarotherodon* and *Coptodon* (Dunz and Schliewen, 2013). Tilapias are mainly freshwater fish that inhabit shallow stream, ponds, rivers and lakes, and sometimes live in brackish water. The tilapia fish has been introduced to many tropical countries in the world (Pullin *et al*., 1997), mostly for aquaculture, augmentation of capture fisheries and sport fishing because of its wide range of trophic and ecological adaptations (Welcomme, 1988).

Distribution wise, *O. niloticus* is an African freshwater fish with broad natural distribution from Nile River Basin; the south-western Middle East; the Niger, Benue, Volta and Senegal Rivers, and Chad, Tanganyika, Albert, Edward, Kivu Lakes (Trewavas, 1983; Daget *et al.*, 1991; Boyd, 2004). It is among the important food fish species both in capture fisheries and aquaculture production. A complex sub-species structure of *O. niloticus* has been documented across different water bodies in Africa. Based on the traditional taxonomic methods, seven sub-species of *O. niloticus* have been identified, of which six are distributed amongst the East African Rift Valley lakes (Trewavas, 1983).

Genetic differentiation of *O. niloticus* has been observed in which three main groups: the Ethiopian Rift Valley populations, Nile drainage and Kenyan Rift Valley populations, and Sudano-Sahelian populations were identified based on molecular studies (Eknath and Hulata, 2009; Bezault *et al*., 2011). The genetic differentiation of the species at macro-geographic scale was mainly affected by the paleo-geographic and climatic events, while the present-day river systems are influential on genetic connectivity and patterns of genetic structure at smaller geographic scales (Bezault *et al*., 2011).

The main morphological features of *O. niloticus* include laterally compressed body; cycloid scales; upper jaw length showing no sexual dimorphism; spiny and soft ray parts of dorsal fin continuous. The lower and upper lethal temperatures of *O. niloticus* are 11-12 °C and 42 °C respectively. The fish is an omnivorous grazer that feeds on phytoplankton, periphyton, aquatic plants, small invertebrates, benthic fauna, detritus and bacterial films associated with detritus and even other fish and fish eggs (Agumassie Tesfahun and Mathewos Temesgen, 2018). It can also filter feed suspended particles including bacteria and phytoplankton, on mucous in buccal cavity as additional source of nutrition.

In pond culture, *O. niloticus* reaches its sexual maturity at age of 5-6 months when the temperature reaches 24 °C. The male establishes a territory, digs and guards a spawning nest in which a ripe female spawns during the breeding process. The ripe female releases its eggs into the nest while the male releases its milt (the male gametes) onto the eggs so as external fertilization takes place in water. After fertilization, the female collects the eggs in her mouth immediately and moves off. The female incubates the eggs in her mouth and broods the fry after hatching until the yolk sac is absorbed; it ceases to feed while brooding (Loiselle, 1985). The released fry may swim back to their mother's mouth in case of danger alarm. If the temperature doesn't limit, spawning can take place the whole year in ponds, which causes the production of unwanted fry in mixed sex culture. Because of this maternal mouth brooding, the number of eggs per spawn in *O. niloticus* is small in comparison to other pond fish (FAO, 2009).

1.3 Production of male-mono-sex in tilapia culture

Mono-sex culture of male tilapia has been popular for better growth performance and population control, and is considered at global standard of tilapia culture. Tilapia mono-sex culture can be achieved in different mechanisms. These include:

Hybridization: Cross-breeding between *O. niloticus* female and *Oreochromis aureus* (blue tilapia) male or *Oreochromis mossambicus* (Mozambique tilapia), for example, results in all male population. However, the blue tilapia and the Mozambique tilapia are not found in Ethiopia to use the technology. The problems associated with this technology are therefore the risk of introducing exotic species, and maintaining different brood stocks.

YY-super male technology: is another method to produce all-male tilapia populations. This technology takes multi step process and longer time to develop the YY-male tilapia. In the genetic sex determination, the *O. niloticus* are female homo-gametes (XX) and male heterogametes (XY). It involves sex reversal steps by which genetically male *O. niloticus* is forced to change into phenotypic female (XY-female which is referred to as functional female) by feminization process through dietary hormone administration in the first step (Juarez-Juarez *et al.*, 2017). The consequent generations are produced without hormone treatment, by mating functional female (sex reversed XY-female) with normal-XY male followed by screening YY-males through progeny sex ratio screening.

Sex reversal: This involves enabling genetically female organism, possessing XX- sex chromosome in case of *O. niloticus,* to develop male sexual organs and biologically behave like a male or vice-versa. The mechanisms involve:

- ***Hormone treatments***: **Hormone treatments** are commonly used in some countries to reverse the sex of *O. niloticus*. Dietary supplementation of synthetic androgens, especially methyl testosterone is a widely practiced method for production of all-male tilapia population (Gale *et al.,* 1999; Beardmore *et al.,* 2001; Smith and Phelps, 2001; Juarez-Juarez *et al.,* 2017). However, the consumption of hormone treated organisms is forbidden in some countries.

- ***Heat treatment***: **Heat treatment** of *O. niloticus* fry can result in all males or male biased sex ratios. Elevating fry rearing temperature as a means of producing mono-sex tilapia has been tried in several laboratories (Abucay *et al.,* 1999; Baroiller and D'Cotta, 2001; Misikire Tessema *et al.*, 2006; Abou El-Fotoh *et al.*, 2014). Temperature affects sexual differentiation of gonads of *O. niloticus* during the critical developmental period. When fries of *O. niloticus* at age of 9-13 days post fertilization are exposed to elevated water temperatures for 10 or more days, the proportion of males increases (Baroiller *et al.*, 1995; Hendry *et al.* 2002; Abou El-Fotoh *et al.*, 2014). In *O. niloticus*, liability of sex ratios to temperature treatment is heritable (Misikire Tessema *et al.* 2006). According to Misikire Tessema *et al.* (2006), proportion of males reared under the above condition can reach 100% in certain breeding pairs. The sex reversing efficiency of heat treatment in *O. niloticus* is affected by gene (Angienda *et al.,* 2010). The researchers achieved 86% male in general and 95% male for *O. niloticus* carrying a genetic marker called *Abur36*.

Other methods such as ploidy manipulation and rearing in cages are also applied for controlling overpopulation in *O. niloticus* cultures.

Environmental factors, mainly temperature and other factors such as density, pH and hypoxia affect the sex ratio of many fish species. The factors can either determine sex or influence sex differentiation on domestic stocks and field populations. According to Baroiller *et al.* (2009), genetic variability of thermo-sensitivity existed between populations and also between families within the same population of fish. The above authors also identified the existence of XX-male tilapias from wild natural populations and the temperature sensitivity nature is heritable trait. In tilapia, both genetic sex determination and environmental sex determination exist.

In Ethiopian Rift Valley case, water bodies such as Lakes Koka (in Awash Basin), Ziway and Chamo (both found in different drainage basins) are geographically isolated. The *O. niloticus* living in these geographically isolated water bodies are expected to develop wider genetic variation in order to adapt to their environments. Sex reversal of *O. niloticus* fry by heat treatment was attempted on populations of Lakes Hora and Ziway origin at 36 ± 1 ^{0}C whereby 77.6% and 80.3% males respectively were achieved (Megerssa Endebu *et al.*, 2017), suggesting differences in heat treatment sensitivity between the two populations.

Evaluation of population differences in the sex reversal efficiency of heat treatment helps in selecting the sensitive groups for its practical application in production of male *O. niloticus* fingerlings used in aquaculture. Along with their thermo-sensitivity trait, evaluation of their growth performance in culture conditions makes them desirable.

Growth of *O. niloticus* in pond culture is a function of genetics and environment. Tilapias develop genetic diversity within a given population and also differ in their characteristics across the geographically isolated environments (Agnese *et al*., 1997; El-Zaeem, 2012). Hence, one of the aims of this study was to assess the culture merits of *O. niloticus* of Ethiopian Rift Valley lakes in order to use them in aquaculture production.

1.4 Drainage basins and distribution of *O. niloticus* in Ethiopia

Ethiopian ecology and climatic condition is highly diversified mainly due to its topography which ranges from 125 m below sea level in Dallol depression to 4,620 m above sea level at the top of mount Ras Dashen. The land mass of Ethiopia is divided into Western and Southeastern highlands by the great East African Rift Valley which runs through Ethiopia diagonally from northeast to the southern border of the country.

Because of the Ethiopia's diverse topography, the river systems of the country drain to various directions. Accordingly, the river basins of the country are categorized into 12 drainage systems; the Abay, Awash, Baro-Akobo, Omo-Gibe, Rift valley, Tekeze, Wabi-Shebelle, Genale-Dawa, Ogaden, Denakil, Mereb-Gash and Ayisha River Basins (Figure 1).

Of the 12 river basins, the major ones are eight and these include Abay (Blue Nile within the limit of Ethiopia), Baro-Akobo (White Nile Basin within the limit of Ethiopia) and Tekeze (joins Atbara River in Sudan); all the three basins drain the western landmass of Ethiopia towards the Nile River and ultimately end up into Mediterranean sea; while the Omo-Gibe Basin which also drains the western landmass of Ethiopia heads to south and joins Turkana Lake at Ethio-Kenya border; the Genale-Dawa and Wabi-Shebele River Basins drain the Southeastern landmass of Ethiopia towards Somalia lowland and ultimately end up into Indian Ocean; Rift valley lakes and Awash River Basin (together with the Danakil Depression) drain the escarpments of the valley and remain in the rift valley system (Figure 1). The Wabi-Shebele River Basin is the widest basin in Ethiopia covering an area of 202,220 km^2 (Fraol Abebe *et al*., 2021) followed by the Abay Basin which covers an area of 199,812 km^2 (Haileyesus Belay *et al.*, 2020), Genale-Dawa Basin with 170,000 km^2 drainage area and Awash River Basin with drainage area of 110,439 km^2 (The World Bank, 2020). Many natural and artificial lakes of different sizes are distributed in these river basins of the country. The majority of the Ethiopian lakes are confined within the rift valley, a part of which can be divided into four systems: namely Lake Turkana, Chew Bahir, the Main Ethiopian Rift (MER), and the Afar depression (Tenalem Ayenew, 2009).

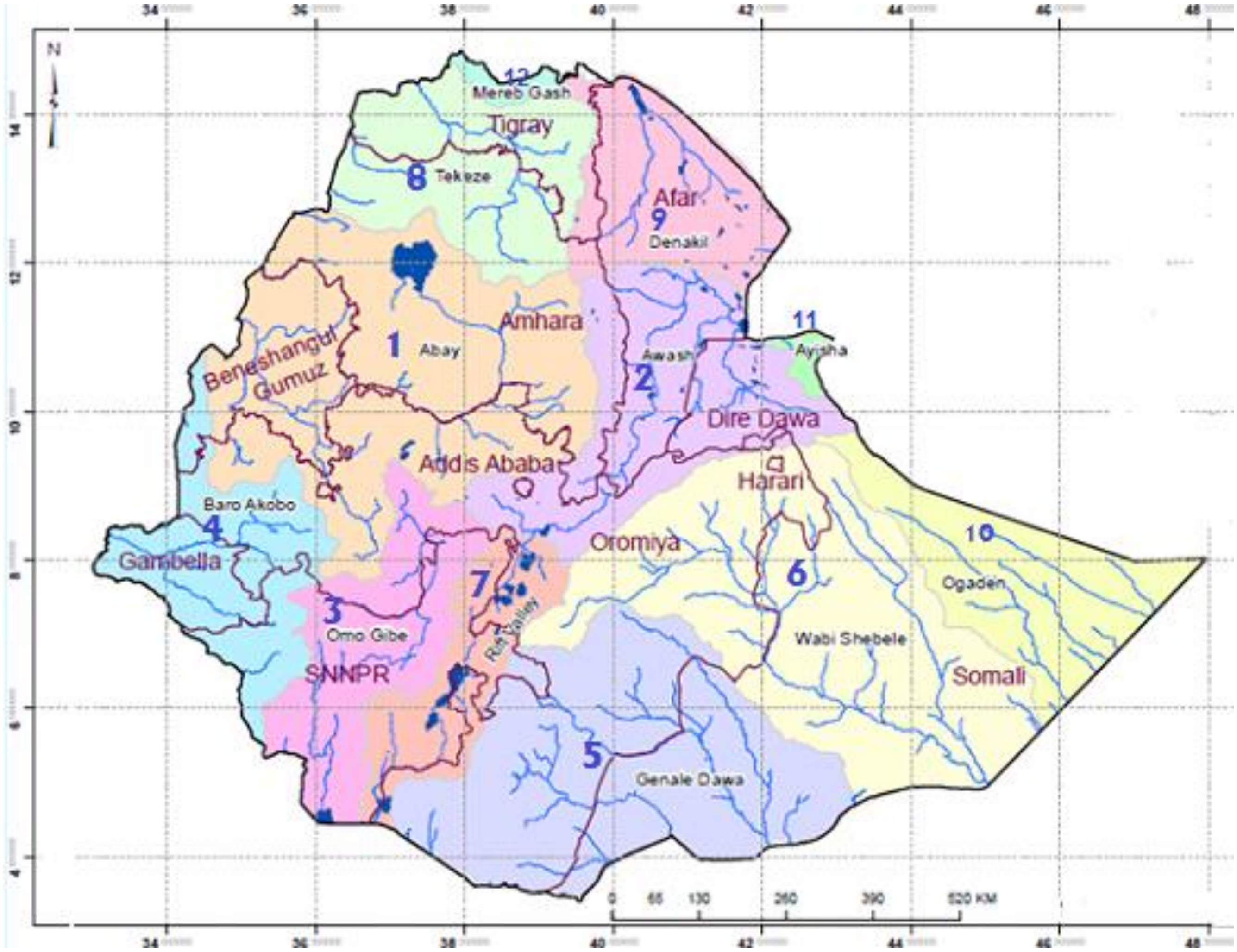

Figure 1. River basins of Ethiopia. (After OCHA, 2006).

(1 = Abay (Blue Nile), 2 = Awash River, 3 = Omo-Gibe, 4 = Baro-Akobo, 5 = Genale-Dawa, 6 = Wabi-Shebelle, 7 = Rift Valley lakes, 8 = Tekeze, 9 = Denakil depression, 10 = Ogaden, 11 = Ayisha, 12 = Mereb-Gash).

The Ethiopian Grand Renaissance Dam (GERD), now under construction, with 1,874 km^2 area and 74 km^3 volume capacity (IPoE, 2013) is found within Abay Basin. Several other reservoirs of hydro-electric and sugarcane irrigation dams such as Didessa, Genale and many other smaller reservoirs are under construction and some of which are ready to be used in increasing the water resources of the country.

Each of the water bodies in all the drainage basins harbors diverse fish species including endemic as well as exotic species. *O. niloticus* is found in all the Drainage Basins with water resources and constitute the major proportion of fish catch in many of the water bodies (Tenalem Ayenew, 2009; Tadlo Awoke *et al.*, 2015; Abebe Getahun, 2017).

1.5 General description of the study areas

The study areas cover three Ethiopian Rift Valley lakes: Chamo, Koka and Ziway within the Rift Valley Lakes Basin (Figure 2). These water bodies were selected for their significant contribution in the fish production where *O. niloticus* populations were targeted as these are candidate fish species in the development of aquaculture in Ethiopia.

Lake Chamo is situated in Southern part of the Ethiopian Rift Valley lakes within the Abaya-Chamo drainage basin at 5°42' to 5°58' N Latitude and 37°27' to 37°38' E Longitude and an altitude of 1110 m.a.s.l. The lake has a surface area of about 297 km^2 (Alemayehu Hailemicael, 2011), maximum depth of 13 m, mean depth of 6 m (Seleshi Bekele *et al*., 2007) and recharged mainly by feeder rivers called Kulfo, Sago and Sile with no visible outlet; the lake has no visible outlet. Chamo has a watershed area of 1,109 km^2 (Fassil Teffera *et al*., 2018). The basin system is characterized by highly diversified fish fauna of about 21 species (Golubtsov and Radeat Habteselassie, 2010).

Lake Koka is a man-made reservoir located at about 90 km Southeast of Addis Ababa, in Awash River Basin, between 8° 18′ to 8° 28′ N and 39° 0′ E to 39° 9′ E at an altitude of 1,590 m.a.s.l. It was constructed on Awash River in 1960 for the purpose of hydro-electric power generation. Upper Awash basin drains about 11,250 km^2 area up to the inlet of Lake Koka. Lake Koka has a water-covered area of about 200 km^2 (Mesfin Gebrehiwot *et al.*, 2020) with a maximum and mean depth of 14 m and 9 m, respectively (LFDP, 1997). Lake Koka's water level fluctuates from season to season ranging from very shallow depth during dry seasons as witnessed in May 2019 to the maximum capacity that results in overflows of the dam during rainy seasons that resulted in displacing the surrounding communities as witnessed in July to August 2020. It has two feeder rivers, Awash and Modjo Rivers from west. The Awash River continues flowing in East direction as outlet river after generating hydro electric power at the dam site.

Lake Ziway (also known as Lake Danbal) is located in the Ethiopian Rift Valley between 7^0 52' to 8^0 8' N and 38^0 40' to 38^0 56' E at an altitude of 1636 m.a.s.l. with maximum length of 32 km and maximum width of 20 km (LFDP, 1997). It has a watershed area of 6,991 km^2 (Abraham *et al.*, 2018). The lake is the second largest lake in Ethiopian Rift Valley after Lake Abaya, having an area of 434 km^2 and shore line length of 137 km. The lake is, however, the shallowest of the Rift Valley lakes with maximum and mean depth of 8.95 m and 2.5 m, respectively (LFDP, 1997). The lake has two feeder rivers, Meki River from Northwest and Katar River from East side, and has one outlet river in its southern part, the Bulbula

River, which seasonally flows into Abijata Lake. Lake Ziway is home to endemic and exotic fish species that are commercially important to various degrees.

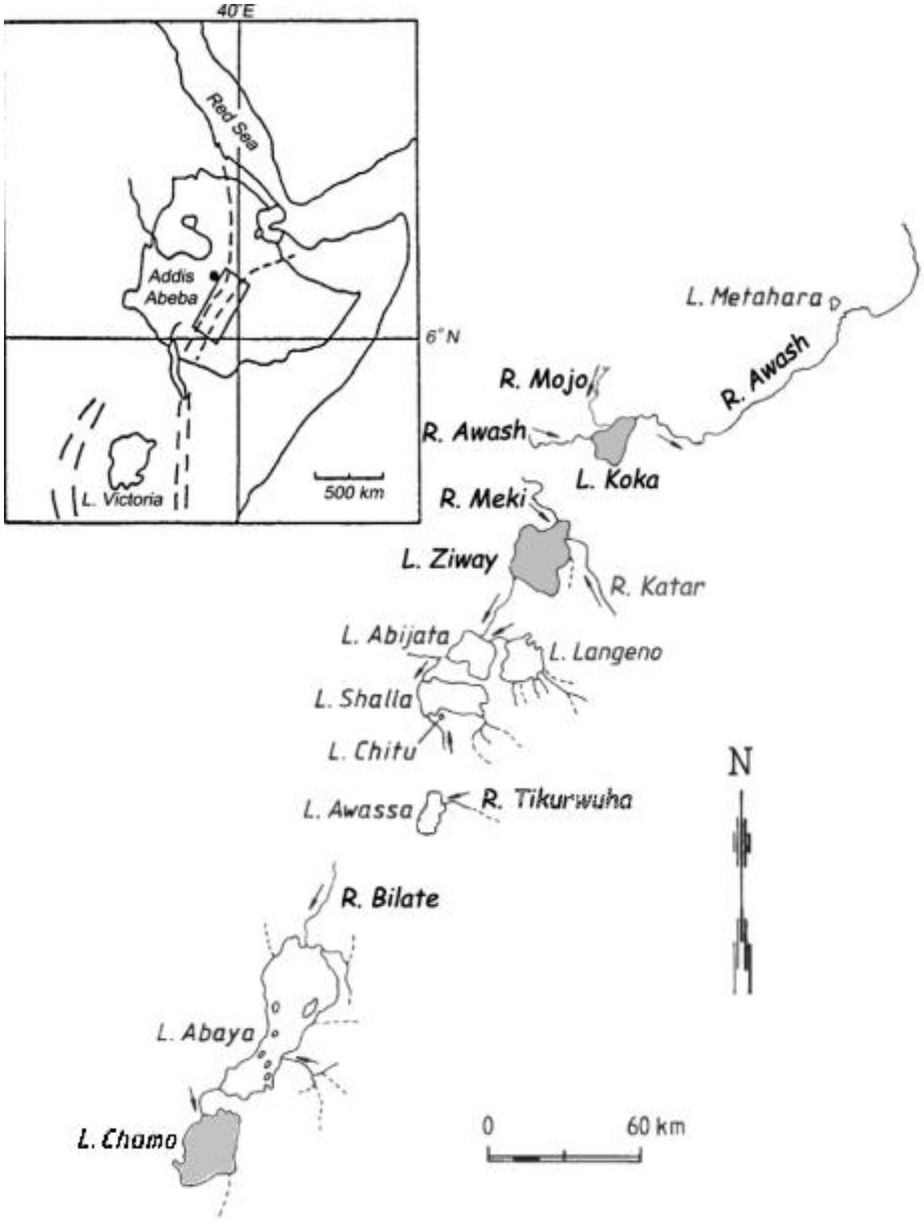

Figure 2. Location of lakes Chamo, Koka and Ziway in the Ethiopian Rift Valley (modified after Elizabeth Kebede *et al*., 1994).

1.6 Rationales, significance, research questions and objectives of the study

Aquatic environments in the Ethiopian Rift Valley, like water bodies in other areas are liable to human induced factors and climatic changes. These factors cause nutrient loadings to the water bodies, changing water physico-chemical properties, composition and coverage of lake shore vegetation and status of invassive water hyacinth, all of which have impacts on sustainability of aquatic resources. Hence, the assessment of current physico-chemical status of the water bodies help in setting proper management measures to conserve the aquatic environments and their fishery resources. The phenotypic and reproductive characters of a fish species are governed by both genetic and environmental factors. The study of the parameters of *O. niloticus* populations of Chamo, Koka and Ziway lakes helps in understanding their characteristics in these isolated water bodies; the information used in conservation of the fish in their natural environments by detecting any change when happened, and identify the potential strains aquiring desired quality in aquaculture. Furthermore, this study addressed the response of the three fish populations to elevated fry rearing temperature and their growth performances under pond culture. This information will have important contribution in developing aquaculture strains of the fish species in Ethiopia.

The researches on fisheries of *O. niloticus* in Ethiopia have focused mainly on species composition, length-weight relationship, condition factor, feed and feeding habits, breeding season and gear selectivity of the species in different water bodies (Gashaw Tesfaye and Zenebe Tadesse, 2008; Lemma Abera, 2012, 2013; Gashaw Tesfaye *et al*., 2016; Agumassie Tesfahun and Mathewos Temesgen, 2018; Assefa Tessema *et al*., 2019).

However, phenotypic and reproductive characters of the fish especies, especially that of the popular and economically important *O. niloticus* (Yared Tigabu, 2010; Gashaw Tesfaye and Wolff, 2014) in terms of their in situ conservation and their potential use in aquaculture were not well studied. These characteristics are also influenced by ecological parameters of the environment that the current eological status of the study area were assessed. Moreover, *O. niloticus* is a candidate fish for aquaculture development in the country where screening of potential strains among the local populations is underway (Kassaye Balkew and Gjoen, 2012; Daba Tugie *et al.* 2017). The use of mono-sex male *O. niloticus* in commercial aquaculture is common and efficient worldwide for the reason that males usually grow faster and more uniform in size than females (Phelps and Popma 2000; Beardmore *et al*., 2001; Bwanika *et al*., 2007). As a part of screening *O. niloticus* strains for aquaculture development, the potential of the populations in reversing their sex by elevated fry rearing temperature treatment towards mono-sex male and the growth performance of the sex-reversed fish should be studied.

Based on the above rationales, the following research questions were adressed:

- Do the ecological status of Lakes Chamo, Koka and Ziway differ across the lakes and change over time?
- Are the *O. niloticus* populations of Lakes Chamo, Koka and Ziway different in their morphometric characters and meristic counts? Which of the fish populations possess the required quality for aquaculture in terms of length and weight?
- Are the *O. niloticus* populations of Lakes Chamo, Koka and Ziway different in their reproductive characters? Do reproductive characters of the populations change over time?
- How do the *O. niloticus* populations of Lakes Chamo, Koka and Ziway rsponed to elevated fry rearing temperature in terms of survival and growth rates, and their sex ratios?

The present study attempted to answer the above research questions focusing on the following objectives.

General objective:

To investigate ecological status and desired culture characteristics of *O. niloticus* populations of the three Ethiopian Rift Valley lakes in order to sustain the fishery and improve their productivity in aquaculture system.

Specific objectives:

The specific objectives of the studies were to:

1. assess current and past water physico-chemical status of Lakes Chamo, Koka and Ziway
2. characterize phenotype of *O. niloticus* of Lakes Chamo, Koka and Ziway
3. investigate sex-ratio, size at first sexual maturity, fecundity and gonadosomatic index of *O. niloticus* of Lakes Chamo, Koka and Ziway and,
4. assess effect of elevated fry rearing temperature on survival rates, growth rates and sex ratios of *O. niloticus* populations of Lakes Chamo, Koka and Ziway.

1.7 Ethical consideration

Ethical guidelines or procedures for research works that involve animal (fish) subjects are not available in Ethiopia. However, formal permits to sample fish in the study areas were obtained from the Regional Livestock and Fishery Development Bureaus (letters in Amharic language). The general provisions of world medical association (WMA) statement on welfare of animals used in research for humane treatment of fish during sampling and handling operations were obeyed. Moreover, general principles pertaining to field activities with wild fish as laid down by AFS *et al*. (2004) was considered. To minimize prolonged stress to live fish in the experiment, the required data were collected from the sampled fish as promptly as possible, representative samples were kept in container with ample oxygenated water and extra specimens were returned back to their ponds.

1.8 Structure of the dissertation

The parts of this study were structured sequentially, based on the research questions and the specific objectives.

Chapter 2 attempted to answer the question on the ecological status of Lakes Chamo, Koka and Ziway; differences across the lakes and change over time. For this chapter, in situ water physico-chemical parameters were measured seasonally for two years, water samples were taken from the lakes during rainy season and dry seasons for nutrient loading analysis, observations were made for the status of lake shore vegetation and presence of invasive waterhyacinth and litretures were reviewed to compare with previous values.

In **Chapter 3**, the question of differences in morphometric characters and meristic counts of *O. niloticus* populations of Lakes Chamo, Koka and Ziway and which of the fish populations possess the required quality for aquaculture in terms of length and weight? were addressed. In this chapter, *O. niloticus* samples of commercial catchs were collected from the three lakes at different seasons. Twenty six morphometric characters, eight meristic counts, length and weight as growth parameters, length-weight relationship and fish condition factor were considered for analysis in the characterization and comparision of the populations and their potential to be used in aquaculture.

In **Chapter 4**, the following questions were addressed: Are the *O. niloticus* populations of Lakes Chamo, Koka and Ziway different in their reproductive characters? Do reproductive characters of the populations change over time? For this chapter, data on reproductive parameters of *O. niloticus* were collected from Lakes Chamo, Koka and Ziway four times a year: at onset of rainy sesason, during main rainy season, after rainy season and during dry season. Fish breeding season, length-at first sexual maturity and absolute fecundity of the populations were analyzed and compared among the lakes. The size at first sexual maturity of the populations over time was also compared.

In **Chapter 5** the following question was analyzed: How do the *O. niloticus* populations of Lakes Chamo, Koka and Ziway responed to elevated fry rearing temperature in terms of survival rates, growth rates and their sex ratios? For this chapter, progenies were produced from the three *O. niloticus* populations and subjected to elevated fry rearing temperature in a laboratory. The progenies' survival rate, their growth performance and sex ratio were analysed and compared among the populations.

Chapter Two

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2 Current physico-chemical conditions of Lakes Chamo, Koka and Ziway

2.1 Introduction

Freshwater ecosystem plays pivotal functions ecologically and economically. Ecologically, the system supports various floral and faunal diversities, nutrients recycling, and water purification. Economically, the system serves as a source of irrigation for agricultural production, domestic water use, drinking water for livestock and wildlife, fisheries, transportation, and recreational purposes (Dudgeon *et al*., 2007; Hildrew *et al.*, 2007; Limburg, 2009). Freshwater aquatic ecosystems have different characteristics, support diversity of life and render different types of services depending on their nature, size and locations. For instance, the Ethiopian Rift Valley lakes Chamo, Koka and Ziway are among the ecologically and economically important freshwater ecosystems used heavily in local fisheries production and for irrigation purposes (Abebe Getahun, 2017).

The main Ethiopian Rift Valley lakes are situated in different hydrological basins that include the Awash, Ziway-Shala, Hawassa and Abaya-Chamo Basins (Tenalem Ayenew, 2009). Lake Chamo is located in the Abaya-Chamo Basin, which consists of three lakes: namely, Lakes Abaya, Chamo and Chew Bahir. These three lakes that are separate today were linked with each other in the past with intermittently flowing rivers and with the overflow to Lake Turkana in the south. The Awash River basin consists of Bishoftu crater lakes in its upper basin and Koka, Beseka, Afambo, Gemeri and Abe Lakes in its middle and lower basin. Lake Koka is an artificial reservoir created to generate hydro-electric power. The Awash River Basin covers an estimated land area of 110,000 km^2 that runs for 1,200 km from Ginchi, 90 km west of Addis Ababa, to the Danakil Depression. The upper Awash Basin drains about 11,402 km^2 area up to the inlet of Lake Koka (Fekadu Aduna *et al*., 2021). The basin is among the most important water resources used for large-scale irrigation schemes in Ethiopia. Ziway Lake and Lakes Langano, Abijata and Shala are located in the Ziway-Shala Basin, which covers an estimated catchment area of about 13,000 km^2 and characterized by volcano-tectonic depressions in its center. Despite the fact that the majority of the tropical lakes including the Ethiopian Rift Valley lakes are natural river fed lakes or reservoirs (Lewis, 2000), previous studies reported that Chamo, Koka and

Ziway Lakes have different morphological, physico-chemical and biological characteristics (Elizabeth Kebede *et al*., 1994; Tenalem Ayenew, 2009; Abebe Getahun, 2017). Such variations in biological, chemical and physical attributes are due to anthropogenic activities, and various natural factors in the lakes and in their catchments and their interactions have been reported to affect water qualities, biodiversity and fisheries production in the lakes (Alemayehu Hailemicael, 2011; Fasil Degefu *et al*., 2011; Megerssa Endebu *et al.*, 2015; Tadesse Fetahi, 2019).

Despite its significant economic and ecological services, the freshwater biodiversity and its services are under threat worldwide, in some areas at an alarming rate (Dudgeon *et al*., 2007). Threats to biodiversity in freshwater ecosystems have been acknowledged and summarized into five major types called "HIPPO", an acronym standing for the habitat loss and fragmentation, invasive species, pollution, population growth and overexploitation of resources (Limburg, 2009; Torrance, 2010). These problems are further exacerbated by human population increase with stagnated rate of food production unmatched with increasing food demand. Population growth has played major roles in freshwater ecosystem functioning but also in the change of the land use system in Ethiopia causing land degradation, habitat fragmentation, and deforestation (Tenalem Ayenew and Dagnachew Legesse, 2007). Such changes are largely due to the use of water for irrigation that affected the hydrological settings of some Rift Valley lakes including Lakes Chamo, Koka and Ziway. The Rift Valley lakes, like other tropical lakes, are sensitive to increase in nutrient loading from anthropogenic activities in the catchment areas mainly through inlet rivers and change in water quality and biodiversity in response to eutrophication (Lewis, 2000; Tadesse Fetahi, 2019). The nutrient containment in tropical lakes is more strongly oriented towards nitrogen, the most probable limiting factor than phosphorus (Lewis, 2000).

Both abiotic factors that mainly constitute the water physico-chemical properties and biotic factors together with land management practices contribute to the dynamics of freshwater ecosystem including the lakes ecosystem, particularly its physico-chemical attributes reflected by water quality parameters such as water temperature, pH, electric conductivity (EC), total dissolved solids (TDS), salinity, turbidity measured in Secchi disc depth, nitrate and phosphate concentrations. Electric conductivity (EC) and salinity of the lakes are related to dissolvable salts such as sodium chloride, magnesium sulfate, potassium nitrate, sodium bicarbonate contents. Talling and Talling (1965) reported that dissociation of these salts are the drivers of salinity and EC of the Rift Valley lakes mainly due to carbonate and bicarbonates followed by chloride, fluoride and sulfate anions, and by the four main cations; namely, sodium, calcium, magnesium and potassium. Water EC is determined by the concentration and types of ions, and water temperature. Total dissolved solids (TDS), the great majority of the loads in natural water are from the cations and anions are also responsible for the EC of the water, is a measure of all dissolved contents of inorganic and organic substances present in the water in molecular, ionized or colloidal suspended forms.

Abiotic factors characterized by the water physico-chemical properties determine the lakes biological functions and biological diversity in the ecosystem. Warm waters with the optimum temperature range of 25-30°C promote a healthy and balanced lakes ecosystem that includes the reproduction and growth of several economically important local fish species. The change in temperature patterns of a lake from the optimum range required for a rather efficient metabolic rate of various fish species alters the fish feeding behavior and interaction with its habitat (Walberg, 2011), and spawning and hatching patterns (Faruk *et al*., 2003). Electric conductivity, an electrical potential of ions in water is affected by the ions concentration, charge and mobility, where the latter increases as the water temperature increases (Hayashi, 2004). The neutral pH level, which is a measure of the concentration of free hydrogen and hydroxyl ions in the water, of freshwater ecosystems optimum for the fish species can be changed by pollution. Water quality degradation due to excessive nutrients loading particularly nitrogen and phosphorus has been acknowledged to result in eutrophication and increased water hyacinth *(Eichhornia crassipes)* invasion (Hossain *et al*., 2015). Previous studies reported on three Ethiopian Rift Valley lakes; namely Lakes Chamo, Koka and Ziway, indicated selected physico-chemical properties of the lakes were far from the levels expected from healthy lakes (Table 1).

In addition to the physico-chemical attributes that reflected the deteriorating quality status, the Ethiopian lakes are under threat by an aquatic weed called Water hyacinth (*Eichhornia crassipes*). Water hyacinth was originally from Amazon Basin with first report in 1965 in Koka Lake and Awash River is now an invasive alien aquatic weed species (Firehun Gebregiorgis, 2017) that has become a national concern threatening aquatic biodiversity and socioeconomic activities in the Ethiopian water bodies. It has been reported that this weed spread widely invading the Awash River Basin (Abasamuel, Koka and Wonji sugarcane irrigation reservoirs), Abay River Basin (Lake Tana and Blue Nile), Baro-Akobo River Basin (Sobat, Baro, Gillo and Pibor Rivers) and Rift Valley Basin Systems (Lake Ellen, Lake Abaya, Lake Ziway, Lake Elltoke) (Firehun Gebregiorgis *et al.*, 2007, 2013; Dereje Tewabe, 2015; Dereje Tewabe *et al.*, 2017; Firehun Gebregiorgis, 2017).

Table 1. Previous studies of some physico-chemical parameters of Lakes Chamo, Koka and Ziway

	Chamo	**Koka**	**Ziway**
Water temperature (°C)	26.0 - 30.4 [i]	20.6 - 24.0[g]	23.1 - 27.5[g]
Secchi disc depth (cm)	65[c] 12 - 60[i]	28 [c]	35[c]
pH range	8.9 [c] 8.87 - 9.93[i]	8.2[c] 8.1- 8.5[e] 7.4 - 8.0[g]	8.5[c] 8.4 - 8.9[g]
Salinity (g/L)*	1.1 [a], 1.0 [c], 0.6 - 0.93[i]	0.319 [a] 0.2[c]	0.349 [a] 0.4[c]
Total dissolved solid (mg/L)	595 - 924[i]		379[f]
Conductivity (µS/cm, 25°C)	1,100[a]; 927[b] 1,320[c] 1,253-2,127[i]	274[a]; 286[c]; 200[d] 251 - 458[g] 380-1200[j]	322 [a]; 410[c] 372 - 427[b] 479 - 530[g]
Soluble reactive phosphorus (µg /L)	25.5[c]	9.5 [c]; 36.10[h]	Below detection level
Total phosphorus (µg /L)	135.0[c]	224.0[c]; 477.2[h]	170[b]; 219.0[c]
NO_3^--N(µg /L)	18.6[c]	1.4 [c], 44.4 [h] 690 - 1,430[g]	3.9 [c] 0 - 50 [g]

Adapted from [a] Wood and Talling 1988 (data Feb-March 1964); [b] Talling and Talling, 1965; [c] Elizabeth Kebede *et al.*, 1994; [d] Melaku Mesfin *et al.*, 1988; [e] Hadgembes Tesfaye, 2007; [f] Teodros Rango *et al.*, 2009; [g] Alemayehu Esayas *et al.*, 2011; [h] Fasil Degefu *et al.*, 2011; [i] Addisu Fekadu and Solomon Chanie, 2017; [j] Mesfin Gebrehiwot *et al.*, 2020.

The three lakes targeted for this study: namely, Lakes Chamo, Koka and Ziway are vulnerable to changes in water quality level due to rapid changes in land use and management systems and other anthropogenic activities in their catchment. As a result, this study attempted to provide information on the current status of some physico-chemical and biological aspects of the lakes at three sampling regions of the water body namely the inlet region (IR), the middle region (MR) and the outlet region (OR). Assessing variations in different parts of the water would provide critical information to design effective intervention options to rehabilitate these lakes.

2.2 Materials and Methods

2.2.1 Study areas

This study targeted selected water physico-chemical and biological attributes of three Ethiopian Rift Valley lakes, namely, Chamo, Koka and Ziway (Figure 2, Table 1).

2.2.2 Study seasons and sampling sites

This study was conducted from May 2018 to April 2020 categorized as Year 1 (May 2018-April 2019) and Year 2 (May 2019-April 2020). Data and sample collection followed the local rainy season that dictated the agricultural activities in the region and thus quality of water in the inlet rivers to the three lakes. Accordingly, the seasons were grouped as (1) February to March (FBM) – a dry season for Ziway and Koka lakes regions, but it was the onset of main rainy season for Lake Chamo region; (2) May – the onset of main rainy season for Ziway and Koka lakes regions, but it was the main rainy season for Lake Chamo region; (3) July-August (JUA) – the main rainy season for Ziway and Koka lakes regions, but it was the winding of main rainy season and the harvesting time for the Chamo lake region; (4) October to November (OCN), the season right after main rainy season for Ziway and Koka Lakes regions, but it was a short rainy season for Lake Chamo region. To cater for changes during the day, measurements were recorded, and samples were collected in the mornings 7:00-9:00 AM and the afternoons from 2:00 to 4:00 PM on the days the samples were collected.

Sites for water sample and in situ data collection were selected purposely to represent the lakes from inlet region, middle of the lake and outlet away from the major inlet regions. The landing sites are called Leto-1, Leto-2 and Elgo for Lake Chamo; Awash, Metoaleka and Bekele for Lake Koka and Golbe-Tsedecha, Meki-Girisa, and Batu-Bochesa for Lake Ziway.

2.2.3 Data collection

In-situ measurements: - Seven water physico-chemical parameters, namely (1) conductivity (CND), (2) pH, (3) Secchi disc depth (SCH), (4) resistivity (RST), (5) salinity (SLN), (6) temperature (TMP) and (7) total dissolved solids (TDS) were measured in-situ at the sampling sites of the three lakes.

Secchi disc depth (SCH) indicated water turbidity level measured using a standard Secchi disc, a white metallic disc of 20 cm diameter having six circular holes around as a contrast for observation in water. The Secchi disc measurements were taken by sending the disc into water from a boat and observing depth of disappearance (d1) when lowering and depth of appearance (d2) when lifting slowly from depth. The average depth of d1 and d2 was recorded in cm and described as Secchi disc depth.

Water pH was measured using handheld Elmetron pH-meter of model CP-411. Conductivity, salinity, total dissolved solids (TDS) and water temperature (TMP) were measured using handheld multi-meter of model SX723 pH/mV/Cond meter. These parameters were measured in-situ at different depths, surface (0-25 cm) and depth about 1 m twice a day in the mornings and the afternoons.

Sampling for laboratory analysis: - Water samples were collected from the sampling sites of the lakes to determine the nutrient loadings measured by (1) nitrate concentrations (NTN), (2) soluble reactive phosphorus (SRP), and (3) total phosphorus (TP). The parameters were analyzed following the standard methods for the examination of water and wastewater (APHA, 1995) at the Limnology Laboratory of Addis Ababa University. The method followed Ascorbic acid procedure to determine SRP, persulfate digestion procedure to determine total phosphorus, and Salicylate method to determine nitrate level.

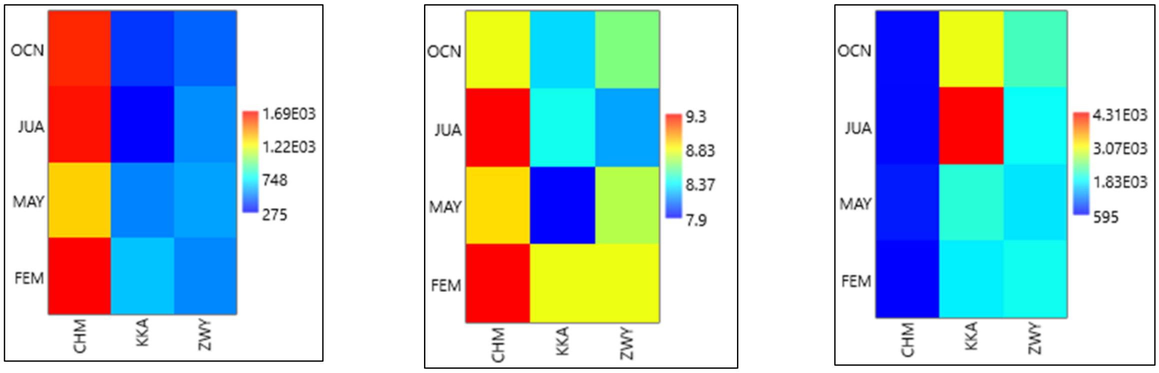
Vegetation assessment: - To judge the wetlands vegetation status of the lakes, observations were made along the shores of lakes. Water hyacinth, the invasive alien species, was visually observed across the three lakes and recorded as present or absent.

2.2.4 Data analysis

Data on the water physico-chemical attributes and nutrient loadings were subjected to one-way Analysis of Variance (ANOVA) in SPSS-20 package (IBM SPSS, 2011) and two-ways ANOVA by GENSTAT (VSN International, 2020) where unbalanced regression analysis estimated the means and the presence of statistical significance across Lakes, sampling sites, seasons, and their interactions. Mean differences of the parameters between the three lakes and among the four seasons within each lake were further separated using LSD post hoc analysis at 5% significance level. Comparison between the lakes and the seasons were made based on the mean values. Pearson Correlation analysis was performed with SPSS and graphs were constructed with PAST statistical program (Hammer *et al*., 2001).

2.3 Results

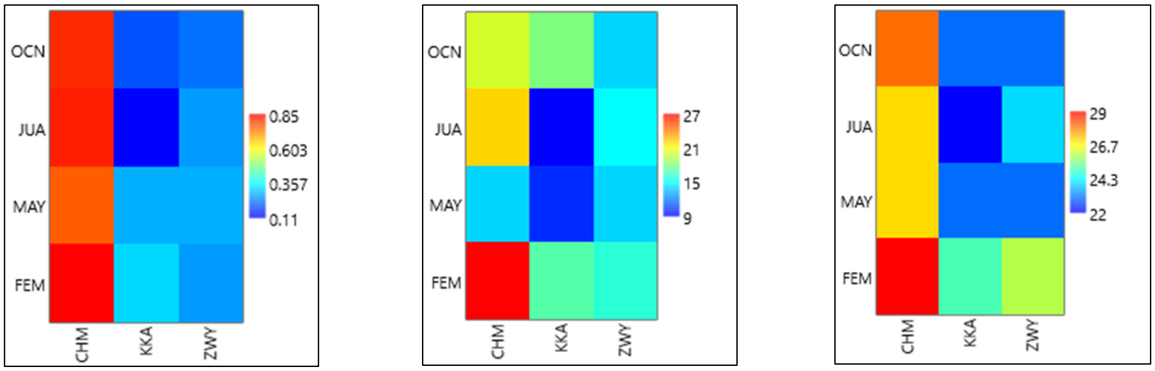
The physico-chemical parameters measured across two years at Inlet, Middle and Outlet Regions of Lakes CHM (Chamo), KKA (Koka) for seasons FEM (February to March), MAY (May), JUA (July to August) and OCN (October to November) were summarized in a matrix plot (Figure 3).



A. CND **(μs/cm)**

B. pH

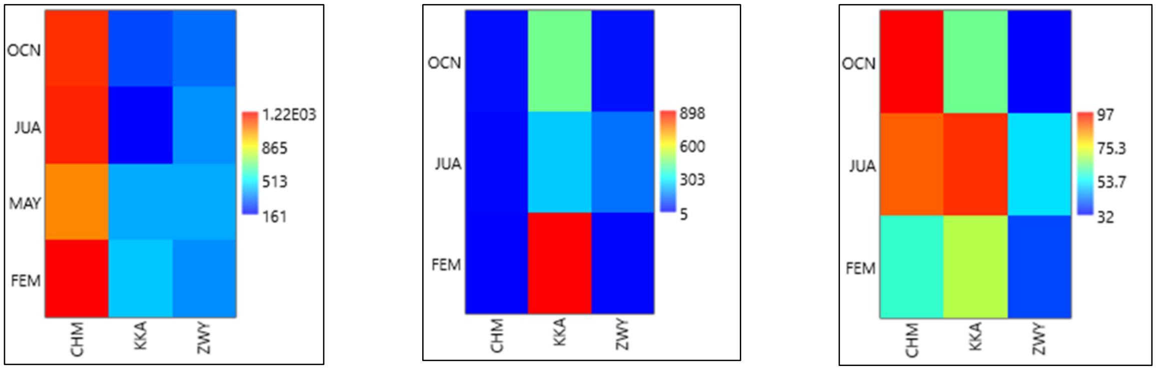
C. RST **(ohm)**



D. SLN **(ppt)**

E. SCH (cm)

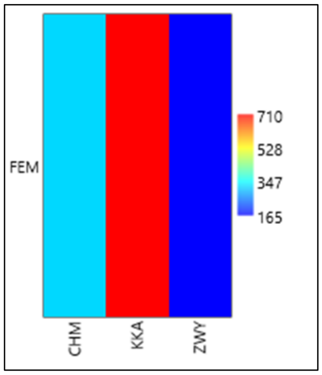
F. TMP (^{0}c)



G. TDS **(mg/L)**

H. NTN **(μg/L)**

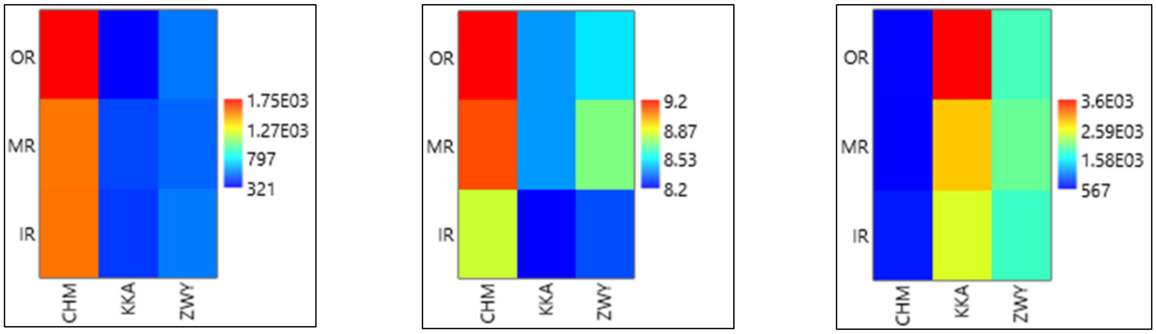
I. SRP **(μg/L)**



J. TPP **(µg/L)**

Matrix plot of means of physico-chemical parameters measured across two years at Inlet, Middle and Outlet Regions of Lakes CHM (Chamo), KKA (Koka) for seasons FEM (February to March), MAY (May), JUA (July to August) and OCN (October to November). Physico-chemical properties (I) measured in-situ included (A) CND = Conductivity; (B) pH; (C) SCH = Secchi depth as Turbidity level indicator; (D) RST = resistivity; (E) SLN = Salinity; (F) TMP = Temperature; (G) TDS = total dissolved solids, and (II) measured in the laboratory included (H) NTN = nitrate in nitrogen concentration; (I) SRP = soluble reactive phosphorus; (J) TPP = total phosphorus. Data presented in X-axis representing Lakes and Y-axis seasons for all parameters except for TPP sampled from only FEM season.

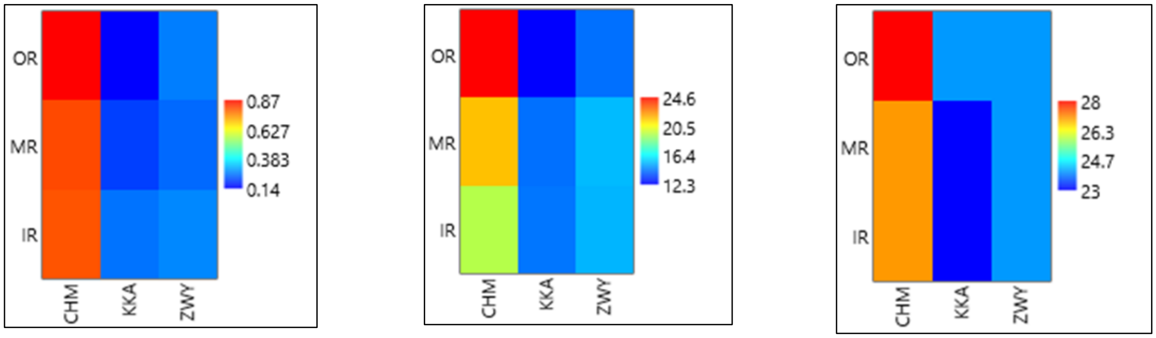
Figure 3. Matrix plot of means of physico-chemical parameters by lakes and seasons.



A. CND (µs/cm)

B. pH

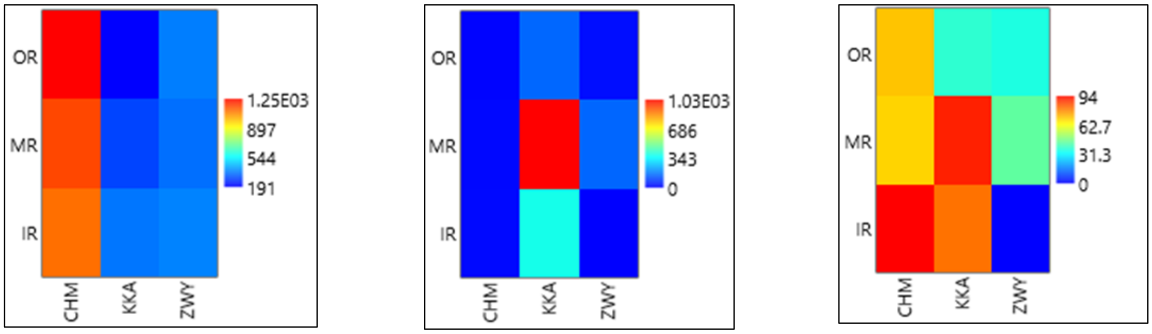
C. RST (ohm)



D. SLN (ppt)

E. SCH (cm)

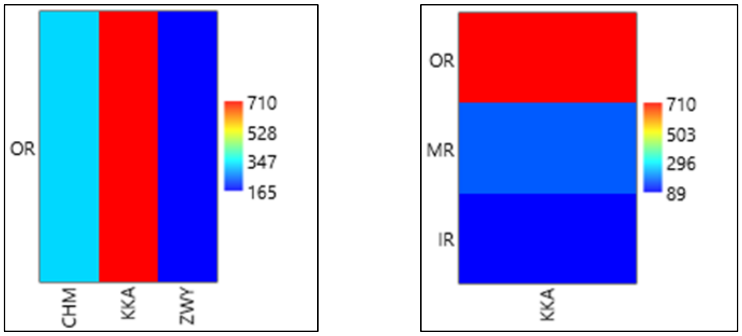
F. TMP (^{0}c)



G. TDS (mg/L)

H. NTN (µg/L)

I. SRP (µg/L)



J. TPP (µg/L)

K. TPP (µg/L)

Figure 4. Matrix plot of means of physico-chemical parameters by lakes and sampling sites.

(Matrix plot of means of physico-chemical parameters measured across two years and four seasons/ per year at IR (Inlet Region), MR (Middle Region) and OR (Outlet Region) of Lakes CHM (Chamo), KKA (Koka). Physico-chemical properties (I) measured in-situ included (A) CND = Conductivity; (B) pH; (C) SCH = Secchi disc depth as Turbidity level indicator; (D) RST = resistivity; (E) SLN = Salinity; (F) TMP = Temperature; (G) TDS = total dissolved solids, and (II) measured in the laboratory included (H) NTN = nitrate in nitrogen concentration; (I) SRP = soluble reactive phosphorus; (J) and K TPP = total phosphorus. X-axis represents Lakes and Y-axis sampling sites.)

The correlation matrix in Pearson's correlation coefficient for nine variables of water physico-chemical parameters measured across Lakes Chamo, Koka and Ziway over two years in four seasons per year and three sites per lake is presented Table 2. The correlation pattern of the parameters can be categorized into three broad groups; (I) highly significant and positively correlated, (II) highly significant but negatively correlated and (III) weakly positively or negatively correlated parameters. Conductivity, TDS, salinity, water temperature, Secchi disc depth, and pH were highly significant and positively correlated with each other. Likewise, nitrate concentration with soluble reactive phosphorus was also highly significant and positively correlated. Resistivity was highly significantly and negatively correlated with the conductivity, salinity, TDS, water temperature, Secchi disc depth and pH. Nitrate concentration, soluble reactive phosphorus and total phosphorus concentration were weakly positively or negatively correlated with all other variables except for the strong significant and positive correlation between NTN and SRP.

Table 2. Pearson correlation coefficient between physico-chemical parameters measured across Lakes Chamo, Koka and Ziway over two years in four seasons per year and three sites per lake

	CND	**pH**	**RST**	**SLN**	**SCH**	**TDS**	**NTN**
pH	0.63** (52)						
RST	-0.85** (44)	-0.59** (42)					
SLN	0.99** (45)	0.60** (43)	-0.85** (44)				
SCH	0.67** (48)	0.50** (47)	-0.59** (43)	0.62** (43)			
TDS	1.00** (44)	0.61** (42)	-0.85** (44)	0.99** (44)	0.63** (43)		
TMP	0.82** (53)	0.63** (52)	-0.69** (43)	0.81** (44)	0.57** (49)	0.81** (43)	
SRP	0.23 (18)	0.15 (18)	-0.09 (18)	0.22 (18)	0.002 (18)	0.230 (18)	0.62** (18)

**Correlation is significant at the 0.01 level (2-tailed), and numbers in brackets indicate correlated observations.

2.3.1 Water temperature

The mean water temperature values varied across the lakes and across the seasons (Figure 3F). The mean water temperature differences between the lakes and between the seasons were significant (Table 3). However, the Lake-Season interaction effect and the mean differences for the sampling sites were not significant. The water temperature was not differently affected by season in any of the lakes.

The annual mean water temperature was highest at Lake Chamo, 27.46 ± 0.84^{o}C; seasonal mean water temperature ranged from 26.55^{o}C in May (main rainy season) to 28.54^{o}C in Feb-March (dry season); while the annual mean values were 23.97 ± 1.44^{o}C at Ziway and 23.35 ± 1.03^{o}C at Koka with significant seasonal mean temperature variations (Figure 3F). The water temperature during the dry season, February-March months, was higher than the temperature during the onset of rain, short rain or main rain and post rainy seasons at each of the three lakes.

Table 3. Analysis of variance for water temperature (^{o}C) across Lakes Chamo, Koka and Ziway in four seasons per lake

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Lake ignoring Season	2	156.304	78.152	69.82	< 0.001
Season ignoring Lake	3	33.642	11.214	10.02	< 0.001
Lake x Season	6	10.462	1.744	1.56	0.184
Residual	41	45.895	1.119		
Total	53	379.116	7.153		

2.3.2 Secchi disc depth

The mean Secchi disc depth (water turbidity measure) values of the lakes varied across the three lakes and across the four seasons (Figure 3E). The differences in mean annual Secchi disc depth between the lakes, between the seasons and Lake-Season interaction were statistically significant (Table 4) but the mean Secchi disc depth values across the sampling sites (Figure 3E) were not significantly different. The mean annual Secchi disc depth value was highest at Lake Chamo (20.96 ± 5.36 cm) and statistically different from that of Lake Ziway (14.53 ± 0.88 cm) and Lake Koka (13.35 ± 4.70 cm). Seasonal differences in mean Secchi disc depth were also observed at each of the lake during the sampling period. The seasonal mean Secchi disc depth values were lower at the onset of the rain and during rainy season, in May and July-August months (especially in Lake Koka) while it was high during the dry season, in February-March months (especially in Lake Chamo); showing the Lake-Season interaction. The range was from 14.13 cm in May to 27.05 cm in Feb-Mar at Chamo, from 13.73 cm in May to 15.54 cm in Feb-March at Ziway and from 8.65 cm in July-August to 17.94 cm in Oct-Nov at Lake Koka. Though not statistically different, the mean Secchi disc depth values for the sampling sites within the lakes also varied with the lowest mean values recorded around the confluence of the inlet rivers during rainy season and the highest mean values recorded around the region of the lake away from the main inlet especially in Lake Chamo (Figure 4E).

Table 4. Analysis of variance for mean Secchi disc depth (cm) across Lakes Chamo, Koka and Ziway in four seasons per lake

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Lake ignoring Season	2	575.01	287.5	19.96	< 0.001
Season ignoring Lake	3	285.44	95.15	6.6	0.001
Lake x Season	6	309.96	51.66	3.59	0.007
Residual	36	518.61	14.41		
Total	48	1725.42	35.95		

2.3.3 Water pH

The mean annual water pH values of the lakes were 9.08 ± 0.25, 8.58 ± 0.25 and 8.37 ± 0.37 in Lakes Chamo, Ziway and Koka, respectively, which are in decreasing order. The differences were statistically significant ($p<0.001$) with the pH of Lake Chamo significantly higher than that of the two lakes. Seasonal variations in mean pH values, with relatively lower mean values during the rainy seasons than the mean values in the dry seasons were observed in each of the three lakes (Figure 3B) though the differences were not statistically significant (Table 5). The mean pH values across the sites within each lake were not significantly different (Figure 3B). The Lake-Site interaction on pH value was also not significant.

Table 5. Analysis of variance for mean pH across Lakes Chamo, Koka and Ziway in four seasons per lake.

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Lake ignoring Season	2	3.9949	1.9974	12.9	< 0.001
Season ignoring Lake	3	1.4364	0.4788	3.09	0.038
Lake x Season	6	1.5737	0.2623	1.69	0.148
Residual	39	6.0397	0.1549		
Total	51	16.1912	0.3175		

2.3.4 Conductivity

Electric conductivity of the water was significantly higher in Lake Chamo with mean value of 1,570.43 ± 177.46 µS/cm than that of Lake Ziway with mean value of 524.88 ± 48.97 µS/cm and Lake Koka with mean value of 450.45 ± 158.63 µS/cm (Figure 3A). The differences in seasonal mean values of conductivity at each lake were significant (Table 6) and the values ranged from lower mean of 1,308.00 µS/cm in May (rainy season) to 1,693.40 µS/cm in Feb-March (dry season) in Lake Chamo; from lower mean value of 458.30 µS/cm in Oct-Nov (Post-rainy season) to 575.70 µS/cm in May (pre-rainy season) in Lake Ziway and from lower mean value of 274.70 µS/cm in July-Aug (rainy season) to higher value of 636.00 µS/cm in Feb-March (dry season) in Lake Koka. The resistivity (ohm) of the water in the three lakes was in similar pattern but had inverse correlation with the electric conductivity.

Table 6. Analysis of variance for mean conductivity (µS/cm) across Lakes Chamo, Koka and Ziway in four seasons per lake

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Lake ignoring Season	2	12907755	6453877	282.26	< 0.001
Season ignoring Lake	3	297121	99040	4.33	0.01
Lake x Season	6	545021	90837	3.97	0.003
Residual	41	937476	22865		
Total	53	16247056	306548		

2.3.5 Total dissolved solids

Mean total dissolved solids (TDS) values of the three lakes across four seasons were shown in Figure 3G. Similar to the electric conductivity values, significantly higher annual mean value of TDS (mg/L) was recorded in Lake Chamo (1,141.9 ± 80.4 mg/L), than that of Lakes Ziway (356.6 ± 34.8 mg/L) and Koka (312.8 ± 125.9 mg/L). The values also vary significantly among sampling seasons at each of the lakes (Table 7). The TDS ranged from 1,028.70 mg/L in May to 1,217.40 mg/L in Feb-March in Lake Chamo; from 311.13 mg/L in Oct-Nov to 395.40 mg/L in May in Lake Ziway and from 160.50 mg/L in July-Aug to 434.70 mg/L in Feb-March in Lake Koka.

Table 7. Analysis of variance for mean total dissolved solids (mg/L) across Lakes Chamo, Koka and Ziway in four seasons per lake

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Lake ignoring Season	2	6116652	3058326	295.07	< 0.001
Season ignoring Lake	3	160378	53459	5.16	0.005
Lake x Season	6	165288	27548	2.66	0.034
Residual	31	321311	10365		
Total	43	7430110	172793		

2.3.6 Salinity

The salinity values varied significantly across the three lakes and four seasons (Table 8; Figure 3D); whereby the mean value at Lake Chamo (0.81 ± 0.03 ppt) was significantly higher than that of Lakes Ziway (0.25± 0.02 ppt) and Koka (0.22 ± 0.09 ppt). Slight temporal changes in salinity was also observed across the lakes, whereby highest seasonal mean salinity levels of the lakes were recorded in Feb-March (dry season) in Lakes Chamo (0.85 ppt) and Koka (0.317 ppt) and in May in Lake Ziway (0.284 ppt). The lowest salinity levels were recorded in main-rainy seasons in Lakes Chamo (0.765 ppt) and Koka (0.113 ppt), while it was lowest in Oct-Nov (post rainy season) in Lake Ziway (0.224 ppt). The spatial differences in salinity were observed in Lake Chamo, the terminal lake without visible outlet river, where salinity level increased from the region of major inlet-river confluence (IR) towards the region away from the inlet rivers (OR). In contrast to the case of Lake Chamo, salinity level decreased from inlet-region (IR) towards outlet region in Lake Koka (Figure, 4D).

Table 8. Analysis of variance for mean salinity (ppt) across Lakes Chamo, Koka and Ziway in four seasons per lake

Source	**d.f.**	**s.s.**	**m.s.**	**v.r.**	**F pr.**
Lake ignoring Season	2	3.069223	1.534611	381.03	< 0.001
Season ignoring Lake	3	0.078387	0.026129	6.49	0.001
Lake x Season	6	0.068928	0.011488	2.85	0.024
Residual	32	0.128881	0.004028		
Total	44	3.706108	0.08423		

2.3.7 Nutrient load to the lakes

The nutrient loads to the three lakes were analyzed in terms of soluble reactive phosphorus (SRP), total phosphorus (TP) and the nitrate nitrogen (NTN) at different seasons and different sites of the lakes (Figures 3H, 3I, 3J; 4H, 4I, 4J and 4K). Statistically, the overall mean concentration of soluble reactive phosphorus (SRP), total phosphorus (TP) and the nitrate nitrogen (NTN) were not significantly different across the lakes, across the seasons and across the sites within the lakes. However, the overall mean for the concentration of soluble reactive phosphorus (SRP) was lower in Lake Ziway (39.22 ± 8.19 µg P/L) than in Lakes Koka (75.25 ± 15.49 µg P/L) and Chamo (81.36 ±20.61 µg P/L). The concentration of total phosphorus (TP) measured in dry season (February-March) was higher in Lake Koka than Lakes Chamo and Ziway especially in the outlet region of the lakes (Figures 3J, 4J). The spatial concentration increased from inlet region to outlet region in Lake Koka (Figure 4K). The nitrate-N load (NTN) was high in Lake Koka, ranging from seasonal mean value of 240.90 µg/L in July-August (main rainy season) to 898.0 µg/L in Feb-March (dry season) with mean value of 524.60 ± 337.61 µg /L NO^-_3 - N while the dry season and overall mean values were lower in Lakes Ziway (11.3 and 77.6 ± 69.18 µg /L) and Chamo (5.2 and 12.5 ± 7.73 µg /L NO^-_3 - N), respectively.

2.4 Discussion

Water physico-chemical parameters differ from lake to lake affected by many factors and the parameters can determine types and habitats of organisms living in the lakes. Water temperature, influenced by the amount and angle of solar radiation and ambient temperature, varies in water bodies depending on geographical locations, latitudes, altitudes and morphometry of the water bodies. The differences in mean annual water temperatures values for the lakes, 27.46 ± 0.84^{o}C at Chamo followed by 23.97 ± 1.44^{o}C at Ziway and 23.35 ± 1.03^{o}C at Koka observed in this study were also caused by the variations in geographical locations, morphometry and environmental status of the three lakes. The lower the altitudinal and latitudinal location of a lake, the higher the water temperatures (Layden *et al*., 2015).

Lake Chamo is located at relatively lower latitude, between 5° 42' - 5° 58' N and lower altitude, 1,110 m.a.s.l. than Lakes Koka and Ziway; as a result its water temperature is warmer than that of the two lakes. However, the locations of Lake Ziway (7° 52’ - 8° 8’ N at 1,636 m.a.s.l.) and Lake Koka (8° 18′ 57″ - 8° 28′ 21″ N at 1,590 m.a.s.l.) are not far apart to cause significant temperature differences. The slight mean annual water temperature difference observed between the later two lakes was rather attributed to the morphometric differences between the lakes (Lake Ziway with area of 434 km^2 and mean depth of 2.5 m while Lake Koka with area of 200 km^2 and mean depth of 9 m). Broad and shallow lakes are warmer than deeper and narrower lakes (Meerhoff *et al*., 2012).

Seasonal water temperature changes were observed in all the three lakes as the ranges indicated in Figure 3F where lower water temperatures during the rainy seasons and higher temperatures during the dry seasons were associated with the ambient seasonal temperatures of the area. However, the mean annual water temperatures for the lakes in the current study were within the ranges of the water temperatures history of the lakes (Table 1), though the mean annual water temperatures of the lakes in the past were not clearly presented. The current temperature values were in the range of water temperature history of the lakes, very likely because of the reason that water temperatures are mainly governed by factors such as location (altitude and latitude) of the lakes and their morphometry, which are not dynamic over time.

Water turbidity, the amount of suspended solids in water, was high (described as low Secchi disc depth, Figure 3E) at Lake Koka followed by Lakes Ziway and Chamo. The main cause of the lakes' turbidity is suspended material coming from catchment areas during the rainy season. The catchment area of Koka is wide and intensive agricultural activities are practiced in the area (Berhan Teklu, *et al.*, 2018; Tadesse

Fetahi, 2019) where erosion carries massive suspended particles from the agricultural fields to the lake, increasing its turbidity. Similar to that of Lake Koka, the agricultural intensification making soil liable to erosion in the catchment of Lake Ziway has been significant to pose similar impact of higher turbidity at the lake, but is less than that of Koka because of the lower catchment area from where erosion takes place. The relatively lower turbidity (higher Secchi disc depth) recorded at Lake Chamo was attributed to relatively lower intensification of agricultural activity in the catchment and lower catchment area of the lake (1,109 km^2) compared to the other two lakes (6,991 km^2 for Lake Ziway and 11,250 km^2 for Lake Koka). Seasonal variations in mean Secchi disc depth values at all the three lakes in the current study showed relatively higher turbidity (lower Secchi disc depth) during the onset of rain and main rainy seasons was caused by eroded soil in a surface runoff from the catchment area of the lakes, which was intense at the confluences of the inlet rivers. The turbidity gradually decreases after the rainy season and away from the confluence of the inlet rivers when the suspended particles settle. The mean Secchi disc depth values in the current study were lower (two to three fold) at all the three lakes as compared to their chronological Secchi disc depth data of previous records (Elizabeth Kebede *et al.*, 1994) showing that loads of suspended solids to the lakes are increasing. The increase in water turbidity affects the lake environment, increasing silt load, changing lake bottom sediment, overall productivity of the lakes and also the water temperatures since the suspended particles absorb heat from solar radiation more effectively than water (Paaijmans *et al.*, 2008).

The mean values for water pH, electric conductivity (EC), total dissolved solids (TDS) and salinity were significantly different between the three lakes with the higher mean values of the parameters recorded at Lake Chamo and lower mean values at Lake Koka. The parameters were highly significantly and positively correlated. The mean differences across the lakes were mainly attributed to geology of the lakes and the chemistry of their watershed soils, size of the watershed and changes in size of the lakes (Tenalem Ayenew and Dagnachew Legesse, 2007; Alemayehu Hailemicael, 2011).

The soil salinity around Lake Chamo, including in annual field cropping systems was reported to be high (Degife Asefa *et al*., 2019). Seasonal variations of the parameters values within the lakes were influenced mainly by the incoming flood during the rainy season (or post-rainy season as in the case of Lake Ziway), which increases the lakes' volume and dilute chemistry of the lakes. The current range of water pH value at lake Chamo, 7.48 - 9.50 includes the 8.9 value reported by Elizabeth Kebede *et al.*, (1994) but lower than the 8.87 - 9.93 value reported by Addisu Fekadu and Solomon Chanie (2017). The pH value at Lake Koka increased from previous report of 7.4 - 8.5 range (Elizabeth Kebede *et al.*, 1994; Hadgembes Tesfaye, 2007; Alemayehu Esayas *et al.*, 2011) to the current range of 7.6 - 9.21 with mean of 8.26. Similarly, the pH range at Lake Ziway is widened in the current study (7.71 - 9.00) with mean value of 8.54, which is within the previous range of 8.4 - 8.9 (Figure 3B). The changes in pH ranges over time and the variation across sampling seasons and sampling sites in the lakes were influenced by the water chemistry of inlet rivers during the rainy seasons and the trophic levels of the lakes (Tadesse Fetahi, 2019). The current conductivity values at all the three lakes ranged higher than the previous reports, in increasing trend over time (Table 1), indicating that ions concentration in the lakes is increasing, especially at Lake Chamo. The TDS is also related to electrical conductivity of a lake; where the relationship with EC is linear (Pal *et al.*, 2015) as also presented in the current data.

The differences in the mean values of the nitrate-N and phosphate-P concentrations at the three lakes are related to the types and levels of pollutants (fertilizers from agricultural lands, municipal and industrial wastes) in the catchment areas of the lakes and geologic origin. The higher concentration of nitrate-N and total phosphorus in Lake Koka are also correlated with the intensification of agriculture, industrial and municipal wastes in the catchment of upper Awash. The total phosphorus concentration gradient increasing towards the outlet region in Lake Koka is perhaps due to gradual settlement and deposition of phosphate compounds in sediments around the mouth of the lake; natural wetland vegetation except the water hyacinth, are absent/little in Lake Koka to utilize the nutrients. Nitrate-N and phosphate-P concentrations in the current study are higher than the previous reports at all the three lakes. The maximum recorded concentrations of nitrate-N increased from 18.6 µg /L (Elizabeth Kebede *et al.,* 1994) to 26.3 µg /L in Lake Chamo; from 1.4 µg /L (Elizabeth Kebede *et al.,* 1994) and 1,430.0 µg /L (Alemayehu Esayas *et al.*, 2011) to 2,587.7 µg /L in Lake Koka and from 3.9 µg /L (Elizabeth Kebede *et al.,* 1994) and 50.0 µg /L (Alemayehu Esayas *et al.*, 2011) to 142.00 µg /L in Lake Ziway (current study). Similarly, the maximum recorded concentrations of phosphate-P increased from 25.5 µg /L (Elizabeth Kebede *et al.,* 1994) to 102.8 µg /L in Lake Chamo; from 9.5 µg /L (Elizabeth Kebede *et al.,* 1994) and 36.1 µg /L (Fasil Degefu *et al*., 2011) to 146.8 µg /L in Lake Koka and from below detection level (Elizabeth Kebede *et al.,* 1994) to 50.8 µg /L in Lake Ziway in the current study. The land cover pattern of Ethiopia in general and that of Central Rift Valley in particular is changing. The area coverage of small and large scale farming, settlements and mixed cultivation/acacia were increasing while those of forest and woodland were decreasing in Central Rift Valley of Ethiopia (Eyasu Elias *et al*., 2018). Use and application rate of chemical fertilizers in the country is increasing following the expansion and intensification of agricultural lands, lose of soil fertility due to erosion and removal of crop residue for animal feed (Abraha Reda and Alem Hagos Hailu, 2017; Ermias Engida *et al*., 2019). Large areas of farms are covered by variety of vegetable crops in Central Rift Valley especially around Lakes Ziway and Koka where fertilizer application rates among the vegetable growers were reported to be in excess (Edossa Etissa *et al*., 2013). Land degradation, intensification of agriculture at small-scale farmers and large horticultural companies using fertilizers and pesticides, especially in the watershed areas of Lakes Ziway and Koka, are common, which ultimately caused increased rate of pollution in the Rift Valley lakes (Tenalem Ayenew and Dagnachew Legesse, 2007; Dereje Meshesha *et al.*, 2012; Berhan Teklu *et al.*, 2018; Tadesse Fetahi, 2019).

Water eutrophication caused by nitrate and phosphate resulted in a number of human health problems including hazards for infants and pregnant women (Isiuku and Enyoh, 2020). Concentrations more than 10 mg/L Nitrate-N and 5 mg/L phosphorous in drinking water are considered as hazardous according to EPA (Environmental Protection Agency), though the current concentrations did not exceed the limits.

Natural wetland vegetation mainly dominated by *Typha domingensis, Echinochloa pyramidalis, Cynodon dactylon* and *Cyperus articulata* in the shoreline of Lake Chamo were found to be dense and relatively undisturbed, though land use and land cover changes overtime were reported in the catchment (Alemayehu Hailemicael, 2011). The wetland vegetation (including typha, *Cyperus papyrus* L. (papyrus), *Nymphaea nouchali* (blue water lily), *Paspalidium geminatum* (bulrush), and *Aeschynomene elaphroxylon*) are distributed in most parts of the shoreline of Lake Ziway with some disturbances caused by animal grazing and other anthropogenic impacts. In Lake Koka, the shoreline is bare of natural wetland vegetation where they are not found or rarely seen at some areas. Wetlands have great role for the well functioning of aquatic ecosystem by mitigating pollution of nutrient loadings through a combination of physical, chemical and biological processes. The wetlands remove phosphorus, nitrogen and other chemical pollutants through the natural process of absorbing/adsorbing, transforming and sequestering as the water flows through (Nicholas, 1983) and need to be conserved.

Water hyacinth is a persistent floating weed on Lake Koka during the two years of study period which flourish during rainy season, making mat and covering all the shoreline denying access to the lake, impairing fishing activity and clogging at electric power station of the dam. The biomass of the mat increases on the lake until the post rainy months after which it starts to adhere to ground at shore and start drying as the water recedes back in the dry season. Vegetable growers around Koka Lake collect the dried biomass of the water hyacinth from flooded ground to use the land for farming and burn the weed to clean the area. In Lake Ziway, water hyacinth appeared for the first time at Meki-Girisa irrigation canal in the North-east corner of the lake in June, 2017. The weed started spreading to all directions in the lake gradually and colonized all corners of the lake in rainy season of 2020, after three years of appearance. In Lake Chamo, there is information from fishermen that the weed appeared on the lake in its northern corner at the confluence of Kulfo River in 2006. Overflow from Lake Abaya (already invaded by water hyacinth) at maximum level joins Lake Chamo through Kulfo River. However, water hyacinth did not establish and was not seen in Lake Chamo during the present study period. The performance of the weed was highly related to the nutrient loading (Hossain *et al*., 2015).

Water hyacinth prefers nutrient-rich water; higher the pollution rates of lakes, higher would be the growth rate of water hyacinth (Verma and Sivappa, 2017). The ratio of Nitrogen to Phosphorus in water also affects the growth rate of water hyacinth, in which the optimum growth of the water hyacinth is achieved when the N: P ratio in water is between 2.3 - 5 (Reddy and Tucker, 1983). The productivity of the plant increases with N supply rate from 0.5 to 5.5 mg N/L, but higher N concentrations do not significantly increase the yield (Reddy and Tucker, 1989). Gao (2016) reported that high phosphorus concentration of >1.25 mg/L can significantly increase numbers of ramets (vegetative clones) and leaves, and N concentrations exceeding 62.5 mg/L increase biomass of water hyacinth in greenhouse experiment, though the clonal growth of water hyacinth was not correlated to N and P concentrations in field experiment. Hence, the dominance of the water hyacinth in Koka and Ziway Lakes is attributed to the higher nutrient loading from the wide catchment areas where agriculture and urbanization are being intensified followed by relatively lower natural wetland vegetation cover to remove the nutrients. The catchment area of Lake Chamo is relatively less where agricultural activities and urbanization are not yet intensified as compared to that of Lakes Koka and Ziway to pose significant nutrient loading. Moreover, the dense natural wetland vegetation at the periphery of the lake is capable of removing the nutrients keeping the lake’s environment safe.

2.5 Conclusions and recommendations

Based on the physico-chemical water quality parameters studied during the two years (May-2018 to April-2020), Lakes Chamo, Koka and Ziway have different characteristics in water temperature, pH, electrical conductivity (EC), total dissolved solids (TDS) and salinity. These characteristics mainly depend on geographical locations of the lakes, the lakes' morphometry, geology and their catchment areas, and soil chemistry of their watersheds. The parameters showed seasonal changes at all the three Rift Valley lakes and had increasing trend over time.

Water turbidity, nitrate and phosphate concentrations also differed in Lakes Chamo, Koka and Ziway. These parameters are mainly influenced by anthropogenic activities such as agricultural activities, deforestation, land degradation, industrial and municipal wastes in watershed areas of the lakes exist at different intensification levels. The parameters in the present study have shown alarming increase from their previous status at all the three lakes especially at Lakes Koka and Ziway causing eutrophication, siltation and change in biodiversity of the lakes.

Invasive water hyacinth which existed over sixty years in Lake Koka and recently colonizing Lake Ziway has not yet established itself in Lake Chamo. The invasion of the weed in Lake Koka was aggravated by higher nutrient load from its catchment and absence of natural wetland vegetation in the shore of the lake which compete for space and the nutrients uptake, unlike that of Lake Chamo.

In order to minimize the silt and nutrient loads in the lakes and safeguard their biodiversity, watershed management activities and proper agricultural practices which minimize soil erosion and agro-chemical pollution; proper municipal and industrial waste management to minimize chemical and physical pollutions should be enforced by the government and participation of stakeholders.

Natural wetlands vegetation around the lakes should be protected and buffer zone of the lakes should be delimited to keep them free of anthropogenic disturbances.

Chapter Three

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3 Phenotypic characters of *O. niloticus* populations of Lakes Chamo, Koka and Ziway

3.1 Introduction

O. niloticus is cultured worldwide and currently ranked second only to carps in global farmed food fish. The fish is indigenous to Ethiopia and constitutes major proportion (65%) in the country's fish production (Hussein Abegaz, 2015). In the aquaculture development efforts of Ethiopia, wild *O. niloticus* were collected from natural environments, especially from the Ethiopian Rift Valley lakes and stocked into ponds. In an attempt to select better performing strains for aquaculture, *O. niloticus* populations from different Ethiopian Rift Valley lakes showed different growth performances in pond culture. Daba Tugie *et al.* (2017) evaluated growth performances of four *O. niloticus* populations of Ethiopian Rift Valley lakes (Hawassa, Chamo, Koka and Ziway) in pond culture at Batu Fishery and other Aquatic Life Research Center where the Chamo population was found to grow significantly faster than others. Similar studies were conducted to evaluate the growth performances of *O. niloticus* populations of Ethiopian Rift Valley lakes in pond culture at different times for different experimental periods and found variations in growth performances (Kassaye Balkew and Gjoen, 2012; Daba Tugie *et al.*, 2014) whereby the Koka and Ziway *O. niloticus* populations were mentioned as promising candidate populations for aquaculture development in Ethiopia compared to *O. niloticus* populations of Hora, Hawassa and Beseka lakes.

The three lakes, Chamo, Koka and Ziway are geographically isolated (Figure 1); situated in different sub-drainage basins: Abaya-Chamo, Ziway-Shala and Awash Basins, respectively, all within the Ethiopian Rift Valley (Tenalem Ayenew, 2009). Lake Chamo has more diversified ichtyo-fauna than other lakes in Ethiopia except Lake Abaya. There are six important fish species for the fishery in Lake Chamo. These, according to LFDP (1997) are Nile perch (*Lates niloticus*), *O. niloticus*, labeo (*Labeo horie*), African catfish (*Clarias gariepinus*), Bagrus (*Bagrus docmak*) and labeobarbus (*Labeobarbus intermedius*), of which *O. niloticus, L. niloticus* and *C. gariepinus* were numerically the three dominant species in the fish landings (Zerihun Dejene, 2008).

Lake Koka harbors three commercially important fish species: the Nile tilapia (*O. niloticus*), common carp (*Cyprinus carpio)* and African catfish (*Clarias gariepinus)* where *O. niloticus* were found in healthy state, *C. gariepinus* have shown signs of growth overfishing and *C. carpio* have shown under exploitation (Gashaw Tesfaye and Wolff, 2015).

Indigenous fish species such as *O. niloticus*, Labeobarbus (*Labeobarbus intermedius)*, straightfin barb (*Enteromius paludinosus*) and Garra (*Garra dembecha)*, and introduced fish species such as African Catfish (*Clarias gariepinus*), Crucian carp (*Carassius carassius*), Common carp (*Cyprinus carpio*) and the red-belly tilapia, *Tilapia zillii* (*Coptodon zillii*) are found in Lake Ziway (Megerssa Endebu *et al.*, 2015). Among these species, *O. niloticus*, African catfish, Crucian carp and Common carp are commercially important ones. According to Megerssa Endebu *et al.* (2015), the current annual fish production from Lake Ziway is declining in general and the proportion of *O. niloticus* declined tremendously in particular, from 94% of the catch from the lake in 1984, to 89.3% in 1994, 50.9% in 2010, 42% in 2013 and finally to 31% in 2014 in exploratory survey.

Aquatic environment of the three lakes in terms of their basic morphometric features, altitude, water quality parameters and fish species diversity are different (Brook Lemma and Hayal Desta, 2016). Under these different environmental conditions of the three lakes, the *O. niloticus* are expected to develop different phenotypic and genetic characters.

Phenotypic variation is wide in organisms spread in different geographical locations, and often involves ecologically relevant behavioral, physiological, morphological and life history traits. Phenotypic plasticity can be inclusively defined as the production of multiple phenotypes from a single genotype, depending on environmental conditions (El-Zaeem *et al.*, 2012).

Characterization of the *O. niloticus* population helps in utilization of the resource in aquaculture, and further contributes to protect the population in their natural environment. Hence, the objective of the present study was to investigate desired culture characteristics of *O. niloticus* of the three Rift Valley lakes in order to improve their productivity in aquaculture system with specific objective of characterizing the *O. niloticus* populations of Chamo, Koka and Ziway Lakes based on their phenotypic characters.

3.2 Materials and methods

3.2.1 Administration of fishing activities in the study areas

The fish were sampled from three Ethiopian Rift Valley lakes: Chamo, Koka and Ziway Lakes (Figure 2) from May, 2018 to March 2019. These water bodies were selected for their targeted *O. niloticus* populations to be used in the development of aquaculture in Ethiopia.

Lake Chamo is situated within Gamo Zone of South Nations Nationalities and Peoples (SNNP) Region in Southern Ethiopia. The Lake borders Nech Sar National Park in its North and North-eastern part. Organized fishery cooperatives are harvesting fish from the lake using gillnet and longlines, targeting the fish species like Bagrus (*Bagrus docmak*), *O. niloticus*, Nile perch (*Lates niloticus*) and African catfish (*Clarias gariepinus*). Relatively fishery of Lake Chamo is under close supervision of government and the local community; at least unauthorized fishermen are denied access to the lake, though the authorized are using the forbidden illegal fishing gears like monofilament nets. The lake shore and the watershed area of Lake Chamo are relatively well covered with vegetation.

Lake Koka is located between East-Shoa and Arsi administrative Zones of Oromia Region in Central Ethiopia. The lake is within the watershed area of larger towns including Addis Ababa, Dukem, Bishoftu, Modjo and Koka with notable municipal and industrial wastes. There are many small and larger irrigation farms around the lake. Fishermen cooperatives are organized into different groups according to their administrative districts and harvest fish; *O. niloticus*, common carp, *C. carpio,* and African catfish, *C. gariepinus* (Gashaw Tesfaye and Wolff, 2015). The fishermen use gillnets and longlines. Fishing activity stops in some parts of the lake (especially in northern part) during the late dry season. Level of the lake highly changes seasonally that the shore line of the lake has no definite boundary. As a consequence, shore-vegetation is not well established in Lake Koka.

Lake Ziway (also locally known as Lake Danbal) is located in between East-Shoa and Arsi administrative Zones of Oromia Region in Ethiopia. Several small scale and large scale horticultural farms are found in the periphery of the lake and along its inlet rivers. Natural wetland vegetation are found in majority of the lake's periphery buffer the pollution but encroached for grazing, irrigation and other anthropogenic uses. Registered and organized fishermen cooperative members and unregistered fishermen in three administrative districts harvest fish from the lake using beach seines, gillnets and longlines, targeting *O. niloticus*, *C. carassius*, *C. carpio,* and *C. gariepinus* (Megerssa Endebu *et al.*, 2015).

The fish samples used in this study were collected from fish landing sites representing the fish catches from inlet region, middle of the lake and outlet region of each lake. The landing sites are called Leto-1, Leto-2 and Elgo for Lake Chamo; Awash, Metoaleka and Bekele for Lake Koka and Golbe-Tsedecha, Meki-Girisa, Batu-Bochesa for Lake Ziway.

3.2.2 Data collection

Fish samples were collected during four seasons: pre-rainy season, main rainy season, post rainy season and dry season from three regions of the lakes to represent the spatial and temporal distribution of the fish. The samples were obtained from fishermen at the landing sites on arrival through facilitation of the cooperative chairpersons. The data were collected for two years 'seasonally', from May 2018 to March 2020. The data collection periods were classified into four 'seasons' in a year as pre-rainy season, main rainy season, post-rainy season and dry season, represented by sampling months of May, July-August, October-November and February-March, respectively for Lakes Koka and Ziway in this study. The rain distribution and season in the three study areas differ; whereby the main rainy season is during the months of June, July and August at Lakes Koka and Ziway while it is during April and May at Chamo Lake. Moreover, October-November months are characterized as season of short rain at Chamo. Accordingly, the data months of May, July-August, October-November and February-March represent the 'seasons' of main rainy season, post-rainy season, short-rain season and dry/pre-rainy season, respectively at Lake Chamo.

3.2.3 Phenotypic characterization of *O. niloticus*

Morphometric characters and meristic counts (Table 9) were recorded within each population from at least 50 fish per study site as described in El-Zaeem (2012).

Table 9. Morphometric and meristic characters of *O. niloticus* populations of Lakes Chamo, Koka and Ziway

A. Morphometric analysis			
Characters	**Acronyms**	**Characters**	**Acronyms**
Total length	TL	Caudal peduncle length	CPL
Standard length	SL	Caudal peduncle width	CPW
Head length	HL	Caudal peduncle depth	CPD
Body depth	BD	Pectoral fin length	Pec FL
Body width	BW	Dorsal fin base length	DFBL
Head width	HW	Pelvic fin base length	Pel FBL
Abdomen length	AL	Length of longest dorsal fin spine	LLoDFS
Orbit diameter	OD	Length of last dorsal fin spine	LLaDFS
Pre-orbital length	Pr-OL	Length of longest dorsal fin ray	LLoDFR
Post-orbital length	Po-OL	Length of last dorsal fin ray	LLaDFR
Trunk length	TrL	Length of longest anal fin spine	LLoAFS
Pelvic fin length	Pel FL	Length of first anal fin spine	LFiAFS
Anal fin base length	AFBL	Length of longest anal fin ray	LLoAFR
Caudal fin length	CFL	Length of last anal fin ray	LLaAFR

B. Meristic analysis			
Characters	**Acronyms**	**Characters**	**Acronyms**
Dorsal fin spines count	DFSC	Pectoral fin rays count	Pec FRC
Dorsal fin rays count	DFRC	Anal fin spines count	AFSC
Pelvic fin spines count	Pel FSC	Anal fin rays count	AFRC
Pelvic fin rays count	Pel FRC	Caudal fin rays count	CFRC

Along with the morphometric measurements, weight (TW) of each specimen was measured to the nearest 0.1 g. At least 150 fishes per lake were assessed. Condition factor of each fish was measured using the following equation:

$$K = 100\ (TW/TL^3)$$ (Lagler, 1956)

Where, K = Fulton's condition factor

TW = total weight in grams

TL = total length in centimeter

The fish were characterized based on the morphometric and meristic parameters. Values for the quantitative traits of the populations were expressed as mean and standard deviation as mean ± SD. Differences in mean values of the traits between the populations were analyzed in one-way analysis of variance (ANOVA) at significance level of $p \leq 0.05$ using Tukey's mean separation method.

3.3 Results

In this phenotypic characterization, morphometric character indices, meristic counts, total weight, total length, standard length and fish condition factor were analyzed from a total of 450 samples: 150 fish samples for each of the populations (Table 10). The standardized morphometric character indices and meristic counts for each of the *O. niloticus* population were analyzed and the differences in the mean values among the populations were shown in superscript letters for witch values with different superscript letters in each row are statistically significantly different ($p \leq 0.05$). The mean total weight (g), mean total length (mm), mean standard length (mm) and condition factor of the commercial catch of *O. niloticus* populations of Lakes Chamo, Koka and Ziway were presented in Table 10. The mean values of the parameters, as indicated with different superscript letters, were statistically different between the populations with Lake Chamo *O. niloticus* population having the highest vales in the weight and length parameters, while Lake Koka *O. niloticus* population found to have the highest mean value in condition factor (F).

The differences in mean total weight (g) and mean total length (mm) between the populations can easily be recognized when presented graphically (Figure, 5) whereby Lake Chamo *O. niloticus* population scored highest mean weight (412.24 ± 218.21 g) and total length (27.81 ± 4.79 cm) which differed significantly ($p \leq 0.05$) from similar parameters of populations of Lakes Koka and Ziway.

Table 10. Means and standard deviations of quantitative phenotypic traits based on morphometric character indices and meristic counts

Characters	Population		
	Chamo	Koka	Ziway
Morphometric indices			
HL/SL	0.324 ± 0.02^{a}	0.312 ± 0.01^{b}	0.324 ± 0.02^{a}
BD/SL	0.392 ± 0.02^{a}	0.360 ± 0.02^{c}	0.370 ± 0.02^{b}
BW/SL	0.158 ± 0.01^{b}	0.170 ± 0.01a	0.167 ± 0.02^{a}
HW/HL	0.550 ± 0.03	0.559 ± 0.03	0.553 ± 0.10
AL/SL	0.302 ± 0.02^{b}	0.314 ± 0.03^{a}	0.304 ± 0.02^{b}
OD/HL	0.209 ± 0.03^{b}	0.220 ± 0.03^{b}	0.249 ± 0.09^{a}
Pr-OL/HL	0.320 ± 0.03	0.287 ± 0.03	0.312 ± 0.24
Po-OL/HL	0.497 ± 0.03^{a}	0.493 ± 0.03^{a,b}	0.484 ± 0.09^{b}
TrL/SL	0.681 ± 0.03^{c}	0.710 ± 0.02^{a}	0.690 ± 0.06^{b}
PelFL/SL	0.257 ± 0.02^{b}	0.273 ± 0.05^{a}	0.263 ± 0.02^{b}
AFBL/SL	0.194 ± 0.01^{a}	0.195 ± 0.01^{a}	0.182 ± 0.01^{b}
CFL/TL	0.200 ± 0.01	0.201 ± 0.01	0.203 ± 0.11
CPL/TL	0.119 ± 0.01^{a}	0.113 ± 0.01^{b}	0.120 ± 0.01^{a}
CPW/TL	0.040 ± 0.00^{b}	0.044 ± 0.01^{a}	0.040 ± 0.01^{b}
CPD/TL	0.105 ± 0.01^{a}	0.098 ± 0.01^{b}	0.096 ± 0.01^{b}
PecFL/SL	0.365 ± 0.02^{a}	0.342 ± 0.04^{b}	0.359 ± 0.02^{a}
DFBL/SL	0.598 ± 0.03^{b}	0.622 ± 0.06^{a}	0.601 ± 0.03^{b}
PelFBL/SL	0.056 ± 0.01^{a}	0.052 ± 0.01^{c}	0.055 ± 0.01^{b}
LLoDFS/SL	0.156 ± 0.01^{a}	0.141 ± 0.02^{c}	0.149 ± 0.01^{b}
LLaDFS/SL	0.156 ± 0.01^{a}	0.141 ± 0.02^{c}	0.149 ± 0.01^{b}
LLoDFR/SL	0.250 ± 0.03^{a}	0.224 ± 0.03^{b}	0.217 ± 0.02^{c}

LLaDFR/SL	0.077 ± 0.01^{b}	0.082 ± 0.01^{a}	0.080 ± 0.01^{a}
LLoAFS/SL	0.151 ± 0.01^{a}	0.138 ± 0.02^{b}	0.149 ± 0.02^{a}
LFiAFS/SL	0.064 ± 0.01^{a}	0.050 ± 0.01^{c}	0.056 ± 0.01^{b}
LLoAFR/SL	0.226 ± 0.02^{a}	0.221 ± 0.03^{b}	0.215 ± 0.01^{c}
LLaAFR/SL	0.075 ± 0.01^{b}	0.081 ± 0.01^{a}	0.076 ± 0.01^{b}
Meristic counts			
DFSC	16.59 ± 0.49^{b}	16.82 ± 0.39^{a}	16.85 ± 0.37^{a}
DFRC	12.29 ± 0.49^{a}	12.21 ± 0.41^{a}	12.09 ± 0.46^{b}
Pel FSC	1.00 ± 0.00	1.00 ± 0.00	1.00 ± 0.00
Pel FRC	5.00 ± 0.00	5.00 ± 0.00	5.00 ± 0.00
Pec FRC	13.06 ± 0.35^{a}	12.63 ± 0.51^{b}	12.42 ± 0.56^{c}
AFSC	3.00 ± 0.00	3.00 ± 0.00	3.00 ± 0.00
AFRC	9.29 ± 0.47^{b}	9.53 ± 0.54^{a}	9.48 ± 0.51^{a}
CFRC	17.46 ± 0.88^{b}	17.23 ± 0.98^{c}	17.93 ± 0.61^{a}
TW(g)	412.24 ± 218.21^{a}	259.17 ± 87.65^{b}	115.13 ± 47.14^{c}
TL(mm)	278.15 ± 47.89^{a}	239.00 ± 26.35^{b}	184.43 ± 24.61^{c}
SL(mm)	225.63 ± 41.73^{a}	191.74 ± 22.26^{b}	149.44 ± 20.59^{c}
Condition factor (K)	1.78 ± 0.16^{b}	1.83 ± 0.22^{a}	1.75 ± 0.14^{b}

Note, values with different superscript in a row are significantly different at 95% confidence interval.

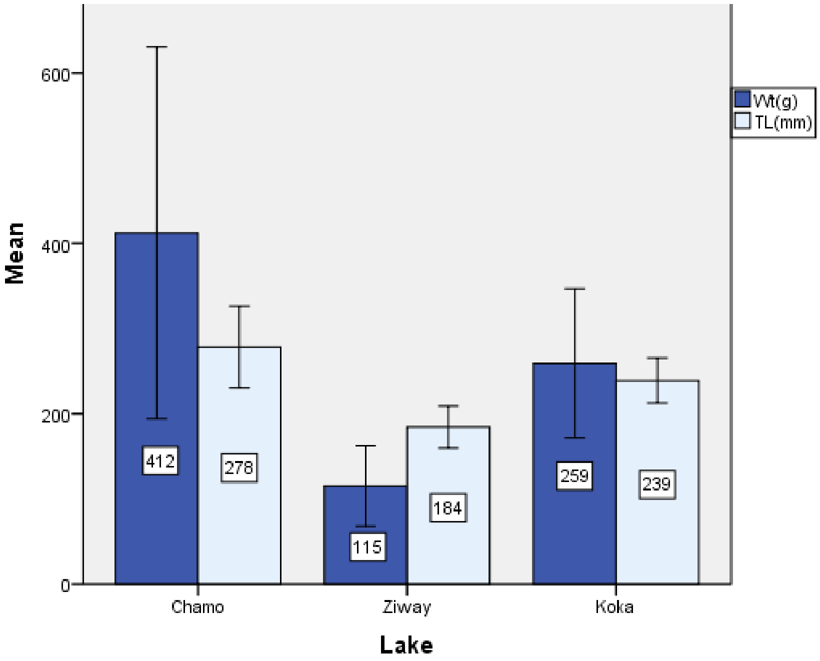

Figure 5. Mean ± SD of total weight (gm) and TL (mm) of *O. niloticus* populations of Lakes Chamo, Ziway and Koka.

The physical appearance of the fish were also different in which *O. niloticus* population of Lake Chamo appeared to be robust and vigor in size; while that of Lake Koka were medium sized, fat fish. Lake Ziway population was dominated by thinner and smaller sized fish (Figure 6).

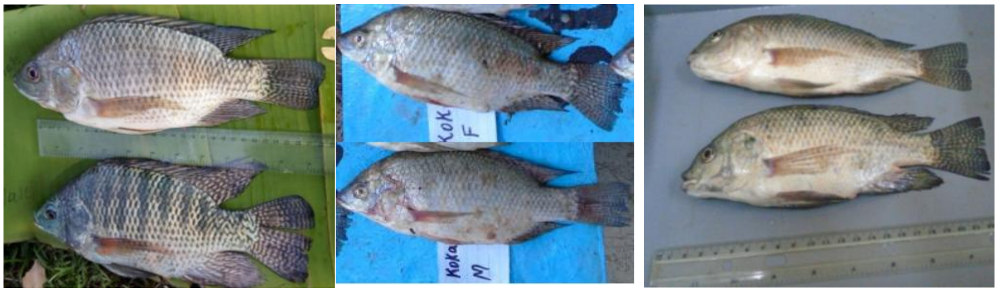

Figure 6. Samples of *O. niloticus* from Lakes Chamo (left), Koka (middle) and Ziway (right).

3.4 Discussion

Based on the morphometric character indices, Lake Chamo *O. niloticus* population were characterized by highest mean weight (412.24 ± 218.21 g), total length (27.81 ± 4.79 cm) and standard length (22.56 ± 4.17 cm), which differed significantly ($p \leq 0.05$) from similar parameters of populations of Lakes Koka and Ziway. The current mean total length of *O. niloticus* population of Lake Chamo is within the range of 19 - 43 cm length reported by Zerihun Dejene (2008). The Chamo population have also scored highest morphometric character indices of BD/SL, CPD/TL, Po-OL/HL, PelFBL/SL, LLoDFS/SL, LLaDFS/SL, LLaDFR/SL, FiAFS/SL, LLoAFR/SL and highest record of meristic character in PecFRC in which all the characters differed significantly ($p \leq 0.05$) from the mean values measured from the populations of Lakes Koka and Ziway. However, the population in Lake Chamo scored significantly ($p \leq 0.05$) lowest mean values of BW/SL, TL/SL and LLaDFR/SL from morphometric indices, and DFSC and AFRC from meristic characters (Table 10).

Generally, *O. niloticus* population from Lake Chamo were found to be larger in total length and weight (Figure 4), shorter at trunk region with respect to their standard length, dorso-vetrally deep, laterally compressed in body form (Figure 5) as compared to other populations. They also had longest pre-orbital region, dorsal and anal fins as indicated in their morphometric indices (Table 10).

Lake Koka *O. niloticus* populations scored mean weight of 259.17 ± 87.65 g, mean total length of 23.90 ± 2.63 cm and standard length of 19.17 ± 2.22 cm. These mean values for Koka population were significantly ($p \leq 0.05$) lower than that of Chamo population but higher than that of Ziway population (Table 10). A mean total length that a fish of a given stock would reach if they were to grow indefinitely ($L\infty$) was estimated to reach 44.5 cm for the *O. niloticus* population of Koka *(*Gashaw Tesfaye and Wolff, 2015) and 28.1 cm for the *O. niloticus* population of Ziway (Gashaw Tesfaye, 2006). The size differences between the population means in the current result agrees with the above reports.

Highest mean score of Fulton's condition factor (K) was obtained in population of Lake Koka (1.83) and the value differed significantly ($p \leq 0.05$) from that of the populations of Lakes Chamo (1.78) and Ziway (1.75). The average K values of *O. niloticus* were reported to vary over time; 1.87 for Koka population (Gashaw Tesfaye and Zenebe Tadesse, 2008) and 1.89 (Zenebe Tadesse, 1988) and 1.81 (Gashaw Tesfaye and Zenebe Tadesse, 2008) for Ziway and 2.35 for Chamo (Yirgaw Teferi and Demeke Admassu, 2002).

The population of Lake Koka scored highest morphometric character indices of AL/SL, TL/SL, DFBL/SL, CPW/TL, PelFL/SL and LLaAFR/SL but lowest mean values of HL/SL, BD/SL, CPL/TL, PecFL/SL, PelFBL/SL, LLoDFS/SL, LLaDFS/SL, LLoAFS/SL, and LFiAFS/SL which were significantly different ($p \leq 0.05$) from that of Lakes Chamo and Ziway populations (Table 10). As compared to populations of Lakes Chamo and Ziway, the Lake Koka *O. niloticus* population were generally found to have longer trunk region, laterally wide (fat), not dorso-ventrally deep, with shorter head and fin spines (Figure 3).

Lake Ziway *O. niloticus* population were significantly ($p \leq 0.05$) lower in their mean total weight (115.13 ± 47.14 g), mean total length (18.44 ± 2.46 cm) and standard length (14.94 ± 2.06 cm) than the Lakes Chamo and Koka populations. The population had also lowest morphometric character indices of LLoDFR/SL, AFBL/SL, LLoAFR/SL and the lowest meristic counts of dorsal and pectoral fin rays which were significantly ($p \leq 0.05$) different from mean values observed in Lakes Chamo and Koka populations. However, the population scored the highest mean value of OD/HL morphometric character index and the highest mean caudal fin ray count and differed significantly from that of Lakes Chamo and Koka. Generally, *O. niloticus* population of Lake Ziway were relatively smaller in size, have shorter dorsal fin rays and wider orbit diameter with respect to their head length (Figure 5).

Morphometric characters in fish have been demonstrated to be influenced by environmental factors (Robinson and Wilson, 1995). Chamo and Ziway are natural lakes while Koka is an artificial lake constructed for hydro-electric power generation. Aquatic environment of the three lakes in terms of their basic morphometric features, altitude, water quality parameters and fish species diversity are different (Brook Lemma and Hayal Desta, 2016). The *O. niloticus* populations of the three lakes are accordingly isolated for centuries and developed different morphometric characters (Table 10) to adapt to their corresponding environmental conditions.

Fulton's condition factor (K), which indicates the nutritional level and status of the fish over time, might be greatly influenced by environmental factors. The higher Fulton's condition factor (K), observed in *O. niloticus* population of Lake Koka in the current study could be due to a function of better food availability in artificial reservoirs than in natural lakes. Though the degree vary from lake to lake, anthropogenic impacts such as pollution due to silt and nutrient load from watershed areas, municipal waste, industries (tannery, flower culture), water level fluctuation and fishing pressures have directly or indirectly affected the fish community in the lakes (Lemma Abera, 2016). Floodplains associated with the reservoirs are generally known to be most productive aquatic ecosystems. The K value of *O. niloticus* population of Lakes Chamo, Koka and Ziway varied over time based on environmental changes (Zenebe Tadesse, 1988; Yirgaw Teferi and Demeke Admassu, 2002; Gashaw Tesfaye and Zenebe Tadesse, 2008).

Phenotypic adaptations of fish to their environment do not necessarily cause a change in genetic constitutions of the population (Allendorf, 1988) and hence phenotypic differences among populations cannot usually be taken as evidence of genetic differentiation. However, the *O. niloticus* populations of the three lakes are isolated perhaps, for the last 5000 years when major lakes' lowering occurred (Benvenuti *et al.*, 2002) that development of genetic differences among the populations is most likely. In genetic analysis using total mtDNA digestions, Seifu Seyoum and Kornfield (1992) grouped *O. niloticus* of Ethiopia into different subspecies: *O. n. cancellatus* (Awash basin), *O. n. filoa* (Sodore hot springs), *O. n. tana* (Tana population). Later, Agnese *et al.* (1997) using allozyme, clustered natural populations of *O. niloticus* in the Ethiopian Rift Valley (Lakes Ziway, Hawassa, Koka and Sodore hot springs) in one group and populations of Tana, Nile, Kenya in other group. The authors considered the subspecies classification made by Seifu Seyoum and Kornfield (1992) was premature. According to the species clustering of Agnese *et al.* (1997), the *O. niloticus* of Lake Chamo can be related to the Kenyan and Nile group since the Abaya-Chamo basin had previous connection to the Chew Bahir and Turkana Lakes in northern Kenya.

In a study of phylogenetic differentiation of wild and cultured *O. niloticus* populations based on phenotype and genotype analysis, El-Zaeem *et al.* (2012) reported that phenotype analysis based on a large number of morphometric character indices and meristic counts can be used to discriminate fish populations up to the intraspecific level with the same results as the genotype analysis based on random amplified polymorphic DNA (RAPD) fingerprinting. Hence, the differences observed in phenotypic characters of the three *O. niloticus* populations in the present study based on the analysis made using 26 morphometric character indices, 8 meristic counts and four other morphometric characters indicates that the differences have also potential genetic bases.

3.5 Conclusions and recommendations

Based on the parameters considered for characterization, *O. niloticus* populations of Lakes Chamo, Koka and Ziway differed in many phenotypic characters in their natural environments. As desired characters in aquaculture production, *O. niloticus* population of Lake Chamo had higher mean weight and length than population of Lake Koka followed by population of Lake Ziway.

The phenotypic characters are governed by genetic and/or environmental factors. Thus, it is important to confirm whether the populations could maintain these characters when grown under controlled environments.

Chapter Four

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4 Reproductive characters of *O. niloticus* populations of three Ethiopian Rift Valley lakes

4.1 Introduction

The current Ethiopian fish production potential estimates using empirical models from its inland fisheries is about 94,500t per year, of which 73,100t from lentic (lakes, reservoirs and ponds) and about 21,400t from lotic (rivers) ecosystems (Gashaw Tesfaye and Wolff, 2014). The majority of the Ethiopian lakes are confined within the Rift Valley that extends from the Kenyan border in the south to the Afar depressions in the north, with the major lakes including Beseka/Metahara, Ziway, Langano, Abijata, Shala, Hawassa, Abaya and Chamo (Tenalem Ayenew, 2009). Fish productions in the country are mainly artisanal and commercial fisheries are concentrated to Lakes Tana, Chamo, Hawassa, Ziway and Turkana (Abebe Getahun, 2017); where all these lakes except Tana are found in the Rift Valley.

Indigenous to Ethiopia, *O. niloticus* is among the commercially important fish species contributing from 61% - 90% of the total landings in the Rift Valley lakes (reviewed in Gashaw Tesfaye and Zenebe Tadesse, 2008). The national fish production report which sometimes inter-mix the catch data of different species together, estimates proportion of *O. niloticus* to 65% of the country's fish production (Hussein Abegaz, 2015).

The fish is among the most studied group of fish in the country due to its economic importance and its different biological properties in different natural and manmade environments. The studies so far undertaken covered their length weight relationship, reproductive and feeding biology (Yirgaw Teferi and Demeke Admassu, 2002; Gashaw Tesfaye and Zenebe Tadesse, 2008; Lemma Abera, 2012; 2013; Workiyie Worie and Abebe Getahun, 2014; Endalh Mekonnen *et al*., 2018; Yirga Enawgaw and Brook Lemma, 2018; Assefa Tessema *et al*., 2019), gear selectivity against maturity (Mathewos Hailu, 2014; Gashaw Tesfaye *et al*., 2016) and their maximum sustainable yield in fishery stock assessment (Gashaw Tesfaye and Wolff, 2015; Yitayal Alemu *et al*., 2017; Buchale Shishitu, *et al*., 2019). However, comprehensive investigations regarding reproductive characters of the populations were not conducted so as to use the information for proper fishery management and also as basic information for genetic improvement in aquaculture development.

Environmental factors affect growth performances and reproductive characters of *O. niloticus* populations in the process of adapting to different environments (Lowe-McConnell, 1982; Duponchelle *et al.*, 1998; Dwivedi *et al.*, 2016), though *O. niloticus* tend to breed throughout the year in tropical region. Aquatic environments of the three rift valley lakes (Chamo, Koka and Ziway) in terms of their basic morphometric features, altitude, water quality parameters and fish species diversity are different (Tenalem Ayenew, 2009; Brook Lemma and Hayal Desta, 2016). Under these different environmental conditions of the three lakes, the *O. niloticus* populations are expected to develop different phenotypic and genetic characters. Phenotypic variations are wide in organisms spread in different geographical locations, and often involve ecologically relevant behavioral, physiological, morphological and life history traits. Phenotypic character differences were observed between the *O. niloticus* populations of Chamo, Koka and Ziway in a study made parallel to this one (Megerssa Endebu *et al*., 2021a).

In an effort to develop the aquaculture sector in Ethiopia, seeds of *O. niloticus* were collected from natural environments, especially from the Ethiopian Rift Valley lakes to stock aquaculture ponds. Moreover, in an attempt to select better performing strains for aquaculture, *O. niloticus* populations from different Ethiopian Rift Valley lakes were evaluated for their growth performances. The *O. niloticus* populations from different Ethiopian Rift Valley lakes: Chamo, Hawassa, Hora, Koka, Metahara and Ziway showed different growth performances in pond culture (Kassaye Balkew and Gjoen, 2012; Daba Tugie *et al.*, 2014; Daba Tugie *et al.*, 2017) whereby the Chamo, Koka and Ziway strains were reported to have performed better.

Investigations on biological parameters such as length-weight relationship, condition factor and size at first sexual maturity are the easiest means of determining the stress of fishing pressure and water pollution on fish populations (Gupta and Tripathi, 2017). Studies on breeding season and associated factors are needed to protect new recruits and predict recruitment variability. Number of recruitment in fish stock depends on availability of sexually mature fishes in the water bodies (LFDP, 1997; Tesfaye Muluye *et al.*, 2016).

Characterization of the *O. niloticus* population helps in utilization of the resource in aquaculture, and further contributes to protect the population in their natural environments. Hence, the aim of the present study was to investigate the reproductive characteristics of the *O. niloticus* of Rift Valley lakes with specific objective of investigating sex ratios, breeding season, size at first sexual maturity and fecundity of the *O. niloticus* populations of Lakes Chamo, Koka and Ziway as an input for proper fishery management and indication of their reproductive quality in aquaculture development.

4.2 Materials and Methods

4.2.1 Study areas

This study was conducted in three Ethiopian Rift Valley lakes: Chamo, Koka and Ziway (Figure 1) from May 2018 to April 2020. These water bodies were selected for their significant contribution in the fishery production and *O. niloticus* populations were targeted as these are candidate fish species in the development of aquaculture in Ethiopia.

Sites for data collection and fish landing from each lake were purposely selected to represent the fish catches from inlet region, middle of the lake and outlet region. The landing sites are called Leto-1, Leto-2 and Elgo for Lake Chamo; Awash, Metoaleka and Bekele for Lake Koka and Golbe-Tsedecha, Meki-Girisa, Batu-Bochesa for Lake Ziway. Fish samples were collected seasonally from three landing sites per lake from the three lakes.

4.2.2 Data collection

Fish samples were sampled from fishermen (considering different fishing gears and different setting times) at the landing sites on arrival through facilitation of the cooperative chairpersons. The data were collected for two years 'seasonally', from May 2018 to March 2020. The rain distribution and season in the three study areas differ; whereby the main rainy season is during the months of June, July and August around Lakes Koka and Ziway while it is during April and May around Chamo Lake. Moreover, October-November months are characterized as season of short rain at Chamo. Accordingly, the data collection periods were classified into four 'seasons' in a year. The months of May, July-August, October-November and February-March represent the 'seasons' of main rainy season, post-rainy season, short-rainy season and dry/pre-rainy season, respectively at Lake Chamo. For Lakes Koka and Ziway, the pre-rainy season, main rainy season, post-rainy season and dry season were represented by sampling months of May, July-August, October-November and February-March, respectively in this study.

4.2.3 Sex ratio determination

A total of 1,547 random fish samples from the three lakes were used in sex ratio determination. At least 30 to 40 fish samples per landings were sampled every time as a minimal sample size to represent the normally distributed population for statistical computation, except when there was no/less fishing in some landing sites because of 'lake drying' as in Bekele landing site of Lake Koka for the month of May or increasing of Lake level (prohibiting the fishermen to set nets), and coinciding with busy crop cultivation period.

The samples were immediately taken to temporary shed or processing shed (at Lakes Chamo and Koka) or to fishery lab in the case of Lake Ziway for data (sex, length, weight) collection. Sex identification of *O. niloticus* was made by visual observation into their genital papilla and observation of gonads after dissecting their abdomen. The proportion of females and males in the samples was calculated (Zar, 1999) after recording the frequencies of the sexes in each of the lakes in every sampling season. Sex ratio was expressed as Female:Male and tested against an expected ratio of 1:1 using the chi-squared test at p-value of 0.05.

4.2.4 Length at first sexual maturity

Lengths of the sampled fish were measured on a portable measuring board of 50 cm length graduated at 0.1 cm level. Total length (TL) of the fish was measured to the nearest 0.1 cm from all sampled fish. Fish total weight (TW) was measured to the nearest 0.1g using a sensitive balance, LD610-2, Max=610g, d=0.01g.

The L_{50} is the onset of sexual maturity at which 50% of the fish have reached sexual maturity. The female's and male's gonad maturity stages were identified based on macroscopic gonadal maturation stages (Holden and Raitt, 1974; Abebe Getahun, 2017) whereby the female's gonad classified into five maturity stages and that of males into four stages. The five stages in ovaries classified as immature, maturing, ripe, spent or resting. The male's four gonad maturity stages are classified as immature, maturing, ripe or spent.

Based on the maturity stages, the fish were grouped into immature (maturity stage-I and stage-II) and mature (maturity stage- III and above). The relationship between the percentage of mature fish (P) per length class and fish total length (L in cm) was described with a logistic curve and L_{50} was estimated according to Gunderson *et al*. (1980):

$$P = \frac{1}{1+e^{(bL+a)}}$$

Where "P" is proportion of mature fish at specific length class; "L" is total length; $"a"$ and $"b"$ are model parameters (a, intercept and b, slope of the logistic regression). The L50 was derived from the relationship of "a" and "b".

$$L_{50} = -\frac{\mathrm{a}}{\mathrm{b}}$$

4.2.5 Gonado-Somatic Index

Data for gonado-somatic index (GSI) of the fish, which helps in determination of the breeding season, were collected by weighing the fish samples, dissecting the sample and taking its gonad weight both for females and males in each of the study site. The GSI was analyzed only for mature fish groups after the L_{50} was determined (Demeke Admassu, 1996) for each sex for all the three lakes.

The GSI of each fish was computed as the weight of the gonads as the percentage of the total body weight using the following formula:

$$\mathrm{GSI} = \frac{\mathrm{GW\ (g)}}{TW\ (g)} \mathrm{\ x\ } 100$$

4.2.6 Fecundity estimation

The data for fecundity was taken from ripe gonads. After taking the ripe females' total length, total weight data, the females were dissected and their gonads weighed. Sub sample were taken from the gonad and fecundity was determined by gravimetric method (Abebe Getahun, 2017) by counting all eggs in the sub samples taken from ripe ovaries. Absolute fecundity was then calculated using the following formula.

$$Fecundity\ (F) = \frac{\mathrm{No.of\ eggs\ in\ sub\ sample\ x\ gonad\ weight}}{Weight\ of\ sub\ sample}$$

The relationships between absolute fecundity and female's morphometric measurements, and total length (TL), total weight (TW) and gonad weight (GW) were determined using least squares regression.

$F = aTL^b$, $F = aTW^b$, $F = aGW^b$

Where a and b are parameters of the fitted lines, TL is total length of fish in cm; TW is total weight of fish in grams and GW is gonad weight in grams.

One way ANOVA was employed to investigate differences in mean total lengths, mean weights of fishes among commercial catches of the populations; and mean Gonado-somatic index (GSI) of the fish between sampling months at the three lakes.

4.3 Results

4.3.1 Sex ratios

The two years' sampling results were grouped into four seasons, October-November, February-March, May and July-August months for each lake. The sex ratios of *O. niloticus* were expressed as Female: Male =1 (Table 11).

Table 11. Sex ratios of *O. niloticus* from Lakes Chamo, Koka and Ziway

Lakes	F:M	N	Chi-square	*p-Value*
Chamo	1.05:1.00	361	0.224	*0.636*
Koka	0.99:1.00	494	0.008	*0.928*
Ziway	1.07:1.00	692	0.576	*0.448*

When the results were tested by Chi-square test, the sex ratios of Female:Male in all the three lakes did not significantly deviate from the expected 1:1 ratio.

4.3.2 Length at first sexual maturity (L_{50})

The length at first sexual maturity (L_{50}) of females and males were not significantly different for the *O. niloticus* populations of Lakes Chamo and Koka in which the L_{50} was derived from mixed sexes (Table 12). However, the females and males had exhibited significantly different L_{50} in Lake Ziway. The L_{50} of *O. niloticus* for the three lakes differed as illustrated in Table-12 below. Fifty percent of the population of *O. niloticus* in Lakes Chamo and Koka reach sexual maturity for the first time at total lengths of 23.48 cm and 21.91 cm, respectively (no significant differences between males and females) while the

L_{50} in Lake Ziway was 17.49 cm for males and 16.00 cm for females, values for sexes are significantly different.

Table 12. Length at first sexual maturity (L_{50}) of *O. niloticus* from Lakes Chamo, Koka and Ziway

	Chamo Mixed sex	**Koka Mixed sex**	**Ziway Female**	**Ziway Male**
L_{50}	23.48	21.91	16.00	17.49
95% CI	23.08:23.87	21.41:22.35	15.59:16.30	17.14:17.84

Length at first sexual maturity (L_{50}) where 50% of the population of *O. niloticus* reaches sexually mature for the first time was at total length (TL) of 23.48 cm in Lake Chamo (Figure 7a) for mixed sex; there was no significant difference between males and females. The L_{50} for mixed sex *O. niloticus* in Lake Koka was 21.91 cm (Figure 7b). The L_{50} values for female and male groups were significantly different in Lake Ziway where it was 16.00 cm for females (Figure 7c) and 17.49 cm for males (Figure 7d). Distribution pattern of the proportion of mature fishes along the total length of the fishes was different for the populations in the different lakes. The smallest sexually mature female *O. niloticus* found were at size of 13.4 cm, 19.8 cm and 21.9 cm TL in Lakes Ziway, Koka and Chamo, respectively. Similarly, the smallest sexually mature male *O. niloticus* observed were at sizes of 14.7 cm, 20.0 cm and 22.0 cm TL in Lakes Ziway, Koka and Chamo, respectively.

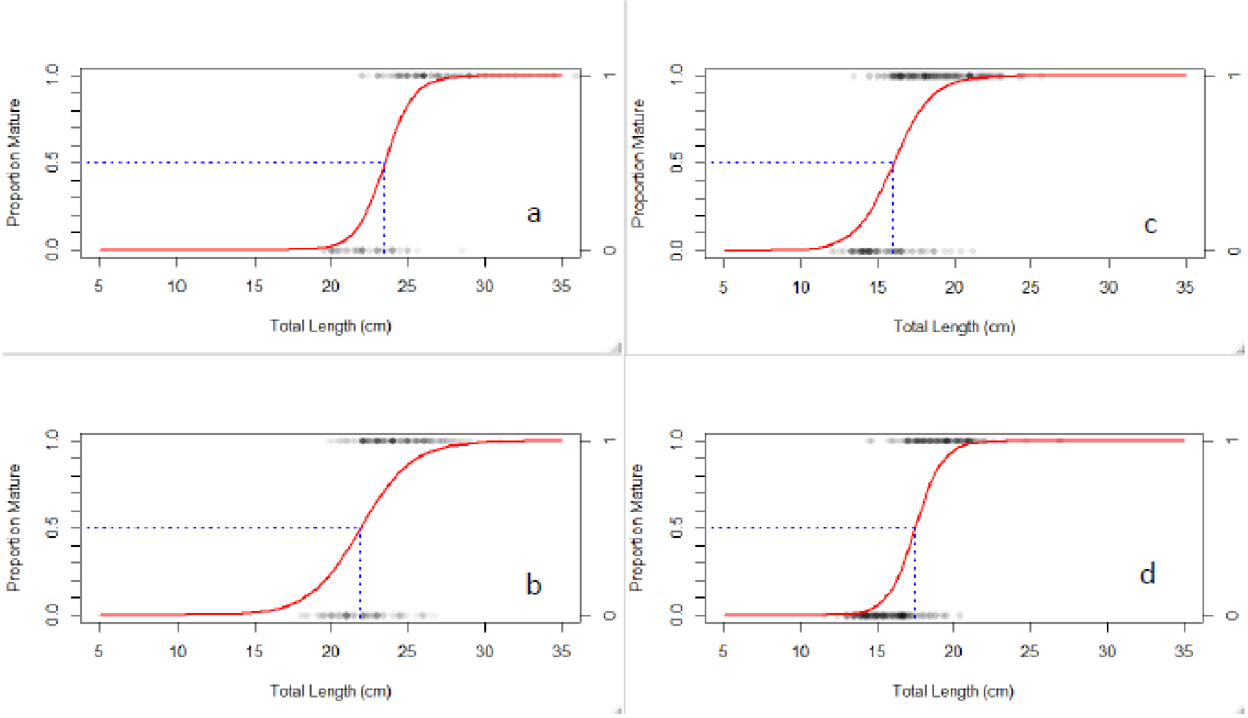

Figure 7. Length at first sexual maturity (L_{50}) of *O. niloticus* in Lakes Chamo for mixed sex(a), Koka for mixed sex(b), Ziway female(c) and Ziway male(d).

4.3.3 Gonado-somatic index

The gonado-somatic index (GSI) of the *O. niloticus* species from Lakes Chamo, Koka and Ziway was analyzed separately for sexes in the four different sampling seasons. The mean GSI was relatively higher in October-November (short rainy season) and February-March (pre-rainy season) at Chamo Lake for both male and female sexes. The highest mean GSI for the females (Figure 8a) of Koka population was recorded in May (pre-rainy season) and in July-August (main rainy season) for males (Figure 8b). The relatively highest mean GSI was recorded both for females and males in February-March (dry season) for *O. niloticus* of Ziway population.

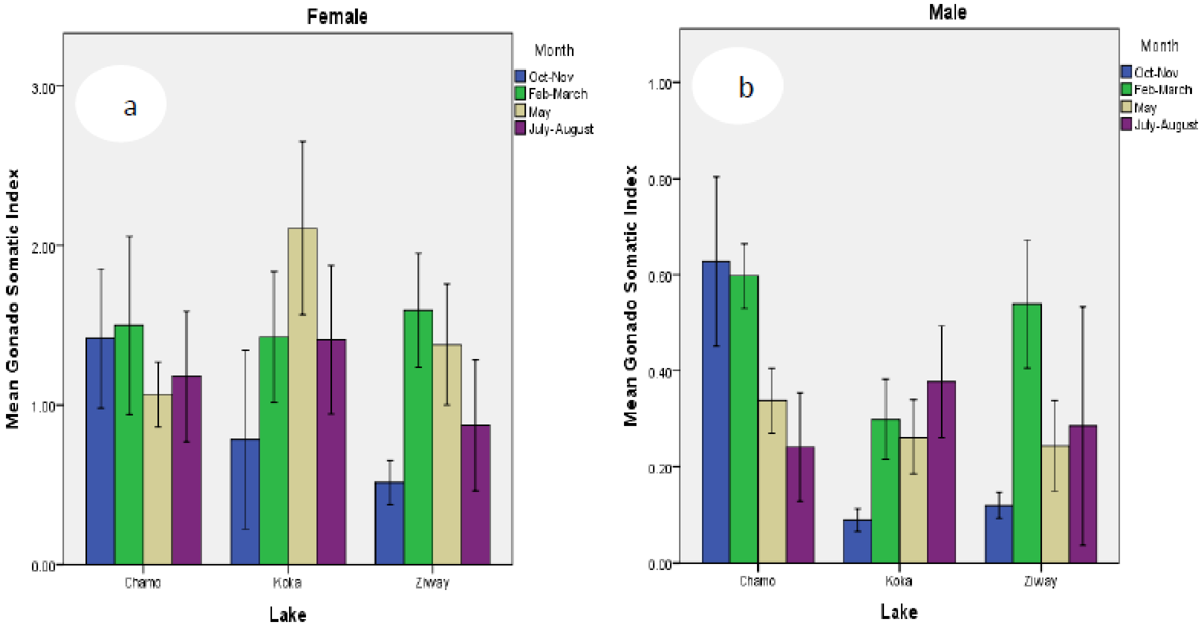

Figure 8. Mean Gonado Somatic Index of *O. niloticus* by the lakes (Chamo, Koka, Ziway) and seasons. *(Season= Oct-Nov, Feb-March, May, July-Aug) for female (a) and male (b) groups, Error bars represent the 95% CI (Confidence Interval)).*

4.3.4 Fecundity

Fecundity (number of ripening eggs in the ovaries of a female prior to the next breeding season) was calculated based on the egg samples taken from gonads of ripe females following standard procedures and presented in Table 13. The absolute fecundity ranged from 209 at Ziway to 1886 eggs per female at Chamo. The mean absolute fecundity was high for *O. niloticus* of Lake Chamo (1,322 eggs/female) followed by Lake Koka (1,147 eggs/female) and lowest for Lake Ziway (450 eggs/female).

Table 13. Absolute fecundity of female *O. niloticus* from Lakes Chamo, Koka and Ziway

Lake	**Chamo**	**Koka**	**Ziway**
Mean ± Std.	1321.76 ± 342.92	1146.89 ± 115.227	450.07 ± 180.829
Minimum	739	962	209
Maximum	1886	1357	800

Fecundity has a direct curvilinear relationship with the females' total length (TL), total weight (TW) and gonad weight (GW) from a pooled data of the three lakes *O. niloticus* populations. The relationship between absolute fecundity (F in eggs/female) and TL in cm was $F = 0.409TL^{2.4117}$, $R^2 = 0.908$; F and TW in gram (g) was $F = 10.186TW^{0.8125}$, $R^2 = 0.9013$; and between F and GW (g) was $F = 118.9GW^{0.9121}$, $R^2 = 0.8415$. These relationships do not however characterize the three *O. niloticus* populations as these data are pooled. Rather, the graphs are simply to learn the relationship of the F (eggs/female) with females' TL, TW and GW.

4.4 Discussion

4.4.1 Sex ratio

The sex ratios of *O. niloticus* in all the sampling seasons at the three lakes did not statistically deviate from the expected 1:1 ratios. Balanced sex ratios are expected in a wild *O. niloticus* population, though environmental sex determination was reported, the case by which the male ratio increases with temperature (Baroiller and Clota, 1998; Misikire Tessema *et al*. 2006).

The current sex ratio results agree with the previous report from Lake Chamo (Yirgaw Teferi and Demeke Admassu, 2002). Sex ratios of *O. niloticus* samples can also deviate from the expected 1:1 ratio across seasons due to sexual segregation during spawning, fishing site and gear type (Demeke Admassu, 1994; Assefa Tessema *et al*., 2019). Variations in sex ratios were also reported with more females than males at Lake Beseka (because of fish sampling using gillnet, for which females are more vulnerable than males in movement, Lemma Abera, 2013), Lake Hayq (Workiyie Worie and Abebe Getahun, 2014), Lake Ardibo (Endalh Mekonnen *et al*., 2018) and males predominated over females at Lake Tana (Zenebe Tadesse, 1997), Lake Victoria (Njiru *et al.*, 2006), Amerti Reservoir (Mathewos Hailu, 2014), Lake Hayq (Assefa Tessema *et al*., 2019) because of the sampling season, fishing site, fishing gear or drug pollution to the environment which potentially alter the sex ratio.

4.4.2 Length at first maturity (L50)

The length at first sexual maturity (L_{50}) of the *O. niloticus* populations in the present study were 23.48 cm, 21.91 cm, 17.49 cm and 16.00 cm (TL) for Lakes Chamo, Koka, Ziway (males) and Ziway (females), respectively (Table 12). The values were different for the three lakes with the highest for population of Lake Chamo and lowest for females of Lake Ziway. The present L_{50} values of the *O.*

niloticus populations were within the previous L_{50} report ranges from different lakes and reservoirs in the country; 14.0 cm for females and 17.0 for males in Lake Beseka (Senait Gebremeskel, 2015), 14.1 cm and 20.3 cm for females and 17.8 cm and 20.8 cm for males in Lake Hawassa (Bjorklis, 2004 and Tesfaye Muluye *et al*., 2016, respectively), 18.9 cm for females and 21.5 cm for males in Amerti Reservoir (Mathewos Hailu, 2014), 19.5 cm in Lake Langano (Gashaw Tesfaye and Zenebe Tadesse, 2008), 21cm in Lake Tana (Tesfaye Wudneh, 1998, Degsera Aemro *et al*., 2019), 21.8 cm for females and 24.5 cm for males in Finchaa reservoir (Fasil Degefu *et al*., 2012). The current L_{50} of the *O. niloticus* of Ethiopian Rift Valley lakes were lower than that of Lake Victoria, 30.81cm for females and 34.5 cm for males (Njiru, 2006). The *O. niloticus* of Lake Victoria were reported to be increasing in catch proportion and became stable population with high proportions of mature fish likely because of declining stocks of predatory Nile perch and availability of suitable food; these suitable conditions might have favoured the fish to attain higher L_{50} values in the Lake (Njiru *et al*., 2008) unlike the stressful fishing pressures in Ethiopian Rift Valley lakes.

The present L_{50} values of all the three *O. niloticus* populations were lower than the previous reports. The L_{50} for Chamo population decreased from 42.0 cm reported by Yirgaw Teferi and Demeke Admassu (2002) to the present result of 23.48 cm in a period of twenty years. The value for Koka population decreased but slightly, from 23.5 cm (Gashaw Tesfaye and Zenebe Tadesse, 2008) and 24.6 cm (Gashaw Tesfaye *et al.*, 2016) to the present value of 21.91 cm in about five years. Similarly, the L_{50} of Ziway population decreased from 18.8 cm (Yirgaw Teferi and Demeke Admassu, 2002), and 19.6 cm for males and 18.1 cm for females (Gashaw Tesfaye and Zenebe Tadesse, 2008) to the present value of 17.4 cm for males and 16.00 cm for females. The current decrease in L_{50} of *O. niloticus* populations in Lakes Chamo, Koka and Ziway may be attributed to the fishing pressure (Vijverberg *et al*., 2012) and change in the lakes environment (pollution, siltation, fish stock composition).

Size at first sexual maturity is determined both by genetic and environmental factors, and it appears to be variable trait that stocks can adjust depending on demographic and environmental conditions (Gashaw Tesfaye and Zenebe Tadesse, 2008). Early sexual maturation negatively affects growth performance of the fish, influencing the quality and quantity of the fish product both in natural environments and in aquaculture conditions. The quantity and quality of fish product determines income of the fishermen as well as the profitability of the fish farm. Hence, the decrease in size at first maturation alarms the need for the implementation of proper and effective fishery and environmental management measures to sustain the fishery of the lakes. On the other hand, the Chamo and Koka *O. niloticus*, with their relatively higher L_{50} values, become potential populations for further genetic improvement to enhance aquaculture development.

4.4.3 Gonado-Somatic Index

Gonado-somatic index (GSI) is used to determine the breeding season of the fishes. Females with ripe ovaries and males with ripe (larger, full and white) testes were observed in all the four sampling seasons but with different frequencies in all the three lakes implying that *O. niloticus* is breeding all year round. The mean GSI of *O. niloticus* from Lakes Chamo, Koka and Ziway were different for different sampling seasons (Figure 7).

For Chamo population, the mean GSI were not statistically different among the four sampling seasons for females ($p > 0.05$); however, it was relatively higher (1.42 ± 1.05) in October-November (short rainy season) and 1.50 ± 1.09 in February-March (pre-rainy season) than the other two sampling seasons (1.07 ± 0.58 in May and 1.18 ± 1.02 in July-August). The mean GSI values for males during these two sampling seasons were significantly ($p < 0.05$) higher than the mean values recorded during the rainy season and post rainy season (Figure 7).

For Koka population, the highest mean GSI value (2.11 ± 1.61) for females was recorded in May (pre-rainy season) which was significantly higher ($p < 0.05$) than the lowest mean value recorded (0.78 ± 0.88) in October-November (post-rainy season). The lowest mean GSI value for males was also recorded in the October-November sampling season, the value which was significantly lower ($p < 0.05$) than that of the other three sampling seasons (Figure 7).

The relatively highest (mean ± standard deviation) GSI value of 1.60 ± 1.28 was recorded in February-March (dry season) and the lowest value of 0.52 ± 0.44 in October-November (post-rainy season) for females of Ziway population. The males have similar peak patterns among the sampling seasons in the lake (Figure 7). The peak breeding season for Ziway was similar to that of Lake Hawassa (Demeke Admassu, 1996).

The current result shows that *O. niloticus* populations of Chamo, Koka and Ziway breed all year round with relatively higher activity in different months in different lakes; peak activity in October-November and February-March in Chamo, in May in Koka and in February-March sampling season in Ziway. The peak spawning usually coincides with the onset of the rainy season (Zenebe Tadesse, 1997; Lemma Abera, 2012).

4.4.4 Fecundity

The mean absolute fecundity of the *O. niloticus* populations in the present study was higher at Chamo (1,321.76 ± 342.92) followed by Koka (1,146.89 ± 115.23) and significantly lower ($p = 0.00$) than the two at Ziway (450.07 ± 180.83 eggs/female). The relationship between fecundity and some morphometric measurements of the females showed positive curvilinear relationship with total length ($F = 0.409TL^{2.4117}$, $R^2 = 0.908$), total weight ($F = 10.186TW^{0.8125}$, $R^2 = 0.901$) and gonad weight ($F = 118.908GW^{0.9121}$, $R^2 = 0.8415$) for the pooled data; these relationships derived from pooled data do not represent the populations' reproductive character. The higher mean absolute fecundity values of females at Chamo and Koka corresponds to the higher mean total length (28.65 ± 3.72 cm, 25.33 ± 2.19 cm) and total weight (429.41 ± 342.92 g and 282.75 ± 159.52 g) of the females. Similarly, positive relationship of the fecundity with total length, total weight and gonad weight was reported for *O. niloticus* populations in different water bodies (Zenebe Tadesse, 1997; Dwivedi *et al.*, 2016; Kausar *et al.*, 2019).

Generally, the differences observed in L_{50}, breeding season and fecundity of the *O. niloticus* populations might be attributed to differences in the lakes' environment, sizes, bathymetry, physico-chemical and biological properties and fishing pressure (Tenalem Ayenew, 2009, Vijverberg, *et al*., 2012; Megerssa Endebu *et al*., 2015) and perhaps genetic differences between the isolated populations (Agnese *et al*, 1997; Tibihika *et al*., 2020).

4.5 Conclusions and recommendations

In this study, the sex ratios, size at first sexual maturity, breeding season, absolute fecundity and the relationship of the fecundity with total length, total weight and gonad weight of *O. niloticus* populations of Lakes Chamo, Koka and Ziway were investigated.

The populations showed similar and the expected 1:1 Female:Male sex ratios in their natural environments. The populations also showed different sizes at first sexual maturity (L_{50}), with Chamo and Koka showing higher L_{50} than Ziway; the differences in L_{50} were attributed to environmental and/or genetic differences. All the current L_{50} values of the three populations decreased from previous reports especially in Lake Chamo; signs for increasing fishing pressures and environmental changes.

Breeding season of the *O. niloticus* populations, as determined from the Gonadosomatic index (GSI) gonads in four sampling seasons, was found to happen in all seasons in all the three lakes. However, the peak activities were different in the three lakes; peaks in October-November (short rainy season) and February-March (pre-rainy season) at Chamo Lake, in May (pre-rainy season) at Koka Lake and in February-March (dry season) at Ziway Lake. The peak breeding periods have a relation with onset of rain, whereby the three lakes have different annual rain distribution patterns.

The mean absolute fecundity was highest for population of Lake Chamo (1,322 eggs/female) followed by Lake Koka (1,147 eggs/female) and lowest for Lake Ziway (450 eggs/female). Fecundity correlated strongly with the females' total length and total weight, and slightly with gonad weight. These differences in sizes which also determine their fecundity, could be environmental and/or genetic.

The current decreases in the reproductive parameters of the *O. niloticus* populations from the previous reports indicate the decrease in the quality and in turn the quantity of the fish stocks, challenging the sustainability of the fisheries. Implementation of sustainable fishery management and environmental protection practices in the lakes and their watersheds are required. Lake Chamo *O. niloticus* population followed by Lake Koka, possessed better reproductive quality in aquaculture production with higher L_{50} and absolute fecundity and are potential populations for further genetic improvement in *O. niloticus* aquaculture. Further, studies are required to assess the current environmental status of the lakes, and determine whether or not the populations maintain their reproductive characteristics in controlled environments. Furthermore, additional studies that include other populations of *O. niloticus* from other water bodies are required to come up with conclusive recommendations for the establishment of *O. niloticus* based aquaculture in the country.

Chapter Five

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5 Effect of elevated fry rearing temperature on survival rate, sex ratio and growth performance of *O. niloticus* populations of Lakes Chamo, Koka and Ziway

5.1 Introduction

The *O. niloticus* is a freshwater fish species that is cultured worldwide because of its adaptation to wide range of environmental conditions, rapid growth rate, easy and rapid propagation, and tolerance to stress in handling (El-Sayed, 2006; Getinet Gebretsadik and Bart, 2007). Growth performance of the tilapias in aquaculture is affected by genetics and environment, both of which can be modified in fish culture to improve production and productivity. Accordingly, genetically improved strains such as genetically improved farmed tilapia (GIFT) and genetically improved red tilapia have been used in aquaculture production (Ansah *et al*., 2014; Lago *et al.*, 2016). Aquaculture business in general is not yet developed in Ethiopia where the *O. niloticus* species, the dominant catch in the country's fishery production (Yared Tigabu, 2010; Gashaw Tesfaye and Wolff, 2014) are the targeted and promising species for the sector's development. Distribution wise, *O. niloticus* are indigenous to the country and are found in water bodies of different drainage basins situated in different agro-ecologies (Tenalem Ayenew and Dagnachew Legesse, 2007; Abebe Getahun, 2017). Chamo, Koka and Ziway are among the major Rift Valley lakes known for their fishery production (Abebe Getahun, 2017). Growth performances of *O. niloticus* from these lakes have been evaluated in pond culture (Kassaye Balkew and Gjoen, 2012; Daba Tugie *et al.* 2017) and the populations were indicated as potential for further genetic improvement. Establishment of improved core strains of *O. niloticus* populations is, therefore, required for aquaculture development in the country.

Sex of the fish has also effects on growth performance in *O. niloticus* culture. Mixed sex cultures of the species in pond often produce undesired offspring, which increase fish numbers beyond the recommended density and create stressful conditions by competing for the limited resources such as feed, oxygen and space in the pond. The uncontrolled multiplication of fish in mixed sex culture results in stunted fish population of poor market value (Hepher and Pruginin, 1981; Coleman, 2001). Males grow faster than their female counterparts (Macintosh and Little, 1995; Megerssa Endebu *et al.*, 2016) in

O. niloticus culture therefore mono-sex male populations of the species are desired in aquaculture to improve production and productivity. Moreover, the use of mono-sex male in a range of aquaculture production systems has potential advantages including achievement of higher average growth rate, elimination of reproduction, reduction of territorial behavior of males, reduction of risk of environmental impact resulting from escapes of the non-local species and reduction of variation in harvest size (Beardmore *et al.*, 2001).

Sex reversal is one of the mechanisms used to produce male mono-sex in *O. niloticus* production. Sex reversal of *O. niloticus* in aquaculture can be achieved through variety of ways such as through hormonal treatment or through elevated fry rearing temperature at early swimming stage of the fish. *O. niloticus* displays a genetic sex determination system (XX|XY) where exposure to high temperatures (from 32˚C to 36.5˚C) during thermo-sensitive period (10 to 30 days post fertilization), induces masculinization (Baroiller *et al.,* 1995; Hendry *et al.,* 2002; Misikire Tessema *et al*., 2006; Angienda *et al.,* 2010; Nivelle *et al.*, 2019). Proportion of males in *O. niloticus* population increases with increasing fry rearing temperature up to 36°C, a temperature beyond which the number of males does not increase (Abucay *et al.* 1999; Baroiller and D’Cotta, 2001; Angienda *et al.* 2010; Misikire Tessema *et al*., 2006; Khater *et al.*, 2017).

Sensitivity of *O. niloticus* to temperature treatment depends on genetics. On the evaluation of the effects of rearing temperatures on *O. niloticus* populations, Misikire Tessema *et al*. (2006) observed significant differences of degree and range of responses to high temperature between populations and breeding pairs in the populations. Angienda *et al.,* (2010) indicated that the sex reversal efficiency of heat treatment in is affected by autosomal gene; whereby with a genetic marker called Abur36 achieved higher sex reversal efficiency up to 95% male.

Hence, the aim of the current experiment was to evaluate the effect of elevated fry rearing temperature on survival rate, growth rate and sex reversal efficiency in three selected populations of Ethiopian Rift Valley lakes.

5.2 Materials and methods

5.2.1 Sources of the *O. niloticus* populations

Progenies of three different *O. niloticus* populations of Rift Valley lakes, Chamo, Koka and Ziway were evaluated for their survival, sex ratio and growth rate responses to elevated fry rearing temperature at 36°C for 10 days starting from the first swimming. The responses were also evaluated for 6 months in growth period of the fish after the treatment. The parental stocks were collected from the lakes and kept as separate populations in outdoor concrete ponds at Batu Fishery and Other Aquatic Life Research Center earlier to the experiment. The lakes are located in separate drainage basins and had different water qualities (Table-14).

Table 14. Water quality parameter values at Lakes Chamo, Koka and Ziway

Water quality parameters	Chamo	Koka	Ziway
Temperature (^{o}C)	27.46 ± 0.84^{a}	23.35 ± 1.03^{b}	23.97 ± 1.44^{b}
Secchi disc depth (cm)	20.96 ± 5.36^{a}	13.35 ± 4.70^{c}	14.53 ± 0.88^{b}
pH	9.08 ± 0.25^{a},	8.37 ± 0.37^{b}	8.58 ± 0.25^{b}
Conductivity (µS/cm)	1,570.43 ± 177.46^{a}	450.45 ± 158.63^{b}	524.88 ± 48.97^{b}
Salinity (ppt)	0.81 ± 0.03^{a}	0.22 ± 0.09^{b}	0.25 ± 0.02^{b}
TDS (mg/L)	1,141.90 ± 80.40^{a}	321.8 ± 125.90^{b}	356.6 ± 34.8^{b}
SRP-P(µg/L)	81.36 ± 20.61^{a}	75.25 ± 15.49^{a}	39.22 ± 8.19^{b}
NO-3 - N (µg /L)	12.50 ± 7.73^{b}	524.60 ± 337.60^{a}	77.60 ± 69.18^{b}

SRP = soluble reactive phosphorus; TDS = total dissolved solids. Values with different superscript, (^{a,b,c}) in a row are statistically different at 95% confidence interval.

5.2.2 Fry production

The current experiment was conducted at Batu Fishery and Other Aquatic Life Research Center, located at Central Ethiopian Rift Valley, for about three years, from Nov 2017 to Oct 2020. The Batu Research Center is found close to Lake Ziway at 7°56' N latitude, 38° 43' E longitude and altitude of about 1640 m.a.s.l.

Generations of similar age groups were produced in ponds from each of Chamo, Koka and Ziway *O. niloticus* populations. Similar sizes of sexually mature male and female broods of these generations were taken from each of the three populations and kept separately in ponds for conditioning before commencing the experiment. The broods were fed on pellet supplemented with 25-30% crude protein during this conditioning period.

A total of 12 out-door concrete ponds of each 6 m^2 size were used for fry production. The water used in these experimental ponds was pumped from shallow well with determined water quality; water temperature of 24.8 ± 3.1°C, pH 8.9 ± 0.5; conductivity 2,262.5 ± 431.7 µs/cm; TDS 1,993.2 ± 327.4 mg/L and salinity 1.4 ± 0.2 ppt. Five hapa nets each with 1 m^3 volume suspended in the ponds were prepared for each of the three *O. niloticus* populations. Five males and five females were selected from the conditioned brood fishes of each population and male and female pairs of the selected individuals were put into each of the hapa nets to spawn. The males were mouth clipped before pairing, to reduce their aggressiveness to their female partners. Each pair of the broods were checked regularly for the release of fry in the hapa nets. The breeding pairs were replaced with other pairs in case of mortality or inability to spawn in a month after pairing. Once the pairs spawned in the hapa nets, the produced progenies were transferred to lab setup prepared for the purpose of this experiment.

5.2.3 Temperature treatment (phase-I)

Progenies from each breeding pairs of the three *O. niloticus* populations (Chamo, Koka and Ziway) produced in outdoor hapa nets were transferred to lab in two groups at age of first swimming date. Then, the fry were divided into treatment and control groups and the treatment groups were put into a setup for masculinization experiment under elevated fry rearing temperature and the control groups into a setup with room temperature.

The elevated fry rearing temperature adjusted to fixed temperature of 36±1°C was used as a treatment unit in order to induce masculinization (Angienda *et al.,* 2010; Abou El-Fotoh *et al*., 2014). Constant elevated water temperature was maintained by the use of thermostat water heaters, aerator pumps and mercury thermometers. The elevated temperature was allowed to stabilize for several days before introducing the fry into the treatment.

Sixty to one hundred fry of treatment group from each breeding pairs were introduced into treatment facilities within the heating bath at age of their first day of swimming. Fry of each pair were kept separately in perforated but screen covered plastic bottles of five liter capacity for 10 experimental days. The plastic bottles were arranged in the thermostat bath randomly.

Temperature was monitored three times a day using digital thermometer. Feeding the juveniles of both the treatment and control groups commenced with filtered zooplanktons consisting of copepods and rotifers collected from fertilized outdoor ponds. During the elevated fry rearing treatments, the fry were observed daily and deaths were recorded when occurred. After 10 days of the elevated fry rearing temperature treatment, the fry were transferred to similar tankers in lab where the thermostats of the heating units were switched off and the units were allowed to cool down slowly to room temperature of 24°C, normally in about one day. The final numbers of the fry in each container were recorded before they were transferred to outdoor ponds.

In the control groups, the corresponding fry from each breeding pairs were kept in tanks following similar management with the treatment group. The water temperature in the control groups was 24 ± 1°C. Aeration, feeding, treatment duration and other managements were similar with that of the treatment groups.

5.2.4 Growth in outdoor ponds (phase-II)

After the end of the treatment, both treatment and control groups fry were transferred to outdoor concrete ponds where they were grown to size of sexual differentiation. In these outdoor concrete ponds, the siblings in treatment groups and their corresponding controls were arranged in two separate blocks, treatment and control blocks. In each block, fry from different parents were placed in hapa nets with random arrangement.

The concrete ponds were fertilized with poultry manure that the water harboured phyto- and zooplankton (copepods, rotifers and few daphnia) which were used as live feeds for the fingerlings. The fingerlings were also supplemented with a feed prepared from mixture of wheat bran (50%) and noug cake (50%) at an estimated 40% of their body weight daily and gradually decreased to 5% body weight daily from the 2nd month onwards. Finally, the fish were sexed at 180 days when it was easy to identify their sexes by visual observation to their genital papilla.

5.2.5 Data collection and analysis

5.2.5.1 Survival rates

Survival rates of the progenies were calculated based on the numbers of fish that survived up to the end of the experiment period and expressed as percentages of the initial numbers stocked. The survival rates in this experiment were calculated at two stages, phase I and phase II. Phase-I was the survival rate during the first 10 days in laboratory experiment both for treatment and control groups while phase-II was the survival rate in outdoor ponds during the 180 days of growth period. Similar method and time of data collection were employed to the treatment groups and their corresponding control groups.

$$Survival\ (\%) = \frac{Numberof\ fish\ present\ on\ completion\ of experiment}{No.of\ fry\ stocked\ at\ the\ begining\ of\ the\ experiment} x100$$

The survival rates were presented in Table 15 for each of the progenies under treatment group (36°C/10 day) and control groups for both phase-I (10 days) and phase-II (180 days) for each of the populations. The differences between mean survival rates for treatment groups and control groups as well as the mean for the three populations were analyzed using independent-samples T test and one way ANOVA, respectively at 0.05 significance level in SPSS statistical package.

5.2.5.2 Growth rate

Progenies with similar stocking densities (50±3 fish/pond) in each population were selectively considered for growth performance evaluation among the progenies in the experimental ponds (phase-II). At monthly intervals, up to 6 months post heat treatment, 30-40 samples of fingerlings were drawn from the ponds for weight measurements used for determination of growth rate of the populations. The progenies' monthly growth rates of the three *O. niloticus* populations in terms of mean weight (g) were presented in graph under treatment and control groups (Fig 1). The mean final weights (g) of the progenies in each population were analyzed and compared using independent-samples T test for the treatment and control groups. The mean final weights of the progenies across the populations under treatment and control groups were analyzed using one-way-ANOVA. The mean differences were separated at 0.05 level of significance, LSD Post Hoc Multiple Comparison in SPSS statistical package. The fish samples drawn at 180 days post heat treatment were also used for sexing.

5.2.5.3 Sex ratios

Sexing was done by observing their genital papilla. The numbers of males and females of each group were recorded for each population both for the treatment and the control groups. Sex ratios were calculated as proportions of the numbers of male individuals per group. Deviation from 1:1 sex ratio in all the treated and control groups were analyzed by using chi-square test for each of the population.

5.3 Results

5.3.1 Survival rates

The survival rates of *O. niloticus* progenies during the first 10 days of lab experiment (phase-I) and during the growth period in outdoor experimental ponds for 180 days (phase-II) were presented in Table 15. In phase-I, the survival rate of the progenies of the treatment group ranged from 81.6%, 78.3% and 74.0% to maximum of 91.7%, 90.0% and 86.7% in Chamo, Koka and Ziway populations, respectively. Similarly, the survival rate of the progenies in control group ranged from minimum of 93.3%, 85.0% and 83.3% to maximum of 97.0%, 98.3% and 91.7% in Chamo, Koka and Ziway populations, respectively (Table 15).

The mean survival rates of the progenies in treatment groups were significantly lower than the mean survival rates in control groups for all the three populations. Comparing the survival rates among the three *O. niloticus* populations progenies under treatment groups, the mean survival rates of Chamo population (88.38 ± 4.12%) was significantly higher than that of the Ziway populations (80.20 ± 4.95%), while the survival rate for Koka population (85.78 ± 4.91%) was not statistically different from the values of the two populations. Similarly, in the control groups, the mean survival rates of Chamo population (95.40 ± 1.50%) was significantly higher than that of the Ziway populations (88.6 ± 3.16%), while the survival rate for Koka population (91.32 ± 5.32%) was not statistically different from the values of the two populations. Mean survival rates of the *O. niloticus* populations in outdoor experimental ponds (phase-II) during the 180 days of growth period was also presented in Table 15. It was found that the mean survival rates of the progenies of treatment groups were not statistically different from the mean survival rates of their corresponding control groups for all the three *O. niloticus* populations. When the progenies mean survival rates were compared, the values were not statistically different among the populations both for the control groups and the treated groups, except that the mean survival rate of Ziway population (90.18 ± 6.60%) was significantly lower than that of Chamo population (95.38 ± 1.17%) in treatment group.

Table 15. Mean survival rates of the progenies of *O. niloticus* populations of Lakes Chamo, Koka and Ziway in phase-I and phase-II under treatment and control groups

	Mean survival rate (%) in phase-I		
Treatment	**Chamo**	**Koka**	**Ziway**
Treated	88.38 ± 4.12[b,c]	85.78 ± 4.91[c]	80.20 ± 4.95[d]
Control	95.40 ± 1.50[a]	91.32 ± 5.32[a,b]	88.60 ± 3.16[b,c]
	Mean survival rate (%) in phase-II		
Treatment	**Chamo**	**Koka**	**Ziway**
Treated	95.38 ± 1.17[a]	93.94 ± 3.91[a,b]	90.18 ± 6.60[b]
Control	95.32 ± 2.63[a]	93.52 ± 4.05[a,b]	91.86 ± 2.65[a,b]

[a,b,c] significantly different mean survival rates (%) at 0.05 level of significance

5.3.2 Growth performance

Growth performances of progenies of *O. niloticus* populations treated in elevated fry rearing temperature and their corresponding control groups were presented in Figures 9a and 9b respectively. The fry weight at their first month in ponds was 1.17 ± 0.15 g with no significant differences among treatment and control groups and across the populations. But, mean weight of the fry/fingerlings started to segregate gradually between the populations, with the Chamo population attaining better weight than Koka and Ziway both in treatment and control groups (Figure 9).

The mean final weight of *O. niloticus* progenies after six months of growth was significantly different between treatment and control groups in Chamo and Koka populations, but not significant in Ziway population (Table 16). The M:F sex ratio of the progenies considered in growth performance evaluation has not deviated significantly from 1:1 in control groups of all the three populations and the treated group of Ziway population. But the treatment groups had higher male ratios in Chamo (63.46%) and Koka (65.96%) populations. The final weights of male *O. niloticus* were higher than their female counterparts in all the progenies. As a result, the mean weight of the treated groups was higher than that of their corresponding control groups only when the sex ratio was skewed towards male as observed in Chamo and Koka populations.

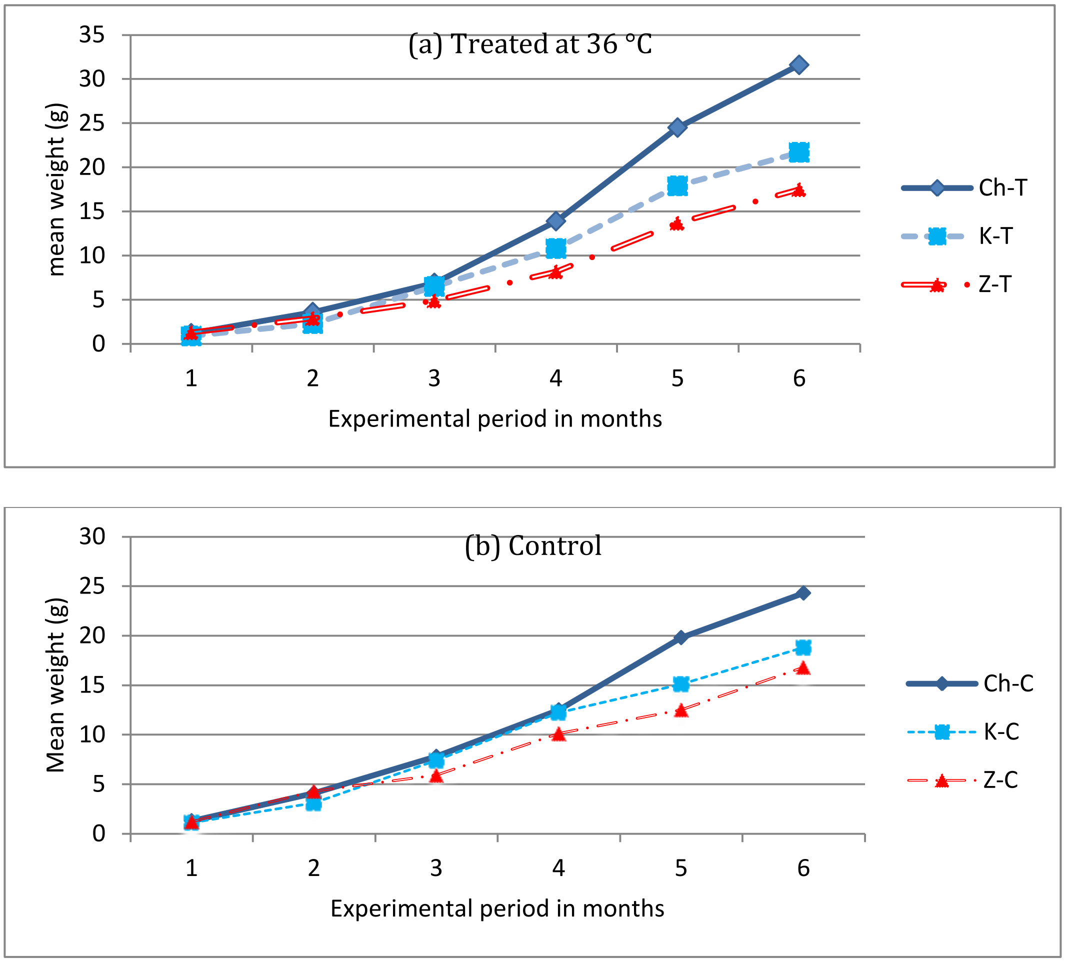

Figure 9. Growth performances of *O. niloticus* populations in phase-II, treated (a) and control (b) groups

Table 16. Final mean weight (g) of treatment and control groups of *O. niloticus* populations of Lakes Chamo, Koka and Ziway

	Mean weight (g) of *O. niloticus* populations		
Treatment	**Chamo**	**Koka**	**Ziway**
Treated	31.58 ± 6.78[a]	21.70 ± 5.10[c]	17.49 ± 4.60[d,e]
Control	24.26 ± 6.67[b]	18.83 ± 4.16[d]	16.81 ± 4.15[e]

[a,b,c,d,e] significantly different mean weights (g) at 0.05 level of significance

5.3.3 Sex ratios

The proportions of male *O. niloticus* individuals varied among treatment and control groups (Table 11). The sex ratios presented as "% male" ranged from 49.06% to 64.29% in the treatment groups, while it ranged from 47.27% to 53.70% in the control groups of **Chamo** population. Among five independent siblings obtained from different breeding pairs of Chamo population, only one sibling, the Ch1, resulted in significantly higher ($p<0.05$) proportion of males than females (Table 17). The overall sex ratios of the treated siblings group of Chamo (Ch1-Ch5) was significantly skewed towards male ($p<0.05$). However, the sex ratios of their corresponding siblings in control group and the overall total sex ratios in the control group did not significantly ($p> 0.05$) deviate from 1:1 (Table 17).

In case of **Koka** *O. niloticus* population, the sex ratios presented as "% male" ranged from 53.09% to 76.92% in the treatment group with the overall 61.68% male, while it ranged from 46.17% to 57.45% in the control group with overall total sex ratio of 50.52% (Table 17). Among five independent siblings obtained from different breeding pairs of Koka population, two treated groups of siblings, the K2 and K4, resulted in significantly higher ($p<0.05$) proportion of male individuals (Table 17). The cumulative sex ratios of the treated group of Koka population (K1-K5) was significantly ($p<0.001$) skewed towards males, while the sex ratios of their corresponding siblings under control group and overall total sex ratio of the control group did not significantly ($p>0.05$) deviate from 1:1 (Table 17).

The sex ratio of *O. niloticus* population of **Ziway** in five different sibling groups ranged from 44.00% to 78.69% in the treatment group with the overall ratio of 56.78% males, while it ranged from 46.81% to 54.00% in the control groups with overall sex ratios of 49.35% (Table 17). Among five independent siblings obtained from different brood pairs of Ziway population, only one sibling group, the Z1, resulted in significantly higher ($p<0.05$) proportion of male individuals (Table 17). The cumulative sex ratio of the treatment group of Ziway population (Z1-Z5) was also significantly ($p<0.05$) skewed towards male, while the sex ratios of their corresponding siblings under control group and overall total sex ratio of the control group did not significantly ($p>0.05$) deviate from 1:1 (Table 17).

Table 17. Effects of elevated fry rearing temperature on progeny sex ratios of *O. niloticus* populations of Lakes Chamo, Koka and Ziway

	Treatment group (36°C)				**Control group**				
	Survival (%)				**Survival (%)**				
Spawn	**10 days**	**180 days**	**Sexed (No.)**	**male (%)**	**10 days**	**180 days**	**Sexed (No.)**	**male (%)**	**χ2**
Ch1	88.0	95.5	84	64.29^{b}	97.0	93.8	91	51.65	0.099
Ch2	89.0	96.6	86	51.16	95.0	91.6	87	48.28	0.103
Ch3	91.7	96.4	53	49.06	96.7	98.3	57	50.88	0.018
Ch4	81.6	93.9	46	52.17	93.3	96.4	54	53.7	0.296
Ch5	91.6	94.5	52	63.46	95.0	96.5	55	47.27	0.164
Overall	88.4	95.5	321	56.39^{a}	95.4	94.8	344	50.29	0.012
K1	89.0	91.0	81	53.09	85.0	96.5	82	48.78	0.049
K2	88.3	88.7	47	65.96^{a}	90.0	96.3	52	46.15	0.308
K3	78.3	95.7	45	62.22	88.3	88.7	47	57.45	1.043
K4	90.0	96.3	52	76.92^{c}	98.3	96.6	57	52.63	0.158
K5	83.3	98.0	49	55.1	95.0	89.5	51	49.02	0.020
Overall	85.8	93.8	274	61.68^{c}	91.32	93.8	289	50.52	0.031
Z1	74.0	82.4	61	78.69^{c}	89.0	93.3	83	48.19	0.108
Z2	76.7	96.2	50	48.84	90.0	92.6	50	54.00	0.320
Z3	82.0	95.1	78	53.85	89.0	92.1	82	48.78	0.049
Z4	76.7	93.5	43	44.00	83.3	94.0	47	46.81	0.191
Z5	81.6	83.7	41	53.66	91.7	87.3	48	50.00	0.000
Overall	80.2	89.5	273	56.78^{a}	88.6	92.0	310	49.35	0.052
Grand	84.8	93.2			91.3	93.5			

Note: Ch1 - Ch5 = progenies of Chamo population, K1 - K5 = progenies of Koka population, Z1 - Z5 = progenies of Ziway population, n = number of individuals included in statistical analysis and χ^2 = Chi-square test value for deviation of sex ratios of control from 1:1; ^{a,b,c} sex ratio of treatment group significantly different from 1:1 (P<0.05, 0.01, 0.001).

5.4 Discussion

Based on the results obtained in the present study, rearing fry produced from three *O. niloticus* populations at 36 ± 1°C for the duration of 10 days decreased the survival rates of all the treatment groups but not affected survival rate during the growth phase after the treatment in all the three populations. Increment in water temperature beyond the optimum rearing temperature of 27-32°C for *O. niloticus* (Drummond *et al.*, 2009; Samuel Bekele *et al.*, 2019) is a stressful condition to induce mortality that the elevated fry rearing temperature of 36°C decreased the survival rate in the present study as it was reported by Khater *et al.* (2017) also. Though different between treated and control groups, the survival rates in the current study were within ranges reported in earlier studies (Khater *et al.*, 2017; Nivelle *et al.*, 2019). Effect of population on survival rate was observed both in treatment groups and control groups, whereby the Chamo population performed better in survival rate, followed by Koka population while Ziway population was the least. The difference between the treatment temperature (36 ± 1°C) and the temperature in the populations' natural environment was relatively higher for Koka (14°C) and Ziway (12°C) as compared to that of Chamo (8°C) to affect the survival rate. Moreover, the three *O. niloticus* populations have shown different phenotypic and reproductive characters in their separate natural environments (Megerssa Endebu *et al.*, 2021b) suggesting potential genetic differences among the populations. Both genetics and environment affect early fry survival rate in *O. niloticus* (Yonas Fessehaye *et al.*, 2007) which influenced the survival rates of the populations differently in the current study.

Growth rate and mean final weight of *O. niloticus* populations differed among the populations in the present study, both in control and treated groups with Chamo population performing better than Koka and Ziway. Growth rate of an organism is affected both by environmental and genetic factors. The environmental factors were kept similar for all the *O. niloticus* progenies under the present study, except the deliberately adjusted temperature differences between the treated and control groups in their early age. Hence, the differences in growth rates between the progenies of *O. niloticus* populations were more likely due to genetic effect. Feed conversion rate and growth rate in juvenile *O. niloticus* is determined by genetics (De Verdal *et al.*, 2018). Similar growth differences were also observed for *O. niloticus* populations of Ethiopian Rift Valley in pond experiments (Kassaye Balkew and Gjoen, 2012; Daba Tugie *et al.* 2017). However, the differences in growth rate and final mean weight between treated and control groups within a population were observed only when the sex ratios were different between the groups. The weight differences were attributed to differences in sex ratios induced by the elevated fry rearing temperature treatment, for which progenies with similar sex ratio had similar growth rate in a population, regardless of temperature treatments. The progenies with higher proportions of male individuals achieved faster growth rate and attained higher mean final weight than those with balanced sex ratios, due to the reason that the males grow faster than females in *O. niloticus* populations (Macintosh & Little, 1995; Chakraborty and Banerjee, 2010; Megerssa Endebu *et al.*, 2016).

The overall sex ratios of *O. niloticus* in the present study were skewed towards males for the heat treated groups in all the three populations (Chamo, Koka and Ziway) while the ratio was balanced in all the control groups of each population. However, the response in sex reversal after exposure to elevated fry rearing temperature varied among individuals, breeding pairs within each population and also across the populations. Even if some siblings have significantly shifted their sex ratios toward male, the proportion of males within these siblings after the heat treatment also varied. This variation, suggest differences in degree of sensitivity among individuals within each population. The number of breeding pairs whose progenies were sex reversed and the overall male ratio in the treated groups were higher in Koka *O. niloticus* population than in Ziway and Chamo populations; the higher response in the population with higher temperature difference between treatment and their natural environment. Different *O. niloticus* populations can show significant differences in degree and range of responses to elevated temperature treatments (Misikire Tessema *et al*., 2006). The differences in sensitivity of *O. niloticus* progenies within the populations suggest the responsiveness variability among individuals (Angienda *et al.,* 2010).

5.5 Conclusions and recommendations

Progenies of three *O. niloticus* populations; Chamo, Koka and Ziway respond to elevated fry rearing temperatures differently in terms of survival rate, growth performance and sex ratios. Survival rate was affected both by population and the elevated fry rearing temperature treatment. The elevated fry rearing temperature decreased survival rate in all the three *O. niloticus* populations. Chamo population attained higher fry survival rate than Koka and Ziway both in treated and control groups. Growth performance of the *O. niloticus* progenies was affected by population whereby Chamo population followed by Koka attained better size at final harvest. Elevated fry rearing temperature influence growth rate only when the sex ratio is altered. Elevated fry rearing temperature induce shift in sex ratios towards male in *O. niloticus* populations of Lakes Chamo, Koka and Ziway. However, variation in sex reversal sensitivity was wide between individuals within each population than across the three populations.

Hence, sensitive individuals can be selected from the populations and their degree of sensitivity be improved through consequent breeding of sensitive parents for masculinization in aquaculture production.

6 General conclusions and recommendations

The current study demonstrated substantial differences between the three Ethiopian Rift Valley lakes, namely Lakes Chamo, Koka and Ziway for physico-chemical water quality parameters studied during the two years, May-2018 to April-2020. Variation in these parameters that included water temperature, pH, electrical conductivity (EC), total dissolved solids (TDS) and salinity appeared to be dependent on geographical locations, morphometry and geology of the lakes, agricultural activities in the catchment areas, and soil chemistry of their watersheds. Seasonal variation played important roles at all the three lakes with increasing trend over time when compared with previous reports. Invasive water hyacinth which existed for over 60 years in Lake Koka has now established itself in Lake Ziway. The invasion of water hyacinth in Lake Koka appeared to be aggravated by higher nutrient loadings from its catchment areas and absence of natural wetland vegetation in the shore of the lake which compete for space and nutrient uptake.

The Nile tilapia (*O. niloticus*) populations of the three Lakes; Chamo, Koka and Ziway were identified to develop different phenotypic characters in these environments. As desired characters in aquaculture production, O. niloticus population of Lake Chamo had higher mean weight and length than population of Lake Koka followed by population of Lake Ziway. The overall Female:Male sex ratios of the populations in the three lakes were balanced and maintained the expected ratio of 1:1. Breeding season of the *O. niloticus* populations, was found to happen in all seasons in all the three lakes. However, the peak activities were different in the three lakes; following the onset of rain, whereby the three lakes have different annual rain distribution patterns. The sizes at first sexual maturity (L_{50}) also varied among the populations with Chamo and Koka showing higher L_{50} than Ziway. The mean absolute fecundity, which was correlated strongly with the females' total length and total weight, was also highest for population of Lake Chamo followed by Lake Koka and lowest for Lake Ziway. The differences in phenotypic and reproductive characters were attributed to environmental and/or genetic differences. Besides these differences between the populations of the three lakes, all the current L_{50} values of the three populations decreased from previous reports. The main reasons for the decrease are environmental changes and fishing pressures; the fishing practices which continuously remove the bigger sized fish from each population without replacement by selectively affecting individuals with better growth performances and favoring individuals with inferior growth performances to dominate the lakes.

In the experiment of elevated fry rearing temperature treatment to produce male *O. niloticus*, progenies of the three *O. niloticus* populations; Chamo, Koka and Ziway respond differently in terms of survival rate, growth performance and sex ratios. The treatment effect decreased survival rates in Ziway than in Koka and Chamo populations. However, the growth performance of the *O. niloticus* progenies was influenced not by temperature treatment alone but by population effect and shift in sex ratio. The Chamo population followed by Koka attained better size at final harvest and the average size is even higher for populations when their sex ratio is skewed towards male. Shift in sex ratios towards male was induced by the elevated fry rearing temperature treatment in all the three *O. niloticus* populations. However, variation in sensitivity for sex reversal was wide between individuals within each population than across the three populations.

Based on the findings of the present study, the following general recommendations are suggested:

- In order to minimize the silt and nutrient loads in the lakes and to restore and safeguard biodiversity in the freshwater lakes ecosystem, appropriate watershed management system should be established and proper agricultural practices should be in place that minimize soil erosion and excessive agro-chemical pollution. Moreover, strict municipal and industrial waste management systems should be established and enforced by the authorities with participation of all stakeholders. Priority should also be given to proper implementation of sustainable fishery management practices.
- The populations of *O. niloticus* from Chamo followed by Koka, possessed better phenotypic and reproductive qualities with higher mean lengths and weights, higher L_{50} and absolute fecundity, which are desired in aquaculture production. The two populations are, therefore, potential populations for further genetic improvement in *O. niloticus* aquaculture. Determining whether or not these populations maintain their phenotypic and reproductive characteristics in controlled environments requires additional studies with the inclusion of other populations of *O. niloticus* from other water bodies. This would help to come up with conclusive recommendations for the establishment of *O. niloticus* based aquaculture in the country. To develop production of male *O. niloticus* in aquaculture, sensitive individuals can be selected from the populations and their degree of sensitivity can be improved through subsequent breeding and selection of temperature sensitive offspring.

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