

Spatial-Temporal Analysis of Physicochemical Parameters of Three Ethiopian Rift Valley Lakes Indicating Threats in Ecological Sustainability

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Abstract
The Ethiopian Rift Valley lakes provide substantial economic, environmental and social benefits across diverse ecological settings. Sustainability of these benefits is affected substantially by the mega-environmental level climate change and cumulative anthropogenic effects at the lakes and in their catchments landscapes. To provide an insight on some of the challenges that affect the lakes' health, this study assessed major water physicochemical status of three Rift Valley lakes: namely, Chamo, Koka and Ziway and compared with previous data. The water physicochemical data were measured *in-situ* for two years, i.e., from May 2018 to April 2020. Nutrients loading to the lakes were analyzed from water samples. The study demonstrated that water temperature, pH, electric conductivity (EC), total dissolved solids (TDS), salinity and total phosphorus (TP) varied significantly between seasons within and between the lakes. The findings demonstrated that the EC and TDS levels during the period of this study were higher than previous reported levels. The findings also showed that establishment and invasion of water hyacinth (*Eichhornia crassipes*) weed had association with nutrient loading into the lakes and vegetation in the lake's shore. The very likely anthropogenic effects associated factors including water turbidity, soluble reactive phosphorus, and nitrate-N concentrations varied among the lakes, across seasons and time. Our findings indicate that the urgent need of education and participatory intervention of watershed management, proper agricultural practices, strict and enforced municipal and industrial waste management practices, protection of wetlands vegetation and delimitation of the lakes' buffer zones to sustain the services of the lakes.
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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. 2006; 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 locally in fisheries production and for irrigation purposes (Getahun, 2017).

Even though the majority of the tropical lakes including the Ethiopian Rift Valley lakes are natural river lakes or reservoirs (Lewis 2000), previous studies reported that Chamo, Koka and Ziway Lakes have different morphological, physicochemical and biological characteristics (Kebede et al. 1994; Ayenew 2009; 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 (Hailemicael 2011; Degefu et al. 2013; Endebu et al. 2015; 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. 2006). Threats to biodiversity in freshwater ecosystem 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 coupled with stagnated rate of food production unmatched with increasing food demand.

Population growth has played major roles in shift in freshwater ecosystem functioning but also in the change of the land use systems in Ethiopia causing land degradation, habitat fragmentation, and deforestation

(Ayenew and 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; 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 physicochemical properties, biotic factors together with land management practices contribute to the dynamics of freshwater ecosystem including that of the lakes ecosystem. Particularly its physicochemical attributes reflected by water quality parameters such as water temperature, pH, electric conductivity (EC), total dissolved solids (TDS), salinity, turbidity measured in Secchi 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 physicochemical properties determine the lakes biological functions and biological diversity in the ecosystem. Warm waters with the optimum temperature range of 25-30°C promote healthy and balanced lakes ecosystem that include 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 the 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 physicochemical properties of the lakes and sample water were far from the level expected from a healthy lake (Table 1).

In addition to the physicochemical 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 (Gebregiorgis 2017) that has become a national concern threatening aquatic biodiversity and socioeconomic activities in the Ethiopian water bodies. It has been reported widely 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) (Gebregiorgis et al. 2007, 2013, 2017; Tewabe, 2015; Tewabe et al. 2017; Gebregiorgis 2017).

The three Lakes targeted for this study: namely, Lake 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 physicochemical and biological aspects of the lakes at three regions of the water body namely the inlet region (IR), the middle region (MR) and the outlet region (OR). Assessing variations in different part of the water would provide critical information to design intervention mechanisms and rehabilitation of these lakes.

2. Materials and Methods

2.1. Study areas

This study targeted selected water physicochemical attributes of three Ethiopian Rift Valley lakes, namely, Chamo, Koka and Ziway (Fig. 1, Table 1). The main Ethiopian Rift Valley lakes are situated in different hydrological basins that include the Awash, Ziway-Shala, Hawassa and Abaya-Chamo basins (Ayenew 2009).

Lake Chamo is situated in southern part of the Ethiopian Rift Valley within the Abaya-Chamo drainage basin, the 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 basin system is characterized by highly diversified fish fauna of about 21 species (Golubtsov and Habteselassie 2010). Lake Chamo is recharged mainly by feeder rivers called

Kulfo, Sago and Sile with no visible outlet.

Lake Koka is a man-made reservoir located at about 90 km southeast of Addis Ababa in Awash River basin. 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 basin consists of Bishoftu crater lakes in its upper basin and Koka, Beseka, Afambo, Gemeri and Abe lakes in its middle and lower basins. Upper Awash basin drains about 11,250 km^2 area up to the inlet of Lake Koka. The basin is among the most important water resources used for large-scale irrigation schemes in Ethiopia. Lake Koka was constructed on Awash River in 1960 for the purpose of hydro-electric power generation. The lake'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. Lake Koka is recharged by two feeder rivers, Awash and Modjo Rivers.

Lake Ziway, 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. Ziway Lake, locally known as Hara Denbel, is the shallowest but the second largest lake in area coverage among the Ethiopian Rift Valley lakes, after Abaya Lake (LFDP 1997). The lake has two feeder rivers, Meki River and Katar River, with one outlet called the Bulbula River in its southern part that seasonally flows into Abijata Lake. Lake Ziway is home to endemic and exotic fish species that are commercially important to various degrees (Table 2).

Fig. 1 Locations of Lakes Koka, Ziway and Chamo within the Ethiopian Rift Valley

Sites for water sampling and in-situ data measurements: Spots or areas in the water bodies for water sampling and in-situ data collection were selected to represent the lakes from inlet region (IR), middle region (MR) of the lake and outlet region (OR), which is the opposite end of the major inlet regions. These water sampling and data collection sites in each of the three regions correspond to major fishermen landing spots and are called Leto-Azo Gebeya (5.922°N, 37.540°E), Leto-2 (5.860°N, 37.578°E) and Elgo-Wazeqa (5.770°N, 37.511°E) for Lake Chamo; Awash(8.407°N, 39.021°E), Metoal eka (8.360°N, 39.010°E) and Bekele (8.446°N, 39.110°E) for Lake Koka and Golbe-Tsedecha (8.028°N, 38.910°E), Meki-Girisa (8.055°N, 38.800°E), and Batu-Bochesa (7.911°N, 38.751°E) for Lake Ziway. Sampling sites followed the rout of fishery activities by the locals, but the *in-situ* measurements and water samples were taken offshore to avoid the shore effect and the mat of water hyacinth which congregate around the shore of the lakes (especially in Koka).

2.2. Seasons.

This study was conducted from May 2018 to April 2020 categorized as Year 1 and Year 2. 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 a main rainy season for Lake Chamo region; (3) July-August (JUA) – a main rainy season for Ziway and Koka lakes regions, but it was the finishing of main rainy season and the harvesting time for the Chamo lake region; (4) October to November (OCN), a 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 collected in the mornings 7:00-9:00 AM and the afternoons from 2:00-4:00 PM on the days the samples were collected.

2.3. Data collection

In-situ measurements: Overall, seven Water physicochemical parameters, namely (1) conductivity (CND), (2) pH, (3) Secchi 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 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 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), (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 by the lakes, observations were made along the shores of the lakes. Water hyacinth, the invasive alien species, was visually observed across the lakes and recorded as present or absent.

2.4. Data analysis

Data recorded on water physicochemical 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 constructed with PAST statistical program (Hammer et al. 2001).

3. Results

Pearson's correlation coefficient result performed on 10 water physicochemical parameters measured across three Lakes, two years, four seasons/ year and three sites/ lake can be categorized in to three broad groups (Table 3). These three broad groups are (I) highly significantly and positively correlated parameters, (II) highly significantly and negatively correlated parameters, and (III) weakly positively or negatively correlated parameters. Conductivity, TDS, salinity, water temperature, Secchi depth, and pH were highly significantly and positively correlated with each other. Likewise, nitrate concentration with soluble reactive phosphorus was also highly significantly and positively correlated. Resistivity was highly significantly and negatively correlated with the conductivity, salinity, TDS, water temperature, Secchi 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. Such degree of variations in correlation between parameters was due to considerable variations observed across lakes, and seasons (Fig. 2) and also across the sample sites at each lake (Fig. 3).

Fig. 2 Matrix plot of means of physicochemical 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)

Fig. 3 Matrix plot of means of physicochemical 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)

3.1. Water temperature

Mean water temperature levels varied highly significantly between the lakes or between the seasons (Table 4, Fig. 2F). However, the Lake-Season interaction effect and the mean differences for the sampling sites were not significant.

Among the three Lakes, the annual mean water temperature with 27.46 ± 0.84ºC was the highest at Lake Chamo. Seasonal mean water temperature ranged from 26.55ºC in May, which was the main rainy season to 28.54ºC in Feb-March, which was dry season at Lake Chamo. Lakes Ziway and Koka recorded, respectively, annual mean temperature levels of 23.97 ± 1.44ºC and 23.35 ± 1.03ºC with significant seasonal mean temperature variations (Fig. 2F). 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.

3.2. Secchi depth

The mean Secchi depth values, which were water turbidity indicator, of the lakes varied across the three lakes and across the four seasons (Fig. 2E). The differences in mean annual Secchi depth between the lakes, between the seasons and Lake by Season interaction were highly significant (Table 5). Lake Chamo with the highest annual Secchi depth of 20.96 ± 5.36 cm was very much transparent than Lake Ziway and Lake Koka with annual Secchi depth of 14.53 ± 0.88 cm and 13.35 ± 4.70 cm, respectively. Seasonal mean Secchi depth values were observed to be lower at the onset of rain and during rainy season. Very high and wide variation in Secchi depth was recorded at Lake Chamo with that ranged from 14.13 cm observed in May to 27.05 cm observed in Feb-March. This variation ranged from 13.73 cm in May to 15.54 cm in Feb-March at Lake Ziway and from 8.65 cm in July-August to 17.94 cm in Oct-Nov at Lake Koka. Comparing the sampling sites within the lakes, Lake

Chamo recorded the lowest mean values around the confluence of the inlet rivers during rainy season and the highest mean values recorded at the region away from the main inlet (Fig. 3E).

3.3. Water pH

Mean annual water pH observed at Lake Chamo (9.08 ± 0.25), Lake Ziway (8.58 ± 0.25) and Lake Koka (8.37 ± 0.37) varied significantly across the lakes (Table 6, Fig. 2B). Relatively lower pH mean values were observed during the rainy seasons than during the dry seasons all the three lakes (Fig. 2B). Mean pH values appeared to be rather stable across the sampling sites within each lake (Fig. 3B).

3.4. Total dissolved solids (TDS)

TDS was observed to be significantly different between the lakes as well as the seasons (Table 7). Alike the electric conductivity, significantly higher annual mean value of TDS (mg/L) was recorded in Lake Chamo (1,141.9 ± 80.4 mg/L), which was about 3.2 times higher than Lake Ziway (356.6 ± 34.8 mg/L) and ~3.6 times higher than Lake Koka (312.8 ± 125.9 mg/L) (Fig. 2G). TDS seasonal variations ranged from 1,028.70 mg/L in May to 1,217.40 mg/L 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.

3.5. Salinity

Salinity levels varied significantly across the three lakes and four seasons (Table 8; Fig. 2D). Among the three studied lakes, Lake Chamo with 0.81 ± 0.03 ppt was significantly more saline than Lakes Ziway with 0.25± 0.02 ppt and Koka with 0.22 ± 0.09 ppt salinity levels. The highest seasonal mean salinity levels 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 Lake Ziway (0.224 ppt) recorded the lowest in Oct-Nov (post rainy season). The spatial differences in salinity were observed in Lake Chamo, the terminal lake without visible outlet river, where salinity level increased from the inlet confluence region (IR) towards the region opposite of the inlet designated as outlet region (OR). In contrast, salinity level decreased from inlet-region (IR) towards the outlet region in Lake Koka (Fig. 3D).

3.6. Nutrient load to the lakes

The nutrient load to the lakes were measured by the soluble reactive phosphorus (SRP), total phosphorus (TP) and the nitrate nitrogen (NTN) across the three lakes during different seasons and three sites in each lake (Fig. 2H, 2I, 2J; 3H, 3I, 3J and 3K). In general, the overall SRP concentration was lower at Lake Ziway (39.22 ± 8.19 µg P/L) than Lakes Koka (75.25 ± 15.49 µg P/L) and Chamo (81.36 ±20.61 µg P/L). TP concentration measured during dry season (February-March) was higher at Lake Koka than recorded at Lakes Chamo and Ziway especially in the outlet regions of the lakes (Fig. 2J, 3J). The spatial concentration increased from inlet region to outlet region in Lake Koka (Fig. 3K). The NTN load was high in Lake Koka with considerable variations between seasons that ranged from 240.90 µg/L during July-August main rainy season to 898.0 µg/L in Feb-March dry season.

4. Discussion

Water quality in freshwater lakes is measured by physicochemical parameters that include water temperature, electric conductivity, salinity and various nutrients loadings that affected water turbidity. These parameters differ from lake to lake and determine the habitats and thus organisms living in the lakes.

Water temperature. It is one of the key physiochemical parameters influenced by the amount and angle of solar radiation, varies in water bodies depending on geographical locations, altitudes and morphometry of the water bodies. This study demonstrated that Lake Chamo located at lower altitudes by 480 meters than Lake Koka and 526 meters than Lake Ziway had higher mean annual water temperature levels of 27.46 ^{o}C (Table 1.). Compared with Lake Chamo, a decrease of 138 meters altitude for Lake Ziway and a decrease of 128 meters altitude for Lake Koka was equivalent to an increase of 1^{o}C water temperature. Our observation in current study was in agreement with Layden et al. (2015) that reported the lower the altitude and latitude location of a lake, the higher the water temperature levels.

Though Lakes Ziway and Koka were closely located, altitudinal differences of 46 meters was equivalent to an increase of 0.6^{o}C water temperature at relatively lower altitude located Lake Koka. The mean annual water temperature difference observed at the three lakes can also attributed to substantial morphometric differences between the three lakes covered in our current study. Previous study by Meerhoff et al. (2012) reported that broad and shallow lakes are warmer than deeper and narrower lakes. Also seasonal variations played important roles in the temperature levels at the three Lakes covered in our present study. As expected, lower water temperatures levels were observed during the rainy seasons and higher temperatures during the dry seasons at the three Lakes covered in our study (Fig. 2F). Despite variations in water temperature levels between lakes and seasons, the mean annual water temperatures for the three lakes covered in the current study were within the range of the water temperature history of the lakes (Table 1).

Water turbidity. Measured by Secchi depth (cm), water turbidity is an indirect measurement of the amount of suspended solids in the water. Our study demonstrated that manmade Lake Koka and Lake Ziway ware more turbid than Lake Chamo (Fig. 2E). The main cause of the lakes' turbidity is suspended material coming from catchment areas during the rainy season. The catchment area of the manmade Lake Koka covers wide intensive agricultural areas with considerable level of agricultural inputs such as fertilizers and pesticides from various farming systems contributes to the nutrients loadings through erosion (Teklu et al. 2018; Fetahi 2019). Similarly, various agricultural inputs to the intensive cereal crops, commercial vegetable, floriculture and orchids production systems widely observed in the catchment of Lake Ziway likely contributed various nutrients loadings and thus resulting in higher turbidity in the lake. The low turbidity recorded at Lake Chamo was likely due to relatively lower intensive agricultural activities in its catchment and lower catchment area of the lake compared to the other two lakes covered in our study. The contribution of agricultural inputs and the erosion is evident from our current study as demonstrated by relatively higher turbidity during the main rainy seasons and inlet region of the lakes, decreased turbidity after the rainy season and away from the inlet regions or at outlet regions (Fig. 2E). Secchi depth values, which is a measure of water turbidity, observed in our current study was two to three folds lower at all the three lakes than their previous records (Kebede et al. 1994). This reflects an increase in loads of suspended solids to the lakes over time. This increase in water turbidity that reflects deterioration of water quality affects the lake environment, increasing silt load and thus changing lake bottom sediment, decrease productivity of the lakes and also contributes to change in water temperatures as the suspended particles absorb heat from solar radiation more effectively than water (Paaijmans 2008).

Water chemistry. Measured by water pH, electric conductivity (EC), total dissolved solids (TDS) and salinity, water chemistry attributes 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. These parameters were highly significantly and positively correlated with each other. 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 (Michaud, 1991; Ayenew and Legesse, 2007; Hailemicael, 2011).

The soil salinity around Lake Chamo, including in annual field cropping system was reported to be high (Zebirel 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 water pH range of 7.48 - 9.50 at lake Chamo covered previously reported pH level of 8.9 (Kebede et al. 1994) but lower the level of 8.87 - 9.93 reported by Fekadu and Chanie (2017). The pH value at lake Koka increased from previous report of 7.4 - 8.5 range (Kebede et al. 1994; Tesfaye, 2007; Masresha et al. 2011) to the current range of 7.6 - 9.21. Similarly, the water pH range of 7.71 - 9.00 at Lake Ziway increased in our current study when compared with previously reported range of 8.4 - 8.9 (Table 2). 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 (Fetahi, 2019). Similarly, our current study identified increase in electric conductivity at all the three lakes when compared with previous reports (Table 2). The TDS is also related to electrical conductivity of a lake; where the relationship with EC is linear (Pal et al. 2015).

Agriculture as a prime contributor to freshwater lakes quality deterioration. It was very hard to get officially recorded data on agricultural acreages, types and duration of production activities along with chemical inputs in the catchment areas of the three lakes covered in this study. This limited our interest to reflect the level of intensive agricultural contribution towards the freshwater lakes water quality deterioration. Despite lack of official data, nitrate-N and phosphate-P are the result of agricultural inputs. Differences in their concentrations mean values at the three lakes is related to the types and level of pollutants such as fertilizers from agricultural lands, municipal and industrial wastes in the catchment areas. The higher concentration of nitrate-N and total phosphorus in Lake Koka is likely due to intensive agriculture and municipal wastes in the catchment of upper Awash. Comparing the sampling sites, an increase in total phosphorus concentration gradient towards the outlet region in Lake Koka is perhaps due to gradual settlement and deposition of phosphate compounds around the mouth of the lake. Additionally, lack of natural wetland vegetation except the notorious and freshwater lakes weed observed in Lake Koka that could otherwise utilized nutrients may have contributed to high nutrients accumulation. Compared with previous studies, nitrate-N and phosphate-P concentrations in the current study are higher at all the three lakes. The maximum recorded concentrations of nitrate-N increased from 18.6 μg /L (Kebede et al. 1994) to 26.3 μg /L in Lake Chamo; from 1.4 μg /L (Kebede et al. 1994) and 1,430.0 μg /L (Masresha et al. 2011) to 2,587.7 μg /L in Lake Koka and from 3.9 μg /L (Kebede et al. 1994) and 50.0 μg /L (Masresha et al. 2011) to 142.00 μg /L in Lake Ziway observed in the current study. Similarly, the maximum recorded concentrations of phosphate-P increased from 25.5 μg /L (Kebede et al. 1994) to 102.8 μg /L in Lake

Chamo; from 9.5 µg /L (Kebede et al. 1994) and 36.1 µg /L (Degefu et al. 2011) to 146.8 µg /L in Lake Koka and from below detection level (Kebede et al. 1994) to 50.8 µg /L in Lake Ziway in the current study.

The land use system pattern in Ethiopia in general and that of the Central Rift Valley where this study focused on in particular is changing. The area coverage of small- and large-scale farming, settlements and mixed cultivation/acacia increased at the expense of natural forest and woodland environments in the Central Rift Valley of Ethiopia (Elias et al. 2018). Use and application rate of chemical fertilizers in the country has increased over years following the expansion of intensive agricultural land, loss of soil fertility due to erosion and removal of crop residue for animal feed (Reda and Hailu 2017; Legesse et al. 2019). Large areas of farms are covered by variety of vegetable crops in the Central Rift Valley especially around lakes Ziway and Koka where fertilizer application rates among the vegetable growers were reported to be in excess (Etissa et al. 2013). Land degradation due to erosion and conversion to intensive agriculture by 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 (Ayenew and Legesse 2007; Meshesha et al. 2012; Teklu et al. 2018; Fetahi 2019). Land degradation in the catchment areas resulted in water eutrophication caused by nitrate and phosphate causes numerous human health hazards particularly to the most vulnerable components of the society including infants and pregnant women (Shih et al. 1997). The Environmental Protection Agency (EPA) recommends a maximum concentration of 10 mg/L Nitrate-N and 5 mg/L phosphorous levels in drinking water.

Wetland vegetation. Wetlands play key roles by maintaining well-functioning aquatic ecosystem by mitigating pollution of nutrient loadings through a combination of physical, chemical and biological process. 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). The three Lakes covered in our study varied considerably for the coverage and species of vegetation. Natural wetland vegetation mainly dominated by *Typha domingensis, Echinochloa pyramidalis, Cynodon dactylon* and *Cyperus articulata* in the shoreline of Lake Chamo were observed to be dense and relatively undisturbed, and though land use changed overtime has been reported previously in this lake's catchment (Hailemicael 2011). Though some disturbances caused by animal grazing and other anthropogenic impacts, the wetland vegetation that included typha, papyrus *(Cyperus papyrus* L.), blue water lily *(Nymphaea nouchali*), bulrush *(Paspalidium geminatum*), and *Aeschynomene elaphroxylon* were observed along the most parts of Lake Ziway shoreline. At Lake Koka, not only lack of natural wetland vegetation along the shoreline that balance freshwater lakes ecosystem, but also growth and persistently floating water hyacinth was observed.

Water hyacinth is a persistent floating weed on Lake Koka during the two years of our study period which flourish during the rainy season, making mat and covering all the shoreline that hampered access to the lake and thus impairing fishing activities and clogging the electric power station at the dam for which it was initially built. The biomass of the water hyacinth mat increased on the lake until the post rainy months after which it started to adhere to ground at shore and start drying as the water retracts back in the dry season. Vegetable growers around Lake Koka collect the dried water hyacinth biomass from flooded ground and burn it on their farm land 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. This noxious weed has gradually spread to all directions in the lake, and colonized all corners of the lake during the rainy season of 2020, which was only after three years of its first appearance at the lake. 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. Despite the overflow from Lake Abaya, which is already invaded by water hyacinth at maximum level, joins Lake Chamo through Kulfo River, water hyacinth was not established in Lake Chamo during our study period.

Establishment of freshwater lakes weed was previously reported to be highly related to the nutrient loading (Hossain et al. 2015). Water hyacinth prefers nutrient-rich water; its severity increases with N supply rate from 0.5 to 5.5 mg N/L with no significant increase in the weed biomass due higher N concentrations (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 Lakes Koka and Ziway is likely attributed to by high nutrient loadings observed at the two lakes.

5. Conclusions and recommendations

The current study demonstrated substantial differences between the three Ethiopian Rift Valley Lakes, namely Lakes Chamo, Koka and Ziway for physicochemical 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 of the lakes, the lakes' morphometry, geology, 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 compare with previous reports.

Invasive water hyacinth which existed for over 60 years in Lake Koka has established itself at Lake Ziway. The invasion of the weed in Lake Koka appeared to be aggravated by higher nutrient loadings from its catchment and absence of natural wetland vegetation in the shore of the lake which compete for space and the nutrients uptake.

In order to minimize the silt and nutrient loads in the lakes to restore and safeguard biodiversity in the freshwater lakes ecosystem, we recommend appropriate watershed management system be established and proper agricultural practices that minimize soil erosion and agro-chemical pollution, strict municipal and industrial waste management systems should be established and enforced by the authorities with participation by all the stakeholders.

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8. Tables and Figures

8.1. Tables

Table 1. Previous studies of some physicochemical parameters of Lakes Chamo, Koka and Ziway, Ethiopia.

Factor	Chamo	Koka	Ziway
Water T temperature (°C)	26.0 - 30.4 [i]	20.6 - 24.0[g]	23.1 - 27.5[g]
Secchi 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] Kebede etal. 1994; [d] Mesfin et al. 1998; [e] Tesfaye 2007; [f] Rango et al. 2009; [g] Masresha et al. 2011; [h] Degefu et al. 2011; [i] Fekadu and Chanie 2017; [j] Gebrehiwot et al. 2020.

Table 2. Previous reports on lakes' morphometry and fish diversity

Morphometry	**Lake Chamo**	**Lake Koka**	**Lake Ziway**
Latitudinal range	5°42' - 5°58' N	8° 18′ 57″ - 8° 28′ 21″ N	7° 52’ - 8° 8’ N
Longitudinal range	37°27' - 37°38' E	39° 0′ 0″ E - 39° 9′ 18″ E	38° 40’ to 38° 56’ E
Altitude (m.a.s.l.)	1110	1590	1636
Surface area (km2)	297	200	434
Mean depth (m)	6	9	2.5
Maximum depth (m)	13	14	8.95
Catchment area (km2)	1,109 (Teffera et al. 2018)	11,250	6,991(Abreham et al. 2018)
Estimated water volume (Gigalitre)	1,782	1,800	1,085
Fish species	Home for highly diversified 21 fish species than any other lakes in Ethiopian Rift Valley lakes (Golubtsov & Habteselassie, 2010). Six important fish species are $Nile perch (*Lates niloticus*), $Nile tilapia (*Oreochromis niloticus*), labeo (Labeo horie), $African catfish (*Clarias gariepinus*), $Bagrus (*Bagrus docmak*) & Barbus (*Labeobarbus intermedius*) (LFDP, 1997).	*Nile tilapia (Oreochromis niloticus), *common carp (*Cyprinus carpio*), & *African catfish (*C. gariepinus*) (Tesfaye and Wolff, 2015).	*$Nile tilapia (*O. niloticus*), indigenous to the lake, barbus spp (*L. intermedius* and *L. ethiopicus*, endemic to the Lake, straightfin barb (*Enteromius paludinosus*) and *Garra dembecha*, & exotic types including **C. gariepinus*, *Crucian carp (*Carassius carassius*), * *C. carpio* & Red belly tilapia (*Coptodon zillii*) (Endebu et al. 2015).

[$] indicates dominant species (Dejene 2008; Mereke & Mulugeta 2016); * indicates commercially important species.

Table 3. Pearson correlation coefficient between physicochemical 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	TMP	NTN	SRP
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)			
NTN	-0.26 (18)	-0.01 (18)	0.08 (18)	-0.26 (18)	-0.18 (18)	-0.260 (18)	-0.34 (18)		
SRP	0.23 (18)	0.15 (18)	-0.09 (18)	0.22 (18)	0.002 (18)	0.230 (18)	-0.05 (18)	0.62** (18)	
TPP	-0.20 (6)	-0.11 (6)	0.45 (6)	-0.18 (6)	-0.31 (6)	-0.189 (6)	0.10 (6)	-0.24 (6)	-0.28 (6)

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

Table 4. Analysis of variance performed on water temperature measured in ºC across three lakes and four seasons.

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		

Table 5. Analysis of variance performed on Secchi depth (cm) measured across three lakes and four seasons.

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		

Table 6. Analysis of variance performed on water pH measured across three lakes and four seasons.

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		

Table 7. Analysis of variance performed on total dissolved solids (mg/L) across the three lakes and four seasons.

Source	d.f.	s.s.	m.s.	v.r.	F pr.
Time	1	763852	763852	73.7	< 0.001
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		

Table 8. Analysis of variance performed on salinity (ppt) measured across the three lakes and four seasons.

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		

8.2. Figures

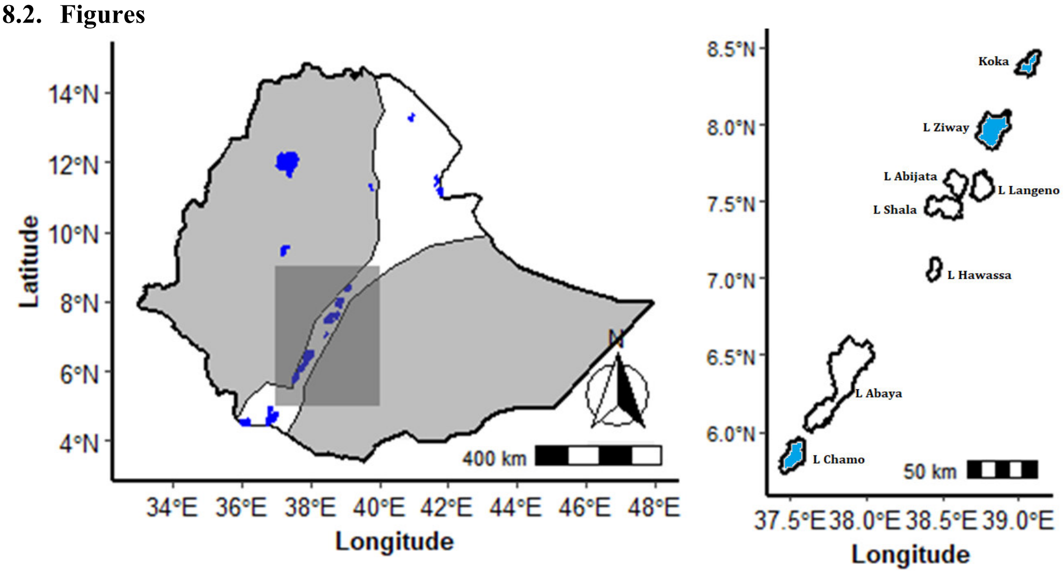
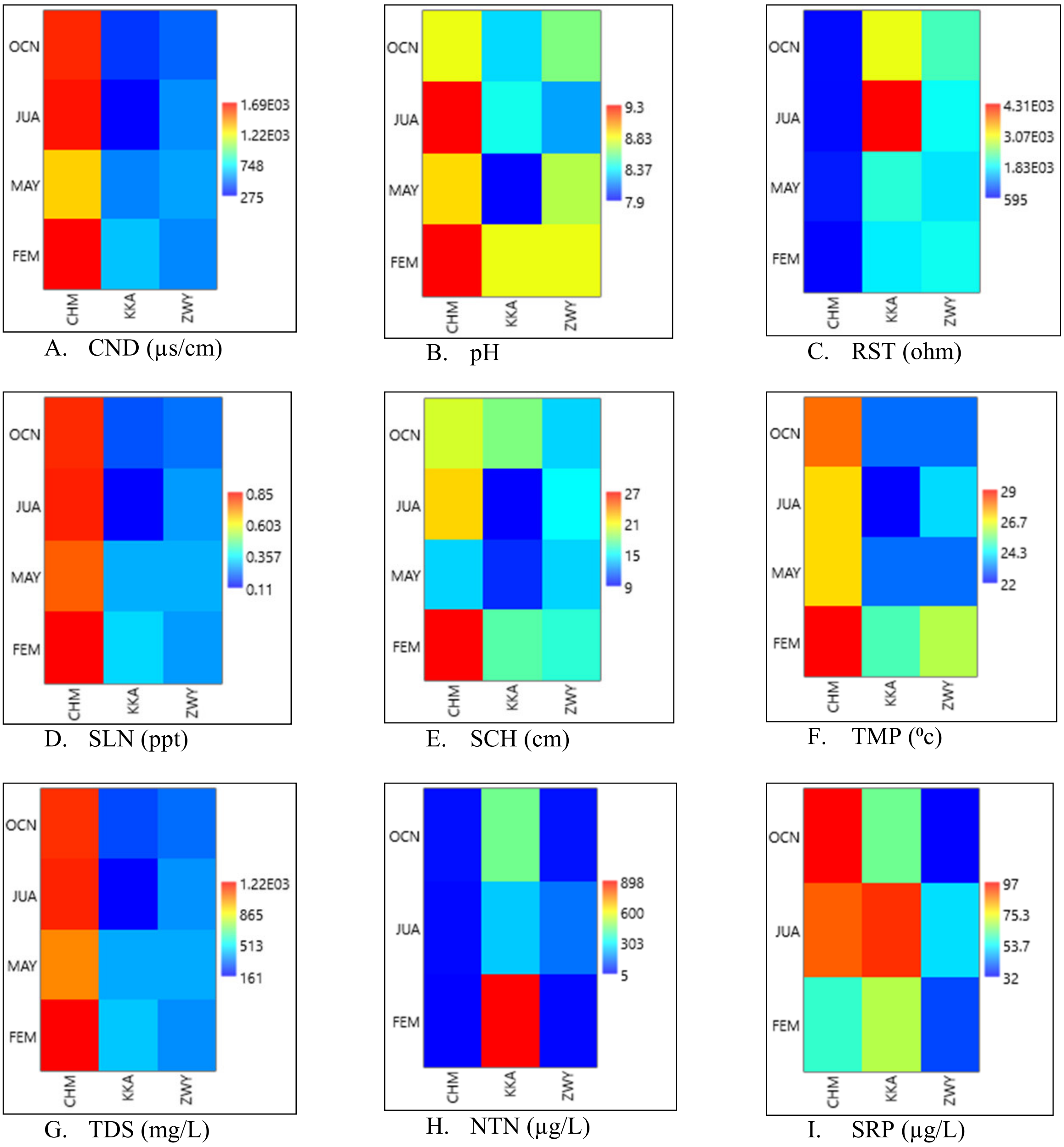


Fig. 1 Locations of Lakes Koka, Ziway and Chamo within the Ethiopian Rift Valley.



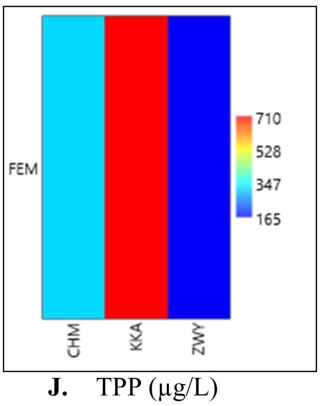


Fig. 2 Matrix plot of means of physicochemical parameters measured across two years at Inlet, Middle and Outlet Regions of Lakes CHM (Chamo), KKA (Koka) for seasons FEM (February to March), MAY (May), JUA (July to August) and OCN (October to November). Physicochemical properties (I) measured in-situ 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.

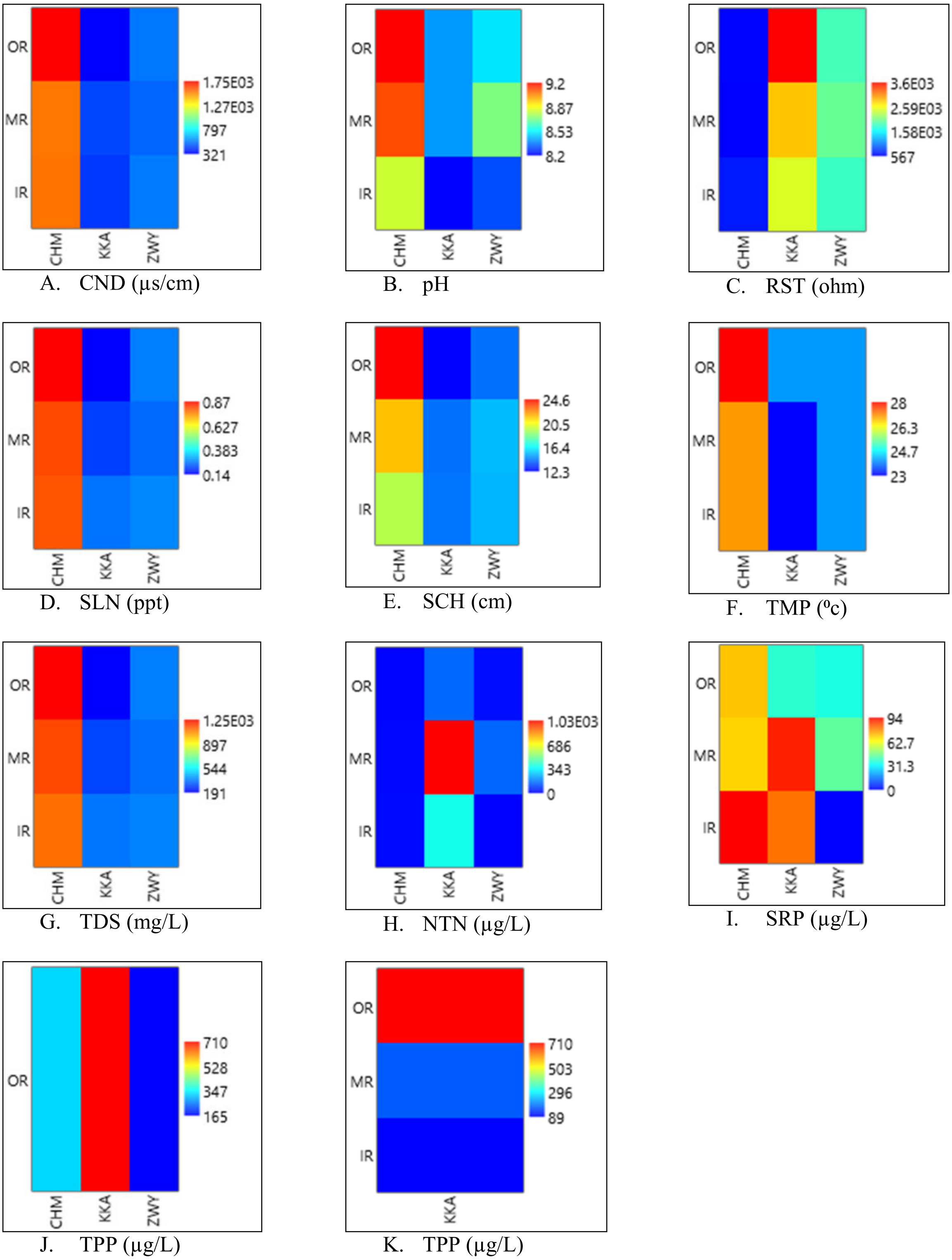


Fig. 3 Matrix plot of means of physicochemical parameters measured across two years and four seasons/ per year at IR (Inlet Region), MR (Middle Region) and OR (Outlet Region) of Lakes CHM (Chamo), KKA (Koka). Physicochemical properties (I) measured in-situ included (A) CND = Conductivity; (B) pH; (C) 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) and K TPP = total phosphorus. X-axis represents Lakes and Y-axis sampling sites.