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Spatial and Seasonal Variations in Physico-chemical Features of Tropical Endorheic Soda Lake Shala, Ethiopia

SOLOMON WAGAW[1]*, SEYOUM MENGISTOU[2] AND ABEBE GETAHUM[2]

[1]*Department of Biology, Wolkite University, P.O.Box 07, Wolkite, Ethiopia*
[2]*Department of Zoological Sciences, Addis Ababa University, Addis Ababa, Ethiopia*
Email: [1]wagawsolomon2@gmail.com; [2]seyoumeng@gmail.com; [2]abebe12002@yahoo.com
***Corresponding author**

ABSTRACT

Lake Shalla is a vital resource for considerable aesthetic, economic, scientific and ecological values. However, the lake is under pressure from various anthropogenic activities and climatic change. Hence, this study evaluated spatio-temporal variations in the physico-chemical parameters of the lake. Water samples were collected from four sampling stations from January to December 2018 and analyzed at Limnology laboratory, Addis Ababa University. All physicochemical factors exhibited significant variation among sites and between seasons (ANOVA, $P < 0.05$), except DO, which showed only seasonal variation. pH (10.08), Alkalinity (391.1 meq/L), NO_3-N (0.17 µg L^{-1}), NH_3-N (108.78 µg L^{-1}), SiO_2 (1.09 mg L^{-1}), TP (2.03 mg L^{-1}) and SRP (1.25 mg L^{-1}) were recorded at Shalla Gike Shore (SGS) and were significantly different compared with other sites. Mean concentrations of pH (10.1), Alkalinity (380.5 meq L^{-1}), NO_3-N (0.19 ìg L^{-1}), NH_3-N (113.69 µg L^{-1}), SiO_2 (1.16 mg L^{-1}), TP (2.14 mg L^{-1}) and SRP (1.45 mg L^{-1}) were recorded during rainy season, whereas DO (8.12 mg L^{-1}), EC (33.99 mS cm^{-1}) and salinity (21.34 g L^{-1}) were recorded during the dry season and were significantly different. Compared with previous studies, long-term increasing trend in pH, Alkalinity, Salinity, EC, NO3-N, NH3-N, SRP and TP, and decreasing trend in SiO2 were observed. These changes might be attributed to increasing anthropogenic activities in the catchments, biogeochemical process in the lake, geomorphic and hydrological characteristics of the region or climate change. The results of this study might be used as input for the long term planning and management of the lake.

Keywords: Anthropogenic activity, Climatic change, Biogeochemical process, Salinity, Electrical conductivity.

INTRODUCTION

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

Physico-chemical parameters play a major role in the distribution and abundance of biological communities in alkaline saline lake, which can in turn influence food web structure and energy flow in the aquatic ecosystem (Schagerl and Oduor 2008, Ogato and Kifle 2017). East African soda lakes are sensitive to changes in seasonality fluctuations in environmental factors, such as nutrients, stratification and mixing patterns, salinity and ionic concentrations, which affect the structure and functioning of biotic communities (Oduor and Schagerl 2007b, Schagerl and Oduor 2008, Lanzen et al. 2013). For instance, fluctuations in physical and chemical conditions have been shown to regulate phytoplankton composition (Oduor and Schagerl 2007a, Schagerl and Oduor 2008, Okoth et al. 2009, Kihwele et al. 2015, Ogato and Kifle 2017). Zooplankton distribution, in terms of species abundance, composition and size structure, is also affected by physicochemical and biological processes (Oyoo Okoth et al. 2011).

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

Limnological researches have been done on temporary and shallow soda lakes (García and Niell 1993, Melack et al. 2002), but few studies have been carried out on permanent saline and deep lakes (Kocer and Sen 2014). Previous studies on the limnological aspect of Lake Shala is well documented, but the overwhelming majority was based on a short time scale and did not address large scale changes (Talling and Talling 1965, Wood and Talling 1988, Kebede et al. 1994, GebreMariam 2002, GebreMariam et al. 2002, Ogato 2015). Since the area has witnessed major changes, with increasing anthropogenic activities, very pronounced climate change and the dynamic nature of physicochemical variables, the availability of up to date limnological data recorded over the long term is believed essential for sustainable management of the lake. Therefore, this study aims to contribute to the overall understanding of the environmental conditions of Lake Shalla by evaluating the seasonal and spatial variations of the physico-chemical variables over a year. The study also made comparisions on some physico-chemical variables starting from 1961 to assess the ecological status of Lake Shalla. Also as a baseline study to gauge future changes as a result of the new project on the lake and its resident biological resources.

MATERIAL AND METHODS

Description of the study area

Lake Shala lies between 7 °24’-7 °33’N and 38 °23’-38 °39’E at altitudes of approximately 1558m within the Abijata-Shala Lakes National Park (Fig 1). The lake is a volcano-tectonic lake (Le Turdu et al. 1999) found in the hydrologically closed system of the Ziway-Shala basin. Lake Shala is the deepest among the Ethiopian Rift valley lakes (maximum 266 m), with a surface area of around 329 km^2 and vast catchment area (3,920 km^2) (Von Damm and Edmond 1984, Baxter 2002). The lake region is characterized by a high evaporation rate that exceeds the mean annual rainfall (Ayenew and Legesse 2007). Climate of the Ziway–Shala region is mainly characterized by alternating wet and dry seasons following the annual movements of the Intertropical Convergence Zone (ITCZ) (Von Damm and Edmond 1984), the dry seasons from October to February and rainy seasons March to September. The rainy season is characterized by a bimodal rainfall pattern, with a minor rainy period extending from March to May and the major rainy period from June to September. Lake Shala receives its water from the Adabat and Gidu River (Baumann et al. 1975, Baxter 2002).

The lake is also surrounded by numerous hot springs, of varying salinity, temperature, size and discharge rate, which feed the lake (Baxter 2002). Lake Shalla is characterized by a high surface water temperature, pH, saline–alkaline conditions and a high phosphate content, but with very low nitrogen levels (Kebede et al. 1994, Ogato 2015). Despite this hostile nature of the environment, Lake Shalla supports phytoplankton, dominated by diatoms (Kebede et al. 1994) and cryptomonads (Ogato and Kifle 2017). Lake Shala also supports sparse zooplankton community and dominated by rotifers *Brachionus* species including *B. dimidiatus*, *B.*

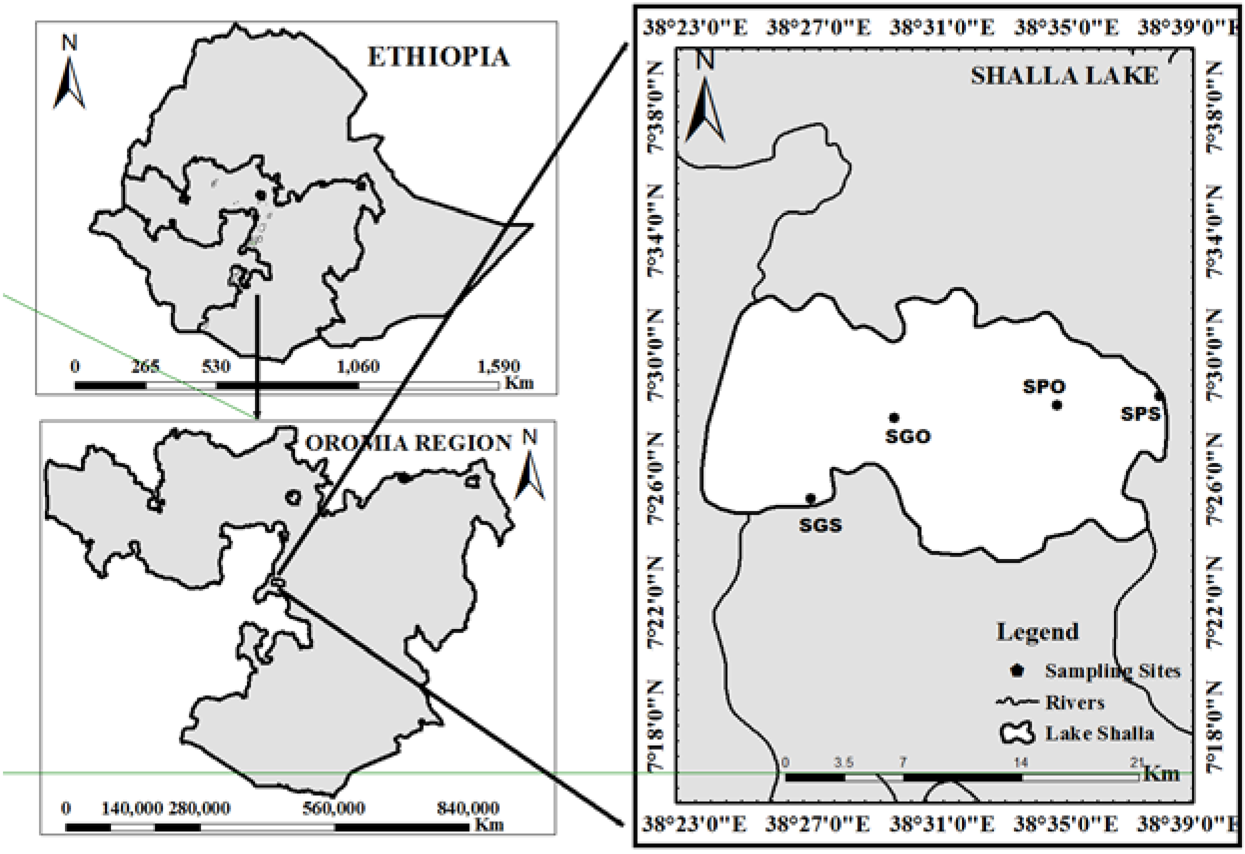


Figure 1. Map of Lake Shala showing the study sites/sampling points. (Abbreviation: SPS: Shala Park Shore; SPO: Shala Park Open; SGS: Shala Gike Shore; SGO: Shala Gike Open).

pliciatilis Hexarthra, and Copepods (Cylopoids and Harpacticoids). The benthic macroinvertebrate community of the lake comprises Tubificidae, Ostracoda and Chironomidae (Tudorancea and Harrison 1988). The lake also known by an outstanding avifauna diversity, mainly Pelicans and Lesser Flamingos, inhabiting the lake and its volcanic island. There is no fishing activity on the lake, with only *Oreochromis niloticus* and another small-sized fish, *Aplocheilichthys* sp., being reported for the lake (Golubtsov et al. 2002).

Physicochemical variables analysis

Four (4) georeferenced sampling site were established for studies onspatial and temporal variations of physico chemical parameters (Fig 1). Physical parameters (pH, dissolved oxygen, temperature, and electrical conductivity) of the lake water were measured *in situ* using a portable digital multi-parameter probe (Model HQ 9012 HACH) at each sampling stations at monthly intervals from January to December 2018. The conductivity measured *in situ* was adjusted to conductivity at 25 °C using a temperature coefficient of 2.3% per °C (Talling and Talling 1965).

Water samples were collected from each sampling site to analyze nutrients and the analysis was done monthly using spectrophotometric method in the limnology laboratory of the Addis Ababa University, following the standard analytical procedures detailed in APHA (1999). After filtration of the water sample through a 45-µm GFF, Nitrite nitrogen (NO_2-N) by the sulphanilamide diazotizing method; Nitrate-nitrogen (NO_3-N) by sodium-salicylate method; Ammonia nitrogen (NH_3-N) by Indo-Phenol blue method; Soluble reactive phosphorus (SRP) by the standard ascorbic acid method and Dissolved silica (SiO_2) by the ammonium molybdate method, were determined. Total phosphorus (TP) was determined by the ascorbic acid method after digesting the unfiltered sample using potassium persulfate according to APHA (1995). Total alkalinity (TA) was determined by titration with 1N HCl to pH 4.5 using a mixed indicator (bromocresol green-methyl red) within a few hours of sample collection according to Wetzel and Likens (2000).

Data analysis

Mean differences in physicochemical parameters among sites and seasons, were analyzed by non-parametric Kruskal–Wallis ANOVA. Logarithmic transformations, Log10 (x + 1), of environmental variables data were performed before all statistical tests to meet assumptions of normality and to reduce the effects of extreme values. The significant differences in the value of physicochemical variables between the study sites and seasons were compared using Kruskal-Wallis H test and Mann-Whitney U test ($P < 0.05$), box-and-whisker plots using Sigma Plot 10.0 were used for graphics.

RESULTS

Spatial variation of physicochemical parameters

The values of physicochemical parameters recorded among the sampling sites during this study are summarized in Table 1 and 2. Except for spatial variation in mean dissolved oxygen values, all other physicochemical parameters demonstrated significant spatial variations ($P<0.05$). The highest mean pH values were recorded at SGS (10.08±0.15) while SPO had the lowest values (9.94±0.27) with a mean value of 10.01± 0.19. Comparison of the mean water temperature values showed that there was a significant difference among sampling stations, $P< 0.05$ (Table 1). Mean water temperature values were highest in SPS (25.13±1.19 °C) and SGO recording the lowest mean temperatures with 24.15±0.82 °C.

Table 1. Spatial variation of physical environmental variables of the studied stations of Lake Shala (SPS: Shala Park Shore; SPO: Shala Park Open; SGS: Shala Gike Shore; SGO: Shala Gike Open; Temp: Temperature; DO: Dissolved Oxygen; EC: Electrical Conductivity; Alka: Alkalinity)

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

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

Table 2. Spatial variation of nutrient variables of the studied stations of Lake Shala. (SPS: Shala Park Shore;: SPO: Shala Park Open; SGS: Shala Gike Shore; SGO: Shala Gike Open; TP: Total Phosphorus; SRP: Soluble Reactive Phosphorus)

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

Based on Krusukali Wallis test, the distribution of NO_3-N, NH_3-N, SiO_2, TP and SRP is not the same across the sites.

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

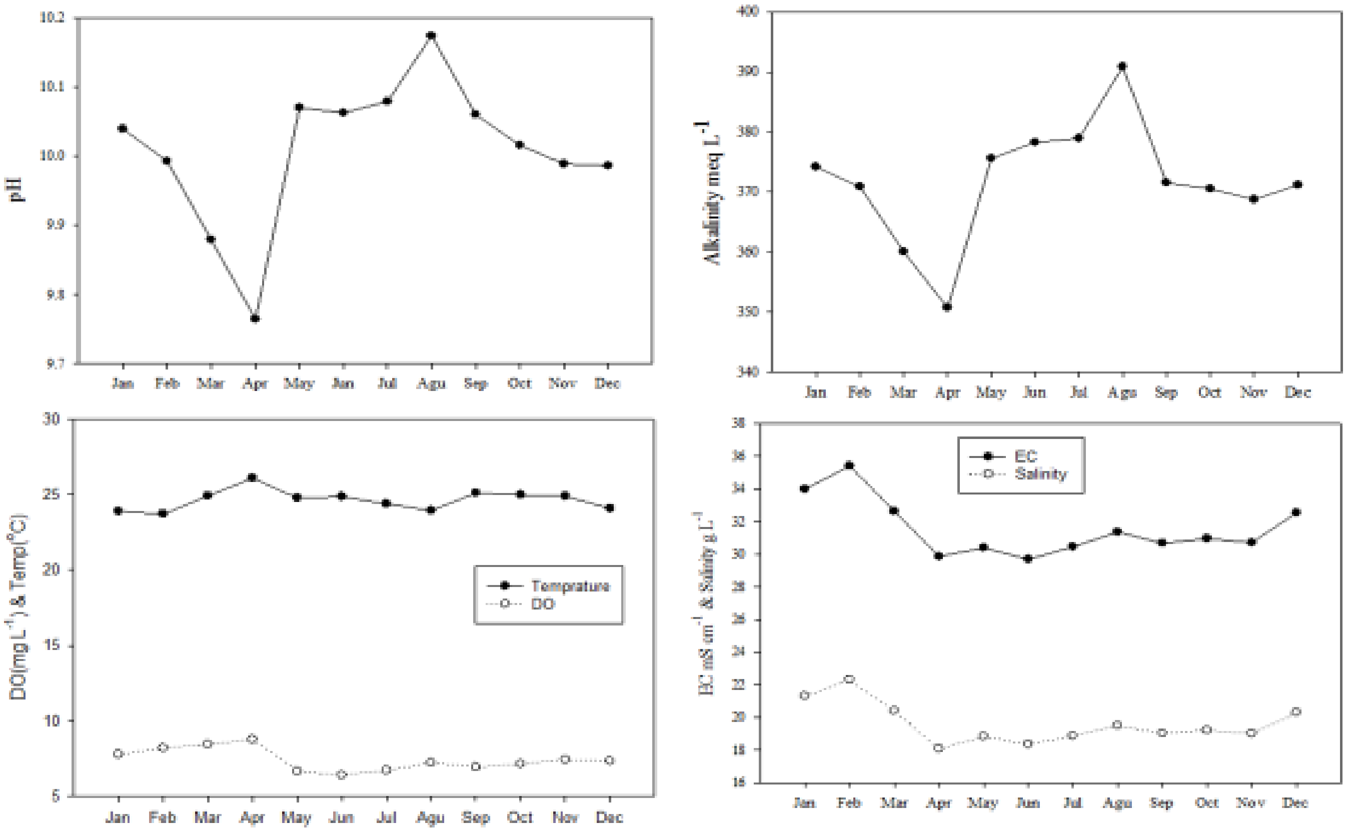


Figure 2. Temporal variations of physical environmental variables among months at the surface of Lake Shalla.

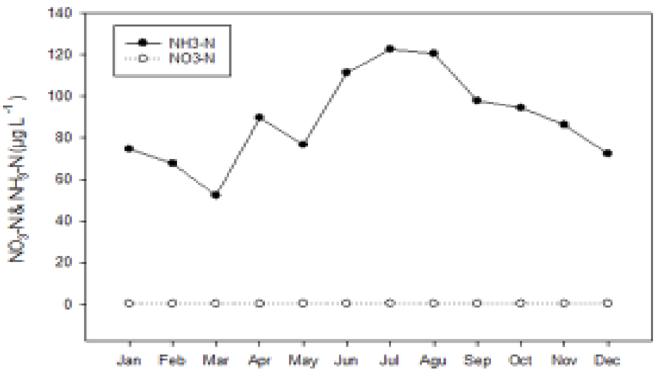
Spatial variations in Electrical Conductivity (EC) and Salinity were also significant ($P < 0.05$). EC (32.89 ± 2.82 mS cm^{-1}) and salinity (20.56 ± 1.96 g L^{-1}) measured at SPO was higher than other sites. Alkalinity in Lake Shalla also showed spatial variations (Table 1). The highest concentration of Alkalinity (291.1 ± 16.05) was recorded at SGS and statistically significant comparing to other sampling stations. Based on Krusukali Wallis test, the distribution of pH, Temp, EC, Salinity and Alkalinity is not the same across the sites.

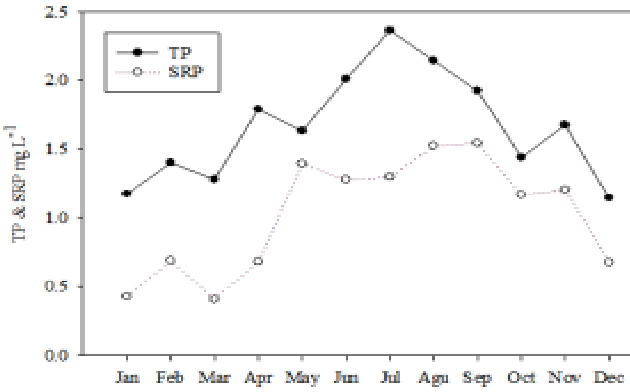
The nutrient concentrations NO_3-N, NH_3-N, SiO_2, TP and SRP in Lake Shalla exhibited spatial variations ($P < 0.05$) (Table 2). The mean value of NO_3-N was almost undetectable over the study sites (<0.2 ìg L^{-1}) and ranged from 0.14 µg L^{-1} of the SPO to 0.17 µg L^{-1} of the SGS, with a mean value of 0.154 ± 0.04 µg L^{-1} (mean±SD). NH_3-N, SiO_2, TP and SRP records at the shore sites were higher than those recorded at the open sampling stations (Table 2).

The mean NH_3-N (µg L^{-1}) recorded were 100.28, 71.37, 108.78 and 74.87 for SPS, SPO, SGS and SGO, respectively. The mean concentration of SiO_2 varied spatially with a pattern similar to that of NH_3-N (Table 2) and with mean values of 0.99 mg L^{-1} (SPS), 0.67 mg L^{-1} (SPO), 1.09 mg L^{-1} (SGS) and 0.72 mg L^{-1} (SGO). The highest mean concentration of TP (2.03) and SRP (1.23) were recorded at Shalla Gike Shore station and exhibited significant spatial variations compared to other study sites ($P < 0.05$).

Temporal and seasonal variations in physicochemical parameters

The physicochemical values of Lake Shala showed temporal and seasonal varations (Fig. 2 and 3). The mean pH value displayed significant difference mong the sampling months and the values varied from 9.76 in April to 10.17 in August, with a mean of 10.01±0.19 (Fig. 2). Alkalinity values ranged from 250.75 meq L^{-1} (April) to 290.88 meq L^{-1} (August) (271.81±22.95 meq L^{-1}) (Fig. 2). Although their seasonal variations were significant, pH and Alkalinity showed an increasing trend during the rain season with a mean value of 10.1 and 380.5meq L^{-1}, respectively (Table 3). Surface water temperature in





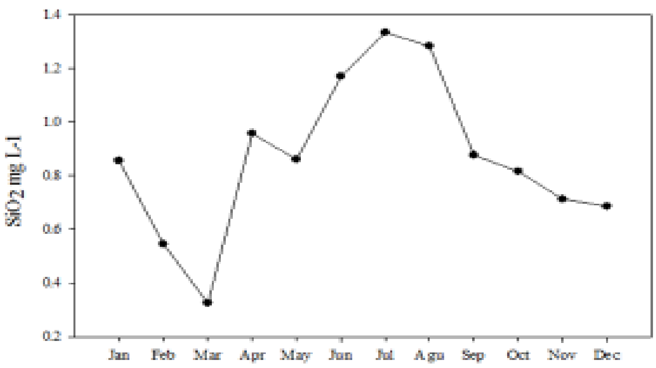


Figure 3. Temporal variations of chemical variables among months in Lake Shala

Lake Shalla also showed variations among months and the values varied from 23.7 °C in Feburary to 26.09 °C in April, with a mean of 24.63±1.08 °C (Fig. 2). The highest water temperature value was recorded during pre rainy seasons (25.24±1.28) and statistically significant ($P < 0.05$) compared to other seasons (Table 3).

The value of DO, EC and salinity showed some variability among months though the variations among the sampling seasons were significant ($P < 0.05$). DO varied from 6.38 in June to 8.76 in April, with mean of 7.40±0.96 mg L^{-1} (Fig. 2, Table 3). EC ranged from a minimum of 29.67 mS cm^{-1} in June to a maximum of 35.39 mS cm^{-1} February, with a mean of 31.54±2.55 mS cm^{-1} (Fig 2; Table 3). The value of salinity also varied from 18.08 g L^{-1}in April to 22.31 g L^{-1} in February, with a mean of 19.60±1.84 g L^{-1} (Fig. 2, Table 3). The average level of DO (8.12±0.83), EC (33.99±3.42 mS cm^{-1}) and salinity (21.34±2.37 g L^{-1}) were generally high during the dry seasons and statistically siginificant ($P < 0.05$) (Table 3). These parameters also increased slightly during the rainy season (Fig. 2, Table3).

Distinct seasonal and temporal variations were observed for all inorganic nutrients (Fig. 3, Table 4). The long rainy seasons in July to September resulted in increased concentrations of NO_3–N, NH_3–N, SiO_2; TP and SRP in Lake Shala. The concentration of NO_3–N and NH_3–N ranged from 0.098 µg L^{-1} in March to 0.223 µg L^{-1}in July (0.154±0.04 µg L^{-1}, mean±SD) and from 52.23 µg L^{-1} in March to 122.62 µg L^{-1} in July (88.82±29.82 µg L^{-1}, mean±SD), respectively (Fig.3, Table 4). The varations in NO_3–N and NH_3–N concentration among the seasons was significant ($P < 0.05$) and the highest mean values of NO_3–N (0.19 µg L^{-1}) and NH_3–N (113.69 µg L^{-1}) were recorded during the rain season (Table 4).

SiO_2 concentration was variable among the study months and seasons with a general increase rainy in the months (Fig. 3, Table 4). SiO_2 ranged from 0.33 mg L^{-1} to 1.33 mg L^{-1} (0.87±0.36 mg L^{-1}, mean±SD) in March and July, respectively. Like other organic nutrients, the mean concentration of SiO_2 among the seasons was statistically significant and the highest value (1.16 mg L^{-1}) was recorded during rainy seasons (Table 4). The concentrations of TP and SRP varied from 1.14 mg L^{-1} in December to 2.36 mg L^{-1} in July (1.66±0.52, mean ±SD) and from 0.4 mg L^{-1} in March to 1.54 mg L^{-1} in September (1.02±0.47 mg L^{-1}, mean ±SD), respectvilty (Fig.3, Table 4). The concentration of TP and SRP also varied seasonally with an increasing trend during the rainy season, the

Table 3. Seasonal variation of physical environmental variables of Lake Shala (Temp: Temperature; DO: Dissolved Oxygen; EC: Electrical Conductivity; Alka: Alkalinity)

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

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

Table 4. Seasonal variation of chemical environmental variables of Lake Shala. (TP: Total Phosphorus; SRP: Soluble Reactive Phosphorus)

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

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

highest values of TP (2.14 mg L^{-1}) and SRP (1.45) were recorded during the rainy season and lowest concentration during the dry season (Table 4).

Trends in physico-chemical parameters

Chronological outline of past work on some physicochemical variables of Lake Shala from the period of 1961 to 2018 is presented in Table 5 and showed some variations. The variations in these physicochemical parameters could be accredited to the specific environmental degradation. Comparing the present mean pH value to studies made during 1961-2012, the highest mean value of pH were recorded in the present study but it is within the ranges found in the previous study (Table 5).

The mean electrical conductivity was generally higher in the present study of Lake Shala compared to data from the 1960s (Table 5) and nearly comparable to the mean value (33000 µS/cm) reported by Talling and Talling (1965) (Table 5). The current mean value of salinity in Lake Shala (19.6 g L^{-1}) is comparable to the value (19.582 g L^{-1}) reported by Talling and Talling (1965), but higher than that reported by (16.8 g L^{-1}) Baumann et al. (1975); 18.1 g L^{-1} (Kebede et al. 1994) and 15.7 g L^{-1} (Talling and Talling 1965).

Concentration of soluble reactive phosphorus (SRP) appears to have decreased from 1964 to 2000 in Lake Shala except in 1991 (809 µg L^{-1}) recorded by Kebede et al. (1994), latter highest concentration were recorded by Ogato (2015) 961 µg L^{-1} and 1020 µg L^{-1} in the present study. Concentrations of silicate decreased markedly in Lake Shala. Compared to the present data, the high silicate values (130 mg L^{-1}) was recorded in the 1960s by Talling and Talling (1965). Ogato (2015) measured lowest concentration in 2012 which is comparable to the current result (Table 5). The mean concentration of NH_3-N increased considerably when compared with some results reported by Kebede et al. (1994) (4.3 µg L^{-1}), GebreMariam (2002) (4.65 µg L^{-1}), Ogato (2015) (42 µg L^{-1}).

DISCUSSION

The physico-chemical variables recorded in Lake Shala are similar to those observed in most soda lakes of East Africa (Talling and Talling 1965, Wood and Talling 1988, Oduor and Schagerl 2007b, Oyoo Okoth et al. 2011, Kihwele et al. 2015). The observed high pH, alkalinity and electrical conductivity is an

Table 5. Some previous and current physicochemical factors of Lake Shala, and trends since 50 years back.

References	Sampling time	pH	EC	Salinity	Alkalinity	SRP	SiO_2	NO_3-N	NH_3-N
Talling & Talling (1965)	May 61		33000	19.582	200		130		
Wood & Talling (1988)	Jan 64				210				
Wood & Talling (1988)	Mar 64	9.9	21940	21.5	212	760	112		
Wood & Talling (1988)	Oct 66		24640		216				
Baumann et al. (1975)	May 71	10		16.8	188				
von Damm & Edmond (1984)	Jan 76				218.8				
Kebede *et al.* (1994)	March-May 1991	9.65	21940	18.1	218	809	56	ND	4.3
GebreMariam *et al.* (2002)	1990-2000	9.7	22863		217.3	727	49.1		
GebreMariam (2002)	Wet & dry seasons between 1990-2000	9.72	22757		216.71	613.85	49.5	0.85	4.65
Ogato (2015)		9.96	25800	15.7	224	961	0.9	ND	42
This study		10.01	31540	19.6	271.8	1020	0.87	0.154	88.82

indication of alkaline-saline nature of Lakes Shalla, this might probably contributed by high concentrations of carbonate salts (e.g. sodium carbonate), release of alkalis from soluble solutes by chemical weathering (Deocampo and Renaut 2016), sodium chloride and other dissolved salts, making them saline alkaline lakes (Talling and Talling 1965, Kebede et al. 1994, Deocampo and Renaut 2016). Also, high surface evaporation rate in the study area and leaching of volcanic rock minerals through weathering and biological activities (Grant et al. 2006), low level of divalent cations (Ca^{2+} and Mg^{2+}), enhance alkalinity due to the reduced precipitation of the divalent cations as carbonates and contribute to the lakes saline-alkaline properties (GebreMariam et al. 2002, Klemperer and Cash 2007).

Some physicochemical parameters examined in this study were considerably higher than previously reported on the same lake (Talling and Talling 1965, Baumann et al. 1975, Kebede et al. 1994, GebreMariam et al. 2002, Ogato 2015), indicating that Lake Shala ecosystem has undergone fundamental ecological shifts. Several limnological studies have reported that physicochemical parameter changes over a time scale associated with the degradation of the lake (GebreMariam et al. 2002, Ayenew and Legesse 2007). Ayenew and Legesse (2007) also noted environmental degradation on neighboring soda lake, Lake Abijata. This environmental degradation may be reflected in the nature of variations in the distribution and community structure of biodiversityin this aquatic system.

Comparing studies made during 1964–2013 (Talling and Talling 1965, Baumann et al. 1975, Kebede et al. 1994, GebreMariam et al. 2002, Ogato 2015), the highest mean value of pH (10.01) was recorded in the present study but was found within the same ranges (Table 5). High pH value was also reported in earlier investigations made in other similar alkaline–saline waterbodies of East African Soda lales (Milbrink 1977, Wood and Talling 1988, Oduor and Schagerl 2007a, Schagerl and Oduor 2008, Kihwele et al. 2015).

In the current study, Lake Shala displayed considerable spatial and seasonal variation in pH. This substantial varations is in fact because of photosynthetic activity, respiration, vacillation of temperature, seasonality in rainfall, freshwater influx and decay of organic matter that can shift the pH (Talling et al. 1973, Govindasamy et al. 2000, Bragadeeswaran et al. 2007, Saravanakumar et al. 2008b, Rajkumar et al. 2009). The high pH and alkalinity mean values in the present study can be also associated with the mineral content of the local geology and hydrolysis of silicate minerals that consumes hydrogen ions from solution and releases alkalications. This has the effect of both raising the pH and increasing the alkalinity in African soda lakes (Deocampo and Renaut 2016). In adition, the observed high surface water temperature might have catalyzed ionization of salts leading to high pH and alkalinity values (Kihwele et al. 2015). Lake Shalla, is an endorheic in nature, high surface evaporation rate and daily wind influence have combined forces making it experiences high concentrations in most of the solute variables due to net accumulation and suspension from the rockbed, which accounts to the observed high values of pH and alkalinity (Schagerl and Oduor 2008).

Salinity and electrical conductivity (EC) are the most important factors which determine the composition of the biological component in the soda lakes (Oduor and Schagerl 2007b, Schagerl and Oduor 2008, Kihwele et al. 2015). The mean salinity and EC values measured in this study 19.6 g L^{-1} and 31.54 mS cm^{-1}, respectively, were higher than values of 18.1 g L^{-1} and 21.94 mS cm^{-1} reported by Kebede et al. (1994); 15.7 g L^{-1} and 25.8 mS cm^{-1} reported by Ogato (2015). The observed somewhat progressive increasing trend of salinity and EC of Lake Shala could be associated with the accumulation of solutes and saline surface runoff from its degraded catchments. Similarly, in recent years, the water environment problems of salinization of the Ziway-Shala basin have become serious accompanied with population growth and the rapid development of industry, water abstraction for irrigation, soda ash production and expansion of agriculture (GebreMariam et al. 2002, Wagaw et al. 2019).

Seasonal and spatial variations in salinity and EC in Lake Shalla seem to be related to the seasonal influence of precipitation and evaporation. The highest value of salinity and EC were recorded during the dry season and offshore sampling station of Lake Shalla. It seems that it is associated with high rate of evaporation in the lake region that exceeds the water inputs (Ayenew and Legesse 2007). Similarly, GebreMariam et al. (2002) observed an increase in conductivity during the dry season in some Ethiopian rift valley lakes (e.g., Lake Hawassa and Langano). The statistical evaluation of salinity and EC from the four different sample sites at each lake showed significant difference ($p < 0.05$). The lowest salinity and EC values at SGS were probably due to the dilution by less saline and conductivity of inflowing hot springs water at this site, which appear to have influence on the salinity and conductivity of the lake. Owen et al. (2008) also noted the influence of hot springs which contain less salt than the lake water on salinity and conductivity of Lake Bogoria, Kenya Rift Valley.

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

Rates of photosynthesis and respiration, oxidation-reduction reactions, and stratification and mixing patterns are considered to be the major factors governing the variability of dissolved oxygen in East African soda lakes (Oduor and Schagerl 2007a, Schagerl and Oduor 2008, Okoth et al. 2009, Krienitz and Kotut 2010). Spatial distribution pattern of DO levels were insignificant among the study stations in Lake Shala. However, there was seasonal varations in DO level. The observed highest amount of DO during the dry season and lowest in the rainy season might be related to the activities of photosynthetic organisms and rate of respiration by decomposers such as bacteria and fungi in soda lakes of East Africa (Jones and Grant 1999, Grant and Sorokin 2011, Kambura et al. 2016). Recent sudy also identified remarkable diversity of microbial communities in Lake Shala (Lanzen et al. 2013), which may responsible for lessening of DO. Wood et al. (1984) and Melack (2009) also suggested the depletion of DO in tropical soda lakes by combination of algal biomass decomposition and high microbial activity. According to those authors, an increases in decomposition rates and decreases in oxygen usually occur during rainy season, when decomposing organic matter input to the lakes increases. This process rapidly leads to a decrease in DO due to microbial respiration during decomposition (Duckworth et al. 1996, Lanzen et al. 2013, Kihwele et al. 2015). The current high record of temperature during rainy season might enhance the decomposition rate by bacterial activity, and consequently decrease DO concentrations (Rocha et al. 2009). In addition, depletion in DO during rainy season period might have been caused by changes in the composition and abundances of phytoplankton (Ogato 2015).

Inorganic nutrients

In the present study, the concentration of nitrate-nitrogen and ammonia-nitrogen are very low in Lake Shala and reflected the characteristic features of most soda lakes of East Africa (Talling and Talling 1965, Wood and Talling 1988, Kebede et al. 1994). Previous studies also reported similar findings in these and other soda lakes of Ethiopia (Wood and Talling 1988, Kebede et al. 1994, GebreMariam et al. 2002, Ogato 2015). However, Ballot et al. (2004) and Schagerl and Oduor (2008) recorded considerably higher values of nitrate in Nakuru, Bogoria and Elmentaita lakes in Kenya compared to our findings in Lake Shala. The wide distribution of ammonia and nitrite-oxidizing organisms in the soda lakes might be responsible for low nitrogen levels in African soda lakes (Jones and Grant 1999, Grant et al. 2006, Lanzen et al. 2013). High diversity and abundance of ammonia and nitrite-oxidizing organisms (e.g. *Thaumarchaeota*) were recently reported from Lakes Shala (Lanzen et al. 2013), seem to have low concentration of nitrogen content . In the present study and in Ogato and Kifle (2017), a number of cyanobacteria found in this lake like *Anabaena* spp. are nitrogen fixers, which may contribute to nitrogen depletion.

Although nitrate-nitrogen and ammonia-nitrogen displayed seasonal and spatial varations in Lake Shala, the rapid increase in NO_3-N and NH_3-N concentration with the beginning of rains suggests that the inflowing rivers and runoffs from the surroundings might bring nitrogen compounds into the lake. Similar observation was made by GebreMariam (2002) and Ogato and Kifle (2017) and showed noticeable external source of NO_3-N and NH_3-N in Lake Shala associated with seasonal hydrological events. The higher concentration of nitrogen nutrients were recorded in Shala Gike Shore site in this study (SGS), in which Lesser and Greater Flamingoes, White Pelicans, Cormorant, Egyptian goose and *Oreochromis niloticus* that inhabit in substantial numbers can have potential contribution of ammonia, nitrates, phosphates and nitrites. Sitotaw (2014) also reported nitrogen sources from waterbird feather degradation in soda lakes as keratin-degrading microbes. In addition large numbers of domestic and wild animal populations in Abijata-Shala Lakes National Park might contribute to the nitrogen through solid wastes during the rains, particularly at the shore of the lake. Oduor and Schagerl (2007b) and Kihwele et al. (2015) also reported faecal droppings from wetland birds and domestic animals as major contributions to escalated nutrient levels in Kenyan Rift Valley saline-alkaline lakes and Lake Manyara, Tanzania.

Concentrations of total-phosphorus(TP) and soluble reactive phosphate (SRP) in surface waters of alkaline lakes are generally high, even exceptionally high in the most extreme African soda lakes (Ballot et al. 2004, Schagerl and Oduor 2008). The current study recorded higher concentrations of phosphate which were comparable to the values previously reported in the same lake and other East African soda lakes (Wood and Talling 1988, Kebede et al. 1994, Ballot et al. 2004, Oduor and Schagerl 2007a, Schagerl and Oduor 2008, Ogato 2015). High phosphorus concentrations in Lake Shalla may be coming from the predominance of phosphatic mineral-rich rocks (Talling and Talling 1965), being anoxic in Lake Shala, coupled with the high pH which might be responsible for release of large amount of phosphorus from the sediments (Oduor and Schagerl 2007b).

Although the concentration of TP and SRP exhibited considereable spatial and sesonal variations, these varations are strongly linked to climatic changes and especially rainfall (Oduor and Schagerl 2007b), biogeochemical processes, phosphorus input from river flows and hotsprings (Deocampo and Renaut 2016), triggering varations in phosphorus concentration along the sampling site and seasons. Lakes Shala aslso showed a considerable increasing trend in phosphorus concentrations compared to data from the 1960s to

2012, probably due to human activities in the catchment like deforestation and surfacewater runoff, organic fertilizers and livestock production which have a strong impact on phosphorus level in Lake Shalla.

The observed seasonal and spatial variations of SiO_2 probably indicate the occurrence of some important processes within the lakes and the presence or absence of diatoms which may markedly influence the variation of silicate in surface waters. Several studies reported the association of SiO_2 depletion with the abundance of diatoms on tropical African lakes (Lemoalle 1981, Hecky 1993). Dissolved SiO_2 could also be significantly removed from the water column due to the sedimentation of diatom frustules (Milbrink 1977). In the present study, diatoms were found as the dominant taxa in terms of number of species and abundance and thus may be important removers of SiO_2 in the lake (Wood and Talling 1988, Kebede et al. 1994, GebreMariam et al. 2002).The high silicate values recorded in the 1960s to 2000 in Lake Shala were not measured in samples taken during 2012 by Ogato (2015) and in the present study. The general decline in silicate concentrations was also observed in some Ethiopian Riftvally lakes such as Lakes Abaya and Langano (GebreMariam et al. 2002). Hecky and Bugenyi (1992) and Hecky (1993) also reported a similar situation in Lake Victoria, where silicon concentrations declined by an order of magnitude between 1961 and 1988. Talling (1966) suggesteted the decline of silica concentration with abundance of diatoms and sedimentation, where accumulated organic matter would impose a slower rate of regeneration in East Africa alkalline lakes (Hecky and Kilham 1973). Silicate will also be removed from solution in the reverse weathering process of sediment formation (Wood and Talling 1988).

CONCLUSIONS

Lake Shala showed distinct seasonal and spatial variations in physico-chemical parameters throughout the study period. Physical parameters such as dissolved oxygen, electrical conductivity and salinity increased during the dry season. In contrast, an increase in nutrients (NO_3-N, NH_3-N, SiO2, TP and SRP) were observed during the rainy season. Spatially all nutrients and some physical varibles (pH, temperature and alkalinity) were found to be higher in the shore sampling stations while higher electrical conductivity and salinity concentration were observed in the open lake site. It is observed that the precipitation received during rainy months has considerable impact on the Lake Shala water characteristics. In addition anthropogenic activities, increasing domestic animals, wetland birds and biogeochemical processes in the lake have an impact on the physical and chemical features of the lake. The present study provides better understanding of the ecological conditions of the Lake Shala by comparing with previous limnological studies and the result showed that Lake Shala ecosystem has undergone fundamental ecological shifts. Moreover, there is upcoming Lake Shala brine water extraction and will have a possible impact on physichochemical features of the lake. Therefore, the result from this study may help management authorities in planning strategies for integrated lake management options to maintain a sustainable ecosystem by reducing external pressures to conserve Lake Shala biota, especially the unique bacteria, plankton and tilapia fish.

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