Int. J. Aquat. Biol. (2022) 10(5): 349-365
ISSN: 2322-5270; P-ISSN: 2383-0956
Journal homepage: www.ij-aquaticbiology.com

Original Article

Diatom community structure in relation to physico-chemical factors in a tropical soda Lake Shala and inflowing hot-springs, Ethiopia

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Abstract: Diatoms are highly diverse and versatile, with members growing under different environmental conditions including extreme environments. Although diatom communities in some extreme environments have been investigated recently, little is known about their community structure within the hot springs of soda lakes in Ethiopia. The study aimed to assess the diversity and distribution of diatoms from Lake Shala and inflowing hot springs in relation to physico-chemical variables. Water and diatom samples were collected from Lake Shala and three inflowing hotsprings. The mean pH, temperature, EC, salinity, TDS, DO, NO_3^-+NO_2^-, NH_3+NH_4^+, SRP, TP and SiO_2 were significantly different among the stations. The significant variations in these factors could be attributed to their heterogeneous geological characteristic and the hydrology of the study area. A total of 45 diatom taxa were identified, with the highest species observed in Shala Hora Mid Hotspring sites (37) and the lowest in Shala Gike Hotspring (29). Diatom community structure was also examined and it was found that the diatom community of Lake Shala and inflowing hotsprings are highly influenced by environmental water conditions. Characteristic taxa including *Anomoeoneis sphaerophora, Nitzschia spp*., *Rhomboids gibberula*, *R. gibba*, *R. acuminata, R. operculata*, *Navicula* spp. and *Frustulia rhomboids*, showed a wide tolerance to pH, salinity, EC, TDS, temperature, nitrogen and phosphate. RDA analysis found a number of discriminating taxa and salinity, conductivity, pH, DO SRP and temperature were key factors that accounted for a significant variation in the diatom community structure.

Article history:
Received 27 May 2021
Accepted 22 October 2022
Available online 25 October 2022

Keywords:
Diatom community
Lake Shala
Hot spring
RDA analysis

Introduction

Soda lakes of the East African Rift Valley are among the world's most productive ecosystems (Ogato et al., 2016). The Lesser Flamingo (*Phoeniconaias minor* Geoffroy Saint-Hilaire, 1798) population inhabits these lakes and can gather in flocks of over one million birds when the phytoplankton community of the lake is dominated by *Arthrospira fusiformis*, their primary food sources (Matagi, 2004; Kumssa and Bekele, 2014). In Ethiopia, the main Flamingo lakes are Abijata, Shala, Metehara, Chitu, and Aranguade, which provide a preferred feeding and breeding habitat for large populations of avifauna (Kumssa and Bekele, 2014).

Despite the ecological, economic and scientific research values of these lakes, only a few are subjected to active conservation (Matagi, 2004). These ecosystems are highly sensitive to environmental change mainly because of seasonal alterations of hydrological conditions and human-induced disturbances, which have been demonstrated to affect biological community structure in Saline lakes (Oduor and Schagerl, 2007a; Krienitz and Kotut, 2010). Saline lakes, especially those in the tropics, remain poorly studied, particularly in the processes controlling species distribution (Mengistou, 2016; Ogato and Kifle, 2017). Diatoms are considered the main component of aquatic ecosystems because they are usually the dominating primary producers (Krienitz and Kotut, 2010) and functionally important in sequestering and transforming many inorganic nutrients into organic

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DOI: https://doi.org/10.22034/ijab.v10i55.1229
DOR: 20.1001.1.23830956.2022.10.5.1.2

forms (Krienitz and Kotut, 2010). The benthic diatoms constitute a significant energy source for higher trophic levels (Bate et al., 2002; Carvalho et al., 2002). Despite their ecological importance, the various factors that regulate community distribution and structure are poorly understood compared to pelagic phytoplankton communities (Carvalho et al., 2002).

Many studies have reported a wide distribution of benthic diatoms and their tolerance to gradients of diverse environmental variables (Gasse, 1986; Wood and Talling, 1988; Kebede et al., 1994; Oduor and Schagerl, 2007a; Krienitz and Kotut, 2010). Saline Lakes and the nearby hot springs are complex ecosystems in which many environmental factors vary on spatial and/or temporal scales. These factors include geomorphic characteristics, nutrient and ionic concentrations and other physico-chemical properties, manifesting great ecological variability in species composition (Gasse, 1986; Wood and Talling, 1988; Gebre-Mariam, 2002; Oduor and Schagerl, 2007b; Krienitz and Kotut, 2010). There have been few studies on the ecology of benthic diatom in Ethiopian Rift valley lakes (Gasse, 1986; Woldesenbet, 2019; Wondmagegn, 2019). However, compared with other East African Rift Valley lakes, only a few data are available on diatoms of saline lakes in Ethiopia (e.g. Gasse, 1986).

Previous studies on Lake Shala have focused on the primary productivity, algal biomass and water chemistry (Talling et al., 1973; Baumann et al., 1975; Wood and Talling, 1988; Kebede et al., 1994; Gebre-Mariam, 2002) and on the taxonomic identification and classification of the phytoplankton species, with limited studies, i.e., Ogato (2015), focusing on the relationships between physico-chemical variables and phytoplankton. However, the physicochemical variable-dependent diatom distributions have not been well-studied in Lake Shala and associated hot-springs. Accordingly, the present study focuses on patterns of benthic diatom community structure in relation to environmental (chemical and physical) and spatial factors in this alkaline saline environment.

Lake Shala is one of the East African Soda ecosystems and is fed by heated groundwater rising from deep aquifers along established fault lines (Grant and Jones, 2016). These hot springs and their drainage channels provide remarkable ecosystems and exhibit spatio-temporal variation in biotics with fascinating gradients of pH, salinity, dissolved oxygen (DO), electrical conductivity (EC) and temperature. The purpose of this work was to answer whether the diatom of Lake Shala and inflowing hot spring habitats differ or not; whereas the lakes are extreme in terms of increased salinity and pH, the hot springs show extreme temperatures.

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 1558 m within the Abijata-Shala Lakes National Park, some 287 km south of Addis Ababa in the main Ethiopian Rift Valley. The lake is volcano-tectonic (WoldeGabriel et al., 2016) and found in the hydrologically closed system of the Ziway-Shala basin. Lake Shala is the deepest among the Ethiopian Rift valley lakes; it has approximately length of 28 km, 12 km width, and an average depth of 87 m (maximum 266 m), with a surface area of around 329 km^2 and a vast catchment area (3920 km^2) (von Damm and Edmond, 1984; Baxter, 2002).

Lake Shala receives its water from River Adabat and Gidu (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 Shala is characterized by a high pH, saline-alkaline conditions and high phosphate content, but with very low nitrogen levels (Ogato et al., 2014). Its water is rich in sodium (Na^+), carbonate (CO_3^{2-}), bicarbonate (HCO_3^-) and chloride (Cl^-), attributable to their presence in large concentrations in the trachytic and rhyolitic rocks of the Ethiopian Rift (Klemperer and Cash 2007), although they are poor in divalent cations (calcium [Ca^{2+}] and magnesium [Mg^{2+}]) (Ogato et al., 2014). The surface water temperatures

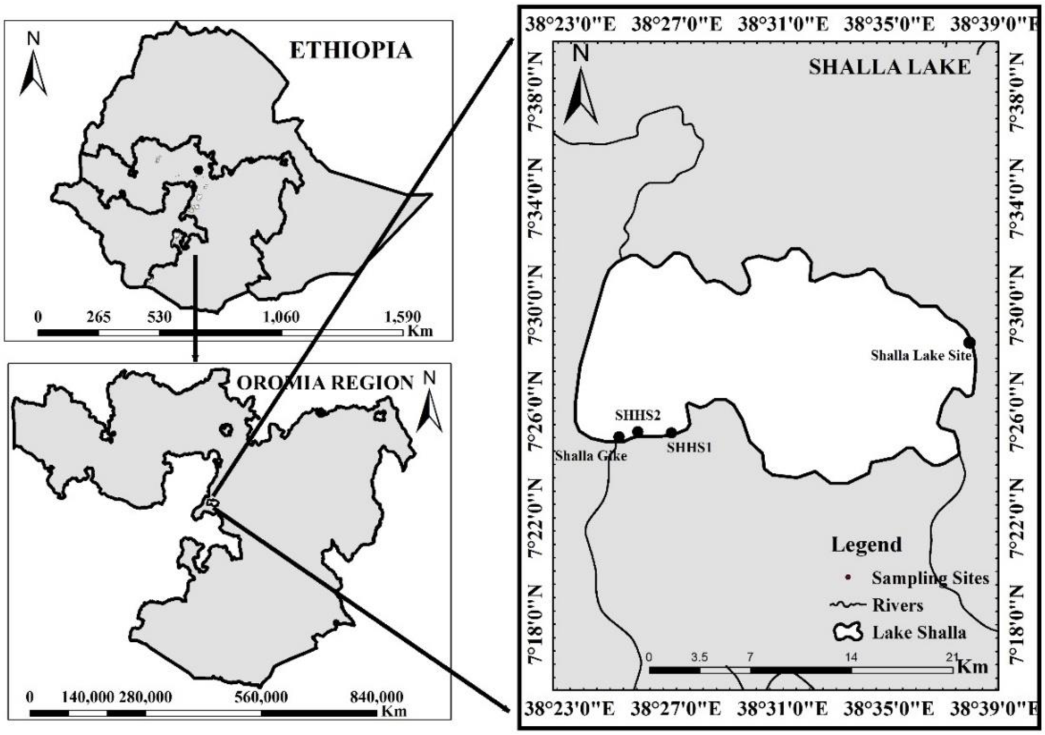

Figure 1. Map of Lake Shala showing the study sites/sampling points. (Abbreviation: (SL: Shalla Lake; SHH1: Shalla Hora Hot spring 1; SHMH: Shalla Hora Mid Hot spring; SGH: Shalla Gike Hot spring).

of Lake Shala range from 22 to 26^{o}C (GebreMariyam, 2002).

Despite its hostile nature, Lake Shala supports phytoplankton and is dominated by diatoms (Kebede et al., 1994) and cryptophytes (Ogato and Kifle, 2017). Lake Shala also supports sparse zooplankton communities and is dominated by rotifers such as *Brachionus dimidiatus*, *B. pliciatilis* and *Hexarthra* (Mengistou, 2016). The benthic macroinvertebrate community of the lake comprises Tubificidae, Ostracoda and Chironomidae (Tudorancea and Harrison, 1988). The lake supports a rich diversity of avifauna, mainly Pelicans and Lesser Flamingos inhabiting the lake and its volcanic island. *Oreochromis niloticus* and other small-sized fish such as *Aplocheilichthys* sp., were reported for the lake in 2002 (Golubtsov et al. 2002).

Water physico-chemical analysis: Sampling for physicochemical parameters was carried out at the same time during diatom sampling. Dissolved oxygen, electrical conductivity, pH, and temperature were measured in situ with an HQ40d Hach Lange multi-meter. For nutrient analyses, water samples were filtered through Whatman GF/C) paper. Ammonium (NH_4-N) was analyzed by the Indol-phenol blue method, Nitrate (NO_3-N) was determined with the sodium-salicylate method and Nitrite (NO_2-N) was analyzed based on the reaction between sulphanilamide and N-naphthyl-(1)-ethylendiamin-dihydrochloride (APHA, 1999). Soluble reactive phosphorus (SRP) was determined by the ascorbic acid method, while total phosphorus (TP) was determined by the ascorbic acid method after the persulfate digestion of unfiltered samples.

Diatoms data collection: Benthic diatoms were collected from the onshore habitat of Lake Shala and inflowing hot springs during April, May, and July 2018. A total of four sampling sites were selected based on the nature of the lake and inflowing hot springs (Fig. 1). At each sampling station, diatoms were sampled by brushing stones with a toothbrush, following Kelly (2000). At least cobles (5-15 cm) sized stones were brushed and the resulting diatom suspensions were put in a small plastic bottle. The samples were preserved in ethanol (70%) and transported to Addis Ababa University, Limnology Laboratory. At the Laboratory, each diatom sample was acid cleaned with potassium permanganate

($KMnO_4$) and hydrochloric acid (HCl) to oxidize organics and remove the carbonates (Cvetkoska et al., 2018). Diatom were identified to the species or to genus levels, when possible, sub species level using appropriate keys under an inverted Nikon microscope equipped with digital camera at a magnification of 200X and 400CX (Gasse, 1986; Komárek and Kling, 1991; Kelly, 2000; Komárek et al., 2003; Bellinger and Sigee, 2010).

Statistical analysis: A nonparametric test, Kruskal-Wallis, analogous to analysis of variance (IBM SPSS Statistics 20) was used to compare means of physico-chemical parameters among the four sampling sites. The association between diatom species distribution and physicochemical variables was evaluated by canonical multivariate analysis using CANOCO for windows 4.5 version software (Ter Braak and Smilauer, 2002). Detrended correspondence analysis (DCA) was employed to check the response of the data, and it was found that the longest gradient (LG) length was 0.859. Therefore, Redundancy analyses (RDA) were used to elucidate the relationships between species assemblages and environmental variables. Diatom species with a total percent abundance <1% were not included in assessing the association between diatom taxa distribution and physicochemical variables.

Results

Physico-chemical parameters: A summary of spatial variations in physicochemical parameters of Lake Shala and its inflowing hot springs are shown in Figures 2 and 3. The highest mean values of pH (10.17) were recorded at Lake Shala (SL), while the lowest value was recorded at Shala Hora Hot-spring 1 (SHH1) and differences are significant between the stations ($P<0.05$). Dissolved oxygen (DO) values were within the range of 0.75-8.11 mg L^{-1} and showed some variability among the studying sites ($P<0.05$). Electrical conductivity (EC), salinity and total dissolved solids (TDS) across all studying stations were significantly different ($P<0.05$). EC varied from 26.74±3.8 mS cm^{-1} in SL to 5.67±7.8 mS cm^{-1} in SHH1. The highest conductivity mean value was recorded at SL (26.74 mS cm^{-1}) and followed by SHMH (15.85 mS cm^{-1}). Salinity and TDS showed a trend similar to that of conductivity and were significantly different ($P<0.05$) between the studied sites.

Nutrient concentrations along the sampling stations are reported in Figure 3 and their distribution showed spatial heterogeneities with studying stations. $NO_3^-+NO_2^-$ and $NH_3+NH_4^+$ concentrations varied from 0 to 2.8 μg L^{-1} and from 0 to 4.15 μg L^{-1}, respectively and were insignificantly different among the stations ($P>0.05$). The mean value of soluble reactive phosphorus (SRP) ranged from 37 μg L^{-1} to 211.5 μg L^{-1}. In SL, the concentration of SRP was greater and showed a significant difference ($P<0.05$). The distribution of total phosphate (TP) indicates that the levels of phosphate variations among the studied sites ($P<0.05$). Highest TP was recorded at SL (8165 μg L^{-1}) and the lowest mean values were documented in SHMH (835 μg L^{-1}). There was a significant difference in dissolved SiO_2 between sampling stations ($P>0.05$). The lowest mean value of dissolved SiO_2 (58.75 mg L^{-1}) was recorded at SL and the highest at SGH (124.5 mg L^{-1}).

Diatom composition and their relative abundance: Forty-five (45) identified diatom species from Lake Shala, and its associated hot springs are presented in Table 1. The number of taxa (species richness) among the samples ranges between 29 and 37. Highest taxa were recorded from SHMH (37) (Table 1). The taxa showed a clear gradient along the physicochemical variables and the number decreased to 36, 30 and 29 from SL, SHH1 and SGH, respectively. Dominant species in most of the samples were *Anomoeoneis sphaerophora, Frustulia rhomboides*, *Nitzschia* spp., *Navicula* spp., *Epithemia frickei*, *E. operculata*, *Rhopalodia gibberula*, *R. rupestris* and *Achnanthes* spp.

Taking into account all samples, 20 (about 44.4%) diatom species such as *Amphora* spp., *A. sphaerophora, Campylodiscus clpeus* var *bicostata, Cyclotella meneghiniana, Epithemia adnata, E. frickei, E. gibba, E. hyndmanii,*

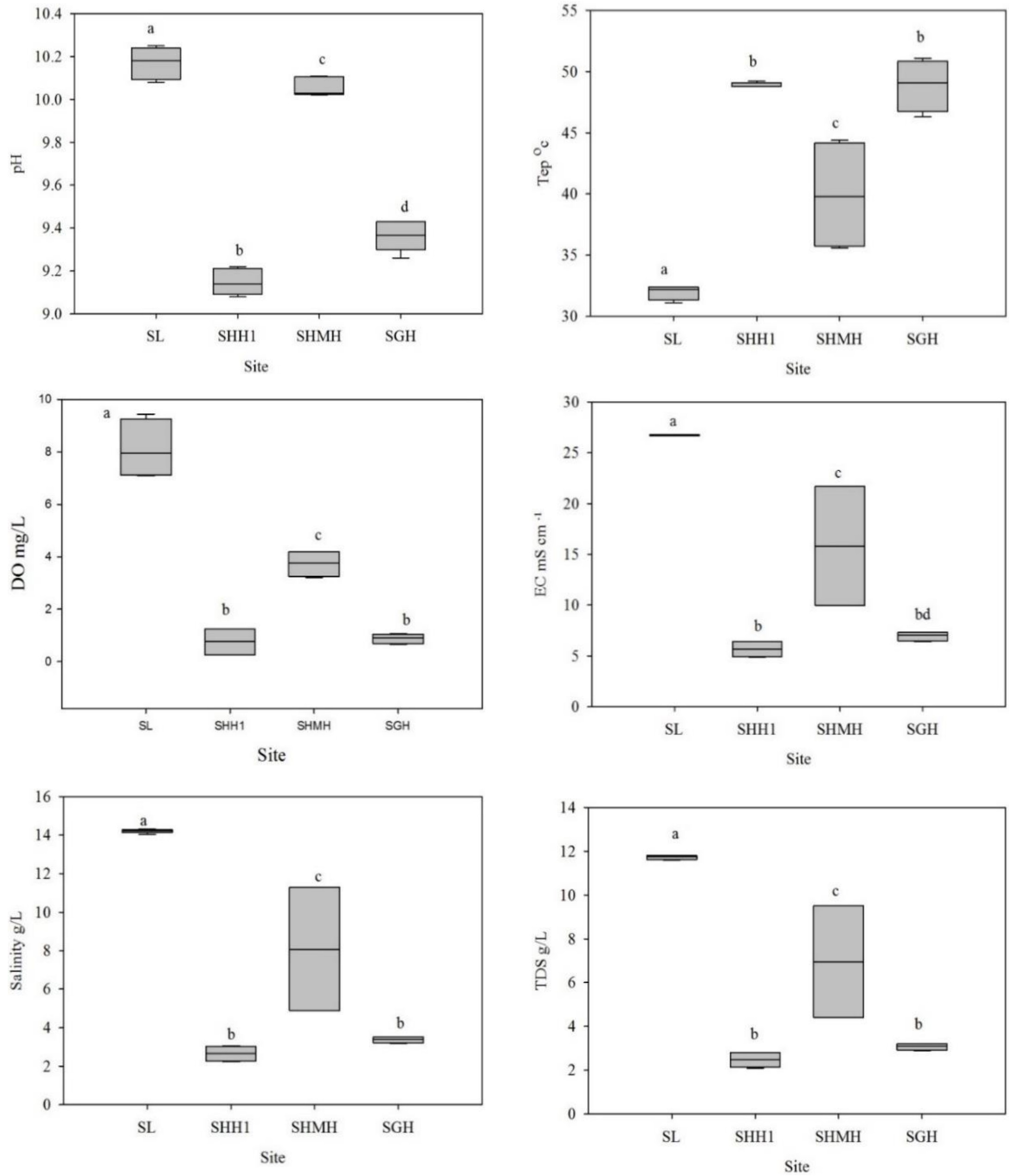

Figure 2. Spatial variation of physical environmental variables along the studied stations. (SL: Shalla Lake; SHH1: Shalla Hora Hot spring 1; SHMH: Shalla Hora Mid Hot spring; SGH: Shalla Gike Hot spring; Tep: Temperature; DO: Dissolved Oxygen; TDS: Total Dissolved Solids) (Values with different letters (a, b, c, d) within a column are significantly different at *P*< 0.05 level (Tukey test is applied)).

E. operculata, Frustulia rhomboides, Navicula spp., *Nitzschia* spp., *Rhopalodia acuminata, R. acuminate Var. Protracta, R. brebissonii, R. gibberula, R. rupestris* and *Stephanodiscus* spp. were common to the studied water bodies (Table 1, Fig. 4). Species that were exclusive to each sampling site were represented by a few individuals. Species found only in Lake Shala were *Campylodiscus hibernicus, Cymatoppleura solea, Encynonema* spp., *Gomphonema* spp. and *Pleurosigma* spp. While Species found only in Shala Hora Mid Hot spring (SHMH) were as follows: *Epithemia turgida* var. *westermannii*, *Rhopalodia constrica* and *R. vermicularis*.

Distribution of diatom species in relation to physicochemical variables: The RDA showed that the first two axes sufficiently (96.5%) explained the cumulative percentage variance in the diatom species-environmental variables relation in studied sites (Fig. 5, Table 2).

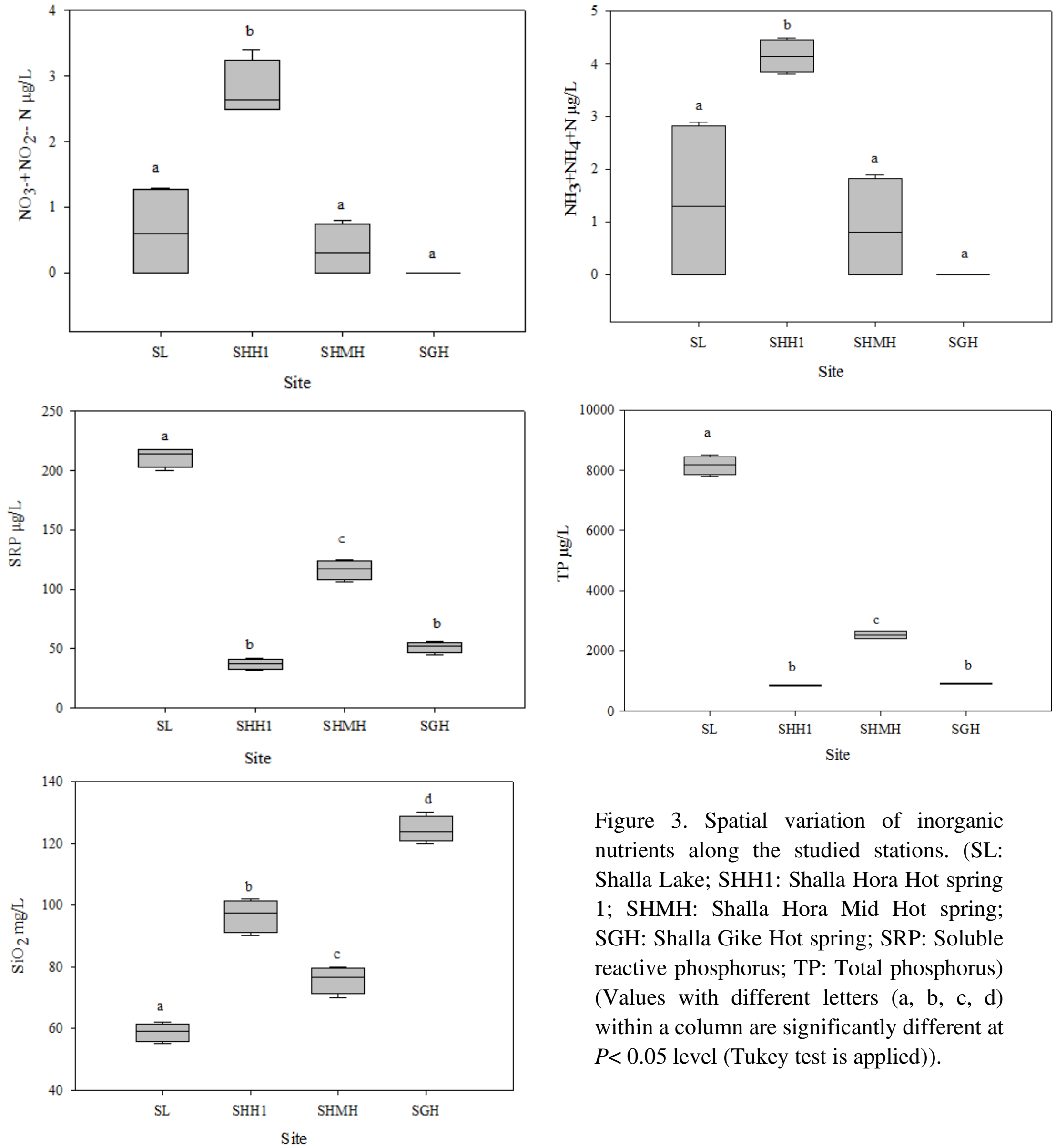

Figure 3. Spatial variation of inorganic nutrients along the studied stations. (SL: Shalla Lake; SHH1: Shalla Hora Hot spring 1; SHMH: Shalla Hora Mid Hot spring; SGH: Shalla Gike Hot spring; SRP: Soluble reactive phosphorus; TP: Total phosphorus) (Values with different letters (a, b, c, d) within a column are significantly different at *P*< 0.05 level (Tukey test is applied)).

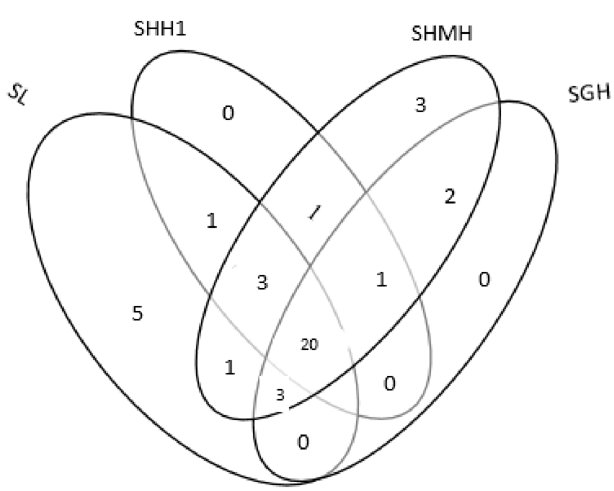

Figure 4. Venn diagram representing the number of diatoms that are unique and shared between the samples from 4 different sampling sites. (SL: Shalla Lake; SHH1: Shalla Hora Hot spring1; SHMH: Shalla Hora Mid Hot spring; SGH: Shalla Gike Hot spring.

Table 1. List of the 45 diatom taxa identified in the Lake Shalla and inflowing hot springs.

Diatom Species	Relative abundances (%)				
	All Stations	SL	SHH1	SHHM	SGH
Achnanthes spp.	4.2	-	6	5.8	4.3
Amphora spp.	2.0	1.5	3.5	1.8	1.9
Anomoeoneis sphaerophora	15.7	9.2	15.3	19.9	15.4
A. styriaca (Grunow) Hustedt	0.6	0.6	0.7	0.5	0.7
Campylodiscus clpeus var *bicostata* W. Sm.	1.7	1.2	1.2	1.2	2.6
C. hibernicus (Ehrenberg)	0.1	0.2	-	-	-
Cyclotella iris Brun & Héribaud	0.7	1.6	2	-	-
C. meneghiniana Kützing	3.0	3.4	3.2	2	4.8
Cyclotella spp.	2.3	-	4.3	3.6	-
Cymatoppleura solea (Brébisson) W. Smith	0.1	0.2	-	-	-
Cymbella spp.	0.3	0.1	0.3	0.3	0.6
Diatoma spp.	0.2	0.2	0.3	0.2	-
Epithemia adnata (Kützing) Brébisson	2.5	1.7	3.3	2.6	2.6
E. argus (Ehrenberg) Kützing	1.7	1.3	-	2.3	2.4
E. argus var. *alpestris* (W. Smith) Grunow	0.2	-	-	0.4	-
E. frickei Krammer	3.8	2.5	3.3	5	3.3
E. hyndmanii W. Smith	1.7	0.9	0.7	2.7	1.9
E. smithii Carruthers	0.6	0.6	-	1.1	-
E. sorex var. *gracilis* Hustedt	0.2	-	-	0.4	0.6
E. turgida (Ehrenberg) Grunow	0.3	-	-	0.3	1.3
E. turgida var. *westermannii* (Ehrenberg) Grunow	0.1	-	-	0.3	-
Encynonema spp.	0.1	0.2	-	-	-
Encyonopsis microcephala (Grunow) Krammer	0.4	0.9	-	0.4	0.4
Eunotia spp.	0.3	0.4	0.3	0.3	-
Frustulia rhomboids (Ehrenberg) De Toni	5.6	3.6	10.4	3.8	8.2
Gomphonema spp.	0.1	0.6	-	-	-
Hantzschia spp.	0.4	0.5	0.5	0.4	-
Melosira *ambigua* (Grun.) Müller	0.5	0.4	1	-	1.7
Navicula spp.	5.4	2	7.3	6.8	4.6
Nitzschia spp.	9.1	18.3	8.5	5.6	4.6
Pinulariaa spp.	0.3	0.4	0.7	-	0.4
Pleurosigma spp	0.1	0.5	-	-	-
Rhopalodia acuminata Krammer	7	9.2	7.1	5.2	8.4
R. acuminate Var. Protracta (Grunow)	2.3	3.1	1.8	2	2.6
R. brebissonii Krammer	1.7	2.8	2.7	0.7	1.5
R. constrica (W. Smith) Krammer	0.1	-	-	0.2	-
R. gibba (Ehrenberg) O. Müller var. *gibba*	2.1	2.9	0.7	2.3	1.9
R. gibberula	7.8	13.1	6.8	5.9	5.6
R. operculata (Agardh) Håkansson	7.3	7.4	3.2	7.9	10.4
R. rupestris (W. Smith Krammer)	3.3	5.4	2.3	2.4	3.7
R. vermicularis (O. Müller)	0.1	-	-	0.4	-
Surirella ovalis Brébisson	0.3	-	0.5	0.3	0.7
Surirella turgida W. Smith	0.7	0.4	-	1	0.9
Stenopterobia spp.	1.4	1.2	0.7	2.3	-
Stephanodiscus spp.	1.7	1.5	1.7	1.7	2
Total no. Species		36	30	37	29

The results indicated that pH was the most important environmental variable accounting for species distribution in the first axis. The distribution of diatom species was also positively correlated with EC, Salinity, TDS and DO in axis 1 and contributed 71.8% of the variance. Relative abundance of *Anomoeoneis sphaerophora, Rhomboids operculata*, *Stenopterobia* spp., *Epithemia argus, Stephanodiscus* spp., *E. frickei, E. hyndmanii, E. adnata, Amphora* spp., *Campylodiscus clpeus* var *bicostata, Navicula* spp., *Cyclotella. meneghiniana* and *Achnanthes* spp. had a strong positive association

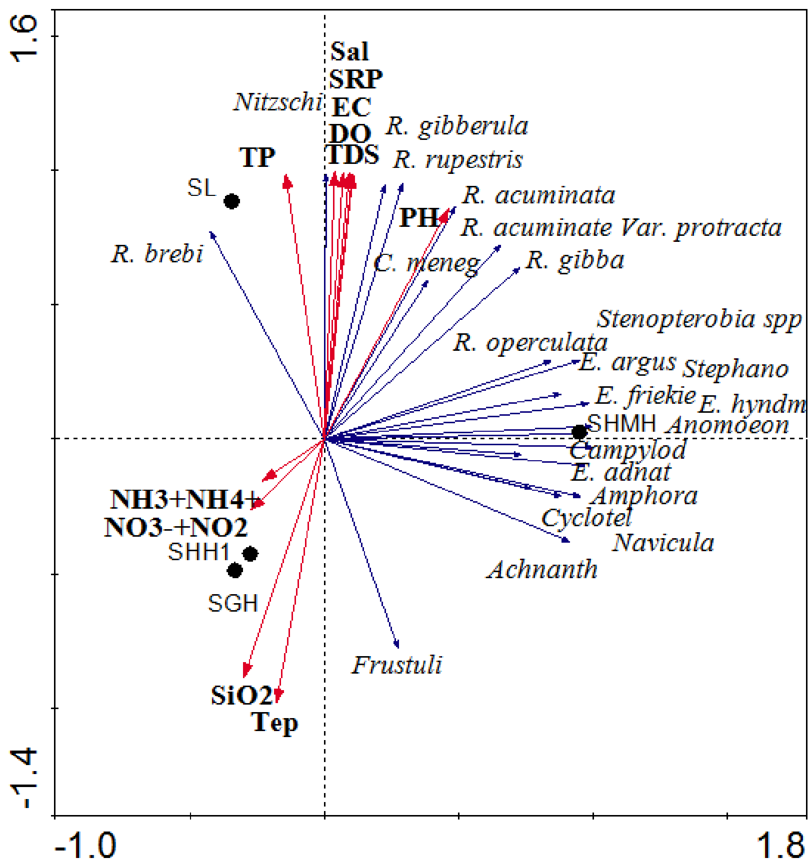

Figure 5. Redundancy Analyses (RDAs) Triplots showing the relationship between diatoms Communities, environmental parameters and sites (show with different color).

Table 2. List of the 45 diatom taxa identified in the Lake Shalla and inflowing hot springs.

Diatom Species	Relative abundances (%)				
	All Stations	SL	SHH1	SHHM	SGH
Achnanthes spp.	4.2	-	6	5.8	4.3
Amphora spp.	2.0	1.5	3.5	1.8	1.9
Anomoeoneis sphaerophora	15.7	9.2	15.3	19.9	15.4
A. styriaca (Grunow) Hustedt	0.6	0.6	0.7	0.5	0.7
Campylodiscus clpeus var *bicostata* W. Sm.	1.7	1.2	1.2	1.2	2.6
C. hibernicus (Ehrenberg)	0.1	0.2	-	-	-
Cyclotella iris Brun & Héribaud	0.7	1.6	2	-	-
C. meneghiniana Kützing	3.0	3.4	3.2	2	4.8
Cyclotella spp.	2.3	-	4.3	3.6	-
Cymatoppleura solea (Brébisson) W. Smith	0.1	0.2	-	-	-
Cymbella spp.	0.3	0.1	0.3	0.3	0.6
Diatoma spp.	0.2	0.2	0.3	0.2	-
Epithemia adnata (Kützing) Brébisson	2.5	1.7	3.3	2.6	2.6
E. argus (Ehrenberg) Kützing	1.7	1.3	-	2.3	2.4
E. argus var. *alpestris* (W. Smith) Grunow	0.2	-	-	0.4	-
E. frickei Krammer	3.8	2.5	3.3	5	3.3
E. hyndmanii W. Smith	1.7	0.9	0.7	2.7	1.9
E. smithii Carruthers	0.6	0.6	-	1.1	-
E. sorex var. *gracilis* Hustedt	0.2	-	-	0.4	0.6
E. turgida (Ehrenberg) Grunow	0.3	-	-	0.3	1.3
E. turgida var. *westermannii* (Ehrenberg) Grunow	0.1	-	-	0.3	-

Table 2. Continued.

Diatom Species	Relative abundances (%)				
	All Stations	SL	SHH1	SHHM	SGH
Encynonema spp.	0.1	0.2	-	-	-
Encyonopsis microcephala (Grunow) Krammer	0.4	0.9	-	0.4	0.4
Eunotia spp.	0.3	0.4	0.3	0.3	-
Frustulia rhomboids (Ehrenberg) De Toni	5.6	3.6	10.4	3.8	8.2
Gomphonema spp.	0.1	0.6	-	-	-
Hantzschia spp.	0.4	0.5	0.5	0.4	-
Melosira *ambigua* (Grun.) Müller	0.5	0.4	1	-	1.7
Navicula spp.	5.4	2	7.3	6.8	4.6
Nitzschia spp.	9.1	18.3	8.5	5.6	4.6
Pinulariaa spp.	0.3	0.4	0.7	-	0.4
Pleurosigma spp	0.1	0.5	-	-	-
Rhopalodia acuminata Krammer	7	9.2	7.1	5.2	8.4
R. acuminate Var. Protracta (Grunow)	2.3	3.1	1.8	2	2.6
R. brebissonii Krammer	1.7	2.8	2.7	0.7	1.5
R. constrica (W. Smith) Krammer	0.1	-	-	0.2	-
R. gibba (Ehrenberg) O. Müller var. *gibba*	2.1	2.9	0.7	2.3	1.9
R. gibberula	7.8	13.1	6.8	5.9	5.6
R. operculata (Agardh) Håkansson	7.3	7.4	3.2	7.9	10.4
R. rupestris (W. Smith Krammer)	3.3	5.4	2.3	2.4	3.7
R. vermicularis (O. Müller)	0.1	-	-	0.4	-
Surirella ovalis Brébisson	0.3	-	0.5	0.3	0.7
Surirella turgida W. Smith	0.7	0.4	-	1	0.9
Stenopterobia spp.	1.4	1.2	0.7	2.3	-
Stephanodiscus spp.	1.7	1.5	1.7	1.7	2
Total no. Species		36	30	37	29

with pH and positively correlated with EC, salinity, TDS and DO while NO_3^-+NO_2^-, NH_3+NH_4^+, SiO_2 and TP showed a negative association in axis 1. *Nitzschia* spp., *Rhopalodia gibberula* and *R. rupestris* were strong and positively correlated with pH (0.86), EC (0.99), TDS (0.99), Sal (0.99) DO (1) and TP (0.99) and showed negative association with Tep (-0.98), NO_3^-+NO_2^- (-0.27), NH_3+NH_4^+ (-0.23) and SiO_2 (-0.30) in axis 2 (Table 2).

Nitzschia spp., *Rhopalodia gibberula, R. rupestris R. acuminata R. acuminata* Var *Protracta, Cyclotella meneghiniana* and *R. gibba* are representative taxa in Lake Shala abundantly (SL) (Fig. 5). These taxa typically occurred in habitats with high specific EC, salinity, TDS, DO, pH and TP. The diatom assemblage in Shala Hora Mid Hot-spring (SHMH) had intermediate EC, salinity, TDS, DO, pH and TP mean values and was represented by *Anomoeoneis sphaerophora, Epithemia frickei, E. hyndmanii*, *E. argus*, *E. adnata*, *Stenopterobia* spp, *Cyclotella spp*, *Rhopalodia operculata, Campylodiscus clypeus, Achnanthes* spp.*, Amphora* spp.*, Navicula* spp. and *Frustulia rhomboids*.

Discussion

Spatial physico-chemical dynamics in Lake Shala and its associated hot springs: There has been significant interest in finding life in extreme environments with high temperatures, salinity and pH like hot springs and soda lakes. Hence, this is the first report on the investigation of diatom diversity and community structure at different physico-chemical factors of Ethiopian Saline-alkaline Lake Shala and inflowing hot springs. This ecological study aimed to examine the influence of the spatial variations in the environmental variables on the diatom distribution within Lake Shala and its inflowing hot springs.

The value of high pH, salinity, EC and TDS recorded in the studied Lakes Shala and inflowing hot-springs did reach previously reported in saline alkaline lakes of East Africa (Talling et al., 1973; Melack et al., 1982; Wood and Talling, 1988; Kebede et al., 1994; Talling and Lemoalle, 1998) and inflows hot springs (Mpawenayo and Mathooko, 2004; Owen et al., 2004). Saline alkaline nature of these soda lakes is further influenced by the heterogeneous surficial geology characteristic, climate and hydrology of the region (Legesse et al., 2004). East African Soda lakes are characterized by high concentrations of carbonate salts, especially sodium carbonate and related salt complexes (Wood and Talling, 1988; Kebede et al., 1994). They also contain high concentrations of sodium chloride and other dissolved salts, making them saline-alkaline lakes (Gebre-Mariam, 2002; Klemper and Cash, 2007).

During the present investigation, the mean pH values were significantly different over the studied sites. The highest mean values of pH (10.17) were recorded in Lake Shala surface waters, with these high values indicating the influence of potential photosynthetic activity and increased salinity concentrations, both possible causes of alkaline conditions (Talling, 2011). While lower mean pH value recorded in hot springs might be due to less concentration of sodium and carbonate species in the cation and anion-dissolved solutes, respectively. This was supported by the results, which found that the majority of lakes and hot springs of soda lakes in the Kenyan rift valley (Grant and Jones, 2016; Salano et al., 2017). However, the relationship between pH and other factors is complex, being influenced by chemical and biological processes (Hammer, 1986; Williams, 1998).

Dissolved oxygen levels were significantly lower in hot spring sites with a mean value ranging between 0.75-3.73 mg L^{-1}. The observed higher amount of DO in the Lake Shala site is probably related to the activities of photosynthetic organisms. Lower oxygen concentrations in hot springs may arise from the high rate of respiration by decomposers such as bacteria and fungi that anchor the gravel and small rocks of the hot springs (Renaut et al., 2008; Grant and Jones, 2016; Salano et al., 2017). Extremely high microbial load within the Great East Africa Rift Valley soda lakes is described by Lanzen et al. (2013) and Grant and Jones (2016). Wood et al. (1984) also suggested the depletion of DO in tropical soda lakes by algal biomass decomposition and high microbial activity.

Although salinity, EC and TDS were significantly different across the studied sites, they show considerable strong gradients from hot springs with lower salinity, TDS and EC or diffuse groundwater inflows along the shores towards the lake with higher mean values. High mean values of salinity (14.21 g L^{-1}), EC (26.74 mS cm^{-1}) and TDS (11.7 g L^{-1}) in Lake Shala could be associated with the accumulation of solutes that originate from rain falling directly on the surface of the lake and drainage basin, weathering reactions between runoff and groundwater, hydrothermal fluids and their interactions with subsurface rocks (Baumann et al., 1975; Von Damm and Edmond, 1984; Ayenew and Legesse, 2007). Similarly, East African soda lakes inflowing hot spring water also show considerably lower salinity, EC and TDS than soda lakes; for example, the salinity of Elmentaita and Bogoria hot springs have been recorded between 1.6-2.3 g L^{-1} and 3.5-3 g L^{-1}, respectively. While in Lake Elmentaita (3.8-4.6 g L^{-1}) and Lake Bogoria (10-20 g L^{-1}), the surface water salinity was higher (Krienitz and Schagerl, 2016). Ogato (2015) also reported the low concentration of salinity (4.5 g L^{-1}) and conductivity (8.2 mS cm^{-1}) of inflowing hot springs around Lake Shala.

Concentrations of soluble and largely inorganic forms of the element's nitrogen, phosphorus and silicon were surveyed and significantly different in the four sampling sites. Nitrogen limitation has been suggested for some other tropical African soda lakes (Melack et al., 1982; Wood and Talling, 1988; Kebede et al., 1994; Talling and Lemoalle, 1998). In the present study, nitrate and ammonia-nitrogen were less and not detected in Lake Shala and inflowing hot springs, which is an indication of nitrifying bacteria occurrence. High diversity and abundance of ammonia and nitrite-oxidizing organisms are widely distributed and responsible for low nitrogen levels in African soda lakes (Sorokin, 1998; Grant and Jones, 2000; Grant and Jones, 2000; Sorokin et al., 2001; Grant, 2006). However, in SHH1 higher concentration of the NO_3^-+NO_2^- (2.8 μg L^{-1}) and NH_3+NH_4^+ (4.15 μg L^{-1}) was recorded. The possible reason could be the visitors of livestock around the hot springs which cause considerable inputs of nitrogenous wastes.

The concentration of phosphorus was quite high in the lake and inflowing hot springs and was significantly different between sites. High mean soluble reactive phosphate (SRP) and total phosphate (TP) concentrations were recorded in Lake Shala. There is a general trend of increasing phosphate content concentration with increasing salinity and conductivity. This result is nearly comparable with the work done in Ethiopian inland waters by Wood and Telling (1998). The significant variations in these factors could be attributed to the specific abiogenic and biogenic transformations (Wood and Telling, 1998), the predominance of phosphate mineral-rich rocks (Talling and Talling, 1965), and the release from the anoxic water column (Oduor and Schagerl, 2007b). High total phosphate and soluble reactive phosphate concentrations are also reported in East African saline-alkaline lakes (Melack et al., 1982; Kalff, 1983; Oduor and Schagerl, 2007b).

In the present study, silicate concentration significantly varied between the sites. Previously the concentration of SiO_2 in Lake Shala (56 mg L^{-1}) (Kebede et al., 1994) and the main hot springs located on the shore of Lake Shala (64.8 mg L^{-1}) (Ogato, 2015) were reported. However, the mean concentration SiO_2 observed in the present study is remarkably high in hot springs. The contributor could be silicate soils, porous volcanic lavas and the enhanced dissolution of solid silicates in saline waters of high alkalinity and pH (Wood and Telling, 1998). The silicate concentration of Lake Shala in this study (58.75 mg L^{-1}) was comparable with the value (56) reported by Kebede et al. (1994) and (49.55) reported by Gebre-Mariam (2002). The silicate concentration is notably low in Lake Shala, indicating the dominance of diatoms in the lake. Several studies on tropical African lakes (Hecky, 1993; Gebre-Mariam, 2002) reported the association of depletion with the abundance of diatoms. Wood and Talling (1988) and Kebede et al. (1994) suggested that SiO_2 could be significantly removed from the solution in Lake Shala, which was dominated by diatoms.

Diatom community structure in Lake Shala and hot springs: The extremely inhospitable conditions in alkaline, saline lakes mean that the biodiversity in these systems is limited to organisms with special adaptations to survive such extreme conditions (Matagi, 2004). In the present study, forty-five diatom taxa were identified from Lake Shala and its inflowing hot spring with Rhopalodiaceae (9 taxa) and Epithemiaceae (9) being best represented. The most abundant species were *A. sphaerophora, Nitzschia* spp., R. *acuminata, R. gibberula*, *R. operculata*, *Navicula* spp. and *F. rhomboids*. This is in agreement with earlier studies done in alkaline, saline habitat which reported *Anomoeoneis*, *Rhopalodia, Nitzschia* and *Epithemia* to be the most dominant (Hecky and Kilham 1973; Gasse et al., 1983; Mpawenayo and Mathooko, 2004; Owen et al., 2004) in contrast with the reported dominance of algal biomass by *Spirulina platensis* (Blue-green algae, Cyanobacteria) in alkaline-saline lakes Ethiopia and Kenya (Talling et al., 1973; Harper et al., 2003; Ballot et al., 2004; Oduor and Schagerl, 2007a). The dominance of *Anomoeoneis*, *Rhopalodia, Nitzschia* and *Epithemia* species in these harsh environments can be attributed to their ability to withstand extreme water conditions like very high temperatures, pH and salinity.

There was a difference in the taxa number and individual abundance of diatoms among the sampling sites. Low taxon number and individual abundance were recorded in SGH (29) and SHH1 (30). This might be due to the special physical features of the habitat, such as high temperature and low dissolved oxygen; living in such ecosystems has tolerated and adapted to this hostile environment. Owen et al. (2004) also argue that the hot spring's low diversity values are due to extreme environmental conditions. Contrary, the highest number of diatom species (37) were recorded at SHMH and this might be due to the exchange and contact of the lake organisms with the surrounding hot spring because depending on the Lake Shala water level and wave, this hot spring area can be covered by lake water, which enables direct exchange of organisms. Even minor changes in the lake water level can impact the ecology of the hot springs and adjacent habitats (Renaut et al. 2008, 2013), impacting species diversity (Krienitz et al., 2005).

Diatoms have complex spatial dynamics within aquatic ecosystems (Cvetkoska, 2018). Numerous researchers (e.g., Gasse et al., 1983; Hecky and Kilham, 1973; Mpawenayo and Mathooko, 2004; Owen et al., 2004) have demonstrated different diatom assemblages across a range of different alkaline habitats. Differences in diatom community structure among the studding site were investigated and there were dissimilarities in the diatom communities in Lake Shala and its inflowing hot springs. Similarly, Owen et al. (2004) and Mpawenayo and Mathooko (2004) reported variations in the diatom populations in Lake Bogoria, Lake Elmentaita and their inflowing hot springs. During the current investigation, several diatom species, e.g., *A. sphaerophora*, *Nitzschia* spp., *R. gibberula*, R. *operculata*, R. *acuminata*, *Navicula* spp., *F. rhomboids*, *C. meneghiniana*, *E. adnata* and *E. frickei*, occurred across a range of physico-chemical variables, suggesting that most species have high tolerance ranges of environmental conditions.

Distribution of diatom in relation to physico-chemical variables: Numerous studies conducted the influence of physico-chemical and nutrient variables on diatom communities and have shown the importance of water pH and related variables (e.g., salinity, alkalinity, conductivity) as main drivers structuring diatom communities (Gasse et al., 1983; Hecky and Kilham, 1973; Smol and Stoermer, 2010). In the present study, RDA analysis demonstrated that the diatom community structure of Lake Shala and inflowing hot springs was highly influenced by pH and also to some extent by EC, DO, Salinity, TDS and SRP in axis 1, which explained 96.5% of the variance in diatom community composition. Moreover, the analyses indicated strong spatial variability, highlighting the importance of the different environmental factors in structuring the benthic diatom community, which could largely be attributed to variations in physico-chemical features and used as an indicator of lake development, erosion, alkalinization, acidification, salinization, climate change, and especially eutrophication.

According to Hecky and Kilham (1973) and Gasse et al. (1983), the distribution of diatom species is essentially influenced by salinity and conductivity. Diatoms in Lake Shala and inflowing hot springs were affected by salinity and nutrients as indicated by the RDA (Fig. 6), with Owen et al. (2004) and Mpawenayo and Mathooko (2004) reporting similar findings. Owen et al. (2004) highlighted the effect of variations in physico-chemical variables of soda lakes and their inflowing hot springs on diatom communities. This result was consistent with a study in East African Soda (e.g. Gasse et al., 1983; Hecky and Kilham, 1973; Mpawenayo and Mathooko 2004; Owen et al., 2004).

Conclusion

Marked variability in Physico-chemical features was observed among the studying sites in Lake Shala and its inflowing hot springs. This variation was related to inter-site differences in geomorphic and hydrological characteristics, resulting in uneven diatom species distribution. A total of 45 diatom taxa were identified, of which 20 (about 44.4%) diatom species were common across the study area. This indicates that the studied hot springs of soda lakes in Ethiopia are important niches that harbor an unexpectedly high richness of diatom species. The most abundant species were *A. sphaerophora, Nitzschia* spp., R. *acuminata, R. gibberula*, *R. operculata*, *Navicula* spp. and *F. rhomboids*, suggesting high tolerance ranges of environmental conditions. Therefore, the findings in this study will be of high significance in the field of phycology and provide initial insight into the diatom distribution from the soda Lake Shala and hot springs; future studies should expand the spatial and temporal scale by including the whole lake and its hot springs area.

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