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Assessment of the Temporal and Spatial Variability in the Phytoplankton Dynamics of a Tropical Alkaline-saline Lake Simbi, Kenya

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Abstract

This study evaluated the phytoplankton dynamics of abundance, species composition and diversity across spatial and temporal scales in Lake Simbi for the period between December 2018 and May 2019. This was necessary, considering the significance of phytoplankton communities in this lake for conservation and ecological role. Sampling was done on a monthly basis for 6 months at six fixed stations systematically selected. A total of 84 phytoplankton species were identified comprising of Cyanophyceae (36 species), Chlorophyceae (25 species), Bacillariophyceae (11 species), Zygnematophyceae (4 species), Dinophyceae (3 species) and Euglenophyceae (3 species). Although, the Cyanophyceae family still dominated in Lake Simbi, a shift in the species composition was realized and this can be probably attributed to the changes in the water quality regime of the lake. The results showed a high phytoplankton density in the lake due to its eutrophic nature. However, reduced abundance of the cyanobacterial species, especially Spirulinaspecies on which flamingos feed and the subsequent dominance of the toxin producing Microcystis species might have contributed to the decline of the flamingo population. All the phytoplankton characteristics of density and diversity indices evaluated in Lake Simbi exhibited no significant spatial and temporal variations. Generally, activities that help to improve and maintain ecosystem integrity need to beadopted by all stakeholders to promote sustainability of all aquatic resources in Lake Simbi.

Keywords: Alkaline Saline lake, abundance, diversity indices, phytoplankton, conservation.

Introduction

Lake ecological assessment using bio-monitoring methods which involves the use of living organisms as bio-indicators is becoming prevalent among current limnological studies. Bio-indicators which are also known as biomonitors are living organisms including plants, micro-organisms, animals and planktonic organisms that are used in evaluating ecological health of natural environments[1]. Of all the bio-indicators, many studies have often explored the phytoplankton community structure and distribution in aquatic ecosystems because of their crucial role in sustaining the ecosystem. All the life forms in the water bodies are supported by the phytoplankton[2]. The phytoplankton provides a pathway for energy flow in aquatic ecosystems through primary production which constitute the foundation for the food chain[3]. The primary productivity in turn drives the secondary productivity[4]. The primary producers (phytoplankton) also play a significant role of sustaining the balance between biotic and abiotic components of the environment[5]. Phytoplankton yields oxygen in the water and are basic food resources for the zooplankton, roles of which supports all aquatic life forms[6]. Being the basis for all aquatic food chains, the phytoplankton are more sensitive to even slight changes in the environmental variables of the ecosystem making them a perfect water quality indicator[7]. Phytoplankton dynamics such as their composition and abundance can reveal the nutritional status of aquatic ecosystem[8], and the trophic state[9] and hence a central indicator of the conditions of an ecosystem[10,11].

Understanding the phytoplankton dynamics especially the community structure is helpful for understanding the ecological balance which could be crucial in the management of lake fisheries[12]. The phytoplankton dynamics of most Kenyan alkaline-saline lakes such as Lake Nakuru and Bogoria are well documented, but there is little information on the phytoplankton community structure of Lake Simbi which is a vital bird sanctuary supporting huge populations of the nearly-threatened lesser flamingos (*Phoeniconaias minor*) among other bird species. Recently, studies reported the dwindling bird populations in this lake, and since these birds majorly rely on the phytoplankton communities in the lake as food resources, an evaluation of the phytoplankton dynamics in the lake is necessary for their proper conservation[13,14]. This study in Lake Simbi focused on the temporal-spatial distribution of the phytoplankton abundance, species composition and diversity indices. Considering the significance of phytoplankton communities in this lake for conservation and ecological role, the study operated on the hypothesis that there were no significant differences in the spatial and temporal distribution of the phytoplankton abundance, species composition and diversity indices of the lake.

Materials and methods

Study area: Lake Simbi Nyaima is a small-sized (about 700m in diameter), deep (27.7m) alkaline-saline crater lake (Figure-1) located adjacent to Kendu Bay Town of Homabay County of Kenya, in a semi-arid area receiving an average rainfall of between 500mm and 1700mm annually with temperature range between 18and 31^{o}C. The lake sits at an altitude of 1142m above sea level and lies at 0°22'5"N and 34°37'47"E coordinates on the Nyanzan Gulf approximately 1000m from the L. Victoria. It is a haven for enormous populations of unique birds, a feature that has earned it the status of a national bird sanctuary with international ecotourism recognition. The lake is permanently stratified (meromictic) with no known inlet or outlet. Even though, the lake lacks the capacity to support any fishery activities because of the extreme conditions of salt-tress and hypoxia it is nonetheless important for ecotourism, and provides great scientific, cultural, religious and educational benefits.

Due to the probable variation in the distribution patterns of phytoplankton communities, and for the purposes of comparison, six sampling stations were selected based on the standard guidelines[15]. Imaginary grids were drawn over the map of the lake and each of these grids sampled in a linearly fashion whereby six stations in two transects were chosen, that is three sites on vertical transect ST1, ST2 and ST3, and three sites on horizontal transect ST4, ST5 and ST6. These stations were stratified in a way that three stations were in shores and the other three off shores.

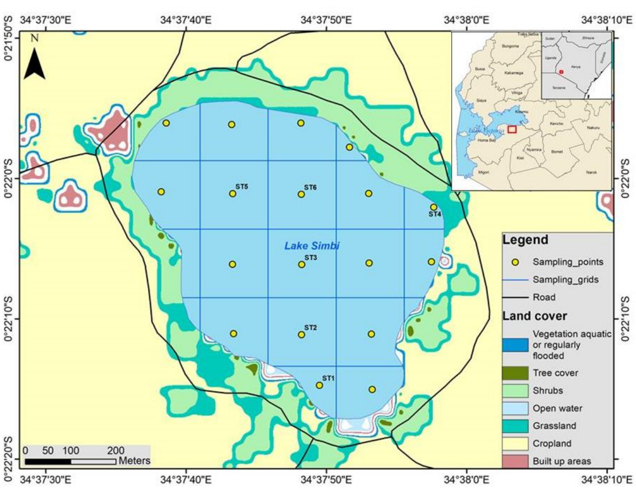

Figure-1: Map of Lake Simbi showing the sampling stations.

Sampling and analyses: Sampling was done on a monthly basis for 6 months from December 2018 to May 2019 at six fixed stations systematically selected (Figure-1). The sampling period encompassed both the dry season months (December, January and February) and wet season months (March, April and May) in Kenya. Sampling was always carried out between 9:00 am and 12:00. From each station, a depth-integrated water samples were taken with the aid of a Van Dorn water sampler following the procedures[5]. From these samples, sub-samples were taken into glass bottles and then immediately fixed with Lugol's solution for preservation before they were transferred to the laboratory. From each of the samples, 1 ml was taken and put in Utermohl sedimentation chamber and left to settle for 3 hours and then immediately taken for microscopic examination and counting using Zeiss Axioinvert 35 inverted microscope at 400x magnification. All the observed single cells, filaments and colonies were counted. Species identification was carried out by reference to the Algae identification field guide and algae identification lab guide[16-18].

The phytoplankton abundance expressed in individuals per liter (Ind.L^{-1}) was then determined based on the formula provided[19]:
Phytoplankton abundance (Ind.L^{-1}) = No. of units counted x Coefficient, C.
But C (L) = A*1000 / (N*a $_1$*V) or C (L) = A*1000 / (a $_2$*V)
where: A = cross-section area of the top cylinder of the combined sedimentation chamber; the usual inner diameter is 25.0 mm, giving A = 491 mm^2, N = number of counted fields or transects a $_1$ = area of single field or transect, a $_2$ = total counted area, V = volume (cm^3) of sedimented aliquot.

After identification of the phytoplankton to the lowest possible taxonomic level (genus/species), four diversity indices (Shannon-Wiener Diversity, Simpson's Diversity, Pielou's, Pielou's species evenness and Margalef's species richness) were computed using the following formulas;

Shannon-Weiner's Diversity Index formula[20];

$$H = -\sum_{i=I}^{S} p_i \ln(p_i)$$

Pielou's Evenness Index[21];

$$E_H = \frac{H}{In\ S}$$

Simpson's Index of Diversity[22];

Simpson index of diversity = 1-D

$$D = \sum_{i=I}^{S} p_i 2$$

Margalef's Richness Index (d)[23];

$$d = \frac{(S-1)}{In\ N}$$

pi - the proportion of individuals calculated as abundance of individual species divided by total number of individuals in the community sampled, In - the natural log, Σ - The sum of all calculation, S - The total number of species, N- The total number of individuals in the sample, H - Shannon -Wiener index of diversity, D – Simpson's diversity index., d – Maglef's richness index.

Descriptive statistics was done for all study variables using SPSS 20.0 and results presented in form of tables and graphs. One-way ANOVA and post hoc Tukey test was used to screen for significant spatial and temporal differences among the study variables.

Results and discussion

The study evaluated the phytoplankton dynamics of abundance, species composition and diversity. These results are presented in the Figure-2 and Tables-1-3.

Characteristics of the phytoplankton community structure: The phytoplankton community structure of Lake Simbi during the entire study period comprised of 84 species belonging to six major phytoplankton families. Among these phytoplankton families, cyanophyceae was the most dominant comprising of 36 species (44%), followed by chlorophyceae (25 species, 30%), bacillariophyceae (11 species, 13%), zygnematophyceae (4 species, 5%), dinophyceae (3 species, 4%) and euglenophyceae (3 species, 4%) (Fig.2). The most dominant species in the cyanophyceae family was *Microcystis flos-aqua* (33%); in the chlorophyceae family was *Scenedesmus obliquus* (80%); in the bacillariophyceae family was *Fragilaria pinnata* (31%); in the zygnematophyceae family was *Hyalotheca mucosa* (50%); in the dinophyceae family was *Ceratium branchyceros* (81%) and finally in the euglenophyceae family *Euglena acus* (63%).

The occurrence of certain phytoplankton species (especially from the cholorophyceae family) explains the acidic nature of the water especially the deeper layers[24]. The species belonging to *Romeria* and *Cyclotella* genera were found in Lake Simbi which implies that the waters are somewhat acidic since the species found in these genera have always been known to tolerate acidic conditions. The acidic nature of the lake comes from the low pH levels in the lake but it could also be attributed to the organic wastes dumped into the lake by the various institutions (schools, church and hospitals) and homes surrounding the lake. These acidic tolerant Chlorophyceans could be thriving in the deeper waters since the top waters of Lake Simbi are permanently highly alkaline. Chlorophyceae family of Lake Simbi was dominated by the species Scenedesmus obliquus (80%), Chlorella vulgaris (3%), Pediastum boryanum (3%) and Botryococcus braunii (2%). Chlorophyceae apparently overtook bacillariophyceae earlier recorded in the previous study[25], as the second most dominant phytoplankton family. This could be due to the changing water quality conditions and climate change effects. Especially the increasing alkalinity in the lake could be a possible reason for the sudden rise of Chlorophyceae over Bacillariophyceae. Some aquatic organisms such as the *Chlorophyta spp* require the protection from erratic pH variations and so they would thrive well in alkaline waters[26]. Generally, nutrient enrichment in aquatic ecosystems has been known to regulate the phytoplankton primary production and succession[27].

Spatial and temporal variation of phytoplankton abundance: The phytoplankton abundance registered an overall mean of 50437.46±16257.21 (Ind.L^{-1}x10^3) in Lake Simbi (Table-1). Although no significant spatial variations (ANOVA, $P<0.05$) in the mean phytoplankton abundance values were realized in the lake ($F_{(5,30)}=0.547$, $p=0.739$), lowest mean phytoplankton abundance value (15505.40±7824.18Ind.L^{-1} x 10^3) was recorded at ST3 whereas the highest (100832.33 ± 87366.17Ind.L^{-1}x10^3) was found at ST6. Based on the results, the inshore stations (ST1, ST2 and ST6) exhibited higher phytoplankton abundance as compared to the offshore stations (ST3, ST4 and ST5), which could be because the inshore stations usually experience total mixing which distributes the nutrients in the water for phytoplankton growth while in offshore stations the nutrient availability is curtailed by the permanent thermocline in the stratified region of the lake which constitutes a barrier.

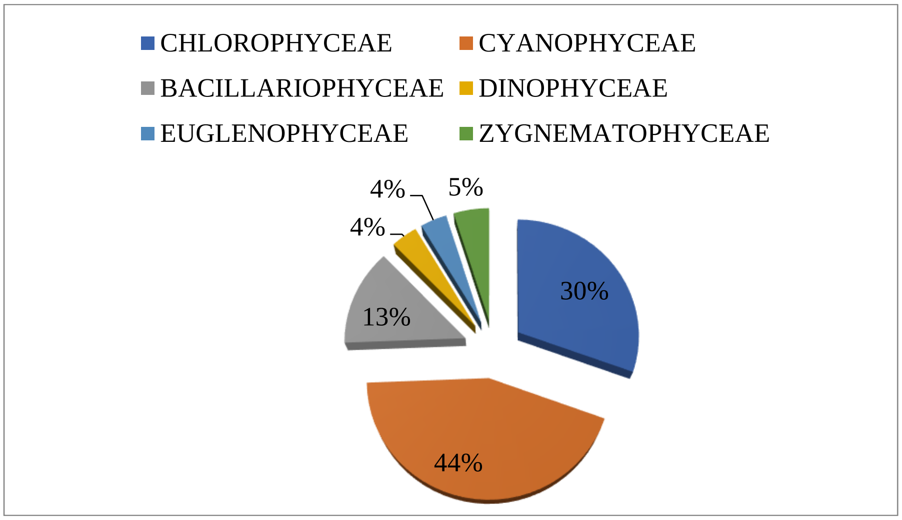

Figure-2: Phytoplankton community structure of Lake Simbi.

Table-1: Spatial and temporal variation of phytoplankton abundance.

Descriptive Statistics for phytoplankton abundance in Lake Simbi								
Spatial Variation			Temporal Variation					
Month		Abundance (Ind.L^{-1} x 10^3)	Month		Abundance (Ind.L^{-1} x 10^3)	Season		Abundance (Ind.L^{-1} x 10^3)
ST1	Mean	61993.82 ^{a}	Dec-18	Mean	80749.19 ^{a}	Dry	Mean	73056.68 ^{a}
	S.E.	25001.52		S.E.	31569.52		S.E.	30703.71
ST2	Mean	52416.14 ^{a}	Jan-19	Mean	124798.75 ^{a}	Wet	Mean	27818.24 ^{a}
	S.E.	30362.64		S.E.	85724.07		S.E.	9239.67
ST3	Mean	15505.40 ^{a}	Feb-19	Mean	13622.09 ^{a}	Total	Mean	50437.46
	S.E.	7824.18		S.E.	4085.64		S.E.	16257.21
ST4	Mean	23327.54 ^{a}	Mar-19	Mean	31599.68 ^{a}			
	S.E.	13442.59		S.E.	17371.38			
ST5	Mean	48549.51 ^{a}	Apr-19	Mean	28444.16 ^{a}			
	S.E.	27414.54		S.E.	16492.51			
ST6	Mean	100832.33 ^{a}	May-19	Mean	23410.88 ^{a}			
	S.E.	87366.17		S.E	17035.21			
Total	Mean	50437.46	Total	Mean	50437.46			
	S.E.	16257.21		S.E.	16257.21			

Note: Mean values in the same column that do not share a superscript letter are significantly different ($p<0.05$).

Also, with no significant temporal variations (Anova, $P< 0.05$) in the mean phytoplankton abundance values realized in the lake ($F(5,30)=1.219$, $p=0.324$), the lowest mean phytoplankton abundance of 13622.09±4085.64 (Ind.L^{-1}x10^3) was recorded in February 2019 and the highest mean of 124798.75 ± 85724.07 (Ind.L^{-1}x10^3) recorded in January 2019. The mean generally had a decreasing trend over time during the sampled months. Although, the mean phytoplankton abundance of dry season (73056.68 ± 30703.71 Ind.L^{-1}x10^3) was found to be higher than the mean phytoplankton abundance of the wet season (27818.24 ±9239.67Ind.L^{-1}x10^3), the t-test revealed no significant difference ($P< 0.05$) between the dry season and the wet season ($t(34)=1.411$, $p=0.167$) mean values (Table-4). The results showed that, the dry season recorded high counts of individuals as compared to the wet season because of the left-over nutrients which were made available by the rainy season preceding the short dry spell of December through February. Since the lake is closed, there's no flushing out of nutrients. The increased solar intensity and reduced turbidity could also be the reason for high phytoplankton abundance during the dry season[28]. The declining trend of the phytoplankton abundance from the dry season to the wet season realized in the lake could have been probably caused by a combination of decreased transparency in the water, diminished light period from the cloud cover and the dilution factor brought by the pounding rains.

Composition and distribution of phytoplankton species: The phytoplankton composition and distribution is given in Table-2. Phytoplankton species composition and succession is important in monitoring the changes in the ecological integrity of water bodies. The dominance of some phytoplankton species can be utilized in categorizing the trophic status of the water[29]. The dominance of the cyanophyceae (known by other names; myxophyceae, cyanobacteria and blue-green algae) in Lake Simbi shows that the lake is highly polluted. This condition is further confirmed by the little occurrence of the bacillariophyceae at about 13% in terms of relative abundance indicating that the waters of Lake Simbi have poor water quality since, the occurrence of bacillariophyceae in a water body is indicative of good water quality[30].

Table-2: A checklist of phytoplankton species showing their composition and distribution patterns long the sampling stations.

Family	Species	Sampling Stations					
		ST1	ST2	ST3	ST4	ST5	ST6
Chlorophyceae	*Oocystis parva*	+	-	-	-	-	-
	Pediastum boryanum	++	+	++	+++	+++	-
	Botryococcus braunii	+++	+++	++	+++	-	+++
	Monoraphidium braunii	+	++	-	-	-	-
	Chlorellla vulgaris	++	++	+++	+++	+++	+++
	Romeria elegans	-	++	+++	+	+++	-
	Pediastum duplex	-	-	++	-	-	-
	Tetraedron trigonum	-	-	++	-	-	++
	Kirchneriella obesa	-	-	++	-	-	-
	Monoraphidium caribeum	-	-	-	++	-	-
	Ankistrodesmus falcatus	-	-	-	+++	-	-
	Tetredronarthromisforme	-	-	-	-	++	-
	Coelastrum microporum	-	+	-	-	-	-
	Monoraphidium sp	+	-	-	-	-	++
	Pediastummuticum	-	-	++	-	++	-
	Scenedesmus acuminatus	+	-	-	++	-	-
	Scenedesmus obliquus	-	-	+	+++	++	+++
	Kirchneriella Lunaris	+++	+++	+++	-	++	-
	Ankistrodesmus gracilis	-	-	++	-	-	+++
	Oocystis nageli	+	-	-	-	-	-
	Crucigenia heteracantha	+	++	-	-	-	-
	Characium sp	-	++	-	-	-	-
	Kirchneriella Schmidle	-	-	++	-	-	-
	Crucigenia sp	-	+	-	-	-	-
Cyanophyceae	*Microcystis flos-aqua*	+++	-	-	-	-	+++
	Fragilaria aethiopica	+	-	-	-	-	-
	Planktolyngbya tallingii	++	-	-	-	-	-
	Planktolyngbya circum creta	+	++	-	-	++	-
	Spirulina princeps	+++	+++	+++	++	++	+
	Chroococcus turgidus	+++	++	+++	+++	++	+++
	Oscillatoria sp	++	++	++	+++	++	++
	Oscillatoria tenuis	+++	+++	+++	++	+++	+
	Planktolyngbya limnetica	-	++	+	+++	+++	++
	Anabaena flos-aquae	-	++	-	+++	-	-
	Cylindrospermopsis Africana	++	++	+	++	-	+++
	Spirulina major	+++	+++	+++	+++	+++	+++
	Spirulina gigantean	++	+++	++	+	-	+++
	Anabaena hylina	+++	+++	+++	+++	+++	+++
	Pseudo anabaena sp	+	++	-	++	-	-
	Pseudo-anabaena circularis	++	-	-	-	-	-

	Oscillatoria geminate	++	-	-	-	-	-
	Aphanocapsa rivularis	-	++	-	-	-	+++
	Spirulina laxissima	-	-	+++	-	-	+++
	Arthrospira fusiformis	+++	+++	++	+++	+++	+++
	Planktolyngbya contrata	++	-	-	-	-	-
	Oscillatoria splendida	+	-	-	-	-	-
	Anabaenopsis circularis	-	++	+++	++	++	+++
	Oscillatoria tanganyikae	-	++	-	+++	++	++
	Microcystis aeruginosa	-	++	-	+++	+++	+++
	Chroococcus disperses	-	++	+++	+++	-	+++
	Cylindrospermopsissp	-	-	+++	-	+	-
	Microcystis robusta	+++	+++	-	-	++	-
	Pseudo-anabaena tanganyikae	+	+++	++	++	++	+++
	Romeriaankensis	-	++	-	++	+++	+++
	Merismopedia tenuissima	-	-	-	-	+++	-
	Microcystis wasenbergii	-	-	++	++	++	-
	Anabaenopsis tanganyikae	-	++	-	+++	-	+++
	Chroococcus limneticus	+	-	-	+++	-	-
	Coelomoron sp	-	-	+++	-	+++	-
	Coelomoronvestitus	-	-	-	+++	-	-
Bacillariophyceae	*Fragilaria pinnata*	+	+++	+	-	++	+++
	Cyclotella ocellata	-	-	+	++	-	-
	Aulacoseira nyan senssis	+	-	-	-	-	-
	Nitzschia palea	-	-	-	+	-	-
	Nitzschiaacicuraris	-	-	-	+	++	-
	Fragillaria virescens	-	-	++	+++	-	-
	Navicula sp	-	-	++	-	-	-
	Nitzschia sp	-	-	++	-	-	-
	Surirella sp.	++	-	-	-	-	-
	Fragilaria construens	-	-	-	-	-	-
Dinophyceae	*Ceratiniumbranchyceros*	-	-	-	+++	++	+++
	Glenordinium bernardii	-	-	-	++	-	-
	Ceratinium sp	-	++	-	-	-	-
Euglenophyceae	*Euglena acus*	+++	++	-	-	++	+++
	Euglena viridis	-	-	-	++	-	-
	Phacus sp	-	-	-	+++	-	-
Zygnematophyceae	*Cosmarium succisum*	-	-	-	-	+	-
	Cosmarium muticum	+	++	-	-	-	-
	Closterium abruptum	-	-	+++	-	-	-
	Hyalotheca mucosa	++	++	-	++	+	-

Note: (-): Absent (0 Ind.L^{-1}); **(+)**: Rare (< 10,000 Ind.L^{-1}); **(++)**: Common (< 500,000 Ind.L^{-1}); **(+++)**: Dominant (> 500,000 Ind.L^{-1})

The dominance of cyanophyceae in alkaline-saline lakes could be due to the elevated levels of salinity, conductivity and alkalinity which are brought by the continuous weathering of the lithology and the closed nature of the lake.

The dominance of the cyanophyceae could also be stimulated by the excessive nutrient loading from the catchment of Lake Simbi where the intensive anthropogenic activities contribute to the interference with the natural balance of phosphate and nitrates in the water.

This situation is worsened by the fact that Lake Simbi is a totally closed lake which ensures that all the nutrients deposited are never washed off by outflows but remain in high concentration for consumption by the pollutant tolerant species, especially of the family cyanophyceae.

The low bacillariophyceae in the lake could be attributed to the polluted nature of the Lake Simbi and low silicate levels. Cyanophyceae family of Lake Simbi was dominated by the species *Microcystis flos-aqua* (33%), *Microcystis robusta* (25%), *Anabaena hylina* (24%) and *Microcystis aeruginosa* (7%) which is contrary to the previous findings[25] which documented *Arthrospira fusiformis* and *Anabaenopsis abijatae* as the most abundant cyanophycean species. This shift in the phytoplankton composition can be probably attributed to the changes in the water quality regime of Lake Simbi.

This shift in the dominance and composition of cyanobacterial species seems to be the plausible reason for the declining numbers of flamingos that inhabit Lake Simbi since their major food resources (*Arthrospira fusiformis* and *Anabaenopsis abijatae*) have been dwindling.

This agrees with previous observations that whenever there is massive biomass of *A. fusiformis* in the saline lakes, there is high flamingo population too since it is part of their food[31].

The declining numbers of the flamingo in Lake Simbi can also be attributed to the toxins (anatoxin-a andmicrocystins), which were previously identified in Lake Simbi[25], emanating from these dominant *Microcystis* species (microcystins) and *Anabaena* species (anatoxin-a). The algal bloom observed in Lake Simbi not only impaired the water quality but also contaminated the little food resources available for the lesser flamingos which could either be making them die off or migrate to other lakes such as Lake Nakuru. The algal blooms from blue-green algae have been widely documented to produce harmful cyanotoxins[25].

Spatial and temporal variation of phytoplankton species diversity indices: Diversity is an indicator of ecosystem health and diversity indices are considered essential tools for assessment of this health by understanding the community structure. Four diversity indices were utilized in estimating the phytoplankton species diversity of the lake: Shannon-Weiner's Diversity, Pielou's Evenness, Simpson's Diversity and Margalef's Richness. Generally, high temporal and spatial diversity was realized in the lake. The results of the spatial and temporal (monthly and seasonal) variation of these indices are presented in Table-3.

The results indicated that there were no significant spatial and temporal variations (ANOVA, $P< 0.05$) observed in the mean values of the four indices. The mean values of Shannon-Weiner's diversity, Pielou's evenness, Simpson's diversity and Margalef's richness indices are 0.10, 0.05, 0.04 and 0.03 respectively.

On the spatial scale, the Shannon-Weiner's diversity index ranged from 1.0 (ST1) to 1.61 (ST3); Pielou's evenness ranged from 0.42 (ST1) to 0.71 (ST3); Simpson's diversity index ranged from 0.29 (ST3) to 0.59 (ST1) and Margalef's richness index ranged from 0.4 (ST6) to 0.58 (ST1). On the temporal (monthly) scale, the Shannon-Weiner's diversity index ranged from 0.91 (December) to 1.5 (January); Pielou's evenness ranged from 0.42 (December) to 0.7 (May); Simpson's diversity index ranged from 0.34 (May) to 0.55 (December) and Margalef's richness index ranged from 0.43 (February) to 0.68 (January).

Seasonally, the mean values for Shannon-Weiner's diversity and Pielou's evenness indices were higher in the wet season as compared to the dry season while the mean values of the Simpson's diversity and Margalef's richness indices were higher in the dry season as compared to the wet season.

The two phytoplankton diversity indices (Shannon-Wiener and evenness) recorded higher values in wet season than the dry season since the increased availability of sufficient nutrients prevents competition among various species hence enabling various families to co-exist.

The quality of water in Lake Simbi recorded a mean value below 2 on the Shannon-Wiener Index which effectively categorizes it as heavily polluted. This characterization is based on a proposed classification[32], which categorizes the water as clean (> 4 Shannon-Wiener index value), mildly polluted (3 - 4 Shannon-Wiener index value) and lastly heavily polluted (<2 Shannon-Wiener index value).

This investigation constantly registered high values of phytoplankton species evenness which is indicative of equitable abundance of different phytoplankton groups during the period of this study.

The high species richness observed during the dry season could be attributed to the eutrophication and tidal movements. Studies postulates that a combination of tidal movements and dry environment enhances increased salinity in the lake which in turn favors the thriving of various phytoplankton species[33].

Table-3: Spatial and temporal variation of phytoplankton species diversity indices.

Descriptive Statistics for phytoplankton diversity indices in Lake Simbi

Spatial Variation

Month		Richness Index	Shannon Index	Evenness Index	Simpson Index
ST 1	Mean	0.58[a]	1[a]	0.42[a]	0.59[a]
	S.E	0.05	0.31	0.13	0.13
ST 2	Mean	0.55[a]	1.3[a]	0.58[a]	0.42[a]
	S.E	0.07	0.32	0.15	0.12
ST 3	Mean	0.55[a]	1.61[a]	0.71[a]	0.29[a]
	S.E	0.05	0.15	0.06	0.05
ST 4	Mean	0.57[a]	1.42[a]	0.61[a]	0.39[a]
	S.E	0.09	0.27	0.11	0.11
ST 5	Mean	0.45[a]	1.01[a]	0.49[a]	0.52[a]
	S.E	0.05	0.24	0.12	0.1
ST 6	Mean	0.4[a]	1.39[a]	0.69[a]	0.37[a]
	S.E	0.05	0.18	0.08	0.08
Total	Mean	0.52	1.29	0.59	0.43
	S.E	0.03	0.1	0.05	0.04

Temporal Variation

Month		Richness Index	Shannon Index	Evenness Index	Simpson Index
Dec 18	Mean	0.48[a]	0.91[a]	0.42[a]	0.55[a]
	S.E	0.06	0.25	0.12	0.1
Jan 19	Mean	0.68[a]	1.5[a]	0.59[a]	0.37[a]
	S.E	0.07	0.32	0.12	0.12
Feb 19	Mean	0.43[a]	1.28[a]	0.62[a]	0.43[a]
	S.E	0.07	0.19	0.07	0.08
Mar 19	Mean	0.5[a]	1.18[a]	0.55[a]	0.48[a]
	S.E	0.05	0.27	0.13	0.13
Apr-19	Mean	0.5[a]	1.36[a]	0.63[a]	0.4[a]
	S.E	0.06	0.25	0.11	0.1
May 19	Mean	0.49[a]	1.48[a]	0.7[a]	0.34[a]
	S.E	0.05	0.24	0.11	0.11
Total	Mean	0.52	1.29	0.59	0.43
	S.E	0.03	0.1	0.05	0.04

Note: Mean values in the same column that do not share a superscript letter are significantly different ($p<0.05$).

Conclusion

This study represents comprehensive baseline information, bridging the knowledge gap present in the phytoplankton dynamics of Lake Simbi. Six phytoplankton families were recorded in Lake Simbi of which the Cyanophyceae family was the most dominant. Even though the Cyanophyceae still dominated the waters in Lake Simbi, this study observed a shift in the dominance of the cyanobacterial composition whereby the cyanobacterial species which form the primary food resources for the lesser flamingos (*Arthrospira fusiformis* and *Anabaenopsis abijatae*) were overtaken by the toxin-producing *Microcystis* species (microcystins) and *Anabaena species (*anatoxin-a) in terms of abundance. The decreasing food resources coupled with food contamination by the toxins might have caused the migration and deaths of some flamingos respectively, hence the declining population observed in Lake Simbi over the recent years. All the phytoplankton characteristics of density and diversity indices evaluated in Lake Simbi exhibited no significant spatial and temporal variations. These findings therefore generally supported the initially stated hypothesis of the study. Generally, activities that help to improve and maintain ecosystem integrity need to be adopted by all stakeholders to promote sustainability of all aquatic resources in Lake Simbi.

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References

1. Trishala. K., Rawtani, D., & Agrawal, Y. K. (2016). #Bioindicators: the natural indicator of environmental pollution.# *Frontiers in life science*, 9(2), 110-118. https://doi.org/10.1080/21553769.2016.1162753
2. Reynolds, C. S. (2005). #The ecology of phytoplankton.# Cambridge University Press. http://dx.doi.org/10.1017/CBO9780511542145
3. Dhanam, S., Sathya, A., & Elayaraj, B. (2016). #Study of physico-chemical parameters and phytoplankton diversity of Ousterilake in Puducherry.# *World Scientific News*, *54*, 153-164.
4. Grace. A., & Schagerl, M. (2010). #Phytoplankton productivity in newly dug fish ponds within Lake Victoria wetlands (Uganda).# *African Journal of Environmental Science and Technology*, 4(6), 234-244. http://dx.doi.org/10.5897/AJEST09.210
5. Wetzel, R.G. & Liken, G.E. (2001). #Limnological Analyses.# Third Edition springe, New York p 429. http://dx.doi.org/10.1007/978-1-4757-3250-4
6. Khan, T. A. (2003). #Limnology of four saline lakes in western Victoria, Australia.# *Limnologica*, 33, 327-339. http://dx.doi.org/10.1016/S0075-9511(03)80026-9
7. Wetzel R.G. (1983). #Limnology.# 2nd Edition. Saunders College Publishing, Philadelphia, PA. https://doi.org/10.1007/978-1-4757-3250-4-2
8. Liu, Y., Fan, Y. W., & Wang, Q. X. (2015). #Study on the achnanthoid diatoms from the Great Xing 'anmoutains.# *Acta Hydrobiologica Sinica*, 39(3), 554-563.
9. Thakur, R. K., Jindal, R., Singh, U. B., & Ahluwalia, A. S. (2013). #Plankton diversity and water quality assessment of three freshwater lakes of Mandi (Himachal Pradesh, India) with special reference to planktonic indicators.# *Environmental monitoring and assessment*, 185(10), 8355-8373. http://dx.doi.org/10.1007/s10661-013-3178-3
10. Domingues, B., Barbosa, B., Sommer, U., & Galvão, M. (2012). #Phytoplankton composition, growth and production in the Guadiana estuary (SW Iberia): Unraveling changes induced after dam construction.# *Science of the Total Environment*, 416, 300-313. http://dx.doi.org/10.1016/j.scitotenv.2011.11.043
11. Wang L, Wei W and Zhou P. (2013). #Phytoplankton community structure and its relationship with environmental factors in the rivers of Tongling city, Anhui Province of East China in Winter.# *Chinese Journal of Applied Ecology*, 24(1), 243-250.
12. Cunqi, L., Lusan, L., & Huitao, S. (2010). #Seasonal variations of phytoplankton community structure in relation to physico-chemical factors in Lake Baiyangdian, China.# *Procedia Environmental Sciences*, 2, 1622–1631. http://dx.doi.org/10.1016/j.proenv.2010.10.173
13. Hayombe, P., Agong', M., Mossberg, L., Malbert, B., & Odede, F. (2014). #Simbi Nyaima: An Interplay of Nature and Mythology in the Lake Victoria Region; Planning and Management for Ecotourism Transformation in Kenya.# *Journal of Arts and Humanities*, 3(1), 173-187.
14. Oduor, B. (2018). #Pollution in Lake Simbi Nyaima sends away flamingos.# *Daily Nation*. Retrieved from https://www.nation.co.ke/news/Pollution-in-Lake-Nyaima-Simbi-sends-away-flamingos/1056-4672182-10n994k/index.html
15. U.S. Geological Survey (USGS) (2018). #Lakes and reservoirs—Guidelines for study design and sampling: U.S. Geological Survey Techniques and Methods.# Book 9, chap. A10, 48 p.
16. Huynh, M., & Serediak, N. (2006). #Algae Identification Field Guide Agriculture and Agric Food Canada.# In *Report number: Cat. No. A125-8/2-2011E-PDF*. Pp 40.
17. Cocquyt, C., Vyverman, W., & Compére, P., (1993). #A Check-List of the Algal Flora of the East African Great Lakes; Lake Malawi, Lake Tanganyika and Lake Victoria.# *Scripta Bot. Belg*., 8, 56.
18. Huber-Pestalozzi, G. (1975). #Das Phytoplankton des Süßwassers.# Systematik und Biologie.
19. HELCOM (2017). #Manual for Marine Monitoring in the Combine Programme of Helcom, Annex C-6: Guidelines concerning phytoplankton species composition.# *Abundance and Biomass*, 1-17. Retrieved from http://www.helcom.fi/Lists/Publications/Guidelines%20for%20monitoring%20phytoplankton%20species%20composition,%20abundance%20and%20biomass.pdf
20. Shannon, C. E., & Weaver, W. (1949). #The mathematical theory of communication.# University of Illinois Press. Urbana, pp 117. http://dx.doi.org/10.1063/1.3067010
21. Pielou, E. C. (1966). #The measurement of diversity in different types of biological collections.# *Journal of theoretical biology*, 13, 131-144. http://dx.doi.org/10.1016/0022-5193(66)90013-0
22. Simpson, E.H. (1949). #Measurement of Nature.# 163, 688. http://dx.doi:10.1038/163688a0
23. Margalef, R. (1958). #Temporal succession and spatial heterogeneity in phytoplankton.# *Perspectives in marine biology*, 323-349.
24. Mason, C. F. (1991). #Biology of Fresh Water Pollution.# 2nd Ed., Wesley and Sons Inc., New York, pp 351.
25. Ballot, A., Krienitz, L., Kotut, K., Wiegand, C., & Pflugmacher, S. (2005). #Cyanobacteria and cyanobacterial toxins in the alkaline crater lakes Sonachi and Simbi, Kenya.# *Harmful algae*, 4(1), 139-150. http://dx.doi.org/10.1016/j.hal.2004.01.001

26. Abubakar, S. (2017). #Aspects of Physico-Chemical Parameters and Phytoplankton Assemblage of River Saye, Zaria, Kaduna State, Nigeria.# Master's Thesis. Ahmadu Bello University, Zaria, Nigeria.

27. Githaiga, J.M. (2003). #Ecological factors determining utilization patterns and inter-lake movement of lesser flamingos (Phoeniconaias minor) in Kenyan alkaline lakes.# Doctorate Thesis. University of Nairobi, Nairobi, Kenya.

28. Ewa, E., Iwara, I. & Ekelemu, K. (2013). #Spatio-temporal Distribution of Phytoplankton in the Industrial area of Calabar River.# *Advances in Environmental Biology*, 7(3), 466-470.

29. Ogendi, M. (2017). #Effects of Anthropogenic Activities on Water Quality of Nyakomisaro Riana and Nyanchwa-Riana Rivers Draining Kisii Municipality, South-West Kenya.# Doctorate Thesis, Kisii University, Kisii, Kenya.

30. Tan, X., Ma, P., Xia, X., & Zhang, Q. (2014). #Spatial pattern of benthic diatoms and water quality assessment using diatom indices in a subtropical river, China.# *Clean Soil, Air, Water*, 42(1), 20-28. http://dx.doi.org/10.1002/clen.201200152

31. Tuite, C. H. (1979). #Population size, distribution and biomass density of the lesser flamingo in the Eastern Rift valley, 1974-76.# *Journal of Applied ecology*, 16(3), 765-775.

32. Shekhar, T. S., Kiran, B. R., Puttaiah, E. T., Shivaraj, Y., & Mahadevan, K. M. (2008). #Phytoplankton as index of water quality with reference to industrial pollution.# *Journal of Environmental Biology*, 29(2), 233.

33. Fonge, A., Chuyong, B., Tening, A., Fobid, A., & Numbisi, A. (2013). #Seasonal occurrence, distribution and diversity of phytoplankton in the Douala Estuary, Cameroon.# *African Journal of Aquatic Science*, 38(2), 123-133. http://dx.doi.org/10.2989/16085914.2013.769086