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Spatio-temporal trends of nutrients and physico-chemical parameters on lake ecosystem and fisheries prior to onset of cage farming and re-opening of the Mbita passage in the Nyanza Gulf of Lake Victoria

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Abstract

Many large lake ecosystems are experiencing increasing eutrophication and persistent cyanobacteria-dominated algal blooms affecting their water quality and ecosystem productivity because of widespread non-point and point nutrient sources. Accordingly, the present study utilized data of July 2003 and January–February 2004, as well as previous measurements of nutrients and physico-chemical variables (electrical conductivity, dissolved oxygen, temperature, pH, turbidity and chlorophyll-*a*), to characterize the spatial and temporal trends, as a means of better understanding the factors influencing lake environmental conditions, as support tools for long-term ecosystem management and for better understanding the long-term trends and effects. Inshore gulf areas were found to represent zones of maximum nutrient concentrations, compared to the deep main lake zones, with significant inter-parameter correlations. Phosphorus, silicon and chlorophyll-*a* concentrations were significantly correlated. Water electrical conductivity was also significantly and positively correlated with soluble reactive silicon (SRSi), alkalinity hardness DO, while exhibiting a negative association with water transparency. Water turbidity and transparency, electrical conductivity, and SRSi concentrations clearly describe a gradient from the gulf into the main lake. For such a shallow gulf, these findings suggest primary productivity is influenced mainly by the availability of nutrients, light transparency and the extent of availability of resuspended nutrients. The increasing eutrophic state of Lake Victoria is a serious concern since it contributes to an increased potential of more frequent occurrences of cyanobacterial blooms, a potential public health risk to both humans and wildlife. Improved understanding of influences from previous fish species introductions and concomitant changes in indigenous fish species, increased lake basin population and anthropogenic activities, water hyacinth resurgences, sustainability of biodiversity, and current interests in cage farming, are among the major concerns and challenges facing the contemporary Lake Victoria. The trends regarding nutrients and physico-chemical characteristics are intended to support better monitoring efforts and data to promote the lake's ecosystem services and the sustainable management of the lake ecosystem.

KEYWORDS
environmental gradients, Lake Victoria, nutrients, Nyanza Gulf, water quality

1 | INTRODUCTION

Nutrient supplies to lake ecosystems play a key role in their productivity, with subsequent implications for their fisheries, water quality, aesthetic and recreational values. Lake Victoria, a relatively shallow basin in eastern Africa, has been characterized as eutrophic, exhibiting major past ecological changes driven by fish species introductions, especially Nile perch and Nile tilapia of the 1950s and 1960s.

Lake Victoria experiences a modified equatorial type of climate, with rainfall throughout the year, especially over the lake and its vicinity. It exhibits a semiarid type of climate, with intermittent droughts over some areas. In studying the interactions among the component of the Lake Victoria system, Downing et al. (2014) summarized the changes occurring in Lake Victoria as being a complex product of social, economic and ecological processes. More recently, Marshall (2018) was in support of a top-down model, proposing Nile perch destroyed the haplochromines and caused the disruption of food chains and nutrient cycling, in turn initiating accelerated eutrophication of the lake. Eutrophic conditions in Lake Victoria (East Africa) have been a concern since the early-1980s (Awange & Obiero, 2006; Gikuma-Njuru, 2008; Hecky, 1993; Hecky et al., 1994; Hecky & Bugenyi, 1992; Hecky, Mugidde, Ramlal, Talbot, & Kling, 2010; Kimirei, Semba, Mwakosya, Mgaya, & Mahongo, 2017; Lung'ayia, Sitoki, & Kenyanya, 2001; Misiko et al., 2014; Musungu, Lalah, Jondiko, & Ongeri, 2013; Odada, Olago, Kulindwa, Ntiba, & Wandiga, 2004; Sitoki, Ezekiel, Wanda, Mkumbo, & Marshall, 2010; Verschuren et al., 2002). Raw sewage is discharged into small rivers or streams, or directly into Lake Victoria, contributing significantly to its pollution (Awange & Obiero, 2006). The lake environmental conditions indicate a heterogeneous system. The inshore to offshore gradients for chlorophyll-*a*, and primary productivity are still present, and while the total phosphorus (TP) concentration in the lake is still relatively spatially homogenous, its concentrations have more than doubled, with increasing TP concentrations since the 1960s promoting higher algal biomasses because N-fixing cyanobacteria cannot be limited by low dissolved inorganic nitrogen concentrations (Hecky et al., 2010). The Kenyan catchment area of Lake Victoria experiences distinct wet (short rainy season months of October to December; long rainy season months of March to June) and dry seasons (months of July to September and January to February). The temporal scales exhibit seasonal influences on nutrient concentrations (Lung'ayia, M'Harzi, Tackx, Gichuki, & Symoens, 2000). The high nutrient levels are thought to sustain water hyacinth growths in the lake, and there is a serious need to initiate more control of nutrient loadings from urban point sources and the widespread diffuse sources along drainage basins and vast agricultural lands.

The Nyanza Gulf forms the eastern gulf of Lake Victoria, containing several shallow to deep bays, deepening toward the west. Major nutrient loads enter the lake via atmospheric deposition as a result of intensive land use in the basin through land clearing and burning (Hecky, Bootsma, & Odada, 2006; Tamatamah, Hecky, & Duthie, 2005). Concerted efforts have been conducted through projects funded by the World bank (LVEMP) and riparian national governments and regional research institutions (e.g., Lake Victoria Fisheries Research Organization, LVFO) to monitor fishing grounds and promote strategies and practical approaches to mitigate against point source pollution, water hyacinth infestations, and watershed management. Both inshore and offshore lake areas are important fish breeding and nursery areas. The Kenyan portion of Lake Victoria comprises the Winam Gulf, consisting of many shallow small and large bay areas of <5-m depth, which are more impacted by land-based anthropogenic activities. Although detailed data on the external phosphorus (P) and nitrogen (N) sources in specific riparian catchments is expanding (Guya, 2019; Zhou et al., 2014), they are still inadequate.

Accordingly, the present study presents trends on the nutrient status of the Gulf, contributing to a better understanding of eutrophication and its effects on fisheries production, with the goal of discussing the nutrient sources amid the potential emergence of new challenges from the developments in fisheries (e.g., cage fish farming) and potential resurgences of water hyacinth along its bays. Recent studies indicate an increasing number of fish cages (Aura et al., 2018; Hamilton et al., 2020; Njiru, Aura, & Okechi, 2018). There also are growing concerns regarding the water quality around those areas attributable to non-adherence to best practices in cage fish farming (Musinguzi et al., 2019).

The present study examined the spatial and temporal patterns, and the associated implications of the environmental factors on the lake ecosystem, based on the longitudinal extent of the Nyanza Gulf, which receives numerous riverine inputs located in the extensive southern and northern watersheds, and other direct inputs into the lake from precipitation. It also presents nutrient measurements and data on the physico-chemical characteristics, including previously generated data and information on the Nyanza Gulf before the re-opening of the Mbita Passage, the latter suggested as being a barrier to effective lake – gulf water exchanges between the between the Rusinga Channel north of Rusinga Island.

2 | MATERIALS AND METHODS

2.1 | Study area

Lake Victoria is one of the largest lakes in the world (68,800 km^2 in surface area) and the largest in Africa, supporting both export commercial and artisanal fishery. The catchment area is mostly dominated by agricultural activities. The Lake Victoria shoreline is shared by Kenya, Uganda and Tanzania, being indented with several bays and gulfs. The present study was conducted in the Nyanza Gulf of Lake Victoria (East Africa), which is a relatively shallow basin connected to several streams and major inflowing rivers. The Yala River enters Lake Victoria through the largest freshwater wetland (Yala Swamp) in Kenya (MEMR, 2012) in which three important satellite lakes (Namboyo, Sare and Kanyaboli) are located. The Kuja, Nzoia and Yala rivers have less direct effects on the gulf, compared to the Sondu-Miriu, Nyando, Awach and Kibos rivers, and the smaller urban streams (e.g., Kisat) that drain directly into the gulf. Nyanza Gulf is the extreme eastern gulf of Lake Victoria, comprising the Kenyan portion of the lake (about 6% of its total surface area). Rusinga Island is a major physical feature, with hydrological exchanges between the main lake and the Winam Gulf occurring through the Rusinga channel. The government constructed a causeway across the Mbita passage in 1983, connecting the mainland and Rusinga Island and thereby reducing the risks of sailing across the passage associated with its strong underwater currents. Planned replacement of the causeway with a bridge commenced in 2013. This ended in 2017 with the re-opening of the passage to address strong scientific arguments regarding water quality degradation and negative effects on the fisheries resulting from reduced water exchanges and flushing of the gulf. Khisa et al. (2005) reported localised effects on water circulation and flushing, as well as effects on the lake water quality using a 3-D hydrodynamic ELCOM model (Estuary, Lake and Coastal Ocean Model) (Hodges, Imberger, Saggio, & Winters, 2000) simulation study between April and May 2005, providing the first quantitative evaluation of the effects of the causeway construction on the water circulation patterns. There also is observable sediment deposition on both sides of the causeway after its construction across the Mbita passage, resulting in a reduced water depth around the Mbita pier.

Cage fish farming is practiced in several areas of the lake (Aura et al., 2018; Njiru et al., 2018), contributing to improved fish production and livelihoods of the communities dependent on the lake fisheries resources. Fish cage culture in the Kenyan portion of Lake Victoria began around 2005, and fish cage farming continues to expand in this area up to the present time, with a 262% increase in the number of fish cages (Hamilton et al., 2020).

The water budget of the lake depends on the balance between evaporation and direct rainfall, with the latter contributing about 117 km^3 (about 82% of the total water inflow) and the former accounting for about 105 km^3 (about 76% of the water losses from the lake, Sewaggude, 2009). River discharges contributed significantly to the water inputs, and water exits the lake physically through Nile River and underground exchanges. The equatorial climate around Lake Victoria results in two rainy seasons (March to June; November to December) and a dry season between September and October and January to February. Lake Victoria experiences three phases of thermal stratification (moderate stratification in September and December; stable stratification in January to March/April; and deep water mixing during June to July) (Mugidde, Gichuki, Rutagemwa, Ndawula, & Matovu, 2005; Njiru et al., 2012; Talling, 1966). Thermal stability hinders the ability of the lake to mix effectively, promoting low dissolved oxygen (DO) conditions in the deep lake waters during the stratification period between September and April (Mugidde et al., 2005; Njiru et al., 2012).

The lake is still eutrophic, with increasing anthropogenic inputs of nitrogen and phosphorus. The available estimates of TP and TN loads from the Kenyan catchment of the lake indicate similar magnitudes, with about 1,724 tons TP/year and 9,603 tons TN/year (Opango, Gor, Okungu, Abuodha, & Hecky, 2005); and 1,925 tons TP/year and 9,764 tons TN/year (COWI, 2002). Based on recent estimates of the net anthropogenic N loads to Lake Victoria, the largest source of reactive nitrogen to the lake itself was atmospheric oxidized N deposition (>50%), excluding the lake biological N_2 fixation source (Zhou et al., 2014).

2.2 | Sampling and determination of physical and chemical parameters

Sampling was conducted at 29 sites (17 sampling sites in the gulf and 12 in the main lake) during the months of July 2003 to January–February 2004. In situ profile measurements of water depth, pH, DO concentration, temperature, electrical conductivity and oxidation-reduction potential (ORP) were taken with a YSI 650–MDS multi-parameter display system and YSI 6600 Sonde (USA) after calibration, including appropriate compatible software for data analysis. The Winkler Method for determining the DO concentration was used in conjunction with in-situ DO measurements. Secchi disk transparency was measured with a 25-cm diameter white and black disk, being calculated as the average of the depth of disappearance and reappearance of the Secchi disk. Total alkalinity and water hardness and turbidity were determined according to Standard Methods (APHA, 1985).

2.3 | Nutrient and chlorophyll-*a* concentrations

Water samples for determining the chlorophyll-*a* concentration were obtained with a Van Dorn water sampler and dispensed into plastic bottles. Water samples of 50–100 ml) were filtered through Whatman GF/F filters for chlorophyll-*a* analysis. The filters were desiccated over silica gel in the field and were subsequently immersed in the laboratory in 10 ml of 95% methanol for about 20 hr at 4°C in the dark. The absorbance of the extracts was then measured spectrophotometrically at 665-nm and corrected for turbidity at 750-nm.

Water samples for nutrient determinations were collected below the water surface and filtered (0.45 μm membrane filters) for measurement of soluble nutrient elements. Dissolved nutrients (i.e., ammonium nitrogen [NH_4–N], soluble reactive phosphorus [SRP], soluble reactive silicon [SRSi], nitrite nitrogen [NO_2–N] and nitrate nitrogen [NO_3–N]) were determined according to Standard Methods (APHA, 1985; Wetzel & Likens, 1991). Soluble reactive phosphorus was determined using the ascorbic acid method, with

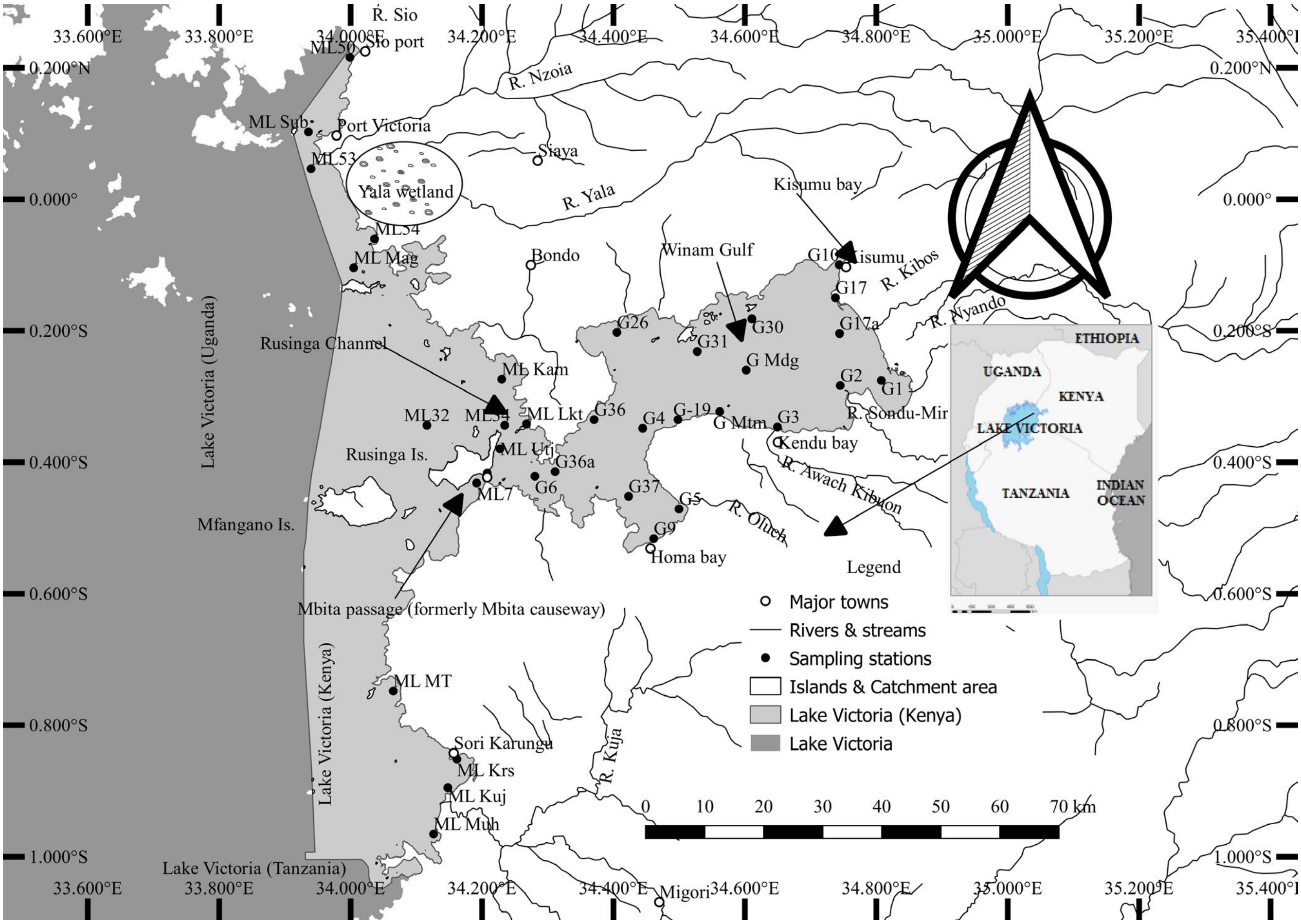


FIGURE 1 Map of Lake Victoria (Kenya) showing sampling sites in Nyanza Gulf (G) and main body of Lake Victoria (ML)

the absorbance measured at 885-nm. The NH_4–N concentration was measured using the indophenols method, whereas NO_3–N and NO_2–N concentrations were measured using the cadmium reduction method, while soluble reactive silicon was determined using the ammonium molybdate reaction method. Analytical laboratory quality control and quality assurance (QA/QC) procedures for instrumental analysis were employed during the nutrient analyses. Nutrients measurements were conducted in duplicates, using internal calibration standards and analytical grade chemical reagents (Figure 1).

2.4 | Data analysis

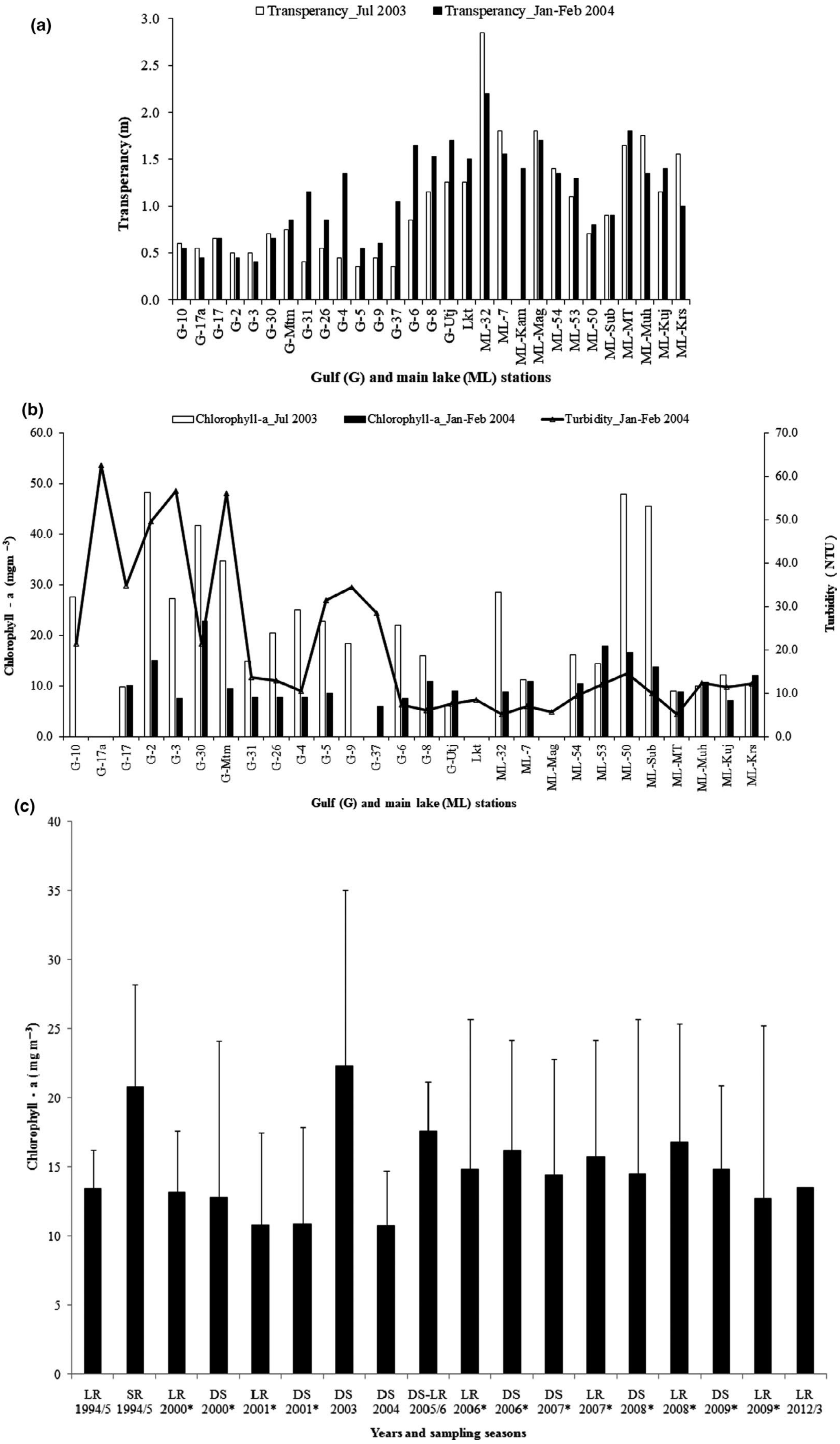
The generated data on the parameter concentrations were checked for normality and described statistically using SPSS software and Excel package. One-way analysis of variance (ANOVA) was used to determine whether or not spatial and temporal variations of the different concentrations and levels were significantly different for the various sampling sites.

3 | RESULTS

3.1 | Environmental gradients between the gulf and main lake during 2003 to 2004

The spatial trends in observed water quality characteristics (Figure 2a–h) tend to separate the gulf and main lake waters. Table 1 illustrates significant variations in mean values (ANOVA, $p < .05$) of the measured physico-chemical parameters and nutrients between the gulf (G) and main lake (ML) areas, based on pooled data from the two surveys (Table 2). During 2003 and 2004, the highest values

FIGURE 2 (a) Changes in water transparency, turbidity and chlorophyll-*a* concentrations in Nyanza Gulf and main lake during mixing (July 2003); (b) Stratification (January to February 2004) periods; (c) Chlorophyll-*a* concentrations for gulf and whole lake over past 29 years (LR, long rains from January to May; DS, dry season from June to August; SR, short rains from September to December; year values marked with * represent whole lake mean, including Nyanza Gulf sites). (d, e) Changes in electrical conductivity, total alkalinity and water hardness in Nyanza Gulf and main lake during mixing (July 2003) and stratification (January to February 2004) periods. (f, g, h) Changes in surface and bottom water temperatures and dissolved oxygen concentrations in Nyanza gulf and main lake during mixing (July 2003) and stratification (January to February 2004) periods


(a)
Transperancy_Jul 2003
Transperancy_Jan-Feb 2004
Transperancy (m)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
G-10
G-17a
G-17
G-2
G-3
G-30
G-Mtm
G-31
G-26
G-4
G-5
G-9
G-37
G-6
G-8
G-Utj
Lkt
ML-32
ML-7
ML-Kam
ML-Mag
ML-54
ML-53
ML-50
ML-Sub
ML-MT
ML-Muh
ML-Kuj
ML-Krs
Gulf (G) and main lake (ML) stations
(b)
Chlorophyll-a_Jul 2003
Chlorophyll-a_Jan-Feb 2004
Turbidity_Jan-Feb 2004
Chlorophyll - a (mgm −3)
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Turbidity (NTU)
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
G-10
G-17a
G-17
G-2
G-3
G-30
G-Mtm
G-31
G-26
G-4
G-5
G-9
G-37
G-6
G-8
G-Utj
Lkt
ML-32
ML-7
ML-Mag
ML-54
ML-53
ML-50
ML-Sub
ML-MT
ML-Muh
ML-Kuj
ML-Krs
Gulf (G) and main lake (ML) stations
(c)
Chlorophyll - a (mg m−3)
40
35
30
25
20
15
10
5
0
LR 1994/5
SR 1994/5
LR 2000*
DS 2000*
LR 2001*
DS 2001*
DS 2003
DS 2004
DS-LR 2005/6
LR 2006*
DS 2006*
DS 2007*
LR 2007*
DS 2008*
LR 2008*
DS 2009*
LR 2009*
LR 2012/3
Years and sampling seasons

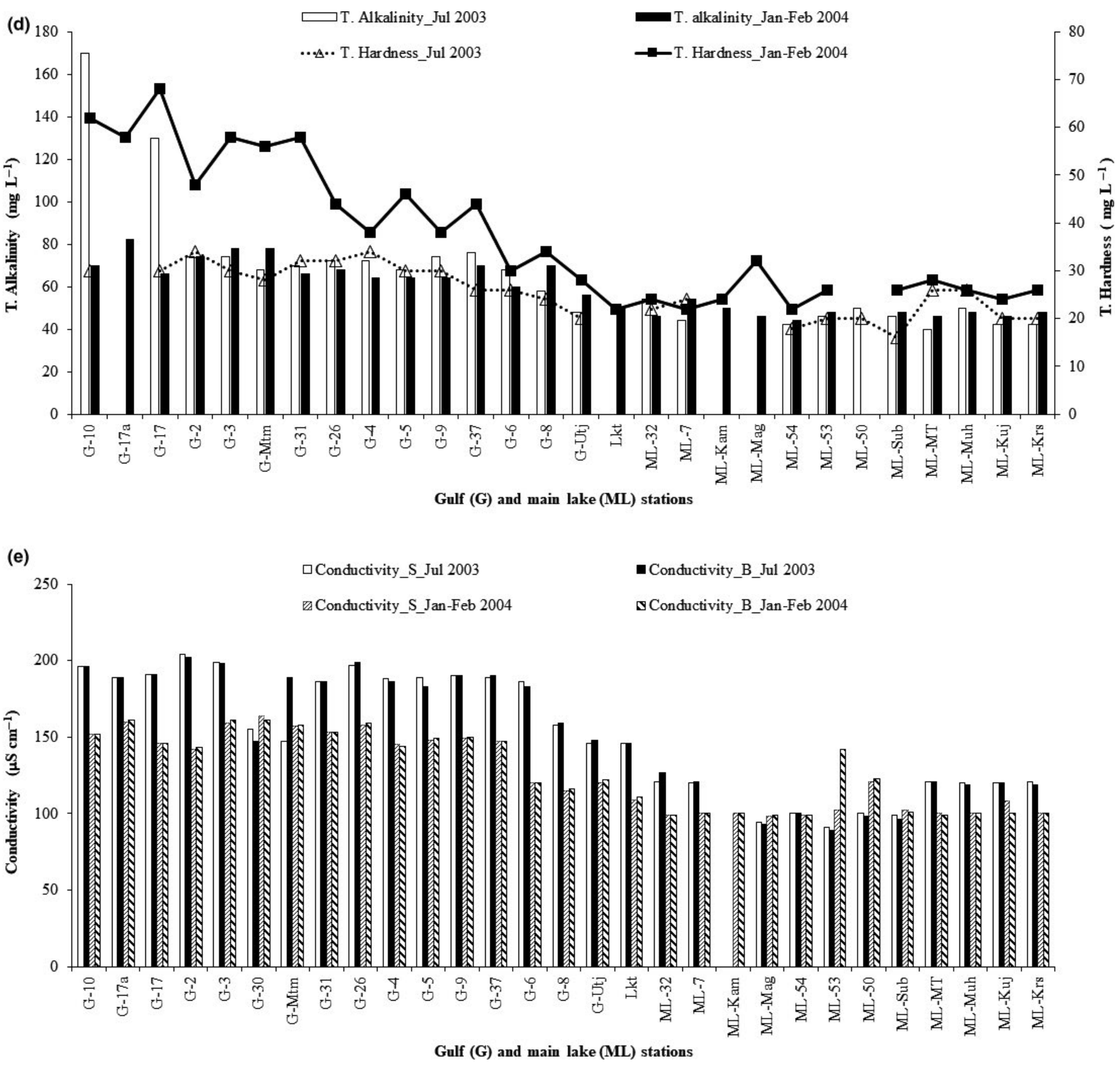


FIGURE 2 (Continued)

of surface water conductivity decreased from 204 to 91 µS/cm and 164 to 98 µS/cm respectively, moving towards the main lake. Before re-opening of the Mbita causeway, the gulf lake waters boundary around the Rusinga channel was marked by values of about 148–120 µS/cm. The observed Secchi depth was much higher in 2003, but with no significant differences in the mean values. The lowest and highest Secchi depth observed at all the sites was 0.4- and 2.9-m, respectively. The water turbidity was >5 NTU, with a maximum value of 62.5 NTU, although no values were provided for 2003. Higher surface water DO concentrations were observed in both durations, compared to the deep waters, with the lowest D.O concentrations of 6.4 mg/L (surface water) and 1.7 mg/L (bottom waters) observed at the shallow gulf (Kisumu Bay) and main lake (off river mouth) sites. The water pH also exhibited spatial changes, but lacked any significant mean ($p < .05$) temporal differences. The surface water pH ranged from 6.4 to 8.3. The difference between the surface and bottom water temperatures exhibited a high range of 3.60°C and 3.13°C (2003), and 2.2°C and 4.2°C (2004), with an overall minimum and maximum value of 22.46°C and 28.5°C, respectively. The total alkalinity and hardness of the surface water ranged from 40 mg $CaCO_3$/L to 170 mg $CaCO_3$/L and 16 mg $CaCO_3$/L to 68 mg $CaCO_3$/L, respectively.

The lowest and highest measures of phytoplankton biomass, expressed as chlorophyll-*a* concentration, ranged from 8.95 to 48.12 mg/m^3 (2003) and 6.01 to 22.73 mg/m^3 (2004). The chlorophyll-*a* concentration trends over the years indicates values >10 mg/m^3, with high concentrations recoded during the investigations of 1994/1995, 2003, 2005/2006 and 2008. Water turbidity values

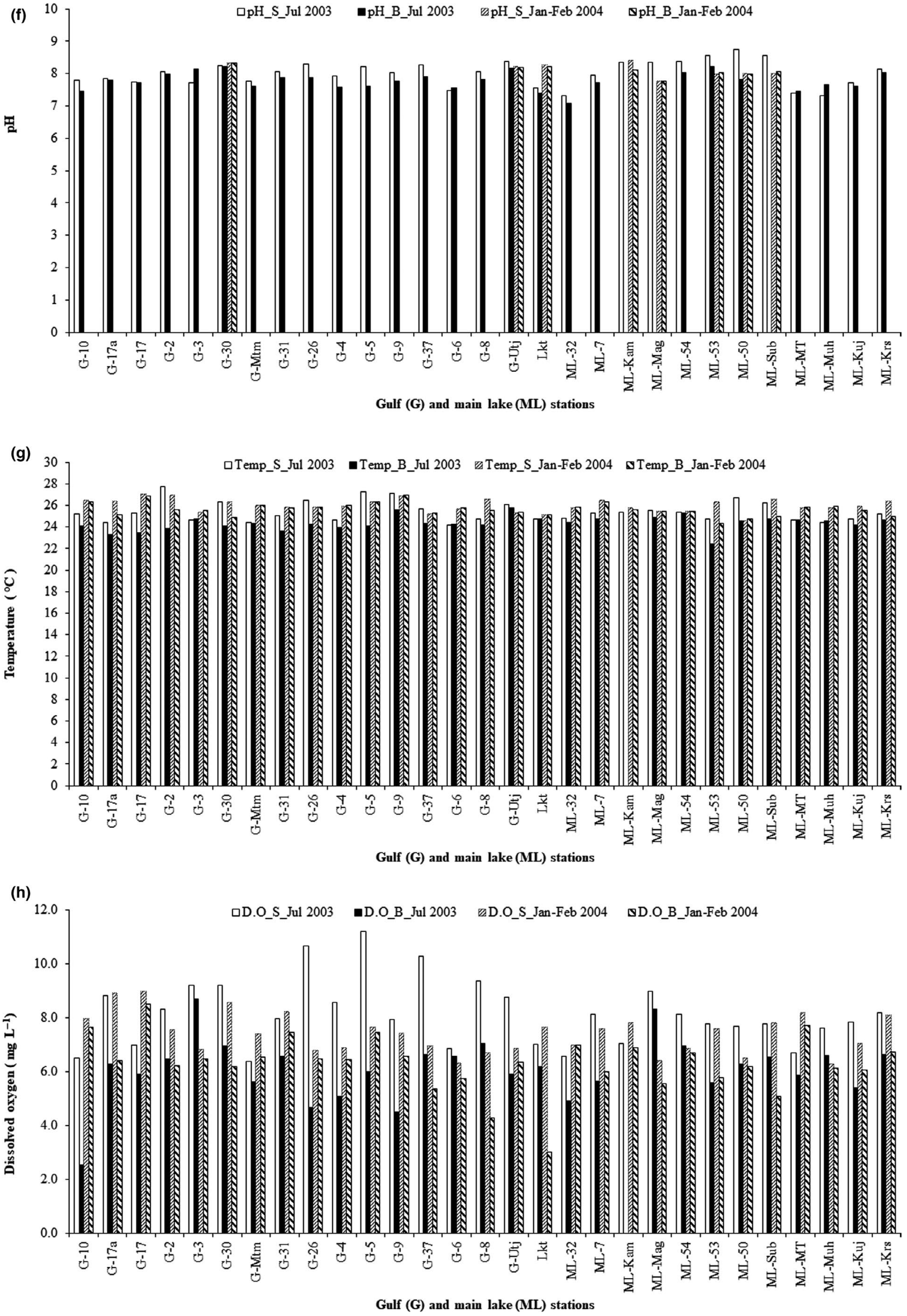


FIGURE 2 (Continued)

(2004) ranged from 5.1 to 62.5 NTU, with the turbidity decreasing from the inshore to offshore gulf sites, and from shallow to deep main lake sites (Figure 2i). The scatter plots (Figures S1–S4) illustrate the associations between these parameters, appearing low, but being significant ($p < .05$; Table 3). The water transparency was negatively and significantly ($p < .05$) associated with the DDO, total alkalinity, hardness and electrical conductivity (Table 3). Other notable positive significant correlations ($p < .05$) were between DO and temperature, pH and DO, turbidity and temperature, and alkalinity and hardness. High significant associations were exhibited by the electrical conductivity and total alkalinity ($r = .679$), water transparency ($r = -.622$), and pH and temperature ($r = .507$). The relatively high electrical conductivity, turbidity, total alkalinity, hardness, silica–Si and DO, and a lower water transparency in the Nyanza Gulf waters were clearly distinct from the values obtained from the from main lake.

3.2 | Changes in nutritive elements between gulf and main lake during 2003 and 2004

The minimum and highest values of the concentrations of nitrate–N, ammonium–N and SRP, were 5.09–247.46 μg/L, 2.84–47.24 μg/L and 8.92–602 μg/L, respectively, between 2003 and 2004, with the maximum nitrate, ammonium and SRP concentrations observed at sites G-6, ML-Muh and ML-54. Higher concentrations of SRP and nitrate–N were found in 2003, compared to 2004. Nutrient concentration variations towards the main lake did not exhibit any clear pattern with respect to nitrate–N or SRP concentrations (Figure 3a–c). The SRP concentrations tended to decrease towards the main lake, however, exhibiting some peaks at some main lake sites (site 54; Sumba channel; Krs or Karungu-Sori). The concentrations were very much lower in 2004, with exhibiting such concentration peaks. Ammonium–N concentrations were lower than nitrate–N, tending to decrease towards the mid-gulf stations, but increasing and leveling out in the main lake.

The lake water often contained much higher concentrations of silica–Si after the rainy seasons, compared to the dry months, although the concentrations generally exhibited a similar decreasing trend transitioning from the shallower inner gulf shore areas towards the offshore main lake zones, with peak concentrations at G_26, G_4 and G_37. The SiO_2–Si concentrations in July 2003 and January to February 2004 (Figure 3c) ranged from 0.15 to 19.39 mg/L (gulf sites) and 0.89 to 6.76 mg/L (main lake sites), and from 0.33 to 6.71 mg/L (gulf sites) and 0.07 to 3.00 mg/L (main lake sites), respectively. The mean concentrations were 7.85 mg/L (gulf water mean = 11.89 mg/L; main lake = 2.19 mg/L) and 1.56 mg/L (gulf water mean = 2.13 mg/L and main lake = 0.76 mg/L) in 2003 and 2004, respectively. Significant temporal differences ($p < .05$) were observed between the mean concentrations of the nutritive elements, except for water pH and alkalinity (Table 1 and 2). The water characteristics revealed no significant variations between each sampling period, except for the mean concentration of SRSi, total alkalinity, hardness and electrical conductivity ($p < .05$). Pooling the two data sets, the mean concentrations of SRSi, water transparency, hardness, total alkalinity and electrical conductivity were all significantly different ($p < .05$) between the gulf and main lake. The peak concentrations along the longitudinal section of the gulf within the gulf coincided with areas exhibiting significant river influences, especially on the southern gulf shores, with these

TABLE 1 Mean values (±*SD*) illustrating significant differences between two sampling surveys (different superscript letter indicates significant difference at $p < .05$)

		July 2003	January–February 2004			
Parameter	**Zone**	**Mean (±*SD*)**	**Mean (±*SD*)**	***df***	***n***	***p***
SRP (μg/L)	S	222.83 ± 136.92^{a}	18.99 ± 10.36^{b}	1.46	24	.000
Nitrate–N (μg/L)	S	93.19 ± 53.63^{a}	32.22 ± 24.54^{b}	1.46	24	.000
Ammonium–N (μg/L)	S	15.21 ± 8.63^{a}	25.75 ± 11.57^{b}	1.40	21	.002
Silica–Si (mg/L)	S	7.85 ± 6.78^{a}	1.56 ± 1.58^{b}	1.46	24	.000
Chlorophyll-*a* (μg/L)	S	22.29 ± 12.71^{a}	10.74 ± 4.03^{b}	1.44	23	.000
Temperature (°C)	S	25.43 ± 0.95^{a}	26.03 ± 0.55^{b}	1.56	29	.005
	B	24.31 ± 0.60^{a}	25.73 ± 0.80^{b}	1.56	29	.000
Dissolved oxygen (mg/L)	S	8.15 ± 1.24^{a}	7.42 ± 0.77^{b}	1.56	29	.010
	B	5.98 ± 1.33^{a}	6.17 ± 1.35^{a}	1.55	29	.501
pH	S	8.01 ± 0.38^{a}	7.98 ± 0.57^{a}	1.37	29	.846
	B	7.90 ± 0.57^{a}	8.11 ± 0.16^{a}	1.37	29	.239
Electrical conductivity (μS/cm)	S	148.85 ± 41.14^{a}	126.67 ± 24.59^{a}	1.37	29	.846
	B	150.15 ± 41.62^{a}	128.33 ± 24.74^{b}	1.51	27	.023
Total alkalinity (mg/L)	S	66 ± 30^{a}	60 ± 12^{a}	1.48	26	.346
Total hardness (mg/L)	S	26 ± 6^{a}	38 ± 14^{b}	1.37	29	.000
Water transparency (m)		0.98 ± 0.58^{a}	1.16 ± 0.47^{a}	1.58	30	.20

concentrations subsequently decreasing gradually to levels commonly associated with lake water (i.e., <5 mg/L). The uniquely high values within the main lake are also sites around the southern main lake river mouths areas (Kuja River; near Muhuru Bay and sites near the main lake northern catchment Yala, Nzoia and Sio river mouths; and areas around the Sumba channel).

Low, but significant ($p < .05$) relationships were observed between the physico-chemical parameters and nutrients in the lake water (Table 3). The scatter plots illustrate a strong association between electrical conductivity and SRSi concentrations (Figures S1–S4). The water transparency was negatively and significantly ($p < .05$) associated with SRSi concentration (Table 3). Other significant correlations ($p < .05$) were observed between hardness and SRP, hardness and chlorophyll-*a*, SRP and SRSi, and SRSi and chlorophyll-*a*. High significant associations were exhibited between SRSi and water conductivity ($r = .813$) and SRSi and total alkalinity ($r = .635$), with the SRSi exhibiting a decreasing trend moving towards the main lake.

4 | DISCUSSION

4.1 | Environmental gradients between the gulf and main lake in past 29 years before re-opening of Mbita Causeway and initiation of cage fish farming

The relatively shallow Nyanza Gulf is fed by many rivers contributing land-derived materials into the lake. Although it is exposed to strong hydrodynamic exchanges between the main lake and the gulf, previous restricted water flows between the southern passage (Mbita Causeway opened and replaced by a bridge in 2017) was often associated with a decrease water quality in the gulf attributed to reduced flushing effects. The results of the present study and other documented spatial data indicate invariant environmental gradients between the gulf and main lake for some parameters, including electrical conductivity, total alkalinity, turbidity, etc. Limnological data from the two surveys of July 2003 (period of deep lake water column mixing experienced from June to July) and January to February 2004 (period when lake water experiences more stable thermal stratification between January to March/April) exhibited this spatial variability between the Nyanza Gulf (G) and the main lake (ML) water, with slight vertical variations in water temperature and DO concentrations at the deep water sites. The spatial trends revealed relatively high electrical conductivity, turbidity, total alkalinity, hardness, silica–Si, dissolved oxygen (DO), and a lower water transparency in the Nyanza Gulf water. The gulf receives deposits of materials from rivers representing natural sources of particulate and dissolved ions from natural rock weathering and mineral dissolution processes in the watershed lithology that are typically exchanged and redistributed within the gulf waters. The abundance and composition of suspended particulate organic matter in the riverine discharges are highly diverse because of differences in its origin and can change substantially in response to variations in the physical, biological and anthropogenic factors in the catchment. Electrical conductivity, total alkalinity and hardness and silicon concentrations exhibited significant associations since they are influenced by similar terrestrially driven factors. Differences can arise, however, as a result of other prevailing hydrodynamic, dilution and mixing effects of the

TABLE 2 Mean values (±*SD*) illustrating significant temporal differences between Nyanza Gulf (G) and main lake (ML) areas using pooled data (different superscript letter indicates significant difference at $p < .05$)

		Pooled 2003 and 2004 data				
Parameter	Zone	Gulf (G) Mean (±*SD*)	Main Lake (ML) Mean (±*SD*)	*df*	*n*	*p*
SRP (μg/L)	S	106.27 ± 104.38^{a}	139.73 ± 178.30^{a}	1.46	28	.420
Nitrate–N (μg/L)	S	69.99 ± 59.90^{a}	52.51 ± 35.67^{a}	1.46	28	.250
Ammonium–N (μg/L)	S	20.50 ± 11.97^{a}	20.46 ± 10.80^{a}	1.40	26	.992
Silica–Si (mg/L)	S	7.01 ± 6.62^{a}	1.56 ± 1.58^{b}	1.46	28	.001
Chlorophyll-*a* (μg/L)	S	17.44 ± 11.17^{a}	16.11 ± 11.46^{a}	1.44	34	.694
Temperature (°C)	S	25.85 ± 0.92^{a}	25.57 ± 0.66^{a}	1.56	34	.353
	B	24.95 ± 0.97^{a}	25.11 ± 1.07^{b}	1.56	29	.000
Dissolved oxygen (mg/L)	S	7.98 ± 1.27^{a}	7.51 ± 0.67^{a}	1.56	34	.104
	B	5.98 ± 1.33^{a}	6.17 ± 1.35^{a}	1.55	34	.210
pH	S	8.03 ± 0.26^{a}	7.96 ± 0.59^{a}	1.37	22	.619
	B	7.89 ± 0.29^{a}	8.03 ± 0.69^{a}	1.37	22	.412
Electrical conductivity (μS/cm)	S	163.72 ± 25.54^{a}	105.92 ± 10.21^{b}	1.51	29	.000
	B	165.34 ± 24.77^{a}	107.25 ± 13.23^{b}	1.51	29	.000
Total alkalinity (mg/L)	S	74 ± 23^{a}	47 ± 4^{b}	1.48	29	.000
Total hardness (mg/L)	S	38 ± 13^{a}	24 ± 4^{b}	1.48	29	.000
Water transparency (m)		0.84 ± 0.41^{a}	1.45 ± 0.50^{b}	1.58	38	.000

TABLE 3 Pearson's correlation coefficient (*r*) between determined water quality variables (significant association among variables are bolded and indicated with * and ** for $p < .05$ and $p < .01$, respectively; 2 tail-test)

	NO_3–N	NH_4–N	SRP	SiO_2–Si	Chl-a	Turb	Secchi	Temp.	DO	pH	T.alk.	T.Hard	Cond.
NO_3–nitrogen	1.000												
NH_4–nitrogen	−.026	1.000											
Soluble reactive phosphorus	.099	−.193	1.000										
SiO_2–silicon	.295	−.120	**.402****	1.000									
Chlorophyll-*a*	.360	−.213	**.444****	**−.463****	1.000								
Turbidity	.087	.279	−.238	.074	.075	1.000							
Secchi depth	−.236	−.053	−.103	**−.562****	−.284	−.145	1.000						
Temperature	−.130	**.389***	−.074	.115	.052	**.390****	−.214	1.000					
Dissolved oxygen	−.219	−.131	**.300***	**.485****	**.300***	.063	**−.375****	**.300***	1.000				
pH	−.205	**.452***	.147	−.079	.254	.067	−.310	**.507***	**.387***	1.000			
Total alkalinity	.396	.022	−.034	**.635****	.042	.083	**−.478****	.059	−.052	−.190	1.000		
Total hardness	.077	.252	**−.437****	.021	**−.322***	.084	**−.379****	.291	.008	−.057	**.313***	1.000	
Electrical conductivity	.367	−.086	.129	**.813****	.212	.047	**−.622****	−.086	**.389***	−.185	**.679****	**.369***	1.000

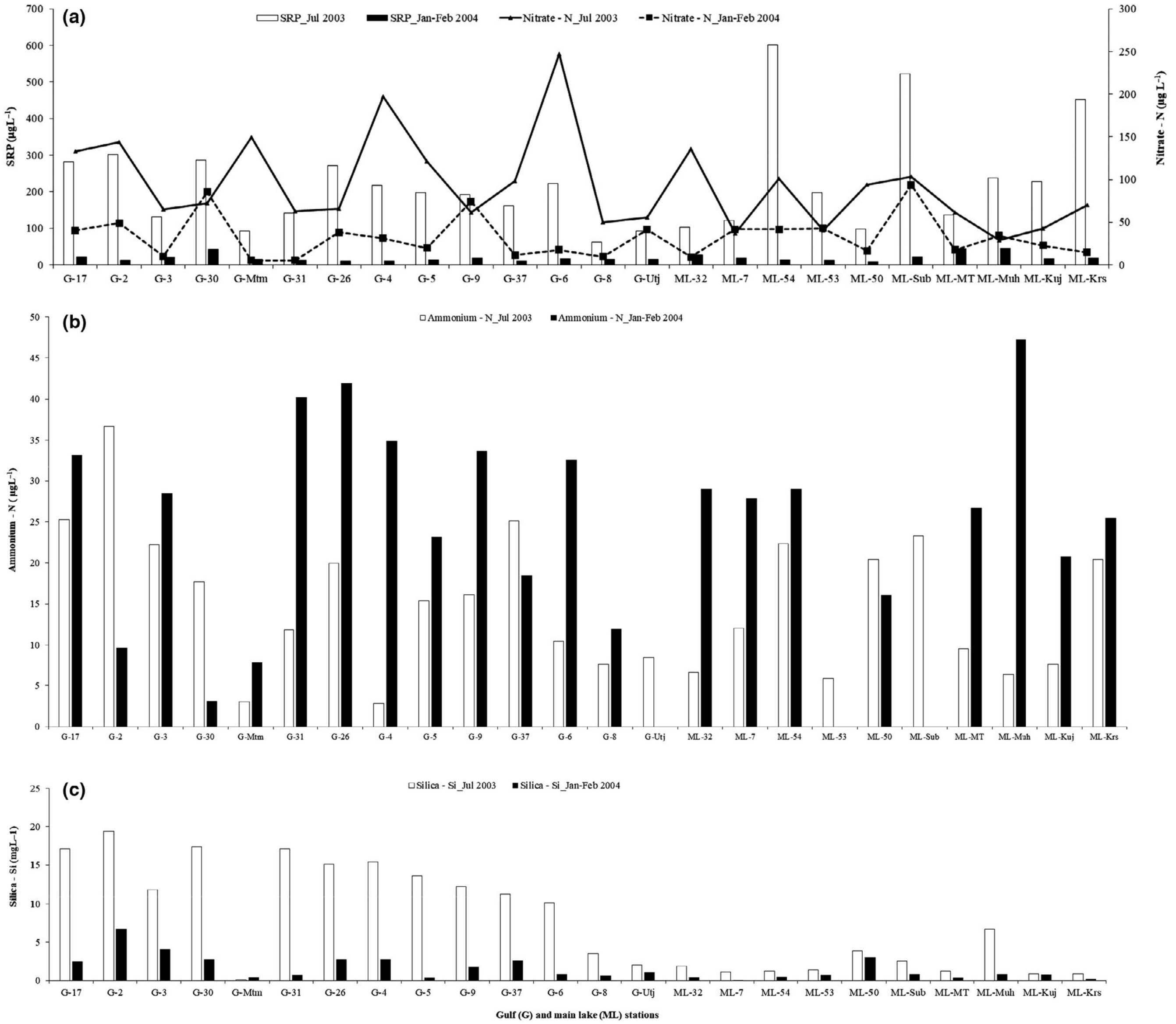


FIGURE 3 (a–c) Changes in soluble reactive phosphorus (*SRP), nitrate-nitrogen, ammonium-nitrogen and silica (Si) concentrations in surface waters in Nyanza Gulf and main lake during mixing (July 2003) and stratification (January to February 2004) periods

lake ecosystem. This observation partially explains the associations in the observed lake water electrical conductivity, total alkalinity and hardness, and the lateral changes moving toward the main lake.

The inner areas of the Winam Gulf from Kisumu Bay toward the open lake are very shallow, with depths ranging from 2.5 to 13 m. The deeper section exists from mid-gulf to areas around the exit to the main lake at Rusinga Channel. The gulf waters exhibited higher mean values of electrical conductivity, alkalinity and water hardness than did the main lake areas (Table 2). The Secchi depth transparency exhibited a similar trend for the two sampling periods (Figure 2a–c), with high light penetration in the deeper waters, increasing from 0.4 to 1.3 m (2003) and 0.4 to 1.7 m (2004), with maximum values in the main lake at the deeper sites. The significant differences observed between the mean and pooled data values of the physical and chemical conditions (Table 1) was mainly due to the sampling after the long rains in July 2003, compared to the dry period of January and February. The influence of increased particulate matter from land-based surface runoff and riverine discharges was evident from the extremely high-water turbidity within the inner gulf. Although no comparative water turbidity data are available for the 2003 survey, lower turbidity variations were observed within the main lake as a result of increased settling of the deposited particulate matter and the large dilution effects of the nearshore influences and river discharges, especially at sites ML-50, ML-53, ML-Kuj, ML-Muh and ML-Krs. Sites such as ML-Krs are located closer to the land-based influences and expanding urban activities and often experience algal blooms next to the shoreline. The influence of increased particulate matter on surface water quality conditions was evident from the negative correlations with electrical conductivity, dissolved oxygen, alkalinity and hardness. Water turbidity was only positively correlated with temperature. Increasing mineral turbidity causes increased ion concentrations in the water column, as evident from the positive correlations between electrical conductivity, alkalinity, hardness and silica concentration values which were found to decrease towards the main lake. The effect of high turbidity is a reduced light penetration into the water column, explaining the negative correlation between electrical conductivity and Secchi depth. Light limitation within the gulf (Gikuma-Njuru & Hecky, 2005) has been associated with limitation of primary production, and eventual dominance by the cyanobacteria group of phytoplankton. Changes in phytoplankton distribution and responses in relation to nutrients is also of significance and may explain some observed less-explainable associations since the data were not accompanied by information regarding phytoplankton composition and distribution. Significant correlations were found between silicon and alkalinity, electrical conductivity and soluble reactive phosphate (SRP) in the surface water. The presented nutrient concentrations were only for the surface water, meaning complex behavior of various nutrient fractions not determined could emerge, especially the contribution of other particulate nutrient forms to the bioavailable nutrient forms. Gikuma-Njuru, Guilford, Hecky, and Kling (2013) observed a net consumption of dissolved inorganic P, organic P, inorganic N and organic N, in contrast to an export of dissolved reactive silicon to the channel waters. There are increasing hydrodynamic changes toward the main lake, and a potential for remobilization of sediment-associated nutrients attributable to increasing water exchanges and turbulence towards the gulf. Mixing of the water around the month of July could be an important factor in nutrient release, perhaps contributing to the observed differences between 2003 and 2004.

Seasonal changes, riverine fluxes of dissolved and particulate substances, and the quantity of precipitation and temperature can alter the concentrations of transported materials. Results reported by Ngugi, Oyoo-Okoth, Gichuki, Gatune, and Mwangi-Kinyanjui (2017) suggest that at sites near rivers that drain industrial activities, there was a smaller contribution of allochthonous sources of organic matter (OM), but a greater contribution from aquatic OM sources usually linked to phytoplankton. There is a significant contribution of catchment land use to the OM sources, composition and distribution of stream at the land–water interface (Ngugi et al., 2017) at the sites located near rivers traversing agricultural activities.

NOVA revealed differences between the surface and bottom water temperatures (Table 1 and 2) and the dissolved oxygen (DO) (all durations). Although no significant differences in surface and bottom water temperature were observed for 2004, the lake water exhibited temporal warming attributed to reduced water mixing during this sampling period. This was contrary to what was expected during the stratification period since more than 50% of the sites are shallow (<10 m depth) inshore areas experiencing significant water exchanges with the littoral zones. Semi-closed bays such as Nyanza Gulf provide conditions where riverine and wetland released dissolved organic matter have sufficient time to undergo degradation mechanisms before entry into the open lake (Loiselle et al., 2008, 2010), compared to open lake bays where the chromophoric dissolved organic matter dynamics may be different. High turbidity in the gulf reflects the high suspended solids content in the water, mostly after the short and long rainy season of March–June in Kenya, while the high values are similar to other data documented from different studies in the gulf.

4.2 | Changes in the nutritive elements in the lake during the past 29 years before re-opening of the Mbita Causeway and initiation of cage farming

Chlorophyll-*a* data over the years is from different sampling durations of the indicated years (Figure 2c). The observed trends, however, indicate the lowest and highest concentrations of phytoplankton biomass, measured as chlorophyll-*a* concentration between 2003 to 2004 ranged from 6.01 to 48.12 mg/m^3, being within the chlorophyll-*a* concentration trends observed over the years (usually values exceeding 10 mg/m^3).

The increased nutrient loading resulting from population growth in the lake basin (Verschuren et al., 2002) is usually considered to be a relatively sudden transition in the mid-1980s from an oligotrophic – mesotrophic condition to a eutrophic one, accompanied by changes in the phytoplankton community. Because of anthropogenic changes in its catchment, the lake changed from a mesotrophic system dominated by diatoms in the 1920s to a eutrophic system dominated by blue green algae (Hecky, 1993; Mugidde, 1993; Talling, 1966, 1987). Changes in lake trophic status (Goldschmidt, Witte, Wanink, 1993; Hecky, 1993), increased turbidity and primary productivity (expressed as increased algal biomass) contribute to continued reduced water transparency. Increased particulate loading as total suspended solids (TSS) can affect fish species in shallow areas wherein high unsettled solids exist. Kolding, van Zwieten, Mkumbo, Silsbe, and Hecky (2008) identified eutrophication as a potential threat to the fisheries in Lake Victoria. According to Seehausen, Van Alphen, and Witte (1997) reduced water clarity can cause loss of genetic and ecological differentiation among the haplochromine species and the decreased water transparency associated with eutrophication probably contributed to the loss of species diversity among the cichlids, noting that water clarity is the strongest environmental predictor of species diversity among haplochromine species (Seehausen et al., 1997). Previous measurements of soluble, particulate and sediment sourced nutrient concentrations, as well as physico-chemical parameters, were conducted between 1994 to 1995 and 1997 (Lung'aiya et al., 2000, 2001), December 2000 and October 2001 (Gikuma-Njuru, 2005) December 2000 and May 2002 (Gikuma-Njuru & Hecky, 2005), March 2005 and March 2006 (Gikuma-Njuru, 2008; Gikuma-Njuru, Mwirigi, Okungu, Hecky, Abuodha, 2006; Gikuma-Njuru, Hecky, & Guildford, 2010; Gikuma-Njuru et al., 2013; Gikuma-Njuru, Hecky, MacIntyre, & Guilford, 2018), September 2008 and November 2009 (Sitoki, 2010; Sitoki, Kurmayer, & Rott, 2012) along a transect between Nyanza Gulf and the open waters of Lake Victoria in order to evaluate spatial and seasonal variations in nutrient fluxes and ecosystem metabolism, and to identify dominant hydrodynamic transport processes (Okely, Imberger, & Antenucci, 2010) and internal regeneration of sediment bound P (Guya, 2013). All these studies support the observation of increased nutrient levels in lake water, which was initially suggested by Hecky and Bugenyi (1992) who noted the chlorophyll-*a* concentration in bays along the lakeshore had increased from 3 to 20 mg/m^3 in March 1961, to 13 to 71 mg/m^3 in May 1988. However, Marshall (2018) recently revisited the decline of the endemic haplochromine cichlids and the ecological consequences of eutrophication in the whole of Lake Victoria, supporting the top-down hypothesis which confirms the ecological changes and process in Lake Victoria's the eutrophication (Verschuren et al., 2002) that indicated the Nile perch explosion, which led to the haplochromine collapse, began about 1980, with massive algal blooms following about 1985. It has also been suggested that the fish species recovery may also have been facilitated by a more benign environment in the lake (Kishe-Machumu, van Rijssel, Wanink, & Witte, 2015; van Zwieten et al., 2016) as indicated by the reduced stratification and anoxia noted in 2007 to 2009 (Marshall *et al*., 2013; Sitoki et al., 2010).

Although there are no vertical nutrient concentration profiles, the DO profiles exhibit high changes or reductions in the DO concentrations. The difference between the DO concentrations in the surface and bottom waters ranged from 0.03 to 3.92 mg/L (gulf areas in 2003) and 0 to 2.28 mg/L (in main lake areas in 2003). The difference in 2004 ranged from 0.11 to 4.56 mg/L (gulf areas) and 0.01 to 6.82 mg/L (main lake areas). The deep sites remained well oxygenated in 2004, with much lower DO levels at relatively shallow areas exposed to increasing organic loading from rivers. More stabilized lake water stratification increases the development of hypoxic conditions, with the importance of such processes becoming important in the nutrient distribution at very low and anoxic states in the bottom water, which can enhance sediment nutrient releases. This has been reported for very deep main lake sites (Hecky, Bootsma, Mugidde, & Bugenyi, 1996; Mugidde, 2001). The water exhibited contained much higher levels of nutrients (nitrate–N, SRP, silicon), electrical conductivity and chlorophyll-*a* in 2003 than in 2004. Although the present study did not include the particulate nutrient fraction in the lake water, particulate P, C and N trends in the water column decreased from the inner gulf to a minimum in the mid-gulf before increasing toward the main lake, all being highly correlated (Gikuma-Njuru et al., 2013).The particulate P contents ranged from a maximum value of 1.2 μmol/L (gulf water) to a minimum of 0.7 μmol/L (mid channel). The dissolved nitrate-nitrogen concentration exhibited a mean of 10.6 μmo/L in the gulf and a lower mean of 3.6 μmol/L in the main lake. The N concentrations represented depth integrated samples, being higher than the pooled N mean

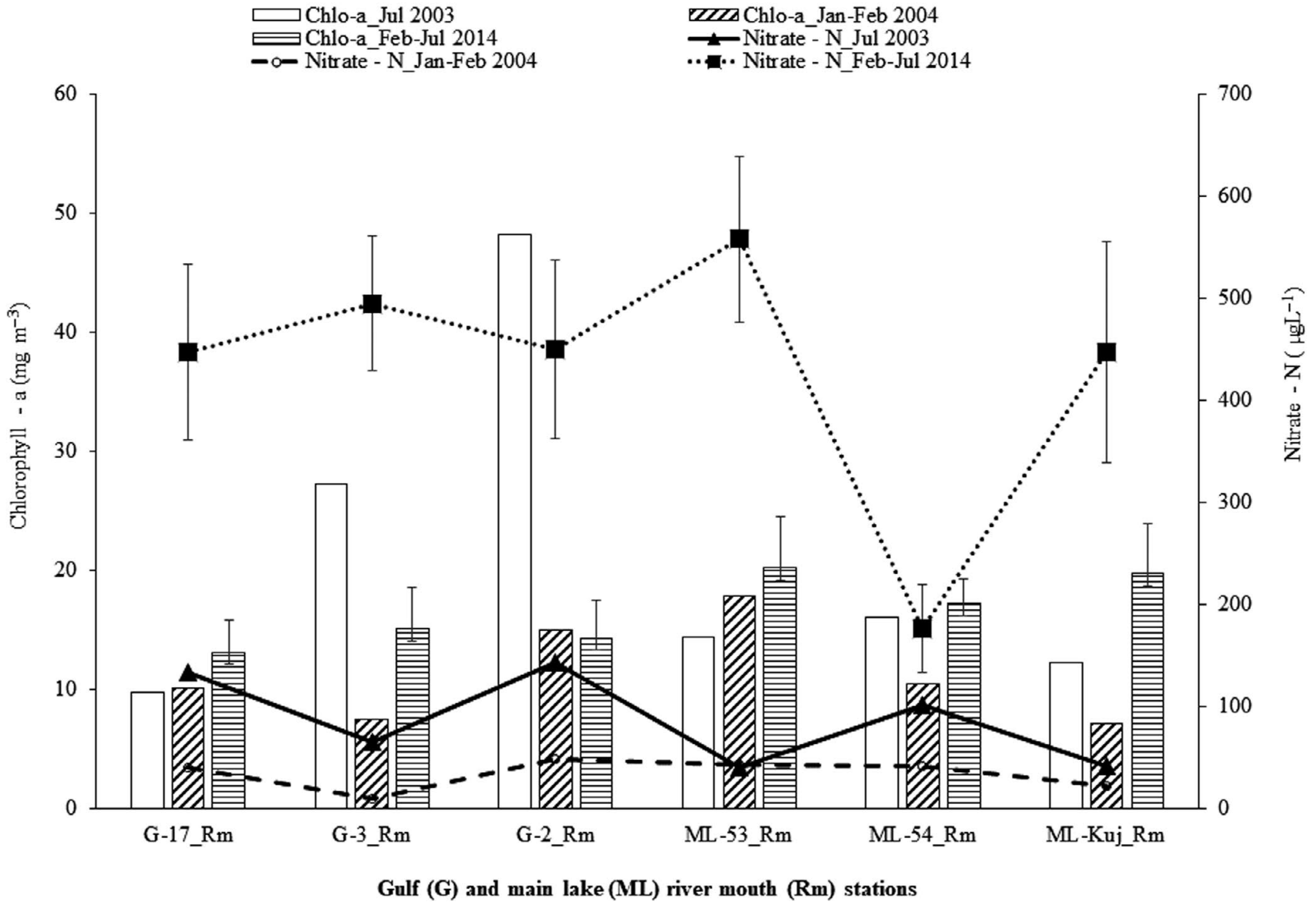


FIGURE 4 Variations in chlorophyll-*a* and nitrate–N concentrations at river mouth sites in Nyanza Gulf and main lake during 2003, 2004 and 2014 (2014 data adopted from Ngugi et al., 2017) sampling

values observed for the two periods for the gulf sites, although the main lake site concentrations were of a similar magnitude. These various fluctuations generally reflect the temporal influences that were not fully accounted for in the present study, or the differences as a result of only having a few data points to represent the vast littoral areas, inner embayment areas and the areas with direct river mouth influences in the transect.

Spatial P concentration variations are often encountered in lake water, although the magnitude of the variations can differ significantly as a function of the sampling time or spatial extents considered. The data from the two periods comprised a higher number of sites located mostly near the littoral zones. The significantly ($p < .0001$; Table 1) higher SRP data values of 2003 were representative of the transitioning period into mixing of the lake water after the long rainy season, compared to the dry period during which the lake water undergoes stratification, during the 2004 sampling period. During the transition to the mixing period, the lake water receives a huge influx of external materials mainly from river inflows, surface and storm water events. These sources are spread along the open shoreline, often contributing to the highly turbid water of the gulf. Thus, the SRP trends did not display any clear spatial trend but could explain the large differences observed between the two sampling periods. A later transect sampling comprising ten sites sampled monthly between March 2005 and March 2006 (Gikuma-Njuru et al., 2013) indicated no defined trends in total P, although the dissolved inorganic P was higher for the main lake sites than in the gulf in water samples collected about 5 m from the gulf toward the Rusinga Channel. The ten site transects (Gikuma-Njuru et al., 2013) exhibited a mean DIP of 1.0 μmol/L (total P of 3.3 μmol/L), comprising sites more concentrated along the mid waters of the gulf and far away from external influences. Shallow sites within the inner gulf that are more influenced by riverine inputs, urban activities and other land-based runoffs inputs were not included in the 2005–2006 transect. This DIP value appears much higher, although still comparable to the mean SRP concentration (Table 1) found in 2004 in the present study. Figure 4 provides a comparison of chlorophyll-*a* concentrations, illustrating relatively high concentrations for sites G3 and G2 (2003 study data), but with a similar magnitude of that in recent data of 2014. The differences could be attributable to nutrient transport through rivers draining different watershed in addition to the site locations, as well as other influences from the main lake, which exhibits higher light penetration and potential phytoplankton community differences.

The high electrical conductivity, turbidity, alkalinity, hardness and nutrient concentration values obtained from the present study generally highlight decreasing trends towards the main lake, as reported by previous studies, with a lower water transparency in the gulf. Spatial heterogeneity of the lake, as illustrated by Downing et al. (2014), indicate terrestrial runoff and detritus are primary sources of light limitation in inshore areas, whereas algal biomass induces light limitation further offshore, thereby restricting photosynthesis to a narrower surface water layer. Differences in nutrient concentrations between the main lake deep sites and shallower gulf sites (Table 4) were previously reported by Ochumba and Kibaara (1989) (NO_3–N of 513 μg/L; PO_4-P of 4–37 μg/L), Mavuti and Litterick (1991) (PO_4-P of 7–16 μg/L; NO_3–N of 56–106 μg/L); (PO_4-P of 2–29 μg/L), Lung'aiya et al. (2000) (SRSi of 0–4 mg/L; PO_4-P of 4–37 μg/L) and Gikuma-Njuru and Hecky (2005). The NO_3–N increased from 10 μg/L in 1990 to 98 μg/L in 2008, whereas the PO_4-P increased from 4 μg/L in 1990 to 57 μg/L in 2008 (Juma, Wang, & Li, 2014). The water transparency ranged between 0.66 and 2.83 m between December 2000 and October 2001 (Gikuma-Njuru & Hecky, 2005), similar to the currently low light penetration depth reported, and much lower than the earliest values of 1.1–1.6 m in Nyanza gulf. Ochumba and Kibaara (1989) reported a temperature range of 23.5–28.0°C. The water temperature, chlorophyll-*a*, phosphate-P, nitrate–N and soluble reactive silicon concentrations ranged from 23.29°C to 28.81°C, 3–11.0 mg/m^3, 7–57 μg/L, 5–37 μg/L and 0.429–3.664 mg/L, respectively (Gikuma-Njuru & Hecky, 2005). The N forms (trends of TN, dissolved organic nitrogen, nitrate–N and ammonium–N), P forms (TP), total suspended solids (TSS) were also much higher in the gulf than at pelagic stations, in contrast to increasingly higher dissolved organic P and PO_4-P values in the pelagic zone. Eutrophication affects the whole lake, with half the total phosphorus input to the lake being from atmospheric deposition (Tamatamah et al., 2005), although there is much spatial heterogeneity in its effects, not only in an inshore-offshore gradient, but also between bays around the lake (Cornelissen, Silsbe, Verreth, Van Donk, & Nagerlkerke, 2014; Loiselle et al., 2008; Silsbe, Hecky, Guildford, & Mugidde, 2006).

Lake circulation patterns drive major in-lake processes that cause distribution of elements, nutrients and organisms. The lake water conditions have been described in different studies as being dependent on the influences of rainfall and evaporation processes, resulting in spatially homogenous conditions. The extent of the previously restricted nature of the water exchanges between the eastern gulf and main lake was thought to be a major factor influencing the water characteristic gradients and variations. Terrestrially linked influences on lake biogeochemical cycles cannot be decoupled from the nutrient dynamics in the lake. Evidence of particulate matter from river discharges sites (Ngugi et al., 2017) within the gulf highlights the contribution of the catchment organic matter inputs, The average TSS and Si concentrations were above 50 and 10 mg/L, respectively, in rivers discharging from the Kenyan catchment (Ngugi et al., 2017; Okungu & Opango, 2005). The high catchment gradients contribute to increased erosion, resulting in increased discharges of significant quantities of leached nutrients from farmlands into recipient lake zones. Low mean SRSi values of 7.85 and 1.56 mg/L were observed in the lake water, with natural waters containing about 5–25 mg/L silica, although concentrations over 100 mg/L occur in some areas. Silica is normally assimilated by diatoms and other algal groups. Soluble silica is related to the developmental cycle of diatom populations since siliceous algae bind silica to synthesize their cells. Phytoplankton communities in the Nyanza Gulf are dominated by cyanobacteria (Sitoki et al., 2012). Increasing diatom dominance in the Rusinga Channel and at the main lake site seems to be facilitated

TABLE 4 Mean (±*SD*) nutrient element concentrations in lake water compared to reported values from previous studies

	Mean (±*SD*) concentration of nutritive elements (μg/L unless otherwise specified) in Nyanza Gulf of Lake Victoria								
	NO_3-N	NO_2-N	NH_4-N	TN	TP	SRP	SRSi (mg/L)	Season	Reference
Kisumu Bay	40.6 ± 2.8	20.9 ± 2.1	91.4 ± 5.8	1,466.8 ± 2.4	256.7 ± 3.7	–	12.2 ± 1.7	LR 2014	a
	46.3 ± 3.3	28.6 ± 2.6	136.1 ± 8	1,572.1 ± 2.2	315.2 ± 3.7	–	28.4 ± 2.5	LR 2014	
Nyanza Gulf	56.17	11.94	66.52	511.61	92.75	60.82	13.02	LR 2012/2013	k
Kisumu Bay	5	–	52	411	80	9	17	All 2008/2009	b
(inshore site)*	309	–	209	1,934	1,073	124	48	All 2008/2009	
Nyanza Gulf†	9	–	18	1,330	159	31	6	All 2008/2009	b
(4 sites)	58	–	126	1,410	220	86	31	All 2008/2009	
Main lake site†	14	–	63	1,230	115	34	6	All 2008/2009	b
Nyanza	-	-	-	40 ± 29	3.1 ± 0.1	0.8 ± 0.1	27 ± 2	All 2005/2006	c
(μM)	-	-	-	83 ± 3.6	3.6 ± 0.2	1.5 ± 0.1	160 ± 5	All 2005/2006	
Nyanza Gulf	5–37	–	–	509–1,447	–	7–57	0.429–3.664	All 2000/2001	j
Nyanza Gulf	10–30	–	8–152	440–1,160	70–103	70	-	1990	d
Nyanza Gulf	0.1–513	–	–	–	–	4–37	–	1989	e
Nyanza Gulf	21–237	–	–	–	–	2–75	0.1–7.6	1984	f
Nyanza Gulf	0.16–0.18	–	–	–	–	–	2–7.9	1979	g
Nyanza Gulf	0.5–122	–	–	–	–	1–122	0.2–3	1977	h
Nyanza Gulf	10–112	–	–	–	–	7–120	4–8	1966	i

Note: LR, long rain season of March to June; (a) Misiko et al. (2014); (b) Sitoki et al. (2012); SiO_2 values provided; (c) Gikuma-Njuru et al. (2013); (d) Gophen (2015); (e) Ochumba and Kibaara (1989); (f); (g) Melack (1979); (h) Akiyama, Kajumulo, and Olsen (1977); (i) Talling (1966); (j) Njuru (2005); (k) LVEMP-II (2013).

*Range values of depth integrated samples up to 10-m water depth.

†Median values.

by reduced turbidity, resulting in a more transparent water column (Sitoki et al., 2012), being reflected by increased utilization of SRSi that results in reduced silicon concentrations. Nitrogen limitation is considered the principal factor leading to the proliferation and dominance of heterocystous cyanobacteria in Lake Victoria (Gikuma-Njuru & Hecky, 2005; Kling, Mugidde, & Hecky, 2001). The shallow turbid gulf was continuously dominated by non-nitrogen-fixing filamentous and chroococcale colonial cyanobacteria, although seasonal stratification and a deeper water mixing depth in the open lake favored diazotrophic cyanobacteria and diatoms. Seston ratios and metabolic nutrient assays indicated the gulf to be sufficiently phosphorus deficient to impose P limitation on phytoplankton growth and biomass. In contrast, the open lake is more likely to experience N deficiency that favors diazotrophic cyanobacteria (Gikuma-Njuru et al., 2013). Based on a study of Kisumu Bay, neither the low TN:TP ratio nor the low DIN:SRP ratio can explain the dominance of the non-nitrogen fixing *Microcystis* (Sitoki et al., 2012). The highest MC concentrations coincided with the wet season, with increased rainfall and nutrient enrichment from the catchment, exhibiting a highly significant relationship between *Microcystis* and microcystin (MC) concentrations and suggesting *Microcystis* is the major MC producer. Physical factors such as the relationship of the euphotic zone to the mixing depth and/or variations in turbidity (organic and mineral seston), rather than TN:TP ratios, are suggested as being the factors regulating phytoplankton composition (Sitoki et al., 2012). Under turbid and continuous mixing lake water conditions, *Microcystis* is likely to have an advantage over Anabaena in shallow waters, even under N – limiting conditions (Sitoki et al., 2012). Below a TN:TP ratio of 20:1, nitrogen generally becomes limiting for phytoplankton growth (Guildford & Hecky, 2000). Nutrients were in excess in the shallow waters in the southern part of the Mwanza Gulf in the Tanzanian side of Lake Victoria (CornelissenSilsbe et al., 2014), with the phytoplankton biomass found to be limited by light. In deeper waters near the entrance of the gulf, N, rather than light, was likely to be limiting, as suggested by the N: P ratio. Although TP and TP data was not part of the 2003 and 2004 data, N is found to be limiting in most cases in the Nyanza Gulf. The most recent studies (2012 and 2013) indicated mean (range values) concentration of TN and TP of 511.61 μg/L (range of 204.18–2,349.64 μg/L) and 92.75 μg/L (range of 26.29–192.0 μg/L), respectively (LVEMP-II, 2013), still highlighting the eutrophic state of the lake. In addition to nutrients, wastewater discharges into inflowing rivers and streams are conduits of low, but accumulating, diverse chemical and antibiotic residues (Basweti, Nawiri, & Nyambaka, 2018; Chirokona, Filipovic, Ooko, & Orata, 2015; Kimosop, Getenga, Orata, Okello, & Cheruiyot, 2018), which can induce antibiotic resistance, thereby highlighting a need for continuous monitoring of recipient lake waters. Riverine input trends (Figure 4) between the gulf and main lake rivers indicates high nitrate – N levels in the main lake because of the amplification around river mouth areas of the high discharge Kuja and Nzoia rivers. Increased pollution loadings from major rivers occurred mostly during rainy months rather than dry months, highlighting significant diffuse source contributions, while little variation was associated with rivers receiving nutrients mainly from point sources. Electrical conductivity, DO, temperature, pH, alkalinity and hardness exhibited significant associations. Based on the 2005 to 2006 data, Gikuma-Njuru (2013) also reported significant positive correlation between electrical conductivity and N fractions longitudinally, suggesting dilution may also be an important factor determining their concentrations. The values of that study, represented by the July 2003 and January–February 2004 periods represent conditions wherein the lake is under cooling and complete mixing of the water column, and initiation of a thermocline between a 30 and 60 m water depth. Significantly differences in temperature were observed, with a wide range for both surface and bottom water (range of 3.60°C and 3.13°C in 2003; 2.2°C and 4.2°C in 2004). These times coincide with the falling lake water levels between 1998 and November 2004. Temperature contributes to evaporation rate changes over the lake water surface. Updated water balance data for Lake Victoria for the period 1950 to 2004 (Okonga, 2005; Sewaggude, 2009) still implicate evaporation and direct rainfall as the most important factors in the Lake Victoria water budget. The downward trend in the net basin water supply, and the predicted reduction by up to 50% by end of the 21st Century, suggests the lake is likely to experience more frequent and prolonged droughts, implying lower lake water levels (Sewaggude, 2009).

Changes in the P and N nutrient concentrations are a reflection of the element species cycling processes within the aquatic environments, involving active uptake by phytoplankton, transformations, sinks and release/retention within sediments. There is active export and retention of nutrients in reservoirs located along river channels (Bouillon et al., 2009; Okuku, Tole, & Bouillon, 2018). Surface mud sediments of the shallow hypereutrophic artificial Lake Chivero, with a high mean total organic carbon (TOC) content of 533.3 ± 168.5 g/kg contained much higher concentrations of SRP, NH_4, TP and TN, compared to sand and silt sediments (Magadza & Tendeupenyu, 2018). Organic rich bottom muds in lakes can retain significant quantities of nutrients, meaning obtaining realistic budgets of lake nutrients must incorporate sediment nutrients. Observations along large rivers indicate reservoirs act as sinks for P and to a lesser extent N because of a high-water residence time that increases sedimentation rates and permanent deposition in a reservoir, compared to a river. The net effects of the complex hydrodynamics in lakes determine the dominant processes and extent of nutrient re-mobilization, especially in shallow and intermediate water depths (5–10 m) of the gulf. Lake Victoria has a relatively long water residence time and large surface area, allowing greater settling of the laterally transported nutrients into the main lake, with additional water column sourced nutrients from high production in the water column settling in the bottom sediments. The sensitivity of planktonic communities to such changes is thought to influence their abundance and distribution within the gulf and lake. Most studies on phytoplankton report N_2 fixation by blue green algae as a possible reason of its dominance in the phytoplankton community, wherein there is a significant effect of turbidity on light availability in the gulf, and again in lake waters, associated with a N-limitation status. Studies on the net effects of internal nutrient loadings from different authors suggests an export of dissolved inorganic P from the channel area, and a general nutrient retention in the gulf (Gikuma-Njuru et al., 2013; Guya, 2013), supporting a similar lakeward trend in nutrient concentrations, as revealed in the present study. The gulf is a narrow basin that deepens westwards, leading to a flow of materials toward the west, depending on the extents of hydrological mixing. There also is a need for good estimates on the extent of sediment resuspension and contributions to nutrient cycling.

External nutrient sources from riverine inputs are significant within the gulf (Gikuma-Njuru *et al*., 2010; Guya, 2013). There is a longitudinal gradient of sediment P and fractions toward the main lake, with apatite P (less bioavailable P form) dominating in the gulf and OP in the main lake (Gikuma-Njuru *et al*., 2010; Guya, 2013). The patterns observed in the study area are supported by similar trends of mean stoichiometric ratio values (molar ratios) of particulate nutrient elements reported by Gikuma-Njuru et al. (2013). The SRSi and chlorophyll-*a* concentration are higher than those reported for the Tanzanian inshore and offshore waters (Ngupula, Ezekiel, Kimirei, Mboni, & Kashindye, 2012), with an SRSi range of 0.2 ± 0.1 mg/L to 1.7 ± 0.2 mg/L a chlorophyll-*a* range of 2.3 ± 0.1 μg/L to 32.0 ± 3.6 μg/L), with a comparatively lower range of nitrate concentration of 60.1 ± 4.6 μg/L to 201.5 ± 46.3 μg/L. Reported median values of the TN:TP ratios in the study area (Sitoki et al., 2012) range from 6.1 to 10.3 (gulf) and 14.2 (main lake), being considered lower than the 20:1 ratio at which N generally becomes limiting for phytoplankton growth (Guildford & Hecky, 2000). Increased N loading, with limited light availability attributable to high turbidity, could cause a reduced abundance of N-fixers.

Catchment land use–lake nutrient relationships are important for understanding the nutrient drivers in large lake basins, and significant differences may occur because of differences in spatial extents for land use/landcover measurements. The Winam Gulf is also impacted strongly by riverine inputs, with shallow basin waters receive major terrestrial discharges through five major permanent inflowing rivers. The impact of land use activities on the loss of vegetative cover and water quality of three selected case studies (River Nzoia basin; Kenya, Nakivubo Wetland; Uganda and Smiyu, Tanzania), based on satellite images in the period from 1974 to 2005 based on Landsat imagery, SPOT data and Quick bird® imagery (Twesigye, Onywere, Getenga, Mwakalila, & Nakiranda, 2011) revealed a reduced size of land vegetation cover, and an increased replacement of landcover by agricultural, industrial and residential activities, implying increased anthropogenic pressures on the wetland resources around those areas.

Regarding catchment management, the Lake Victoria Management Project (LVEMP, 2003) prioritized activities toward increasing forest cover through tree planting and preventing soil erosion, as well as conservation of natural forests, soil and water, and appropriate use of agrochemicals, in order to reduce pollution loading and improve agricultural production, and enhance the sustainable use of wetlands as a means of conserving them as well as improving their buffering capacity. Community involvement might require more concerted efforts, however, and a long time in order to realize these benefits in terms of better land management practices. Specific drainage basin interventions in catchment management can achieve greater success in a wide transboundary basis. The large river catchment areas in the Kenyan basin of Lake Victoria display similar characteristics longitudinally attributable to temporal influences from seasonal precipitation. The surface water contains high TSS concentrations. Specific studies in some major river catchments areas in Kenya (Masese, Raburu, Mwasi, & Etiegni, 2012) indicate a relatively big and positive change in land use/cover areas for farms and settlement, compared to decrease in other land use types (forests and bushland), exhibiting a negative change (decrease) between 1986 and 2009. This is an indication of intensified agriculture and human activities which correlates with a longitudinal degradation of water quality towards the lake waters. Soils and high topographical relief and slopy highlands significantly influence riverine material loads, resulting in a significant transport of dissolved and particulate bound nutrients into the lake. Vuai, Ibembe, and Mungai (2012) reported relatively high dissolved nitrate–N concentrations (0.77–0.97 mg/L), compared to ammonium–N and P (0.12–0.27 mg/L) in the Sondu-Miriu catchment.

Lake Victoria is among the ancient lakes of the world (Hampton et al., 2018), being known to receive about 80% of its water inputs from direct precipitation. It has a large surface area, resulting in significant atmospheric N and P nutrient inputs to the nutrient budget. Nevertheless, there continues to be much uncertainty in regard to the atmospheric nutrient sources to the lake, resulting in a continued lack of accurate nutrient load quantification. COWI (2002) data, however, indicate lakeshore areas are highly affected by eutrophication, especially “hotspots” such as Winam Gulf, Murchison Bay, Napoleon Gulf, and Mwanza Gulf. Phosphorus and nitrogen concentrations have increased, with algal growths increasing five-fold since the 1960s (COWI, 2002). Nevertheless, the fate and quantitative contribution of the new N and P sources emanating from feed wastage in cage aquaculture that commenced around 2005 in the Kenyan basin of Lake Victoria has yet to be understood. Unutilized particulate nutrients become part of the bottom sediments which can, in turn, easily be remobilized into the water column. More recent net anthropogenic N input estimates (NANI) of the whole lake basin by Zhou et al. (2014) indicate atmospheric oxidized N deposition contributed about 14% of the N to the NANI, while either synthetic N fertilizer imports or biological N fixations contributed <6% to the regional NANI. The annual nitrogen inputs to the terrestrial landscapes of Lake Victoria basin between 1995 and 2000 averaged 305.2 Gg N/year, with only 16% of this total finally entering the lake through riverine transport. This suggests about 84% of the anthropogenic N inputs were retained in soils or lost (e.g., via denitrification) from the basin (Zhou et al., 2014).

The East African Rift valley lakes (Tanganyika, Victoria and Malawi) are known for their sensitivity to atmospheric deposition because of the large surface areas and slow flushing rates (Hecky et al., 2006), with an estimated 55% of the P input also derived from atmospheric sources (Tamatamah et al., 2005). Consistent data with reliable estimates of atmospheric deposition for Lake Victoria are lacking. Measurements in Eastern Africa on Lake Malawi and around Lake Victoria indicate P deposition rates during rain events and dry fall are among the highest that have been measured but are not exceptionally high for tropical areas undergoing land clearance. Because of the largest surface area of the lakes available to receive dry fall, and the dominance of rain in the water budget of the great lakes, atmospheric P deposition is an important external source of P to Lake Malawi, and may be the dominant source of external P loading to Lake Victoria (Hecky et al., 2006). It is clear that more studies focused on better understanding future changes in large lakes are needed. Based on 2016 and 2017 findings (Njiru et al., 2018), the number of cages and fish stocking levels are of concerns in regard to the low DO and ammonia levels measured around the cages, which was attributed to poor water circulation across the walls of the cages as a result of nets becoming clogged with algae, and the degradation of fish remains. The most recent occurrences of Microcystin in the water were found mostly associated with *Microcystis* (Simiyu, Oduor, Rohrlack, Sitoki, & Kurmayer, 2018).

Fish cage culture is a new and expanding fishing method for Lake Victoria (Aura et al., 2018; Njiru et al., 2018), requiring guidance with continuous monitoring data in order that observed declining trend in ecological integrity in the gulf (Kundu et al., 2017) is controlled and there is a balance in lake use. The number of cages has increased from 1,663 (in 2016) to 4,357 cages (in 2018) covering 62,132 m^2 of the lake water surface (Aura et al., 2018; Hamilton et al., 2020; Njiru et al., 2018). Although information on potential ecological concerns emanating from fish cage culture continues to increase, pollution, climate change and increasing cage culture are notable emerging issues in the Lake Victoria environment that can affect its fisheries (Kimani, Aura, & Okemwa, 2018), also with the potential to impact benthic habitats, biodiversity, water quality and affect the stability of the ecosystem. The present study was conducted before the onset of cage culture in the Kenyan portion of Lake Victoria. Recent reports, however, indicate that non-adherence to best aquacultural practices, including setting cages in close proximity around protected areas, eutrophic and hypereutrophic waters, shallow water bodies and sites of <5 m average water depth, and being to the shoreline (Musinguzi et al., 2019) are among the challenges facing sustainable aquaculture. Continuous monitoring of the ecosystem is of paramount importance to avert such potential impacts on water quality attributable to the rapid expansion in cage numbers.

There is a need to develop a long-term hydrodynamics database to better understand the complex interactions and the impacts of the re-opening of the Mbita Passage. Potential long-term effects on the lake water quality from re-opening of the causeway include effective circulation and water exchanges in the Rusinga Island area and the Winam Gulf, which is a recipient of diffuse and point loading of terrestrially derived particulate and dissolved materials. Increased free water circulation will benefit the expanding number of cage farms by maintaining good water quality conditions necessary for better fish growth. Cohen (2018) suggested replication to test if paleoecological patterns seen, and hypotheses inferred, from single localities are robust for an entire lake, and to better understand regional variability within and between lakes. There is the potential for developing biological indices for basin-wide and national monitoring of streams and rivers as a cost-effective means of maintaining the integrity and sustainability of our national water resources (Masese et al., 2012), as well as the involvement of resident communities in other hydrological monitoring activities.

5 | CONCLUSIONS

The stoichiometric composition of lake water chemistry affects phytoplankton nutrient limitation. Measurements of the nutrient and physico-chemical characteristics of the narrow eastern gulf of Lake Victoria supports the invariant environmental gradients between the gulf and main lake water, with respect to water conductivity, transparency, turbidity and silicon concentrations. The patterns from previous data indicate increasing N and Si levels, with decreasing water transparency in the gulf. Spatially, the chlorophyll-*a* concentrations were high (above 10 mg/m^3 from 1994 to 2013), indicative of increasing productivity and a changing phytoplankton community, one that is mainly dominated by blue green algae as opposed to the initial diatom dominance. The shallow gulf waters, coupled with the riverine inputs, serve as an invaluable source of nutrients continually exchanged with the main lake areas, although the extent of the new lake hydrodynamics with the opening of the Mbita Causeway must be investigated since the main lake is suggested to be a net P exporter to the gulf. The lake water meets water quality criteria requirements for aquaculture in regard to needed nitrate N and P levels, although the eutrophic conditions can still contribute to increased occurrences of cyanobacterial blooms posing a potential public health risk to both humans and wildlife using such surface waters.

The various habitats of the main lake ecosystem are under the threat of eutrophication, meaning plans for sustainable management of the lake fishery and biodiversity conservation should re-emphasize continued and specific monitoring of the environmental conditions, as well as the subtle interplay between the terrestrially connected river channels, satellite lakes, and wetlands as interlinked complexed components capable of influencing the ecological integrity of the recipient lake waters. Involvement of all stakeholders in the lake wide formulation of strategies focusing on proper management of the surrounding human activities, control of non-point nutrient sources, and better watershed use is critical and invaluable for long-term sustainable management, including increased education programs on environmental conservation for a sustainable fisheries resource.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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