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Nutrient release from sediments and biological nitrogen fixation: Advancing our understanding of eutrophication sources in Lake Victoria, Tanzania

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Abstract

Intensification of anthropogenic activities in the three riparian countries bordering the shoreline of Lake Victoria is exacerbating eutrophication in the main body of the lake. The present study evaluated the importance of sediments and biological nitrogen fixation as sources of nutrient enrichment into Lake Victoria in Magu, Mwanza and Kayenze bays influenced by different anthropogenic activities, over a period of 7 months. Kayenze Bay is a relatively pristine site, while higher anthropogenic activities occur in the Magu Bay and Mwanza North Bay areas. Sediment cores were retrieved from each sampling site and transported to the laboratory for nutrient concentrations and flux analyses. In situ nitrogen fixation rates also were measured in the water column. The results indicated the sediment–water interface in Magu Bay exhibited significantly higher concentrations of nitrate-N and a net release of nitrate-N, compared to Mwanza North Bay and Kayenze Bay ($p < 0.001$). The sediment–water interface in Magu Bay also exhibited a significant net release of total phosphate towards the water column, compared to Mwanza Bay ($p < 0.001$). The sediment–water interface in Mwanza North Bay exhibited higher ammonium-N concentrations, and net release of ammonium-N and total nitrogen than did Magu and Kayenze Bays ($p < 0.001$). The sediment–water interface in Mwanza and Magu Bays exhibited higher total nitrogen and soluble reactive phosphate concentrations than Kayenze Bay ($p < 0.001$). Their sediments also released net fluxes of soluble reactive phosphate to the water column than did Kayenze Bay ($p < 0.001$). In contrast, the Kayenze Bay sediments acted as a sink of ammonium-N from the water column, compared to Mwanza North and Magu Bays ($p < 0.001$). Biological nitrogen fixation rates were significantly higher during the rainy season than the dry season ($p < 0.05$), although no spatial variations in biological nitrogen fixation existed among the three sites ($p > 0.05$). The present study indicated the water column and sediments in Magu Bay and Mwanza North Bay, characterized by high anthropogenic activities are rich in nitrate-N, ammonium-N, total nitrogen and soluble reactive phosphate, compared to the relative pristine Kayenze Bay. Anthropogenic activities and sediments may well be important sources of nutrients enrichment to the overlaying waters, thereby enhancing eutrophication of Lake Victoria. Management strategies are required to

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reduce external releases and internal nutrient fluxes to enhance the lake ecosystem health.

KEYWORDS
anthropogenic activities, biological nitrogen fixation, eutrophication, Lake Victoria, nutrients flux

1 | INTRODUCTION

Lake Victoria (the second largest freshwater lake in the world) has experienced major environment and ecology changes within the last 40 years attributable to natural processes and anthropogenic activities in its catchment area (Odada, Olago, Kulindwa, Ntiba, & Wandiga, 2004). Human activities, compounded by booming population growth in the lake basin, accelerate environmental degradation through deforestation, expansion of agricultural activities, raising livestock, siltation, wetland destruction, induced soil erosion and burning of biomass. Nutrient releases from these activities have resulted in rapid eutrophication of the lake over the past 50 years (Kabenge, Wang, & Li, 2016; Kayombo & Jorgensen, 2005; van Rijssel et al., 2016). The lake is highly impacted by eutrophication and pollution due to the chronic release of water containing higher levels of nutrients from surface runoff, urban/industrial effluents and agricultural activities conducted along the shoreline and in nearby catchments (Scheren, Zanting, & Lemmens, 2000; Waya, Limbu, Ngupula, Mwita, & Mgaya, 2014). Wastewaters from sewage and industries in urban areas are often discharged untreated into the environment thus act as major sources of nutrients, causing eutrophication onto the surface water of the lake (Nyenje, Foppen, Uhlenbrook, Kulabako, & Muwanga, 2010). Increased nutrients inputs into the lake have resulted in algal blooms, decreasing water transparency, increasing water hyacinth infestations and deoxygenating its deep waters (Kling, Mugidde, & Hecky, 2001; Msomphora, 2005; Mugidde, Hecky, Hendzel, & Taylor, 2003; Sitoki et al., 2010).

Previous studies reported site variations in background nutrient levels in different parts of Lake Victoria, depending on anthropogenic activities (Calamari, Akech, & Ochumba, 1995; Gikuma-Njuru & Hecky, 2005; Scheren, 2003; Scheren, Mirambo, Lemmens, Janssen, & Katima, 2005). Calamari et al. (1995) estimated the total phosphate (TP) concentration to be 0.17 mg/L in the Winam Gulf of Lake Victoria on an annual basis. Gikuma-Njuru and Hecky (2005) recorded total phosphorus (TP) concentrations ranging between 0.057 and 0.093 mg P/L in the Nyanza Gulf, whereas the total nitrogen (TN) concentration exhibited the highest value of 1.22 mg N/L, which decreased significantly along the gulf towards the main lake. On a lake wide basis, Gikuma-Njuru et al. (2005) reported nitrate nitrogen (NO_3-N) and phosphate phosphorus (PO_4-P) concentrations ranging between 16.2 to 87.9 μg/L and 39.6 to 92 μg/L, respectively. The TN load to the lake has been estimated to be 49,509 t TN/year by COWI Consulting Engineers (2002), almost twice that of 26,292 t TN/year reported by other workers (Scheren, 2003; Scheren, Bosboom, Njau, & Lemmens, 1995; Scheren et al., 2000, 2005). The estimated TP loadings are relatively comparable, being 5,693 t TP/year (COWI Consulting Engineers 2002) and 5,634 t/year (Scheren, 2003; Scheren et al., 1995, 2000, 2005). In the Mwanza municipality, Vuai, Ibembe, and Mungai (2013) recorded deposition rate of 15.5 and 13.9 kg ha^{-1} $year^{-1}$ for total nitrogen and 6.1 and 2.8 kg ha^{-1} $year^{-1}$ for total phosphorus. Muzuka, Machiwa, and Lugomela (2005) reported nitrogen accumulation in Magu Bay ranging from 0.51 to 4.37 g N m^{-2} $year^{-1}$, which led them to conclude that the bay was experiencing eutrophication problems.

Nutrient fluxes from sediments are regarded as an important process in the nutrient balance for many aquatic systems (Gardner & McCarthy, 2009; Gardner et al., 2006; Hale, 1975), based on two scenarios. The first is that nutrient enrichment from soils is attributed to nutrient releases carried largely by storm-generated water runoff from anthropogenic activities on the land surface, which subsequently drain into aquatic ecosystems where they are adsorbed into the bottom sediments, accumulate over time and ultimately are released back into the water column under specific chemical conditions. The second is that nutrients are released from organic-rich sediments containing plant and animal remains, being largely responsible for the nutrient fluxes for internal nutrient cycling in the African Rift Valley lakes (Hecky & Degens, 1973; Kendall, 1969). Although of benthic nutrient enrichment from sediments is also an important potential source of nutrient loading, information on this process and its contribution to eutrophication in Lake Victoria is still largely unknown. A study conducted on phosphorus and nitrogen flux estimates for the shallow, sub-tropical Lake Okeechobee in Florida, USA, indicated significant contributions benthic nutrient enrichment from sediments to eutrophication. The dissolved reactive phosphorus (DRP) flux was reported as 472 t/year, while the internal dissolved inorganic loads (DIN) were 500 t/year (Fisher, Reddy, & James, 2005). These levels indicate significant eutrophication possibilities because of nutrient enrichment (Dodds & Whiles, 2010). Lake Victoria has been defined by several authors as an eutrophic lake (Hecky, Mugidde, Ramlal, Talbot, & Kling, 2010; Mugidde, 2001; Waya, Limbu, Ngupula, Mwita, & Mgaya, 2017). However, the contribution of nutrients enrichment from sediments to eutrophication is currently unknown.

In addition to nutrients enrichment from anthropogenic activities and sediments, biological nitrogen fixation has been reported to occur in most highly polluted waterbodies (Guildford, Hecky, Taylor, Mugidde, & Bootsma, 2003; Mugidde, 2001; Mugidde et al., 2003). Several previous studies reported biological nitrogen fixation as an important new nutrient source to freshwater ecosystems (Carpenter et al., 1998; Hecky & Degens, 1973; Howarth, Marino, Lane, & Cole, 1988; Paerl, 1997; Rabalais, 2002). Nitrogen input into Lake Victoria

through biological nitrogen fixation was examined by Mugidde (2001), Guildford et al. (2003) and Mugidde et al. (2003). Machiwa (2010) reported Lake Victoria derives appreciable quantities of nitrogen from nitrogen fixation, while Mugidde et al. (2003) concluded that biological nitrogen fixation is the largest input of fixed nitrogen to Lake Victoria, greatly exceeding estimates of atmospheric deposition and river inputs of nitrogen. Mugidde et al. (2003) reported nitrogen fixation rates ranging from 1.8 to 23.1 g N m^{-2} $year^{-1}$, depending on the location within the lake, while Hecky et al. (2010) reported an average nitrogen fixation rate of 14.0 g N m^{-2} $year^{-1}$ in Lake Victoria. These nitrogen fixation values are comparatively higher than those reported by Howarth et al. (1988), which ranged from 0.2 to 9.2 g N m^{-2} yr^{-1} in similar eutrophic lakes. The values obtained for Lake Victoria are higher, indicating possible contribution to eutrophication. It has been indicated that nitrogen fixation varies between lake locations (Mugidde et al., 2003), tending to be low in oligotrophic and mesotrophic lakes, although it is often high in eutrophic lakes (Howarth et al., 1988). Information on biological nitrogen fixation levels, and nutrient fluxes from sediments in various areas impacted differently by anthropogenic activities, is currently insufficient for many lakes, including Lake Victoria. Moreover, the lack of baseline data on nitrogen fixation limits attempts to resolve the true impacts of nutrients on Lake Victoria ecosystem into the future.

The present study examined the contribution of nutrient releases from sediments by comparing shoreline sites highly affected by anthropogenic activities relative to less affected site. It further examined spatial and temporal variations in biological nitrogen fixation rates at three selected shoreline sites. It was hypothesized that sediments from shoreline sites highly affected by human activities will contribute significantly more to nutrient enrichment of the lake than less affected site. Moreover, it was assumed that shoreline sites highly affected by human activities and a rainy season will exhibit higher biological nitrogen fixation than pristine shoreline site and dry season, respectively.

2 | MATERIALS AND METHODS

2.1 | Study sites

The present study was conducted in Lake Victoria in Mwanza North Bay (MZA) located in the Mwanza Gulf (2°28′–3°00′S; 32°45′–33°01′E), Magu Bay (MGU) situated in the Magu district in the southern part of Speke Gulf (2°29′–3°08′S; 33°24′–34°49′E), and at Kayenze Bay, (KYZ) located between the Mwanza Gulf and Magu Bay (Figure 1). Mwanza Gulf has a surface area of about 1,725 km^2, its basin being inhabited by a population of about 1,464,568 people in the city of Mwanza (National Bureau of Statistics 2014). During the sample collection period, the shoreline areas at Mwanza Bay had an irregularly shaped muddy bottom, characterized by the smell of hydrogen sulphide, and fringed by a variety of vegetation. Mwanza Gulf has recently experienced increasing industrial development and urbanization that have increased the rate of pollution in its inshore waters because most of the wastes from domestic and industrial activities are discharged into the lake without proper treatment. Magu Bay is situated within the Magu District, being influenced by nearby flood plains and a wetland that is fed primarily by the Simiyu River. The river drains water from agricultural and livestock-raising areas of Shinyanga, Simiyu and Arusha regions, which enrich the lake with inputs from agriculture and grazing areas. Magu Bay had soft bottom sediments during the study period. The third study site is Kayenze Bay (KYZ), located far from the direct influence of human anthropogenic inputs, thereby being less impacted from anthropogenic activities. The sediments in Kayenze Bay were sandy and not bound.

The climate of the Lake Victoria basin is characterized by two distinct seasons, including a dry season from June to September, and a wet season from October to May. During the study period, the months of March to May were characterized by lake stratification, while June to September were characterized by lake mixing. The

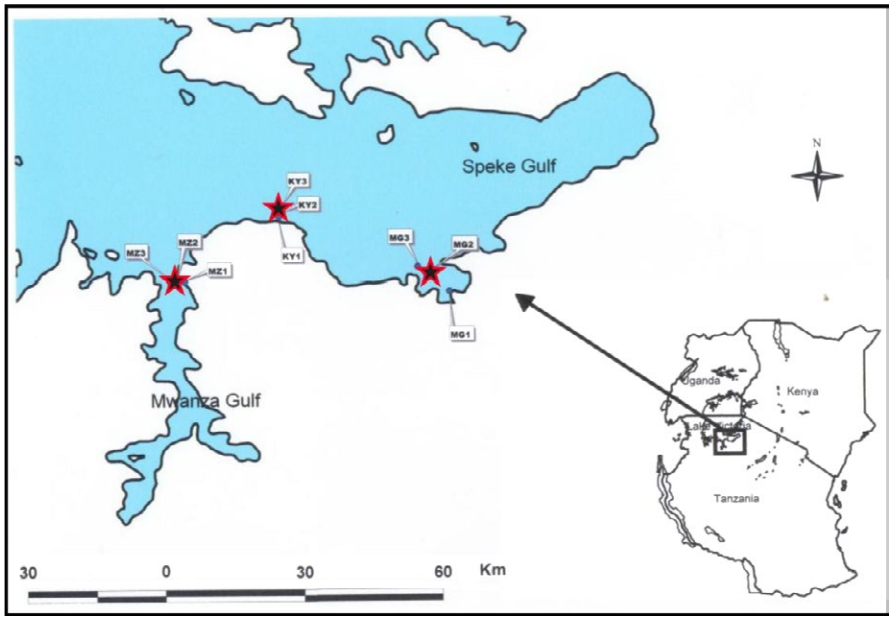


FIGURE 1 Map of southeastern part of Lake Victoria and study sites

months of October to February were characterized by thermal re-establishment and moderate stratification.

2.2 | Sample collection

2.2.1 | Nutrient fluxes

To estimate the net sink or release of nitrogen and phosphorus nutrients across the sediment–water interface, eight sediment cores (5 cm diameter; 50 cm length) were retrieved from each of the three sampling sites by Scuba diving, moving from the shoreline to the deeper water to a maximum depth of 4 m for a period of seven months between December 2003 and December 2004. The cores were wrapped in black plastic sheets and transported to the water quality laboratory in Mwanza for further analysis. They were incubated under room temperature (25 °C) for 12 hr, and the initial nutrient concentrations in the core water were measured and recorded. During the incubation period, 50 ml of water samples for nutrient analysis was drawn on an hourly basis from the incubated corers for a 12-hr period.

Analysis of inorganic nutrients from the sediments and the sediment–water interface was done using standard procedures (APHA, 1995). The nutrients were calculated as concentrations and fluxes over time for the sediment–water interface and sediments, respectively. For the net fluxes, the nutrients were expressed as net sink (nutrient movement towards the sediments, represented by negative values) and net release (nutrient movement towards the water column, represented by positive values).

2.2.2 | Biological nitrogen fixation

In situ nitrogen fixation rates in the water column at each sampling site were measured using the acetylene reduction technique described by Capone (1993). Water samples were collected from three different depths at each site (surface [0.5 m]; intermediate [5 m]; and bottom [10 m]) to determine the vertical distribution of biological nitrogen fixation rates for a period of seven months between December 2003 and December 2004. The biological nitrogen fixation samples were collected after those for sediment flux analysis. The samples were collected by concentrating 5 L of water to 100 ml, using a 20-μm plankton net. Four millilitres of the concentrate from each depth at each sampling site were sealed into triplicate 10 ml glass serum bottles. Ten percent of the air was withdrawn from the gas phase of the bottles and replaced by acetylene gas generated from calcium carbide, with the time at which acetylene was added being the starting point for incubation period. The incubation was done in situ by hanging the sample bottles on a floating raft at their respective depths for 2 hr. To determine the background ethylene values, glass fibre-filtered lake water from each site was incubated in parallel with the samples. After incubation, 5 ml of gas from each bottle was taken and kept in 5 ml pre-evacuated rubber-capped vacuum containers for gas chromatography analysis.

Measurement of the nitrogen fixation rates was done in the laboratory using a HP 5890 II Gas Chromatograph equipped with a porapak N column with 80/100-mesh size. Nitrogen gas was used as a carrier gas (flow rate of 35 ml/min at 200 kpa), and air at flow rate of 220 ml/min. The peak, area and retention time were monitored using the chemistation 4.0 program. The quantity of nitrogen produced was calculated using a conversion factor of four as described by Capone (1993).

2.3 | Water quality parameters analysis

In situ measurement of water temperature and pH was done on the water column at each site between 1000 and 1200 hours by using a portable water quality multi-probe (Model 1XYSI-63-100), and dissolved oxygen concentration was measured using a portable Hydrolab (Modle JPB-607A, Guangdong, China). Water transparency was measured using a 20-cm diameter Secchi disc, and the total suspended solids (TSS) concentration was measured in the laboratory following the gravimetric method described by APHA (1995). The chlorophyll-*a* concentrations were measured using a spectrophotometer as described by Vörös and Padisák (1991). Rainfall data were obtained from Tanzania Meteorological Agency (TMA), Mwanza branch.

2.4 | Statistical analyses

The study results are presented as mean ± *SE*, with the data being tested for homogeneity of variance using the Levene's test. After confirming homogeneity of variances, one-way analysis of variance (ANOVA) was used to test for significant differences in the nutrient concentrations, net fluxes, biological nitrogen fixation and water quality parameters among the shoreline sites and during different sampling months. When significant differences were detected, the Tukey post hoc test was performed to determine specific significant differences among sites. The seasonal variations in biological nitrogen fixation and rainfall were assessed using independent-samples *t*-test. All statistical analyses were performed using SPSS version 20 (IBM, Armonk, New York, USA) for Windows. Significant differences were judged at a probability level of $p \leq 0.05$.

3 | RESULTS

3.1 | Nutrient concentrations and fluxes at the sediment–water interface

3.1.1 | Nitrate-N

The NO_3-N concentrations for the sediment–water interface differed significantly among the three sampling sites ($F = 104.792$; $p < 0.001$; Figure 2a). The sediment–water interface in Magu Bay exhibited significantly higher NO_3-N concentrations than in Mwanza North Bay and Kayenze Bay ($p < 0.001$). The sediment–water interface in Mwanza North Bay had significantly higher NO_3-N concentrations than in Kayenze Bay ($p < 0.045$). Benthic NO_3-N fluxes

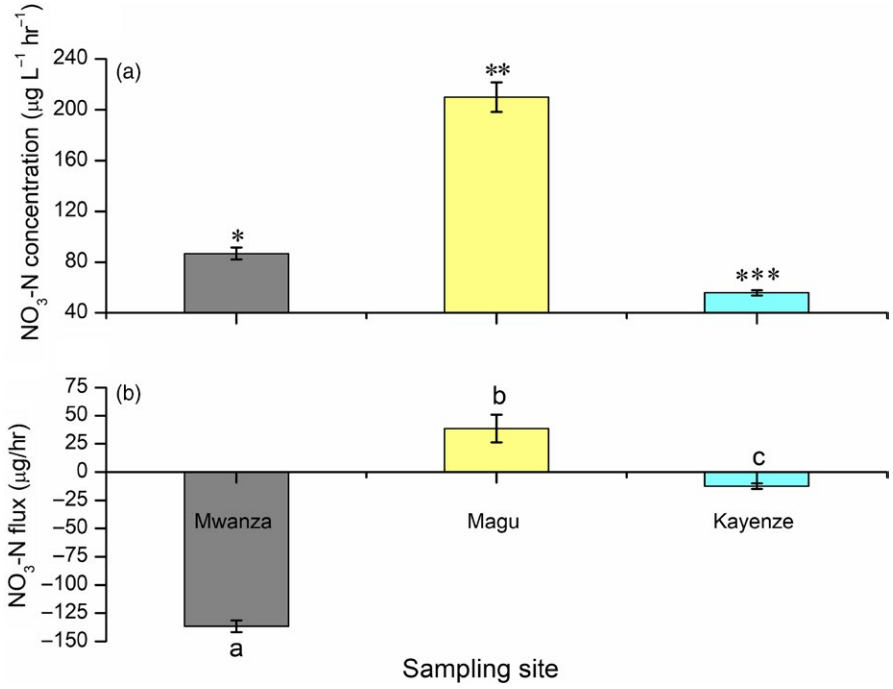


FIGURE 2 Mean nitrate-N (NO_3-N) concentrations (a) and net fluxes (b) for Lake Victoria sampling sites (negative and positive values indicate fluxes towards the sediment and water column, respectively; different letters and asterisks (*) above or below bars indicate significant difference; $p < 0.05$)

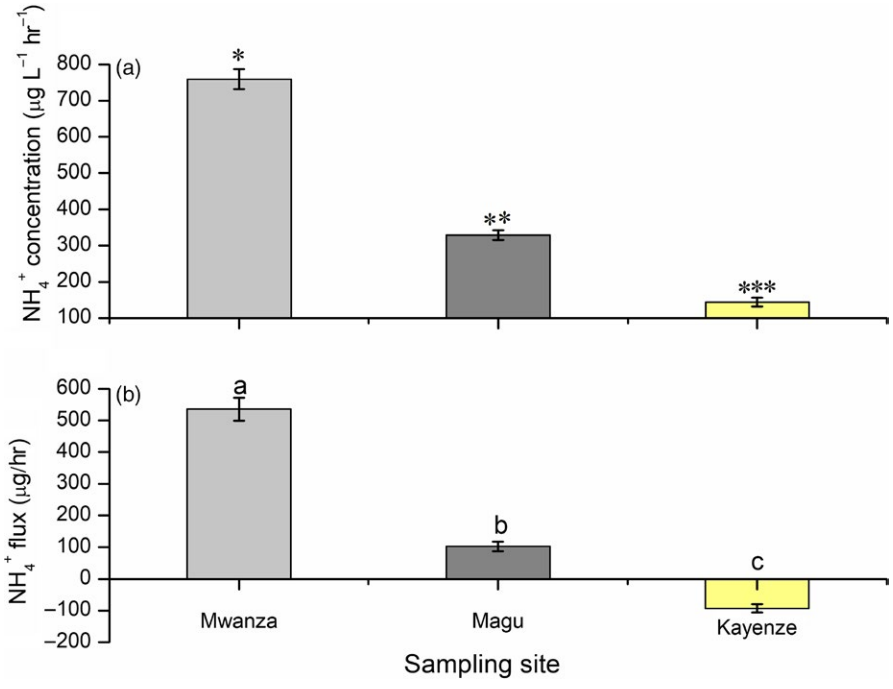


FIGURE 3 Mean ammonium-nitrogen (NH_4^+-N) concentrations (a) and net fluxes (b) for Lake Victoria sampling sites (negative and positive values indicate fluxes towards the sediment and to the water column, respectively; different letters and asterisks (*) above or below bars indicate significant difference; $p < 0.05$)

across the sediment–water interface in Mwanza North Bay and Kayenze Bay exhibited a net sink towards the sediment (Figure 2b). The NO_3-N fluxes in Magu Bay exhibited a net release towards the water column. The net N-fluxes differed significantly among the sediments at the three sampling sites ($F = 77.679$; $p < 0.001$). The sediments in Magu Bay released significant quantities of nitrate-N towards the water column, compared to Mwanza North Bay and Kayenze Bay ($p < 0.001$). Mwanza North Bay sediment–water interface exhibited a greater net sink of NO_3-N towards the sediments than Kayenze Bay ($p < 0.001$).

3.1.2 | Ammonium-N

Similar to NO_3-N, the NH_4^+-N concentrations for the sediment–water interface were significantly different among the three sampling sites ($F = 277.200$; $p < 0.001$; Figure 3a). The NH_4^+-N interface concentrations in Mwanza Bay were significantly higher than in Magu Bay ($p < 0.001$) and Kayenze Bay ($p < 0.001$). Likewise, Magu Bay exhibited higher interface NH_4^+-N concentrations than for Kayenze Bay ($p < 0.001$). The NH_4^+-N fluxes during the present study indicated a net release from the sediment into the water column at the Mwanza

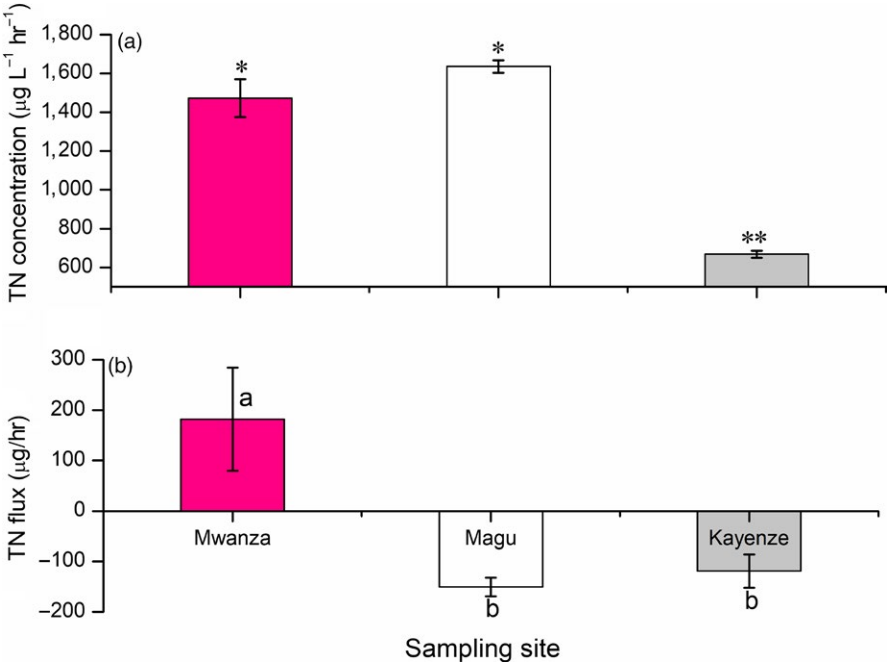


FIGURE 4 Mean total nitrogen (TN) concentrations (a) and net fluxes (b) for Lake Victoria sampling sites (negative and positive values indicate fluxes towards the sediment and to the water column, respectively; different letters and asterisks (*) above or below bars indicate significant difference; $p < 0.05$)

and Magu sampling sites whereas the fluxes indicated net sink towards the sediments in Kayenze Bay (Figure 3b). The NH_4^+-N fluxes movements were statistically different among the three sampling sites ($F = 228.187$; $p < 0.001$), with Mwanza North Bay sediments exhibiting a higher net release of NH_4^+-N than Magu and Kayenze Bays ($p < 0.001$). Similarly, Magu Bay sediments exhibited a significant net release of NH_4^+-N than for Kayenze Bay ($p < 0.001$).

3.1.3 | Total nitrogen

The TN concentrations at the sediment–water interface differed significantly among the three sampling sites ($F = 87.385$; $p < 0.001$; Figure 4a). The sediment–water interface in Mwanza North Bay and Magu Bay had higher TN concentrations than those in Kayenze Bay ($p < 0.001$). However, the sediment–water interface in Mwanza North Bay and Magu Bay had statistically similar TN concentrations ($p = 0.109$). The net fluxes of TN in Magu Bay and Kayenze Bay mainly showed net sinks from the water column to the sediments (Figure 4b). On the contrary, the TN net fluxes at Mwanza North Bay indicated net release to the water column (Figure 4b). The TN net fluxes were significant different among the three sampling sites ($F = 12.726$; $p < 0.001$). Sediments at Mwanza North Bay released significant TN fluxes towards the water column than those at Magu and Kayenze Bays ($p < 0.001$). However, Magu and Kayenze Bays had statistically comparable net sink of TN fluxes from the water towards the sediments ($p = 0.841$).

3.1.4 | Soluble reactive phosphate

The SRP concentrations for the sediment–water interface recorded significant variations among the three sampling sites ($F = 25.485$; $p < 0.001$; Figure 4a). Similar to TN, the sediment–water interface in Mwanza North Bay and Magu Bay had higher SRP concentrations than those in Kayenze Bay ($p < 0.001$), with the former sites recording comparatively similar values ($p = 0.742$). We observed new SRP flux out of the sediment towards the water column at Mwanza North Bay and Magu Bay as opposed to Kayenze Bay, which had a net sink of SRP to the sediments (Figure 5b). The fluxes of SRP differed significantly among the three sampling sites ($F = 30.501$; $p < 0.001$). Sediments at Mwanza North Bay and Magu Bay showed net release of SRP towards the water column than those at Kayenze Bay ($p < 0.001$). However, Mwanza North Bay and Magu Bay sediments had statistically comparable SRP net fluxes ($p = 0.655$).

3.1.5 | Total phosphate

The TP concentrations for the sediment–water interface were statistically comparable among the three sampled sites ($F = 0.703$, $p = 0.497$; Figure 6a). The TP fluxes at the three sites had a similar trend to that obtained for NO_3-N. The fluxes at Mwanza North Bay and Kayenze Bay indicated net sink towards the sediments while at Magu Bay the flux indicated a net release towards the water column (Figure 6b). The TP fluxes at the three sites were significant different among the three sampling sites ($F = 566.445$; $p < 0.001$). The water column at Mwanza North Bay had a net sink of TP fluxes towards the sediments than Magu Bay and Kayenze Bays ($p < 0.001$). No significant differences in net TP fluxes existed between the sediments at Magu Bay and Kayenze Bay ($p = 0.177$).

3.2 | Spatial and temporal variability in biological nitrogen fixation rates and rainfall

Spatially, the biological nitrogen fixation rates for Mwanza North Bay (37.03 ± 4.45 nmole N_2 L^{-1} hr^{-1}), Magu Bay (47.80 ± 9.21

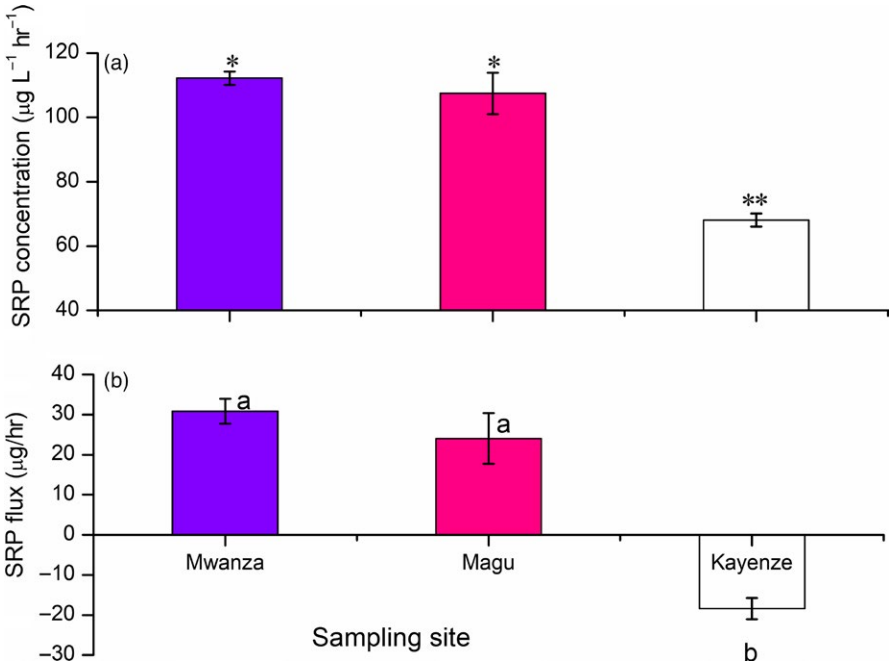


FIGURE 5 Mean soluble reactive phosphate (SRP) concentrations (a) and net fluxes (b) for Lake Victoria sampling sites (negative and positive values indicate fluxes towards the sediment and to the water column, respectively; different letters and asterisks (*) above or below bars indicate significant difference; $p < 0.05$)

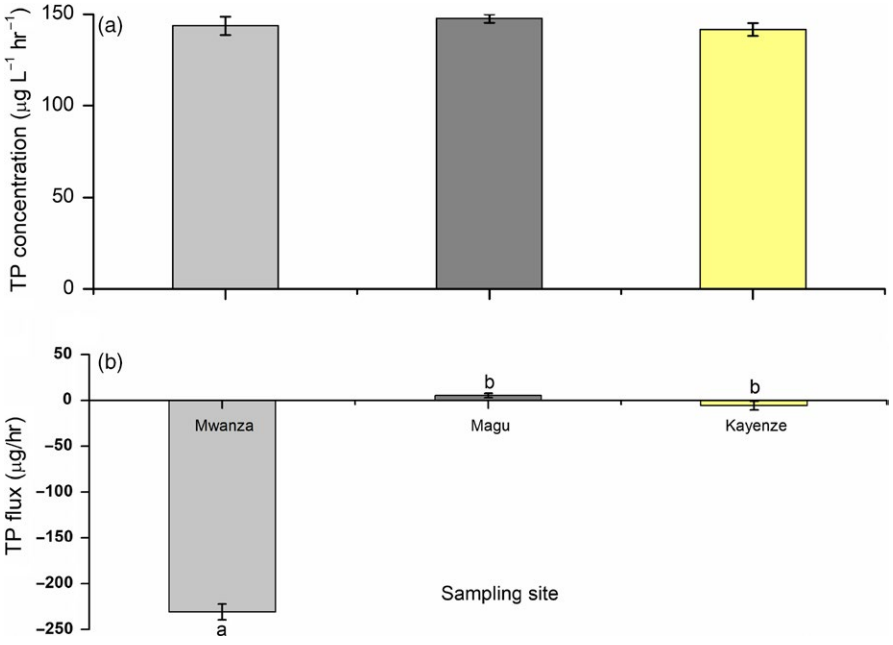


FIGURE 6 Mean total phosphate (TP) concentrations (a) and net fluxes (b) for Lake Victoria sampling sites (negative and positive values indicate fluxes towards the sediment and the water column, respectively; different letters and asterisks (*) above or below bars indicate significant difference; $p < 0.05$)

nmole N_2 L^{-1} hr^{-1}) and Kayenze Bay (46.50 ± 7.28 nmole N_2 L^{-1} hr^{-1}) were statically comparable among the studied sites ($F = 0.657$, $p = 0.522$).

Temporally, the biological fixation rates differed significantly among the sampled months ($F = 4.926$, $p < 0.001$; Figure 7). Nitrogen fixation rates obtained in April 2004 were significantly higher than for other months ($p < 0.05$) except for October 2004 ($p = 0.288$). Nitrogen fixation rates in June 2003 were significantly lower than for all other months ($p < 0.05$). The months of December 2003, March, August and December 2004 exhibited statistically comparable biological nitrogen fixation rates ($p > 0.05$). Seasonally, the wet season exhibited a significantly higher biological nitrogen fixation rate (64.31 ± 8.48 nmole N_2 L^{-1} hr^{-1}) than the dry season (46.05 ± 3.75 nmole N_2 L^{-1} hr^{-1}; $t = 2.176$, $p = 0.034$).

The rainy season had significantly higher quantities of rainfall (138.11 ± 16.31 mm) than the dry season (35.75 ± 6.22 mm; $t = 4.034$, $p = 0.002$).

3.3 | Water quality parameters

Water temperature ($F = 1.284$, $p = 0.279$), dissolved oxygen concentration ($F = 1.349$, $p = 0.265$) and pH ($F = 0.417$, $p = 0.660$) did not vary significantly among the three sites during the study period (Table 1). The water transparency, however, did differ significantly

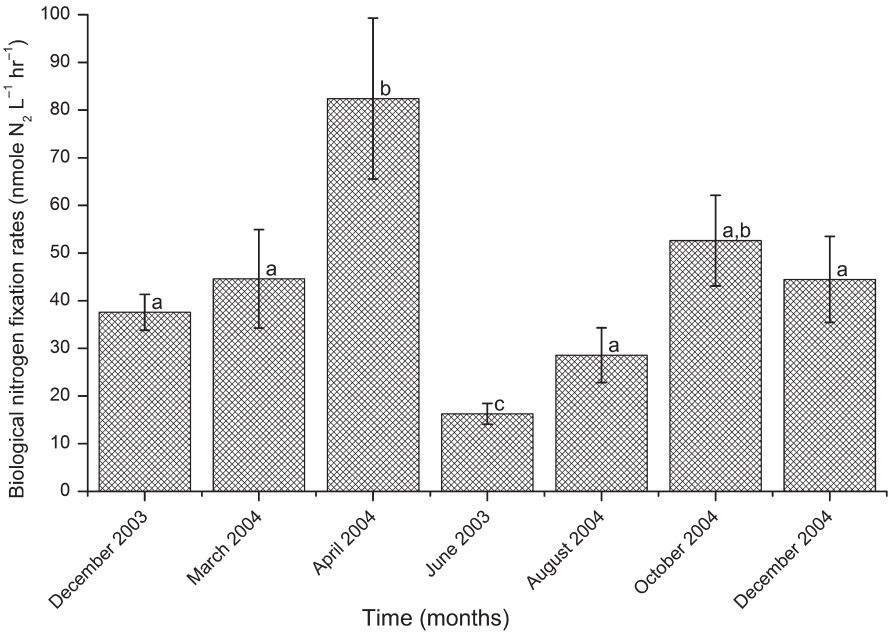


FIGURE 7 Biological nitrogen fixation observed during different sampling months (different letters above bars indicate significant difference; $p < 0.05$)

TABLE 1 Water quality parameters at Lake Victoria sampling sites obtained during study period (values in the same row with different superscripts are significant different; $p < 0.05$)

Water quality parameter	Mwanza North Bay	Magu Bay	Kayenze Bay
Temperature (°C)	25.46 ± 0.10[a]	25.54 ± 0.16[a]	25.28 ± 0.09[a]
Dissolved oxygen concentration (mg/L)	6.65 ± 1.79[a]	7.36 ± 1.54[a]	6.68 ± 1.64[a]
pH	8.10 ± 0.08[a]	8.08 ± 0.08[a]	8.17 ± 0.08[a]
Transparency (m)	1.23 ± 0.14[a]	0.67 ± 0.09[b]	1.80 ± 0.14[c]
Chlorophyll-*a* concentration (μg/L)	12.04 ± 0.64[a]	15.13 ± 1.33[a,b]	16.75 ± 0.97[b]
Total suspended solids concentration (mg/L)	5.23 ± 0.69[a,b]	54.47 ± 7.88[a]	4.73 ± 0.83[b]

among the three sites ($F = 21.467$; $p < 0.001$). Kayenze Bay exhibited significantly higher water transparency than Mwanza ($p = 0.007$) and Magu Bays ($p < 0.001$). Moreover, Mwanza Bay exhibited higher water transparency than Magu Bay ($p = 0.008$). The chlorophyll-*a* concentration (μg/L) was significantly different among the three sites ($F = 5.613$; $p = 0.004$) with Kayenze Bay having a significantly higher chlorophyll-*a* concentration than Mwanza Bay ($p = 0.007$), but similar to Magu Bay ($p = 0.492$). Mwanza and Magu Bays exhibited statistically comparable chlorophyll-*a* concentrations ($p = 0.094$). The total suspended solids (TSS) concentrations also differed significantly among the three sites ($F = 47.430$; $p < 0.001$), with Magu Bay having significantly higher TSS concentrations than Mwanza and Kayenze Bays ($p < 0.001$). Mwanza and Kayenze Bays exhibited statistically comparable total dissolved solids (TDS) concentrations ($p = 0.996$).

4 | DISCUSSION

The present study was conducted to determine the contribution of sediments to nutrient enrichment of Lake Victoria by comparing shoreline sites differentially affected by anthropogenic activities. It further evaluated the spatial and temporal variations in the biological nitrogen fixation rates. The study results indicated the sediments in Mwanza North Bay and Magu Bay, which are highly impacted by anthropogenic activities, are rich in various nutrients, and subsequently release them to the overlaying waters, compared to the pristine station (Kayenze Bay), which mainly acts as a nutrient sink by absorbing them from the overlaying waters. The sediments in Magu and Mwanza Bays appear to be loaded with nutrients from high anthropogenic activities, thereby are acting as sources of NO_3-N, TP, TN, SRP and NH_4^+-N by releasing them back into the water column.

It should be noted that the spatial levels of nutrients are site-specific depending on biological and anthropogenic activities (Machiwa, Lugomela, & Muzuka, 2005). Previous studies on Lake Victoria water column nutrient concentrations exhibited similar variations in Nyanza, Mwanza and Napoleon Gulfs (Gikuma-Njuru et al., 2005). Mwanza North Bay and Magu Bay are highly influenced by anthropogenic activities, including urbanization, domestic, industrial and agricultural pollution, reported to be the major nutrient sources to the overlaying waters and subsequently deposited in the sediments. Mwanza North Bay is under intensive anthropogenic

nutrients release attributable to untreated discharges of industrial and domestic wastes and particulate matter direct into the lake via the Mirongo River. Further, the nearshore waters of the Mwanza municipality contain higher nutrient levels due to industrial and vehicle emission (Vuai et al., 2013). The present study indicated nutrient concentrations of 1,472.20 ± 97.52 μg TN L^{-1} hr^{-1} for total nitrogen and 143.69 ± 4.98 PO_4-P L^{-1} hr^{-1} for total phosphate concentrations in Mwanza North Bay at the sediment–water interface attributed to the high level of anthropogenic activities in the area. Thus, anthropogenic activities contribute to the release of appreciable quantities of nutrients into the water column in Lake Victoria.

Similarly, Magu Bay is characterized by pollution from agriculture and animal husbandry practices, exhibiting high concentrations of NO_3-N, TN, SRP and NH_4^+-N, compared to the pristine site. Previous studies identified agricultural and animal raising as the main contributors of total phosphorus load (Calamari et al., 1995), phosphorus species and reduced forms of nitrogen species (Vuai et al., 2013), with net nitrogen releases between 69% and 85% (Zhou et al., 2014). The nutrients from these sources are carried to the lake as runoff via the Simiyu River, resulting into high levels in the water column. The present study reported sediment–water nutrient concentrations of 1,635.34 ± 32.91 μg TN L^{-1} hr^{-1} and 147.66 ± 2.36 PO_4-P L^{-1} hr^{-1} are released into the water column in Magu Bay from various anthropogenic activities.

The present study results illustrate two possible mechanisms causing nutrient enrichment in Lake Victoria, including anthropogenic activities related to domestic and industrial discharges, agricultural fertilizers, runoff and animal husbandry in one hand, and internal nutrient loading from the sediments, on the other hand. Nutrients from the anthropogenic activities are carried in water runoff to the lake, contributing to eutrophication. Nutrients from direct human-daily activities such as fishing (Johnson, 2010), waste discharges from domestic activities (Njiru et al. 2012) and wastewater treatment plants (WWTPs) (Liu et al., 2018) contribute significant nutrient loads. Although the nutrients contribution from these activities was not directly measured at the study sites, they directly increased the nutrient load to Lake Victoria. Further, Lake Victoria is the major contributor to fish production in Tanzania (over 60% inland waters fish production), employing about 500,000 fishers (Onyango, 2017). The activities conducted by fishers contribute to deforestation because firewood used for frying and smoking purposes expose the land to increased erosion, resulting in increased nutrient inputs into the lake (Odada et al., 2004). Since Mwanza North Bay and Magu Bay are used as fishing grounds, direct nutrients contributions from these sites might also enhance eutrophication.

It also has been reported from a previous study that internal nutrient loads can significantly influence nutrient inputs into shallow lakes that have received excessive external nutrient loads (Jensen & Andersen, 1992). Sediments from highly polluted areas of Lake Victoria contain large quantities of absorbed nutrients, thereby are acting as nutrient sources. The sediments subsequently release the nutrients to the overlaying water column, thereby becoming internal nutrient sources. Thus, anthropogenic and agricultural activities, coupled with diffuse of nutrient fluxes from the bottom sediments, might be acting as major sources of the nutrients that enhance eutrophication of Lake Victoria.

As an overall observation, the combined external (e.g., anthropogenic activities from domestic and industrial discharges, agricultural activities, including animal husbandry and runoff, and direct daily activities of humans, including fishing, waste releases from domestic activities, WWTPs, soil erosion, deforestation, agricultural fertilizers) and internal inputs (diffusion of nutrient fluxes from sediments to overlying waters) are probably enhancing eutrophication at the studied sites in Lake Victoria.

The ability of overlying waters in Mwanza North Bay to exhibit being both a net sink for NO_3-N and TP to the sediments, and a net source for NH_4^+-N, TN and SRP back into the overlying waters, and Magu Bay to act as a net sink for TN, but exhibit a net release of NO_3-N, NH_4^+-N, SRP and TP to the water column indicates a biphasic mode of nutrient release, and possibly determines the net nutrient flux. The net movements of inorganic nutrients between sediments and its overlying waters are controlled by processes occurring at the sediment–water interface and within surficial sediments (Small, Cotner, Finlay, Stark, & Sterner, 2014), such as a nutrient gradient. It is likely that nutrients inputs from anthropogenic activities in Mwanza and Magu Bays into the overlying water are contributing to net nutrient sinks into the sediments. When sediments are saturated with nutrients, however, they reversibly release them into the overlying waters under specific chemical conditions in the waterbody. Thus, a continuous release of nutrients may occur between the water column and the lake sediments, depending on the sediment level of nutrient saturation. The nutrient release especially NO_3-N in Kayenze Bay by the overlying waters towards the sediments is attributable to the pristine nature of the sampling site, with the denitrification process perhaps being the contributing factor to the observed situation. Thus, the Kayenze Bay sediments are acting as a nutrient sink from the overlying waters.

The biological nitrogen fixation rates were statistically similar among the shorelines of the three study sites, although the anthropogenic-impacted sites had comparable higher quantities, perhaps attributable to the availability of sediment phosphorus and water column sources eradicating the phytoplankton limiting nutrient effect. Indeed, the total phosphate levels were comparable among the three sites in the present study. The availability of phosphorus levels have been reported to favour large populations of nitrogen-fixing cyanobacteria (Hendzel, Hecky, & Findlay, 1994; Levine & Schindler, 1999) because they are more efficient than other phytoplankton species in assimilating phosphorus into their biomass (Smith & Demaster, 1996). Phosphorus availability, in fact, has been reported as a driving force for nitrogen demand which, in turn, results in elevated N_2-fixation in Lake Victoria (Lipiatou et al., 1996; Mugidde, 2001; Mugidde et al., 2003). Thus, the similarity in biological nitrogen fixation rates among the three sites might be attributable to statistically comparable levels of total phosphate. Nevertheless, specific local conditions at the study sites (i.e., human activities) should not be overlooked as a causative factor, particularly because

of the comparatively higher values obtained at the anthropogenic-impacted sites, relative to the pristine one, a research area requiring further studies.

Temporally, the month of April 2004 during the rainy season exhibited significantly higher biological nitrogen fixation than the other months of the year. Seasonally, the wet season exhibited higher biological nitrogen fixation than during the dry season. Similar results were obtained by Mugidde et al. (2003). Higher temporal and seasonal biological nitrogen fixation during the heavy rainy season coincided with the period of higher inflows of water containing nutrients in surface runoff from rainfall. The availability of nutrients, especially phosphorus, contributed to a higher biological nitrogen fixation by phytoplankton, noting that surface runoff is a major external nutrient source for Lake Victoria. Moreover, the rainy season is the period when Lake Victoria is shallowly mixed and thermally stratified, resulting in higher biological nitrogen fixation (Mugidde et al., 2003). It was concluded, therefore, that a greater nutrient input during the rainy season likely resulted in higher temporal and seasonal variations in biological nitrogen fixation at the study sites.

The water transparency and chlorophyll-*a* exhibited increased values in Kayenze Bay than for Mwanza and Magu Bays. These results coincide with low influence of anthropogenic activities in Kayenze Bay. This bay is located far away from direct influences of anthropogenic inputs which can reduce water transparency. Thus, the higher water transparency in Kayenze Bay allowed light to penetrate into the water column, thereby ensuring higher production from algae, as evidenced by a higher chlorophyll-*a* concentration. The influence of agricultural and livestock raising was clear for Magu Bay, as evidenced by higher TSS concentrations than Mwanza and Kayenze Bays. Magu Bay receives agricultural and livestock wastes from the Shinyanga, Simiyu and Arusha regions that are carried by the Simiyu River to the sampling site. Despite Mwanza Bay being a polluted site, however, it is more likely that the type of pollutants observed at this site is not contributing to higher TSS. In general, the results of the present study suggest the pristine nature of Kayenze Bay resulted in higher water transparency and chlorophyll-*a* concentrations than the more polluted Mwanza and Magu Bay sites. Further, Magu Bay is influenced by agriculture and livestock raising, which increases the TSS concentration.

In conclusion, the present study indicates that sediment–water interfaces are acting biphasically in releasing nutrients in Lake Victoria. Higher nutrient contents in the polluted waters of Mwanza North and Magu Bays contribute to higher water column nutrient levels, leading to downward nutrient movement into the lake bottom sediments. When sediments from the polluted sites are saturated with nutrients, however, they reversibly release them upward back into the overlying waters. This means the sediment–water interfaces act as nutrient source to the water column at some sites, and as a nutrient sink at other sites, depending on the level of anthropogenic activities at the site. These two scenarios might be contributing significantly to the eutrophication of the overlaying waters in Lake Victoria. The three sampling sites exhibited comparable levels of biological nitrogen fixation rates attributed to the availability of phosphorus in the overlaying waters from the sediments and water column sources, eradicating the effect of limiting nutrients to phytoplankton. The rainy season exhibited higher biological nitrogen fixation attributable to nutrient inputs from runoff waters associated with rainfall, coupled with shallow mixing and thermal stratification occurring during this specific period. Multidisciplinary management interventions focusing on all activities that lead to excessive release of nutrients into the lake including unmanaged pollutant disposals from domestic, industrial and agricultural wastes should be limited to ensure the sustainable health of the Lake Victoria ecosystem.

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