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Evidence of eutrophication in the Tanzania sector of Lake Victoria

OMARI I. MYANZA[1*], ROSEMARY RWEBUGISA[2] AND OMARI MWINJAKA[3]

[1]*National Project Coordinator (LVEMP II), Box 211, Mwanza, Tanzania*
[2]*Water Resources Specialist (LVEMP II), Box 211, Mwanza, Tanzania*
[3]*Water Resources Management Officer (LVBC), Box 1510, 40100, Kisumu, Kenya*

*Corresponding author: wamuyanza@gmail.com

Abstract
Lake Victoria has experienced accelerated eutrophication with elevated phosphorus, nitrogen and chlorophyll-*a* concentrations, coupled with decreased transparency as a result of the growing human activities in the catchment area. A survey in Tanzanian waters from 2011-2016 provided data on phosphorus, nitrogen, dissolved oxygen and transparency from littoral (bays and gulfs) and pelagic stations. The differences between the two groups of stations were generally small, with the exception of chlorophyll-*a*, which was generally higher at the littoral stations. The molar TN:TP ratio indicated nitrogen limitation in most of the lake thus favouring the dominance of nitrogen-fixing cyanobacteria, which currently dominate the phytoplankton. The trophic status of the lake was assessed using the OECD criteria, yielding four 'eutrophic' and two 'hypertrophic' assessments. A similar assessment in 2005-2005 gave two 'eutrophic' and four 'hypertrophic' classifications, suggesting that the lake may have not deteriorated over the last decade and may have stabilised.

Keywords: Eutrophication, Lake Victoria; Nitrogen, Phosphorus, Transparency, Trophic status

Introduction:
The Tanzanian sector of the Lake Victoria basin covers about 115,000 km^2 (LVBWO, 2002) and ranges in altitude from 1134 m, the level of the lake (Akiyama, 1977), to about 1400 m in the surrounding hills (Bronkonsult, 1978). The major rivers that flow into the lake include the Kagera, which flows in Tanzania - Uganda boarder before entering the lake in Uganda waters, the Magogo-Moame and Isanga entering through Mwanza Gulf in the South, the Simiyu, Mbalageti and Grumeti into Speke Gulf to the South East and the Mori and Mara into the Mara Bay in the East.

Nutrient loading from the rivers and atmospheric deposition (Tamatamah *et al*., 2005; Vuai *et al*., 2013; Zhou *et al*., 2014) has resulted in the enrichment of Lake Victoria with plant nutrients, particularly phosphorus and nitrogen, leading to its eutrophication and an apparent deterioration of its water quality. Symptoms of eutrophication in Lake Victoria were manifested by algal scums (Ochumba and Kibaara, 1989; Mugidde, 1993); and toxins derived from algal blooms (Sitoki *et al*., 2012); an outbreak of water hyacinth, now under biological control in some parts of the lake (Albright *et al*., 2004; Wilson *et al.*, 2007); increased turbidity in the water and oxygen depletion of in deep waters (Hecky *et al*., 1994). Eutrophication is also reflected by a change in the species composition of phytoplankton from one dominated by large diatoms to one currently dominated by cyanobacteria bringing about a significant increase in primary productivity and chlorophyll-*a* (Ochumba and Kibaara 1989; Mugidde 1993; Lung'aiya *et al*., 2000; Kling et al., 2001). These algal blooms have contributed to a decline in transparency and depth of the euphotic zone, a more pronounced thermocline and persistent hypoxia in deep waters, a decrease in soluble reactive silicon and an increase in soluble reactive phosphorus and total phosphorus in the water column (Hecky, 1993). Recent evidence suggests that the situation may have stabilised with reduced anoxia in deeper water, with lower chlorophyll-*a* concentrations and increased transparency in open waters (Sitoki *et al*., 2010; Marshall *et al*., 2013).

Methods
Water samples were collected from 11 littoral and 18 pelagic stations in the Tanzanian sector of Lake

Victoria between 2011 and 2016 (Figure 1). Samples were collected at various depths of the water column for nutrients determination. After measuring the secchi depth, samples were collected at 0.5m, at Secchi depth, at 2.3 x Secchi, every 5 or 20m (depending on the depth of the particular sampling station), after start of the dissolved oxygen/temperature gradient, and 1 and 0.5m from bottom. A portion of the sample was filtered through glass fibre filters (1µm) for determination of dissolved nutrients and stored in 1-litre plastic bottles, previously cleaned with phosphorus-free detergent. For chlorophyll-*a* determination, a part of the sample was filtered through membrane filters (0.45 µm pore size) and the volume recorded for further calculations. Both filtered and unfiltered samples and filter papers were a preserved at < 4°C. Physical parameters, including a vertical profile of dissolved oxygen and temperature, were measured *in situ* using a DataSonde Series 4. Water transparency was measured with a Secchi disk.

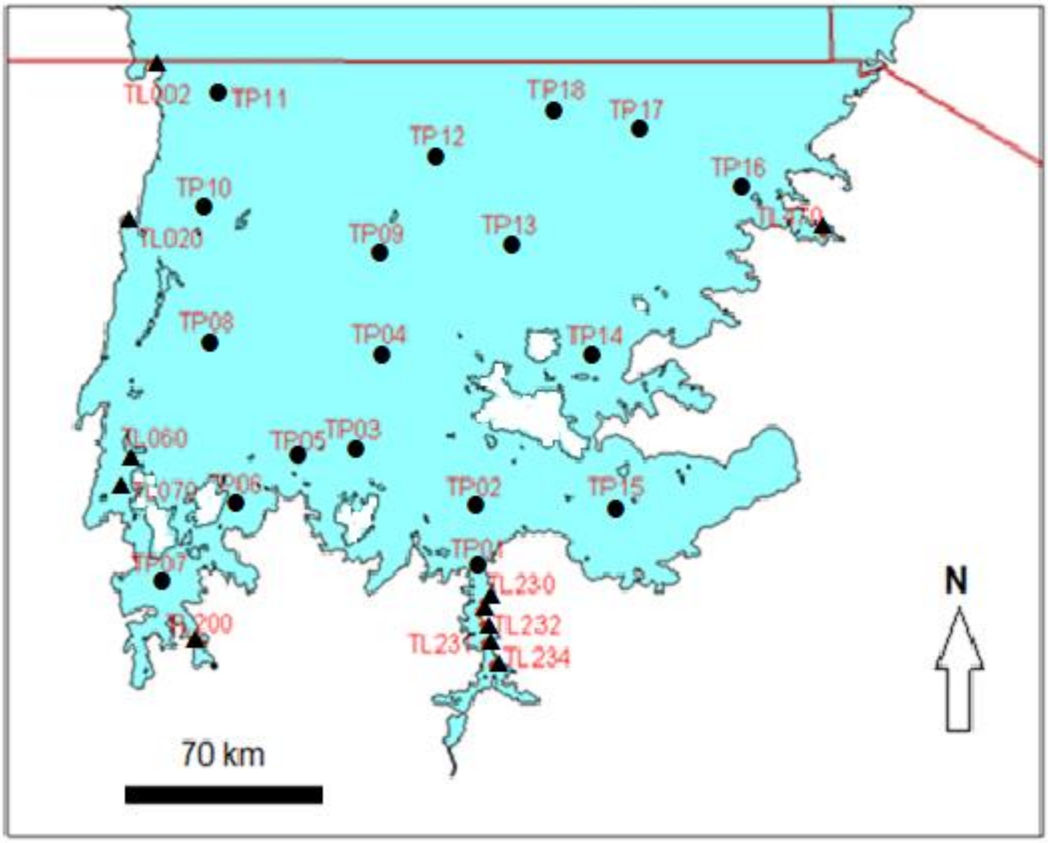

Figure 1: Water quality monitoring stations in the Tanzanian sector of Lake Victoria. TL = littoral stations - depth ≤ 20m and within 5 km the from lake shore (▲), TP = pelagic stations – depth ≥20m (●)

The samples collected were analysed in the laboratory using standard methods including ascorbic acid digestion for total and Soluble Reactive Phosphorus, sodium salicylate for nitrates and persulfate digestion for total nitrogen (APHA, 2012). Chlorophyll-*a* was extracted using ethanol and both nutrients and chlorophyll-*a* were determined with a UV/Visible Spectrophotometer. Analytical Quality Assurance protocol was used in the laboratory to ensure collection of reliable data.

Results

The mean temperature varied from 24.1-25.5°C (Table 1) with the mean maximum and minimum temperatures being 26.6 ± 0.7°C and 23.5 ± 0.7°C respectively. Pelagic stations were generally slightly cooler than littoral ones but the differences were small and the standard deviations overlapped.–Average Secchi disc transparency was consistently higher at pelagic stations, but again the standard deviations overlapped and the differences were unlikely to be significant. The exception to this occurred in October 2011 when littoral transparency was very low, possibly because of increased silt laden resulting from rainfall and surface runoff.

Table 1: Mean values of temperature (Temp), transparency (Secchi disc), dissolved oxygen (DO) total nitrogen (TN), total phosphorus (TP), the TH:TP ratio, and chlorophyll-*a* (Chl *a*) in the Tanzanian waters of Lake Victoria, 2011-2016. ND = not determined.

		October 2011	**April 2012**	**March 2013**	**August 2014**	**January 2016**
Temp (°C)	Littoral	24.6 ± 0.4	24.8 ± 0.7	25.3 ± 0.9	24.7 ± 0.8	25.5 ± 0.7
	Pelagic	24.1 ± 0.6	25.2 ± 1.5	24.4 ± 0.8	24.7 ± 0.7	24.7 ± 0.3
Secchi disc (m)	Littoral	0.8 ± 0.1	1.1 ± 0.5	1.5 ± 0.5	ND	ND
	Pelagic	2.6 ± 1.0	2.0 ± 0.6	2.1 ± 1.3	ND	ND
TN (µg l^{-1})	Littoral	761.9 ± 322.7	316.7 ± 103.4	1042.0 ± 276.4	436.6 ± 129.4	1052.0 ± 434.0
	Pelagic	248.7 ± 100.5	229.0 ± 72.9	491.1 ± 156.4	374.5 ± 182.9	715.0 ± 378.0
TP (µg l^{-1})	Littoral	83.4 ± 15.4	88.5 ± 28.1	126.5 ± 53.1	85.2 ± 29.2	74.7 ± 9.9
	Pelagic	102.7 ± 32.5	171.0 ± 66.8	100.9 ± 84.3	70.9 ± 12.4	78.11 ± 6.5
TN:TP ratio	Littoral	19.6	7.7	17.7	11.0	29.3
	Pelagic	5.2	2.9	10.4	11.3	20.5
DO (mg l^{-1})	Littoral	5.8 ± 1.2	5.3 ± 1.2	4.4 ± 0.8	5.2 ± 2.4	6.2 ± 0.8
	Pelagic	4.8 ± 1.5	5.6 ± 0.7	5.2 ± 2.4	5.9 ± 1.2	7.0 ± 0.0
Chl a (µg l^{-1})	Littoral	21.3 ± 10.6	23.8 ± 8.1	21.2 ± 8.7	5.8 ± 8.7	27.2 ± 6.3
	Pelagic	5.2 ± 3.7	8.5 ± 3.7	9.4 ± 8.2	1.7 ± 0.1	5.1 ± 3.3

The concentrations of TN were significantly higher at littoral stations with a mean value of 1,052 ± 434 µg l^{-1} compared to a mean of 715 ± 378 µg l^{-1} at pelagic stations. There was no difference in nitrate concentrations, however, where the mean value at littoral stations was 70.6 ± 32.8 µg l^{-1} compared to 75.7 ± 39.2 µg l^{-1} at pelagic stations.

There was no consistent pattern for TP where concentrations were rather higher at pelagic stations in 2011, 2012 and 2016 but rather higher at littoral stations in 2013 and 2014. The mean value at littoral stations was 92.6 ± 41.5 µg l^{-1} compared to 108.1 ± 63.5 µg l^{-1} at pelagic ones. The concentrations of SRP was considerably lower at littoral stations (mean = 24.2 ± 14.3 µg l^{-1}) than at pelagic ones (mean = 62.9 ± 50.2 µg l^{-1}). Molar TN:TP ratios were higher at littoral stations in every year, except for 2014 when the situation was reversed.

There was little variation in dissolved oxygen concentrations with mean values being 5.6 ± 4.8 mg l^{-1} and 4.9 ± 1.6 mg l^{-1} at littoral and pelagic stations, respectively. The highest concentrations of dissolved oxygen, at both pelagic and littoral stations, were recorded in January, 2016, during the stratification period.

The concentrations of chlorophyll-*a* were consistently higher at littoral stations (mean = 25.3 ± 14.0 µg l^{-1}) than they were at pelagic ones (mean = 7.1 ± 5.6 µg l^{-1}). Values were relatively consistent throughout the study period, apart from the exceptionally low values that were recorded at both littoral and pelagic stations in August 2014.

Discussion

The mean TP concentrations were about four times higher than those Talling (1966) and reflect the change in the lake's trophic status. This was consistent with data from the northern waters of the lake where concentrations also increased by a similar degree (Mugidde, 1993; Kling *et al*., 2001). The values reported in this study were similar to those reported from pelagic (80-100 µg l^{-1}) and littoral waters (50-90 µg l^{-1}) waters in Tanzania and elsewhere in the lake (Gikuma-Njuru *et al*., 2005). They were generally slightly lower than those reported by Mwirigi *et al*. (2005) who reported mean concentrations of 144 µg l^{-1} in water < 20 m deep and 168 µg l^{-1} in water > 20 m deep in 2004-05. They also reported mean SP concentrations of SRP of 70 and 77 µg l^{-1} in water < 20 m and > 20 m depth respectively. These estimates are considerably higher than those reported in the littoral zone in this study but only slightly higher than those in the pelagic zone.

Mean TN concentrations in 2004-05, 933 µg l^{-1} in water < 20 m deep and 899 µg l^{-1} in water >20 m (Mwirigi *et al*., 2005), were similar to the mean values in this study. There is no indication, however, of how variable the earlier estimates were because this study found that TN was highly variable. The mean concentrations of NO_3-N in 2004-05 were 52 and 63 μg l^{-1} in water < 20 m and > 20 m deep, respectively (Mwirigi *et al*., 2005), which were lower than those reported in this study.

Dissolved oxygen concentrations were similar to those reported in 2004-05 (Mwirigi *et al*., 2005) and in 2006-09, except the deep-water concentrations were rather higher at that time (Sitoki *et al*., 2010). There was no evidence of anoxia in the samples collected during this study (2011-2016) although only the November 2016 sample was collected during the stratified period.

The molar ratio (TN:TP) in both the littoral and main lake in most cases indicates that the lake is potentially nitrogen-limited, supporting earlier observations that conditions favour the dominance of nitrogen-fixing cyanobacteria (Guildford and Hecky, 2000; Gikuma-Njuru *et al*., 2005).

The mean concentrations of chlorophyll-*a* at "littoral" stations (depth not stated) in 2005-05 were 25.2 μg l^{-1} (Mwiringi *et al*., 2005) and were nearly the same as those in this study. Other estimates of mean chlorophyll-*a* in 2004-05 were 9.2 and 6.2 μg l^{-1} in water < 20 m and > 20 m deep respectively, compared to 7.1 μg l^{-1} in this study. Similar values were obtained by Sitoki *et al*. (2010) who also noted that chlorophyll-*a* was higher in shallow waters.

The transparency of the lake, indicated by Secchi disc visibility, has declined especially in offshore waters (Table 2). This decline reflects the change in the lake's trophic status with algal blooms playing a major part, although sediments from degraded land may also have contributed to the decline in inshore waters.

Table 2: Changes in the mean (± standard deviation) Secchi disc visibility (m) measured in inshore (<20 m) and offshore (>20 m) waters of Lake Victoria during lake wide surveys. Data from Graham (1929), Sitoki *et al*. (2010), Mwiringi *et al*. (2005) and the present study.

Year	Inshore	Offshore
1927	2.2 ± 0.8	7.5 ± 1.9
2000-01	2.0 ± 0.6	3.2 ± 1.1
2004-05	1.3	3.1
2006-09	1.4 ± 0.6	3.3 ± 1.2
2011	0.8 ± 0.1	2.6 ± 1.0
2012	1.1 ± 0.5	2.0 ± 0.6
2013	1.5 ± 0.5	2.1 ± 1.3

The trophic status of the lake can then be determined using the OECD criteria, based on TP, chlorophyll and transparency (Table 3). From this, it can be seen that the pelagic waters of the Tanzanian sector of Lake Victoria could be classed as hypertrophic on the basis of TP, but as eutrophic on the basis of chlorophyll and transparency (Table 4). In contrast the littoral stations were eutrophic on the basis of TP and chlorophyll and hypertrophic as far as transparency is concerned.

Table 3: The OECD boundary values for fixed trophic classification (Mason, 1997).

		Chlorophyll-*a* (μg l^{-1})		Transparency (m)	
Trophic status	**TP (μg l^{-1})**	**Mean**	**Maximum**	**Mean**	**Minimum**
Ultra-oligotrophic	< 4	< 1.0	< 2.5	>12	> 6
Oligotrophic	< 10	< 2.5	< 8.0	> 6	> 3
Mesotrophic	10-35	2.5-8	8-25	6-3	3-1.5
Eutrophic	35-100	8-25	25-75	3-1.5	1.5-0.7
Hypertrophic	>100	>25	>75	<1.5	<0.7

Table 4: The trophic status of the Tanzanian waters of Lake Victoria according to the OECD criteria.

		Pelagic		Littoral	
		Value	**Status**	**Value**	**Status**
TP (μg l^{-1})		108	Hypertrophic	92	Eutrophic
Chlorophyll-*a* (μg l^{-1})	Mean	7	Eutrophic	25.3	Eutrophic
	Maximum	32		72.4	
Transparency (m)	Mean	2.3	Eutrophic	1.1	Hypertrophic
	Minimum	0.8		0.5	

A classification of the lake in 2004-2005 using the same criteria found that there were four hypertrophic categories and two eutrophic ones (Gikuma-Njuru *et al*., 2005), compared to only two hypertrophic and four eutrophic categories in 2011-2016 (this study). Sitoki *et al*. (2010) suggested that the condition of the lake had improved considerably and these data tend to confirm this view. While the lake is still eutrophic the data from this study suggest that the situation has not deteriorated over the last decade and may have stabilised to some extent.

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