Changes in pollution indicators in Lake Victoria, Kenya and their implications for lake and catchment management

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Abstract

Monitoring of aquatic pollution is important for ascertaining the relationship between fisheries and the general ecosystem health of a lake. This study evaluated the use of changes in pollution indicators in Lake Victoria, Kenya, as a decision support tool for fisheries management and productivity. Principal component analysis (PCA; $R^2 \geq 0.5$, $P < 0.05$) of physical and chemical parameters delineated sampling sites into ecological cluster zones consisting of the inner gulf (C1), mid-gulf (C2) and open lake (C3). Test results for lead (Pb) and mercury (Hg) levels in the Nile perch tissues were found to be compliant with EU standards. The inner and mid-gulfs of the Winam Gulf had high levels of total (1818.8 ± 102–1937.78 ± 94 cfu 100 mL^{-1}) and faecal (390 ± 21 cfu 100 mL^{-1}) coliforms attributable to urban sewage and industrial effluents exceeded WHO standards. Similarly, Winam Gulf was more polluted than the open lake, with higher total phosphorus and nitrogen concentrations, turbidity levels and electrical conductivity. Low phytoplankton biovolume and a low number of macroinvertebrates genera, and high zooplankton densities and pollution-tolerant catfishes (e.g., *Schilbe victoriae*; *Clarias gariepinus*) were observed in Winam Gulf. Faecal coliforms and dissolved oxygen influenced the abundance of tolerant fish species (e.g., *S. victoriae*) in the lake. This study indicated a declining trend of ecological integrity in the Winam Gulf, compared with the open waters of Lake Victoria. An integrated management approach directed to minimizing pollution levels, especially in the Winam Gulf, is recommended to enhance fishery production.

Key words

fisheries, indicators, Lake Victoria, pollution, water quality standards.

INTRODUCTION

Lake Victoria provides important ecosystem services to over 40 million inhabitants in the three riparian countries (Kenya, Tanzania and Uganda), including fisheries, transport, and water for domestic, agricultural and industrial uses (LVFO 2015). Lake Victoria is the largest tropical and second largest freshwater lake in the world, with a surface area of 68 000 km^2. The lake is shared by Uganda (43%), Tanzania (51%) and Kenya (6%; Njiru *et al.* 2012). Nevertheless, the cumulative pressures influencing Lake Victoria are multiple, intricately interconnected, and threaten all of its fisheries as well as the lake's more general ability to deliver supporting services. Indeed, the entire ecosystem has been affected by climate change (Cózar *et al.* 2012), and degraded by pollution and eutrophication (Dobiesz *et al.* 2010), which have impoverished the system by driving an irreversible biodiversity decline (Seehausen *et al.* 1997). These same pressures may have also caused a more general collapse in the fish stocks (Kolding *et al.* 2008), and tproliferation of aquatic

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weeds such as water hyacinth and algal bloom (Njiru *et al.* 2010).

Pollution and increased eutrophication attributable to anthropogenic activities have occurred around the lake, including wetland reclamations, increased domestic and industrial waste discharges, fertilizer run-off from agricultural-based farms, and sediment transported by rivers (Lung'ayia *et al.* 2001). According to Kyomuhendo (2003), the once clear, life-filled Lake Victoria is now turning more eutrophic. Further, deteriorating water quality and other related consequences are evidenced by algal blooms, water hyacinth invasion, and emerging undesirable traits such as smaller size at maturity and egg sizes of some fish species (Ojuok & Manyala 2007). In addition to physicochemical attributes and nutrient levels, pollution impacts also manifest themselves in the occurrences, prevalence, shifts in abundance and distribution of different biota. This is especially true of plankton, microcontaminants such as *E. coli*, macrophytes and fish species.

Pollution levels in Lake Victoria are increasing. Pollutants from non-point sources (NPS) result in lower dissolved oxygen (DO) concentrations, higher nutrient concentrations and increasing turbidity (Campbell *et al.* 2004). Pollution from tanning, fish processing and abattoirs has also been reported in the rivers and streams draining to the lake. As demand for land increases because of population growth, urbanization and agricultural expansion, forests and wetlands have been cleared, leading to environmental degradation and increased sediment deposition in rivers and lakes (Ntiba *et al.* 2001). This observation suggests sediments may be an additional sink and/or source of pesticides and heavy metals.

The impact of pollution from municipal and industrial discharges is visible in some rivers draining to the lake, along its shoreline, and in areas such as the shallow Winam Gulf, near Kisumu, Kenya (Kyomuhendo 2003). Additionally, the environmental presence and extraneous enrichment of the lake with metals such as lead, cadmium, mercury, methyl mercury and chromium in different environmental media from the Lake Victoria Basin have been reported (Oyoo-Okoth *et al.* 2010; Amanda *et al.* 2012). Metal contaminants are a serious and widespread environmental problem due to their toxicity, persistence in the environment, non-biodegradability and bio-accumulation (Okuku & Peter 2012).

A general feature of Lake Victoria is the deterioration of influent water quality and poor waste disposal systems, which are likely to further exacerbate the pollution status of the lake. Assessment of these problems will contribute to the development of strategies for improved catchment management to control impacts related to the fishery. It is clear that pollution is one of the major problems facing Lake Victoria. Thus, the Lake Victoria management measures have tended to focus on fisheries, with the aim of achieving a certain quality of catch (in terms of size structure of Nile perch). More efforts at present are being put in place to manage total fishing effort or stock biomass (Van der Knaap *et al.* 2002; Njiru *et al.* 2012). Improving the quality of the fishery could facilitate better use of lake space that is in high demand, minimize the risk of environmental impacts, maximize the economic returns, and reduce conflicts with other resource users. Such initiatives would help provide a better understanding of the dynamics of the lake's complex ecosystem in allow visualization of the response scenarios likely to result from alternative management measures, and to manage human activities influencing the lake (Kolding *et al.* 2008). Thus, the aim of this study was to assess and synthesize existing information to determine the relationships between indicators of pollution and ecosystem health in Lake Victoria, Kenya with a view to enhancing its productivity.

MATERIALS AND METHODS

Study area

This study was conducted in Lake Victoria, Kenya (Fig. 1), which is situated at 1134 m above sea level. It is the second largest inland water body in Kenya after Lake Turkana, covering an area of 4100 km^2, an average depth of 6–8 m and a maximum depth of 70 m (in the open waters; Odada *et al.* 2004). The lake is monomictic, experiencing complete annual mixing from June to August. In addition, wind induces strong shear forces at the bottom of the lake and vigorous vertical mixing within the water column, especially around the Mid-gulf area (Okely *et al.* 2010; Guya 2013).

Sampling sites

The monitoring survey was conducted during 2010–2016. A global positioning system (GPS) was used to ensure the sampling sites coincided, as far as possible, with the sites from which most of the historical datasets have been obtained. A total of 21 sites were sampled for water, sediment characteristics and fisheries information (Fig. 1). Each site was sampled three times over the whole year. Figure 2 provides a schematic representation demonstrating pollution levels in Lake Victoria, Kenya. Sampling sites were delineated as C1, C2 and C3 into ecological zones using a principal component analysis

(PCA) that categorized sampling sites ($R^2 \geq 0.5$, $P < 0.05$) on the basis of pollution indicators, including nutrients, water depth and transparency, electrical conductivity and dissolved oxygen. Indicator levels were compared between zones using WHO standards to classify pollution levels.

Sampling for pollution indicators

Lake ecosystem pollution varies in form and magnitude, depending on the given indicator. Many of the non-point source pollutants (NPS) end up in the lake, where they lower the dissolved oxygen concentrations, and increase the nutrient concentrations and turbidity (Kyomuhendo 2003). Thus, *in situ* physical and chemical depth profile measurements of these response variables can provide insight into the pollutants entering the lake (Okely *et al.* 2010). Water samples were collected at every one metre depth at each sampling site, with a portable water quality meter (model WQC 24) used to measure temperature, pH, turbidity, DO concentration and conductivity. Water transparency was measured with a 20 cm black and white Secchi disc (APHA 2005).

Eutrophication is one of the major consequences of lake pollution, attributable to nutrient inflows to the lake. The most important plant nutrients (nitrogen and phosphorus) are the usual causes of nutrient enrichment problems (Campbell *et al.* 2004). Excessive in lake nitrogen and phosphorus concentrations originate from organic and inorganic fertilizers discharged from intensive agricultural activities, sewage from cities and livestock (Longgen *et al.* 2009). Water samples for nutrient analyses were collected from the lake surface using a Van Dorn water sampler, and subsequently subsampled into one-litre polyethylene bottles. Samples were preserved with 0.1 mol L^{-1} sulphuric acid before being stored in insulated boxes at a temperature of about 4 °C and transported to the laboratory. Chemical analyses for chlorophyll-*a* and dissolved nutrients were carried out with photometric methods according to APHA procedures (APHA 2005). Further, total phosphorus (TP) and

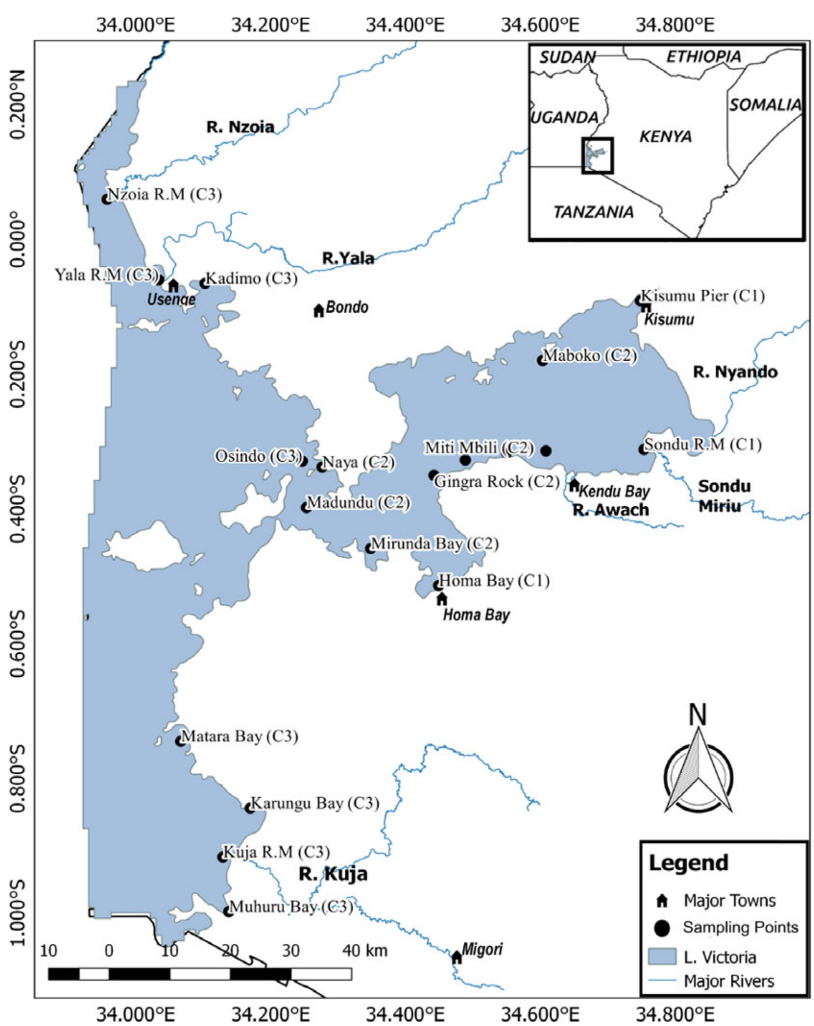

Fig. 1. Sampling sites in clustered ecological zones (C1, C2 and C3) and major towns in Lake Victoria, Kenya.

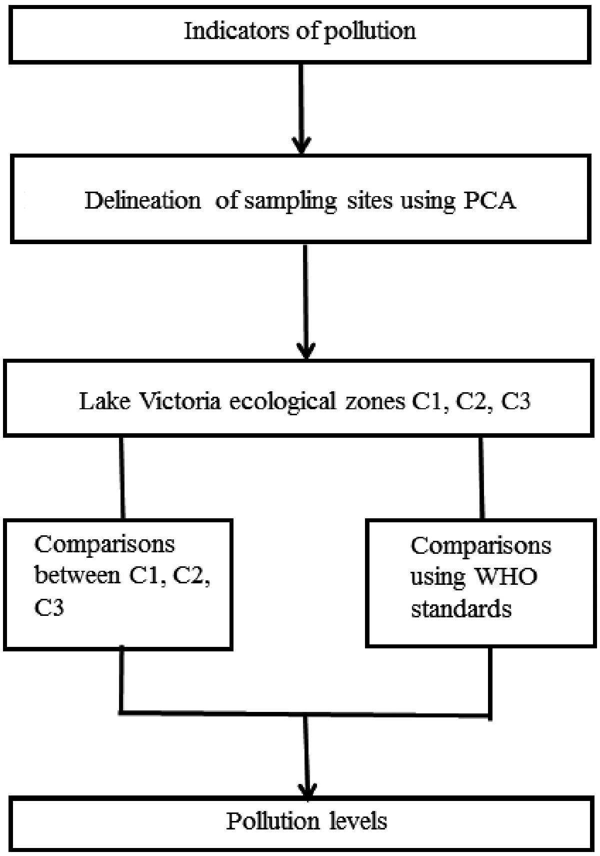

Fig. 2. Schematic representation towards demonstration of pollution levels in Lake Victoria, Kenya.

total nitrogen (TN) concentrations were also analysed according to APHA 2005.

The presence of heavy metals in the water may have a profound effect on the microalgae constituting the main food source for bivalve molluscs in all their growth stages, zooplankton (rotifers, copepods and brine shrimps), and the larval stages of some crustacean and fish species (Ramlal *et al.* 2003). Moreover, bioconcentration and magnification processes can lead to high toxicity of these metals in organisms, even under conditions of low exposure levels (Campbell *et al.* 2003). Under such conditions, the toxicity of a moderately toxic metal could be synergistically enhanced, and fish populations may decline (Ramlal *et al.* 2003). Apart from destabilising the ecosystem, the accumulation of these toxic metals in aquatic food webs is a threat to public health, and their potential long-term impacts on ecosystem integrity cannot be ignored (Mwamburi 2016). Bottom sediments were collected, and the subsamples processed and analysed for lead (Pb) and mercury (Hg) content according to AOAC (1990) procedures at the Kenya Plant Health Inspectorate Service (KEPHIS) laboratories in Nairobi, Kenya.

To identify the broader scale of lake eutrophication impacts, Landsat thematic mapper data were used to detect and identify the two most common noxious macrophytes in the lake and the optical properties of the water to determine the water compound concentrations. Discrimination of vegetation cover was carried out using Landsat 7 EMT+ images from 2010 to 2015, using a combination of supervised and unsupervised classification criteria depending on the specific characteristic of the swathes.

Phytoplankton diversity and abundance reflect lake ecosystem health and productivity (Lung'ayia *et al.* 2000). Phytoplankton are important bioindicators of heavy metal pollution in aquatic ecosystems, for example, because their capacity to eliminate them from the water, and to accumulate and store them over a long period, is high even when the concentrations in the water are low (Talling 1987). Samples for phytoplankton analysis were collected with a Van Dorn sampler, preserved with 25 mL of acidic Lugol's solution and identified to species level using the methods of Huber-Pestalozzi (1938) and Rott (1981). Additional information was gained from publications on East African lakes (e.g., Talling 1966, 1987), the checklists of Cocquyt and Vyverman (1994) and other references cited by Lung'ayia *et al.* (2000) and Sitoki *et al.* (2012).

The occurrence and structure of microorganisms such as zooplankton determine the sensitivity of a given ecosystem (Mwebaza-Ndawula 1994). On a temporal basis, they exhibit peak abundance shortly after that of phytoplankton (Frontier 1973). In strongly eutrophic ecosystems (Bozkurt & Akın 2012), the wide distribution and temporal dominance of species from the genera *Filina* and *Lepadella* indicate a lake is in a process of degradation (Frontier 1973). Samples for zooplankton analyses were collected in triplicate with a 1 m long conical-Nansen plankton net (60-μm mesh size; 0.30 m mouth diameter), which was towed vertically through the water column (Mwebaza-Ndawula 1994). In the laboratory, each zooplankton sample was made up to a known volume by the addition of water, processed according to the procedures of Mwebaza-Ndawula (1994), and identified to the lowest taxonomic level possible using published identification keys (Pennak 1953; Edmondson 1959).

Macroinvertebrates respond to changes in water chemistry, with areas of poor water quality recording lower densities than pristine environments (Mason 2002; Masese *et al.* 2009; Aura *et al.* 2010). Macroinvertebrate sampling was undertaken through sediment collection using a Ponar grab. Three replicate macroinvertebrate samples were collected at each sampling site and washed on-site using a 300-μm sieve, sorted live and then preserved in absolute ethanol. Individuals were identified in the laboratory to genus level, using keys from Merritt and Cummins (1978), with keys from the United States (US) being used on the supposition they were applicable to the study region (Raburu 2003). Macroinvertebrates were furthermore grouped into tolerance levels using existing literature (Mason 2002; Masese *et al.* 2009; Raburu *et al.* 2009; Aura *et al.* 2010).

Coliform bacteria are considered to be the main water quality indicators for domestic and industrial use, and to meet other needs (USEPA 2002). Dispersion, dilution and horizontal and vertical transport processes determine the distribution of pathogens in lakes and reservoirs. Horizontal transport is driven by inflows and basin-scale circulation patterns, including wind-driven currents and internal waves. Riverine inflows are considered the major source of pathogens (Brookes *et al.* 2004). Recent research on indicator bacteria for evaluating source water quality, water and wastewater treatment efficiency, distribution of system contamination, possible health effects and the presence or absence of pathogens, suggest the use of *E. coli* among three other indicators; namely, enterococci, coliphages and *Clostridium perfringens* (Tyagi *et al.* 2006). A membrane filtration technique was used to determine coliform levels at each sampling site, and a sterile water sampling cup was used to collect surface water. Water samples were processed and analysed according to USEPA (2002) methods.

Fish are good indicators of water quality because of their sensitivity to pollution (Mora *et al.* 2003, 2008). Estimating the number of species from a particular area remains a fundamental, but important, challenge to freshwater ecology. Species diversity is related to the functioning of ecological systems and helps elucidate the mechanisms and effects of environmental disturbances such as pollution (McGill *et al.* 2007; Tokeshi & Arakaki 2007; Mora *et al.* 2008). Estimation of species diversity is also useful for detecting trends, impacts or recovery in ecosystems, and for the quantification of extinction risks to support the prioritization of biodiversity conservation in hotspot areas (Mora *et al.* 2008). Ecological assessment of the fishing grounds in the Winam Gulf included indicators of fish stocks (i.e., species diversity and weight). Fish stock assessment was undertaken using experimental trawls, yielding a wide range of fish species and sizes. A total of 96 Nile Perch (*Lates niloticus* L.), about 33 specimen per period, were collected from the sampling sites and tested for heavy metals in their tissues. As pollutants such as mercury bioaccumulate and are known to increase with fish size, Nile perch maximum sizes of >50 cm were tested to provide robust and representative findings. A random sampling matrix technique, without replacement, was used, and the caught fish were stored in an insulated box with adequate ice. Samples were handled hygienically and protected from direct sunlight until delivered to the Kenya Plant Health Inspectorate Service (KEPHIS) laboratories in Nairobi for analysis.

Data analyses

Data were examined with descriptive statistics and visualized with graphs. The data were tested for homogeneity before being subjected to inferential statistics. A principal component analysis (PCA) categorized sampling sites into ecological zones based on their physical and chemical attributes ($R^2 \geq 0.5$, $P < 0.05$). Clusters of sites were presumed to have different levels of pollution, and comparisons were made using ranges, WHO standards, and ANOVA, followed by *post hoc* tests to separate the means. Phytoplankton biovolume and zooplankton densities were calculated on the basis of methods of Frontier (1973) and Sitoki *et al.* (2012). Macroinvertebrate relative proportions and the Shannon-Weiner diversity index were determined according to methods developed by Aura *et al.* (2010). Relationships between fish distribution and abundance, and physical and chemical variables were determined using Pearson correlation.

RESULTS

Figure 3 illustrates a PCA with sampling sites delineated ($R^2 \geq 0.5$, $P < 0.05$) into ecological zones (C1, C2 and C3) on the basis of their physical and chemical parameters. Ecological zones C1, C2 and C3 corresponded to the inner gulf, mid-gulf and open lake, respectively. Inner gulf and mid-gulf constitute the Winam Gulf (also known as Nyanza Gulf). Bridge Island emerged as an outlier.

Physical-chemical parameters

Mean values of some of the measured physical and chemical parameters are provided in Table 1. Mean Secchi depth values were lowest in C1 (0.25 m) in 2012 and highest in C3 (3.5 m) in 2013. The lowest Secchi depth value (0.2 m) was observed at Kisumu Pier in C1 in 2015, with the highest value (3.5 m) observed at Gingra Rock in C3, also in 2015. The mean turbidity was lowest (14.3 NTU) in C3 in 2013, and highest in C1 (111.1 NTU) in 2015. Mean turbidity values were only available for 2013 and 2015, ranging from 8.3 NTU in C3 in 2015, to 111.1 NTU, with a maximum of 498 in C1, also in 2015.

The lowest mean chlorophyll-*a* concentrations were observed in C3 (11.8 μg L^{-1}) in 2013, and the highest

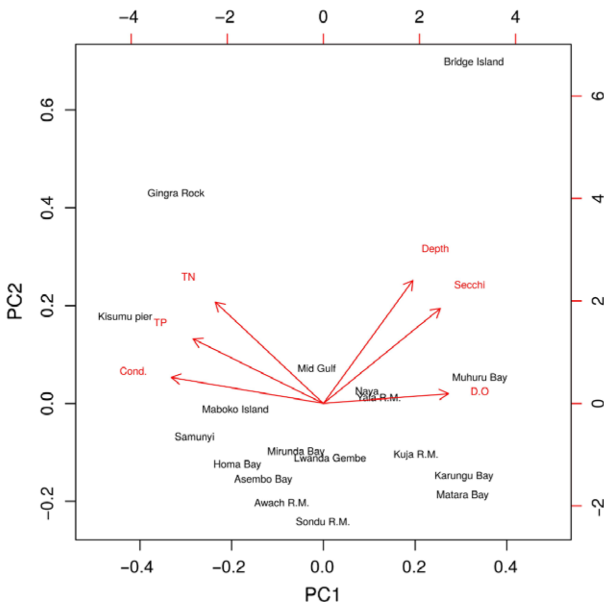

Fig. 3. Principal component analysis (PCA) showing ecological zones (C1, C2 and C3) delineated on basis of strong and significant correlation ($R^2 \leq 0.50$, $P < 0.05$) of sampling sites with key physical and chemical parameters (i.e., dissolved oxygen (D.O.), electrical conductivity (Cond.), Secchi depth, total nitrogen (TN), total phosphorus (TP)); the most prominent sites per cluster were included in the analyse; Cluster 1 (C1 sites: Kisumu Pier, Lwanda Gembe, Sondu River Mouth, Homa Bay, Samunyi); Cluster 2 (C2 sites: Maboko, Miti Mbili, Mid-gulf, Gingra Rock, Naya, Mirunda Bay, Madundu); and, Cluster 3 (C3 sites: Open Lake stations at Muhuru Bay, Karungu Bay, Matara Bay, Kuja River Mouth, Nzoia River Mouth and Yala River Mouth; Bridge Island emerged as outlier site).

values in C1 in 2012 (66.7 μg L^{-1}). Mean dissolved oxygen (DO) concentrations during the surveys ranged from 5.1 mg L^{-1} in C2 in 2013, to 7.6 mg L^{-1} in C3 in 2012. The highest DO value of 11.2 mg L^{-1} was recorded in C1 and C3 in 2012 and 2013, respectively. However, low DO values of 3.1 and 3.5 mg L^{-1} were measured in the bottom waters of C2 and C1, respectively, in 2013. The DO concentrations exhibited significant correlations with pH (0.991, $P < 0.001$) and turbidity (0.984, $P < 0.001$).

Mean electrical conductivity values were at their lowest in C3 (98 μS cm^{-1}) in 2013, and highest in C2 (174.6 μS cm^{-1}) in 2015. The highest value of 210 μS cm^{-1} occurred at Kisumu Pier in 2015 in C2. The total nitrogen (TN) concentrations for 2015 were lowest in C3 (856.9 μg L^{-1}), and highest in C2 (2391.45 μg L^{-1}). The 2013 observations varied between 204.2 μg L^{-1} in C3 and 2349.6 μg L^{-1} in C1. The TN concentrations in 2012 ranged between 482.8 μg L^{-1} in C3 and 2496.6 μg L^{-1} in C1. The total phosphorus (TP) concentrations during the study period varied between 29.1 μg L^{-1} at Mbita in C3 and 244.9 μg L^{-1} at Gingra Rock in C2, with a mean value of 95.5 μg L^{-1}. The TP concentrations in 2013 ranged between 26.3 μg L^{-1} in C3 and 192.0 μg L^{-1} in C2, with a mean value of 92.7 μg L^{-1}. The observed concentrations in 2012 ranged from 52.3 μg L^{-1} in C3 to 322.3 μg L^{-1} in C2, with a mean value of 172.7 μg L^{-1}. The TN concentrations were significantly correlated with conductivity (0.565, $P < 0.001$) and TP concentrations (0.538, $P < 0.001$).

Heavy metals

Mean concentrations of priority toxic metals (i.e., lead (Pb) and mercury (Hg)) in sediments varied among the years 2012, 2013 and 2015, and among the lake cluster zones (Fig. 4a,b). Mean values recorded in 2012 were higher than in the remaining years, especially in C1, where the mean Pb concentration (106.93 $\pm$ 64.16 μg g^{-1} DW) was observed. Lead concentrations fluctuated across years in all the clusters. C3 appeared to exhibit the least toxic metal residues in all the years. Mercury (Hg) concentrations recorded in 2015 were lower than all the previous years, suggesting a reduced availability of metals in the sediments in recent years. Heavy metal levels in Nile perch tissues showed that Hg level was highest in C2 (0.41 mg kg^{-1}) and lowest in C1 (0.15 mg kg^{-1}; Fig. 4c). Pb level was also highest in C2 (0.15 mg kg^{-1}) and lowest in C3 (0.08 mg kg^{-1}).

Mapped turbidity, algae and water hyacinth occurrence

The lake waters were most turbid in 2012, coinciding with the highest algal concentrations. They were less turbid in 2013. Higher turbidity levels and algae were recorded in C1 and C2 (Winam Gulf, showed in red), compared to the open lake waters (C3; Fig. 5).

Plankton

The phytoplankton biovolume was generally low (<20 mm^3 L^{-1}) at many sites within C1, but increased progressively in C2 and C3 (Fig. 6a). Lower biovolume values (<7 mm^3 L^{-1}) were generally observed at sites within C1 and C2, where dinoflagellates were more common and accounted for the increased biovolume. This taxon was represented mainly by *Ceratium branchyceros.* The Zygnematophyceae family was represented by *Cosmarium* and *Staurastrum* taxa, with the former frequently observed in C1 and C2, and the latter in C3. Diatoms were the dominant group, contributing an average of about 55% to the total phytoplankton biovolume at most

Table 1. Mean values (and maximum values in brackets) of physical–chemical parameters in different cluster zones (C1, C2, C3) of the study area (missing values were due to lack of sampling alongside WHO water quality standards; WHO standards for TN and TP are still in a formulation process; USEPA, 2002)

	2012			2013			2015			
Cluster	C1	C2	C3	C1	C2	C3	C1	C2	C3	WHO limits
Secchi (m)	0.25 (0.4)	0.31 (0.9)	2.4 (3.2)	0.4 (0.6)	0.5 (1.2)	1.6 (3.5)	0.3 (0.6)	0.4 (0.9)	1.31 (1.7)	>0.85
Turbidity (NTU)	–	–	–	80.8 (165)	80.3 (350)	14.3 (70)	111.1 (498)	52.7 (199)	8.3 (71)	100
Chla (μg L^{-1})	66.7 (104)	41.9 (92)	29.3 (40)	20.9 (29)	13.9 (39)	11.8 (31)				N/A
DO (mg L^{-1})	7.2 (11.2)	6.5 (9.1)	7.6 (11.2)	7.2 (7.2)	5.1 (7.9)	5.3 (9)	6.34 (7)	7.3 (8.5)	7 (8.2)	≥2.0
Cond. (μS cm^{-1})	150 (200)	153 (230)	112.4 (180)	153.3 (284)	142 (164)	98 (123)	168.3 (210)	174.6 (198)	135.8 (150)	225
TN (μg L^{-1})	1230.71 (2496.60)	1987.30 (2011.35)	834.38 (482.8)	1512.57 (2349.60)	1161.22 (2132.35)	309.41 (204.20)	1092.82 (1260.55)	1391.76 (2391.45)	809.564 (856.9)	
TP (μg L^{-1})	209.70 (158)	177.21 (322.30)	113.0 (52.3)	153.10 (187.0)	89.0 (192.0)	66.0 (26.3)	100.21 (132)	123.69 (244.857)	56 (74.86)	

sites. There were fewer diatoms in C1 and C2, which were dominated mainly by *Aulacoseira* sp. and *Cyclotella* sp., while *Nitzschia* sp. and *Synedra* sp. were the more abundant taxa in C3. *Microcystis* spp. and *Anabaena* spp. were the most abundant taxa, constituting >90% of the cynobacterial biovolume in all clusters.

Zooplankton densities ranged from 74.3 ± 5.5 to 445.4 ± 39.4 individuals L^{-1}, with the highest densities in 2010 recorded in C1 at Samunyi River mouth (445.4 ± 39.4 ind L^{-1}) followed by Kisumu Pier (336.1 ± 29.9 individuals L^{-1}) and Awach River mouth (235.9 ± 25.6 individuals L^{-1}; Fig. 6b). The other sampling sites exhibiting relatively high densities were Oluch River mouth (146.5 ± 14.9 individuals L^{-1}) in C1 and Maboko (132.5 ± 11.4 individuals L^{-1}) in C2.

The observed density of phytoplankton was strongly and inversely correlated with zooplankton (Fig. 6c). The concentration of phytoplankton increased from C1 to C2 to C3, with the reverse being true for zooplankton.

Macroinvertebrates

A total of nine orders of macroinvertebrates, furthermore grouped into seventeen families and twenty genera, were recorded during the study period (Table 2). Macroinvertebrates were dominated by molluscs (72.6%), with Veneroida accounting for 47.8%, Pulmonata 23% and Unionoida 1.8%. The highest number of genera was recorded at C3, around Mbita, while the lowest number of genera was recorded at C2 at Miti Mbili. The Shannon-Weiner diversity index was highest at C3 (2.15), and lowest at C2 (0.23). The evenness index was generally above 0.5, except for the Yala River mouth (0.44) in C3 and Lwanda Gembe (0.48) in C1. During the survey period, the majority of the observed benthic macroinvertebrates (78%) were pollution tolerant. Semitolerant taxa accounted for 17%, with sensitive taxa accounting for only 5%.

Total and faecal coliforms

The highest average total coliform count (1937.78 ± 94 cfu 100 mL^{-1}) was recorded in C1, in 2010 (Fig. 7a). The greatest contributors to this count were sites off Ndere Island (7800 cfu 100 mL^{-1}) and beside Kisumu pier (6166 cfu 100 mL^{-1}). Cluster C2 also recorded high mean count of total coliforms (1818.8 ± 102 cfu 100 mL^{-1}), while cluster zone C3 exhibited the lowest counts throughout the sampling period.

Faecal coliforms counts were highest at C2 (390 ± 21 cfu 100 mL^{-1}) in 2012, with the highest contribution being recorded at Gingra Rock (5100 cfu 100 mL^{-1}; Fig. 7b). Lower counts were recorded in 2013,

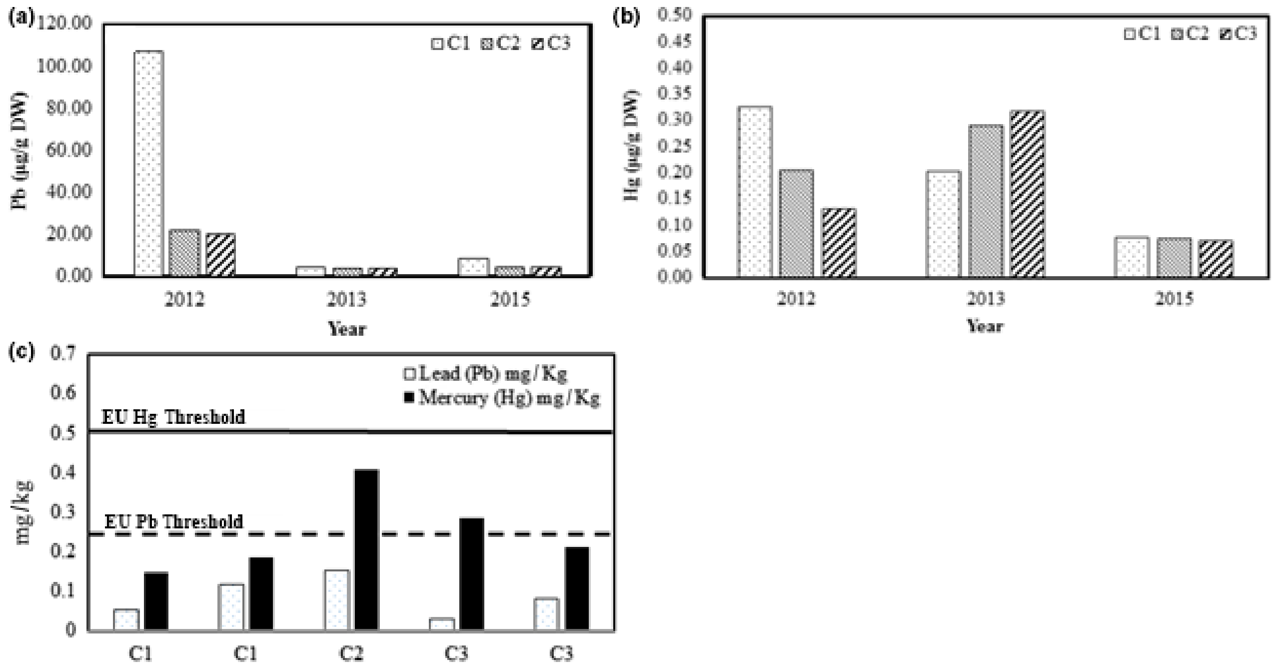

Fig. 4. Concentrations of priority toxic metals at clustered sites C1–C3. (a) average lead (Pb) concentrations in sediments; (b) average mercury (Hg) concentrations in sediments; and (c) comparisons of Pb and Hg concentrations in Nile perch tissues (solid and broken lines represent European Union (EU) thresholds for Hg and Pb, respectively).

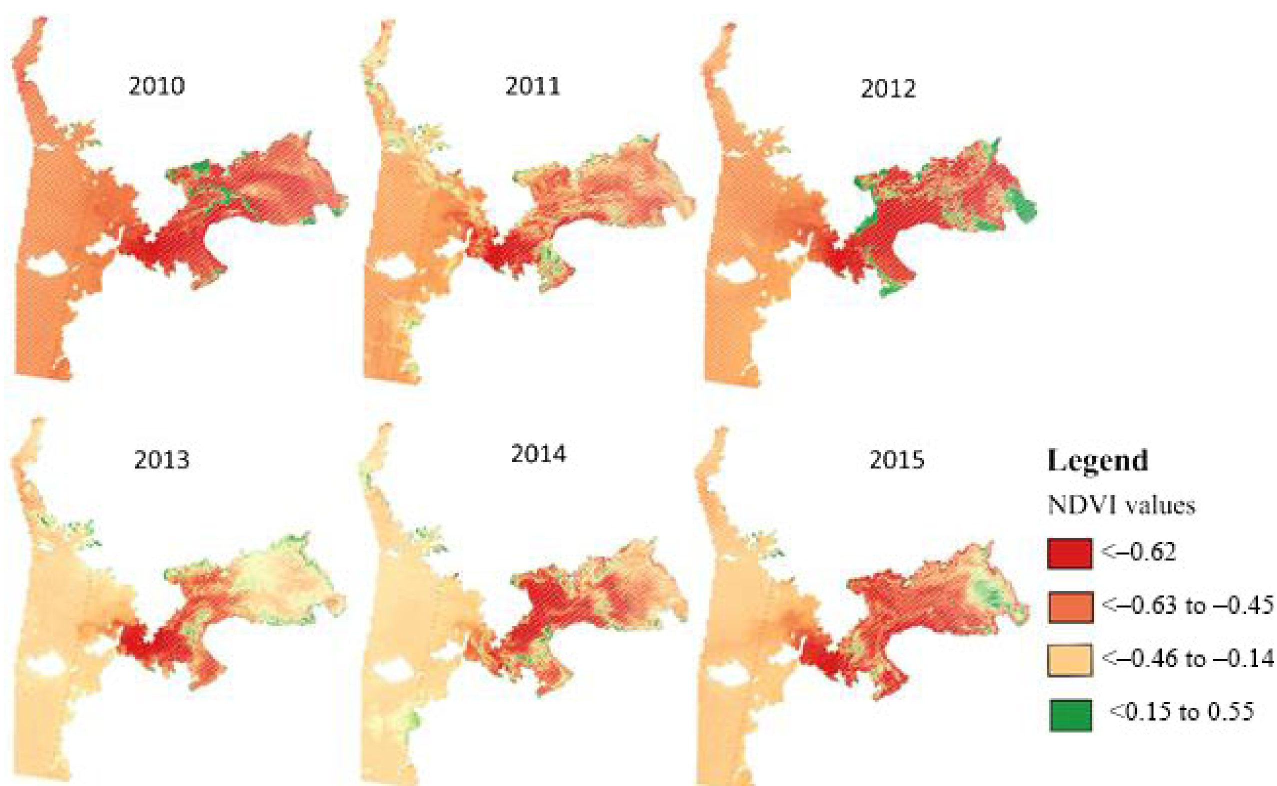

Fig. 5. Maps showing changes in turbidity, algal bloom and water hyacinth distributions over time in Kenyan part of Lake Victoria.

with cluster zone C3 having the lowest faecal coliforms throughout the sampling period.

Fisheries trends

The fish species richness was highest in C2 in 2016 (13 spp.) and lowest in C3 in 2012 and 2016 (8 spp.; Fig. 8). Catfishes (*S. victoriae*; *C. gariepinus*) were dominant in C2, whereas *L. niloticus* was dominant in C3. *L. niloticus*, *C. gariepinus*, *S. victoriae* and Haplochromines formed the bulk of the biomass in C2. The observed biomass levels in 2012 were generally higher than in 2015.

The interrelationships among physical and chemical parameters, and their influence on the distribution/abundance of different fish species, are illustrated in Figure 9. There was a strong correlation ($R^2 \geq 0.5$) between DO and TN, faecal coliforms, and the distributions of *S. victoriae*, *B. Sadieri* and *P. aethiopicus*. Although Secchi depth (transparency) was negatively correlated with electrical conductivity, neither exhibited a significant relationship with other parameters. The total phosphorus (TP) concentration was strongly correlated with *C. gariepinus*, *B. sadieri* and *S. intermedius*.

DISCUSSION

Several factors may contribute to determining temporal and spatial patterns observed regarding the measured physical and chemical parameters, and aid in explaining the variations among different localities, sampling periods and clusters of sampling sites within the Winam Gulf and the open lake. PCA revealed three clusters of sites from the relationship among physical and chemical parameters and sampling sites. These were C1 and C2 (inner and mid-gulfs) and C3 (open lake). These clusters probably reflect different processes acting synergistically to produce different environments within each cluster. The differences observed also influence the species composition and abundance of the aquatic organisms in each cluster, including the plankton and macroinvertebrates, which, in turn, influence the fish trends and lake productivity. The spatial and ecological separations of different parts of the lake seem to have been maintained for a long time (Talling 1966, 1987; Lung'ayia *et al.* 2000), although some marked changes have become apparent in recent decades, and appear to be linked to increased pollution levels.

As indicated by the data, the pattern of change in Lake Victoria's physical and chemical parameters is

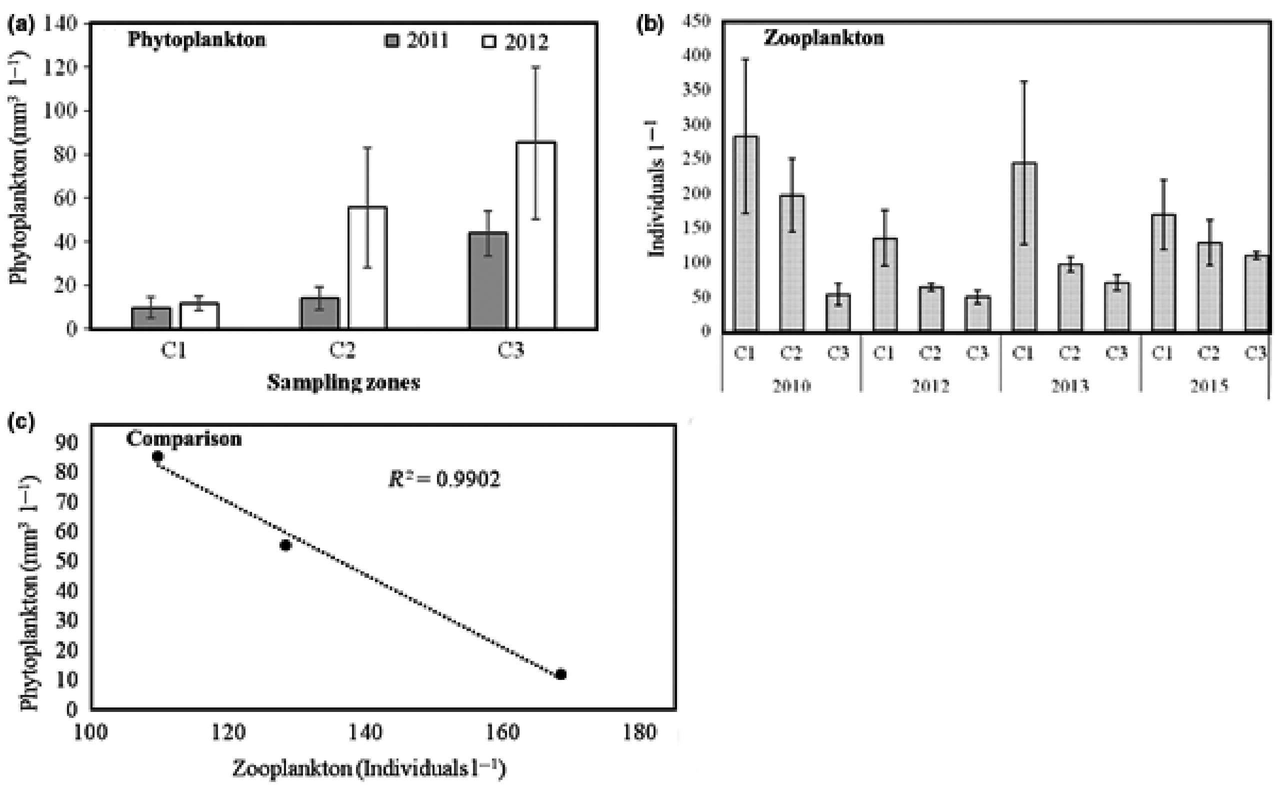

Fig. 6. Plankton concentrations in Lake Victoria Kenyan waters in terms of (a) phytoplankton, (b) zooplankton and (c) relationship between phytoplankton and zooplankton.

Table 2. Sampled macroinvertebrates of Lake Victoria, Kenya in 2012–2015 and their pollution indicator tolerance types

Order	Family	Genera	Common Name	Tolerance	Score
Diptera	Chironomidae	*Chironomus*	Midge fly	Tolerant	2
	Ceratopogonidae	*Palpomyia*	Biting midges	Tolerant	5
	Culicidae	*Culicines*		Tolerant	3
		Aedes		Tolerant	3
		Anopheles		Tolerant	3
Ephemeroptera	Baetidae	*Baetis*	Minnow Mayfly	Tolerant	4
	Ephemerriidae	*Hexagenia*	Burrowing Mfly	Semi tolerant	8
Hemiptera	Belostomatidae	*Limnogeton*		Tolerant	4
Oligochaeta	Naididae	*Tubifex*	Sludge worms	Tolerant	2
Pulmonata	Lymnaeiidae	*Lymnae*	Pond snails	Tolerant	3
	Physisdae	*Physa*	Pouch snails	Tolerant	4
	Planorbiidae	*Biomphalaria*		Tolerant	4
		Bulinus		Tolerant	5
	Thiaridae	*Melanoides*	Thiariid shells	Tolerant	4
Rhynchobdellida	Glossophonidae	*Glossophonia*	Leech	Tolerant	3
Trichoptera	Hydropsychidae	*Hydropsyche*		Sensitive	11
	Rhynchoptilidae	*Rhynchoptila*		Semi-tolerant	8
	Leptoceridae	*Leptocerus*		Semi-tolerant	9
Unionoida	Unionidae	*Anadonta*	Pearly Mussels	Semi-tolerant	7
Veneroida	Sphaeriidae	*Sphaerium*	Pill Clams	Tolerant	5
9	17	20			

extremely variable and unpredictable across sampling sites. This may be attributable to the shallow mean depth and landscape context of the Kenyan part of the lake, which is strongly influenced by extremely variability in seasonal/diurnal wind patterns and shear (Okely *et al.* 2010). Run-off from agricultural land, inputs of industrial effluent, the relatively urban setting, and the nature of its inflows also combine with natural processes to generate these patterns. Bottom sediments are frequently resuspended by the winds, with nutrients associated with these particles being remineralized during this process, thereby comprising the majority of the significantly correlated variables. Pollution inputs from soils and sediments, mainly from catchment run-off, as well as shoreline erosion, resuspension of bottom sediments by waves and currents, and a range of human activities (Mwamburi 2016) may have resulted in the high turbidity, low transparency and excessive concentrations of TN and TP that have produced high phytoplankton productivity in zones C1 and C2 of the Winam Gulf, compared to C3 in the open lake. This pattern is also exhibited by the high chlorophyll-*a* concentrations at sites in C1 and C2, compared to C3.

The dissolved oxygen (DO) concentrations were relatively high, which can be explained by the high primary productivity resulting from eutrophication and vigorous local mixing of the water body, mainly in C1 and C2 of the Winam Gulf. The average DO values observed in the present study ranged from 5.1 to 7.6 mg L^{-1} in C3, with a maximum of 11.2 mg L^{-1}, being similar to previously recorded measurements in the same areas, which ranged from 6 to 11 mg L^{-1} (Lung'ayia *et al.* 2001). Slightly lower DO levels (3 mg L^{-1}) were observed in the bottom waters at some localities within C1 and C2, probably attributable to microbial decomposition of dead organic matter derived from plankton and macrophytes. The DO levels were generally within the permissible WHO levels ($\geq$2.0 mg L^{-1}) for fisheries (Table 1).

Electrical conductivity, TN and TP levels were higher in the shallow waters of C1 and moderate in C2 in the mid-gulf, possibly attributable to inputs of minerals resulting from weathering processes, erosion from increasingly cultivated land, remineralization from resuspended bottom sediments and anthropogenic activity (Mwamburi 2016). These factors greatly stimulate phytoplankton productivity, resulting in higher chlorophyll-*a* levels within the Gulf than in C3 (open lake; Ochumba 1990). The electrical conductivity levels were within the permissible WHO levels for fisheries (Table 1).

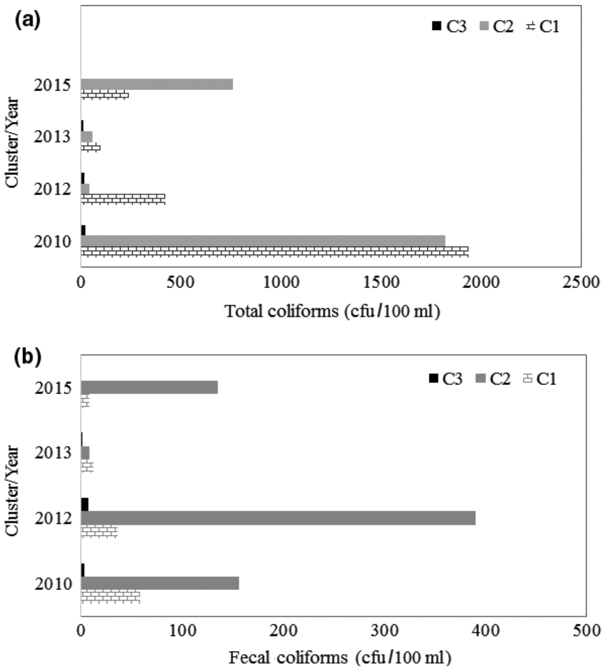

Fig. 7. Concentrations of (a) Total coliforms and (b) Faecal coliforms in cluster zones C1-C3 of Lake Victoria, Kenya.

A fluctuating pattern of lead (Pb) concentrations in sediments across the years emerged suggesting different phases of enrichment and water column remobilization or bioavailability (Ramlal *et al.* 2003). C3 generally exhibited the lowest Pb and Hg concentrations in the sediments, an indicator of more pollution stress within the inner gulf waters and Homa Bay (C1) than in the open waters (C3; Campbell *et al.* 2003; KMFRI 2011). Further, on average, the maximum residue limits (MRLs) for Pb and Hg were 0.14 and 0.25 μg g^{-1} DW, respectively. The Pb and Hg levels in the tissues of Nile perch, the dominant fish species in the lake, were found to be compliant with European Union (EU) food safety standards (Commission Regulation (EC) No 1881/2006) and global market requirements that allow export of Nile perch from Lake Victoria.

Increased turbidity levels and macrophytes in the inland waters of the lake were likely related to the high concentration of parameters like total suspended solids and chlorophyll-*a* (Fig. 5; Lung'ayia *et al.* 2001). Increased turbidity and algal levels in Winam Gulf (C1 and C2) validated the declining ecological integrity of the zone, as indicated by its physical–chemical characteristics.

The phytoplankton composition and abundance fluctuated between a dominance of diatoms and cyanobacteria in Winam Gulf and open waters. The occurrence of high cyanobacteria levels in C1 has remained consistent for several years (Njiru *et al.* 2012), resulting in frequent incidences of surface algal blooms. Diatoms dominate the open waters, contributing to increased biovolume values. The enhanced trophic status (nutrient enrichment) of the lake waters, coincident with the occurrence of phytoplankton pollution indicator species (*Microcystis* spp.), significantly influences the lake's pollution status. The phytoplankton density varied inversely with zooplankton density between Winam Gulf and the open waters. The observed trends reflect the strong grazing pressure exerted on the phytoplankton by the zooplankton. It has been suggested that a moderate mix of phytoplankton and zooplankton, as found within the intermediate trophic conditions in C2, provide favourable conditions for fisheries production (Lung'ayia *et al.* 2000).

The macroinvertebrate abundance per unit area for the sampling period was generally low, which is usually an indicator of unfavourable pollution levels within a lake ecosystem. Aquatic ecosystems usually have diversity indices of between 1.5 and 3.5. For the sampled sites, however, only C3 fell within this range (Mason 2002), indicating the higher pollution status of Winam Gulf (C1 and C2), compared to the open waters (C3). The high relative abundance of pollution-tolerant macroinvertebrate taxa (78%) indicated the lake is exhibiting poor ecosystem health. Previous studies by Raburu *et al.* (2009), Masese *et al.* (2009), Aura *et al.* (2010) and Orwa *et al.* (2013) attributed dominance of tolerant taxa to human disturbance and pollution in the lake basin.

Although there is no clear trend in the total and faecal coliform levels, sampling sites such as Kisumu Pier and Homa Bay in the Winam Gulf, exhibiting high faecal coliform levels, compared to the other sites, are located in areas affected by urban sewage and industrial effluents (Odada *et al.* 2004), consistent with previous studies by Kotut *et al.* (2011), who reported Homa Bay household faecal coliform levels of 3.0×10^3 to 7.4×10^5 cfu 100 mL^{-1}, which end up in the lake in most cases. These values exceed WHO limits for irrigation (1000 cfu 100 mL^{-1}) or domestic use (0.0 cfu 100 mL^{-1}; WHO 1997). Higher faecal indicator counts were recorded at Kisumu Pier from 2010 to 2013, possibly attributable to the discharge of raw sewage from Kisat Sewage Treatment Plant, which between 2010 and 2014, was not functioning at full capacity due to a poor state of repair (Werimo pers. comm.). The total coliform count decreased from 7800 cfu 100 mL^{-1} in 2010 to 2100 cfu 100 mL^{-1} in 2015, likely attributable to subsequent repair of the Kisat Sewage Treatment Plant within the Lake Victoria Environmental Management Project II (LVEMP II) during 2014, and subsequent reduced inputs of sewage into the lake. In the previous 2013 survey, the faecal coliforms levels in Homa Bay were 120 cfu 100 mL^{-1}, compared to the high values up to 2300 cfu 100 mL^{-1} observed in this study, which is a possible indication of human and non-human sources of faecal coliform bacteria in urban watersheds subsequently leading to increased faecal coliform levels. The open waters had detectable levels of both total and faecal coliforms in previous years. In contrast, open water faecal contamination seemed to be diminishing over the last 4 years, possibly attributable to the different sampling seasons during the surveys, with high coliform levels usually observed during the rainy season (WHO 1997).

The Kenyan Government, through LVEMP II, has been involved in reducing the pollution load to the lake to make the water suitable for domestic and other uses. There are still challenges, however, to reducing point source pollution along the shoreline. Faecal matter from expanding unplanned settlements in Kisumu and Homa Bay towns, for example, with pit latrines and septic tanks not connected to sewer lines, sometimes overflow and their discharges end up in the lake (Werimo, pers. comm.).

A declining fish abundance observed during this study could be attributable to either overexploitation or deteriorating water quality resulting from increased pollution and eutrophication (Onyango 2000, 2004). Such findings should be viewed with caution, however, because the combined use of mid-water and bottom-water trawls could help confirm such a finding. There was a difference in species dominance between turbid and eutrophic waters and clearer waters (Figs 5, 9). Bottom-dwelling fish (*C. gariepinus*; *S. victoriae*; *B. docmak*; *P. aethiopicus*; *S. intermedius*) were prevalent in the Winam Gulf, which was characterized by relatively low DO levels, and high

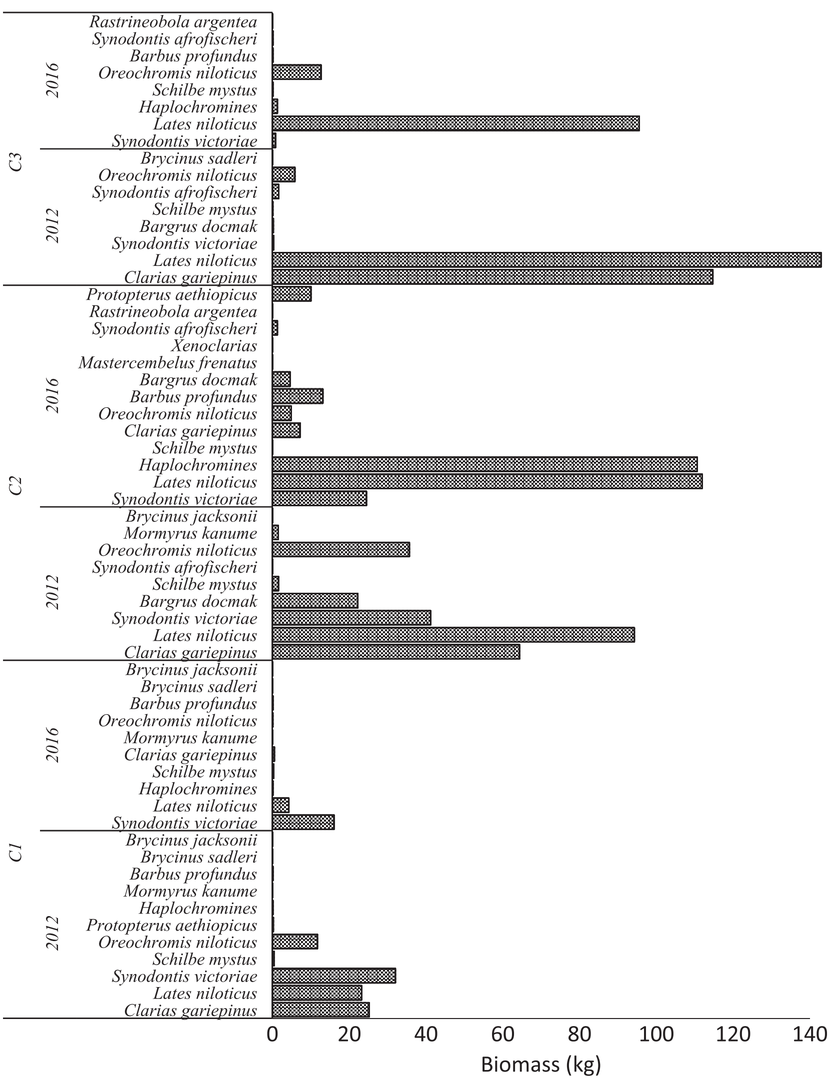

Fig. 8. Fish biomass and dominancy in clustered ecological zones (C1, C2 and C3) of Lake Victoria, Kenya.

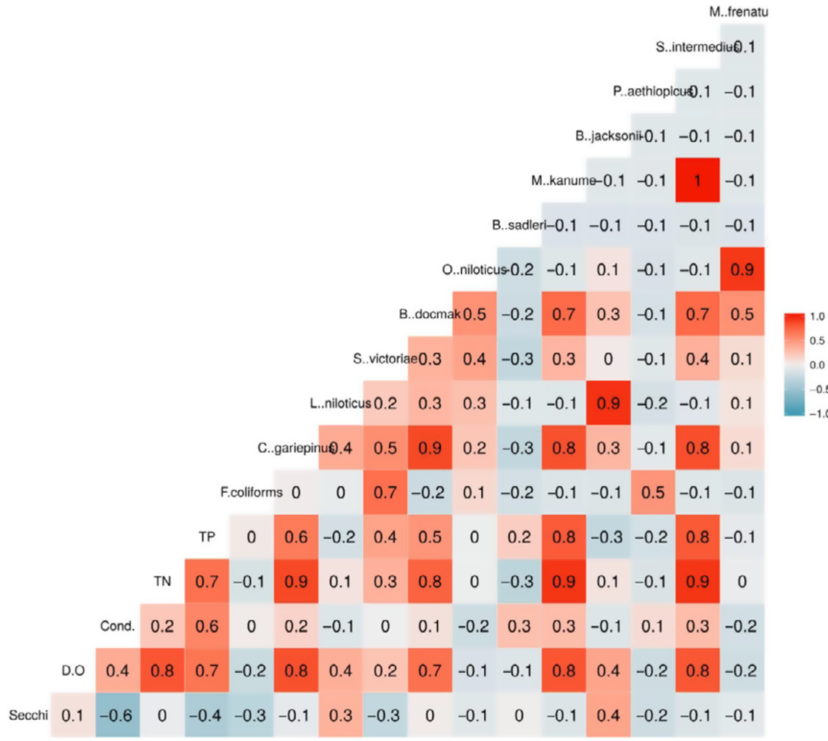

Fig. 9. Correlations between key physical and chemical indicators of pollution and fish abundance (significance difference was at $R^2 \geq 0.5$, and $P < 0.05$; numbers represent correlation coefficient values).

TN, TP, turbidity and faecal coliforms levels. Dominance of most bottom fish species (e.g., catfish) at any given locality is generally used as an indicator of poor water quality (e.g., Ogutu-Ohwayo & Balirwa 2006). Thus, the results of the present study suggest the ecological integrity of Winam Gulf is probably declining, compared to the open waters of Lake Victoria within Kenya.

CONCLUSIONS AND RECOMMENDATIONS

Cluster zones C1 and C2 (Winam Gulf) showed deteriorated water quality levels and thus appear to be more polluted than the open lake (C3). High total and faecal coliforms due to urban sewage and industrial effluents, for example, exceeded WHO standards. Faecal coliforms and DO influenced the abundance of pollution-tolerant fish species (e.g., *S. victoriae*) in the lake. Further, Winam Gulf had higher TP, TN, turbidity, conductivity and zooplankton densities than the open lake. Additionally, the lowest phytoplankton biovolumes, number of macroinvertebrates genera and tolerant catfish (e.g., *Schilbe victoriae*; *Clarias gariepinus*) were observed in C1 and C2 (Winam Gulf) than in the open lake.

The present study indicated a declining trend of ecological integrity within the Winam Gulf, compared to the nearby open waters of Lake Victoria. Thus, a series of policy and management measures to address the serious pollution issues of Lake Victoria, Kenya, is recommended, including: (i) continuation of regular monitoring of the Lake Victoria environment and fisheries resources, with a special focus on contaminant sources, their fate and their implications for the ecosystem health of Lake Victoria; (ii) community engagement seminars on catchment protection areas; and (iii) proper and integrated management of the watershed/catchment in order to reduce inputs of sediments, mineral ions and nutrient/pollutants. Lessons learned would be applicable to water quality management in other areas. To address these challenges, multifaceted strategies and approaches are required. There is a need to strengthen institutions, build the capacity of local communities and involve all stakeholders in the implementation of evidence-based strategies for sustainable environmental and natural resource management directed to improving the health of the Lake Victoria ecosystem.

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