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CHAPTER 6

Eutrophication of the Lake Victoria Ecosystem

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ABSTRACT. *Between 2000 and 2005 water quality and limnological studies were carried out in Lake Victoria in order to establish the eutrophication effects on ecosystem health. Comparison between littoral and pelagic areas of the lake showed marked spatial and temporal differences between and within the zones.*

Nitrate nitrogen (NO_3-N) and phosphate phosphorus (PO_4-P) concentrations ranged between 16.2 - 87.9 µg/l and 39.6 - 92 µg/l respectively and were both higher in the northeast. Silica (SiO_2-Si) concentrations ranged between 0.525 and 0.902 mg/l and the values were higher in the northeast and southwest compared to mid-lake stations. Nyanza Gulf had lower PO_4-P concentrations (16.2 to 21.1µg/l) than the Mwanza and Napoleon Gulfs (54.8 to 68.7µg/l) but registered higher SiO_2-Si concentrations (4.5 to 5.2 mg/l) than the other two gulfs. NO_3-N concentration in the gulfs ranged between 25 and 93 µg/l with Napoleon Gulf having higher values than the other two gulfs. Total phosphorus (TP) in the pelagic waters ranged between 0.078 and 0.10 mg/l and total nitrogen (TN) ranged between 0.53 and 0.83 mg/l. The TN:TP ratio (<20) in the main lake indicated that phytoplankton growth in the lake may be nitrogen-deficient; a situation favoring dominance of nitrogen fixing Cyanobacteria. This low TN:TP ratio is probably associated with the increased phosphorus loading and selective nitrogen loss through denitrification aqs well as enhanced recycling of P associated with increased anoxic conditions in the deep pelagic waters. Comparison with Talling's 1961 values, SiO_2-Si concentrations in the lake have generally decreased by a factor of 3 and up to 8 at the Talling's historical station of Bugaia (UP2). Chlorophyll a concentrations in the pelagic areas ranged between 3.6 and 11.7 µg/l and were generally higher in the littoral than to the pelagic *areas. The phytoplankton community was dominated by Cyanobacteria (>50%) especially the species Microcystis, Anabaena and Cylindrospermopsis in both the littoral and pelagic waters. Relatively high diatom biomass was recorded in the pelagic compared to the littoral areas, but Aulacoseira (Melosira), the formally dominant diatom species was rarely encountered. Compared to previous records, the invertebrate community composition has remained relatively stable despite drastic changes in water quality and fish stocks, but changes in abundance were evident. Zooplankton densities were generally higher in the littoral than pelagic zones. The abundance of Caridina nilotica, lake fly larvae, and other invertebrates have increased in the lake with the decline of haplochromine stocks. Comparison of present zooplankton density estimates with previous records indicates no marked differences in abundance patterns over the past 15 years suggesting a stable and dependable resource to sustain water quality and fishery-related functions. The OECD indicators of trophic status indicate that the pelagic waters range from mesotrophic to eutrophic and the littoral zones are hypertrophic.*

In order to stem further deterioration of lake water quality, management of phosphorus loading into the lake should be given urgent priority.

INTRODUCTION

Eutrophication is an alteration of the production cycle of the lake ecosystem due to enrichment by nutrients (particularly nitrogen and phosphorus). It leads to excessive growth of algae or macrophytes affecting seriously the water quality (e.g. low oxygen content, high turbidity, toxic algae, release of toxic gases from the sediments such as hydrogen sulphide etc). These changes favour the most robust algal and animal species whilst the more sensitive ones may disappear, and the changes interfere with various beneficial uses of water.

Until about mid twentieth century, eutrophication had not been recognized as a pollution problem world wide. Since then, eutrophic conditions have happened in many parts of the world including Lake Victoria (Hecky 1993). More aquatic scientists now have the insight to recognize that human activity including urbanization, deforestation, intense cultivation, animal husbandry, introduction of exotic fish species and overfishing, can accelerate the rate of nutrient inputs and cycling, resulting in changes in the physical, chemical and biological properties of a large water body such as Lake Victoria (Bugenyi and Balirwa 1989, Ogutu-Ohwayo 1990, Hecky 1993, Hecky *et al* 1994, 1996, Lipiatou et al. 1996, Mugidde 1993). Increasing human population and all their associated activities have accelerated the rate of delivery of nutrients and caused eutrophication of Lake Victoria (Chapter 7 Nutrient Loading; Hecky 1993; Lipiatou *et.al*, 1996; Verschuren 2002).

During the last 4 decades, Lake Victoria has undergone major water quality and biological changes. The introduction in the 1950s and early 1960s of the exotic Nile Perch (*Lates niloticus*) and Nile tilapia (*Oreochromis niloticus*) has led to dramatic loss of many native cichlid species (Witte et al 1992). The phytoplankton species composition in the lake has changed from one dominated by large diatoms, mainly *Melosira* and *Stephanodiscus* (Talling 1966) to that presently dominated by Cyanobacteria (blue green algae) (Ochumaba and Kibaara 1989; Mugidde 1993; Lung'aiya et al 2000; Kling et al 2001) and primary productivity and chlorophyll have increased 2-fold and 8 to 10-fold respectively (Mugidde 1992, 1993; Chapter 5). Other reported changes to the lake are decline in the euphotic zone depth, more thermally stable water column leading to more persistent hypoxic deep waters, a decrease in soluble reactive silicon (DRSi) and an increase in soluble reactive phosphorus (SRP) and total phosphorus (TP) in the water column (Chapter 5; Hecky 1993; Lehman and Branstrator 1993). However, prior to the LVEMP, the studies that identified these changes were limited in spatial and temporal coverage and the sources of nutrient enrichment were not fully characterised and quantified. Through the emplacement of lake and catchment monitoring programs LVEMP has now provided the essential comprehensive data to appreciate the scale of the eutrophication problem in Lake Victoria and the most important sources of nutrients (Chapter 7)

The changes in the lake ecosystem have threatened the long-term sustainable utilization of lake resources and have attracted local and international concern (World Bank, 1996). In 1997 the three East African riparian countries, Kenya, Tanzania and Ugandan with the assistance of the World Bank and the Global Environmental Facility initiated a program to study and understand the nature, causes and magnitude of these changes in order to put in place appropriate intervention measures to enhance sustainable utilization of lake resources for socio-economic development of the basin. During the past five years, scientists from the three east African countries have undertaken extensive lake-wide water quality studies in order to establish the current water quality status, identify and quantify changes in the lake, and predict possible future water quality changes in relation to the human activities in the catchment. This chapter reports on the extent of eutrophication in Lake Victoria, and its effects on the aquatic biological resources.

Materials and Methods

In-situ measurements of oxygen, temperature and transparency (Secchi depth) were taken and samples for analysis of nutrients, invertebrates, and phytoplankton biomass and species composition were collected from the harmonized lake wide monitoring network (Figure 1) between August 2000 and April 2005. A detailed description of the study area, the criteria for selection of stations and the sampling and analytical methods are presented in chapter 5.

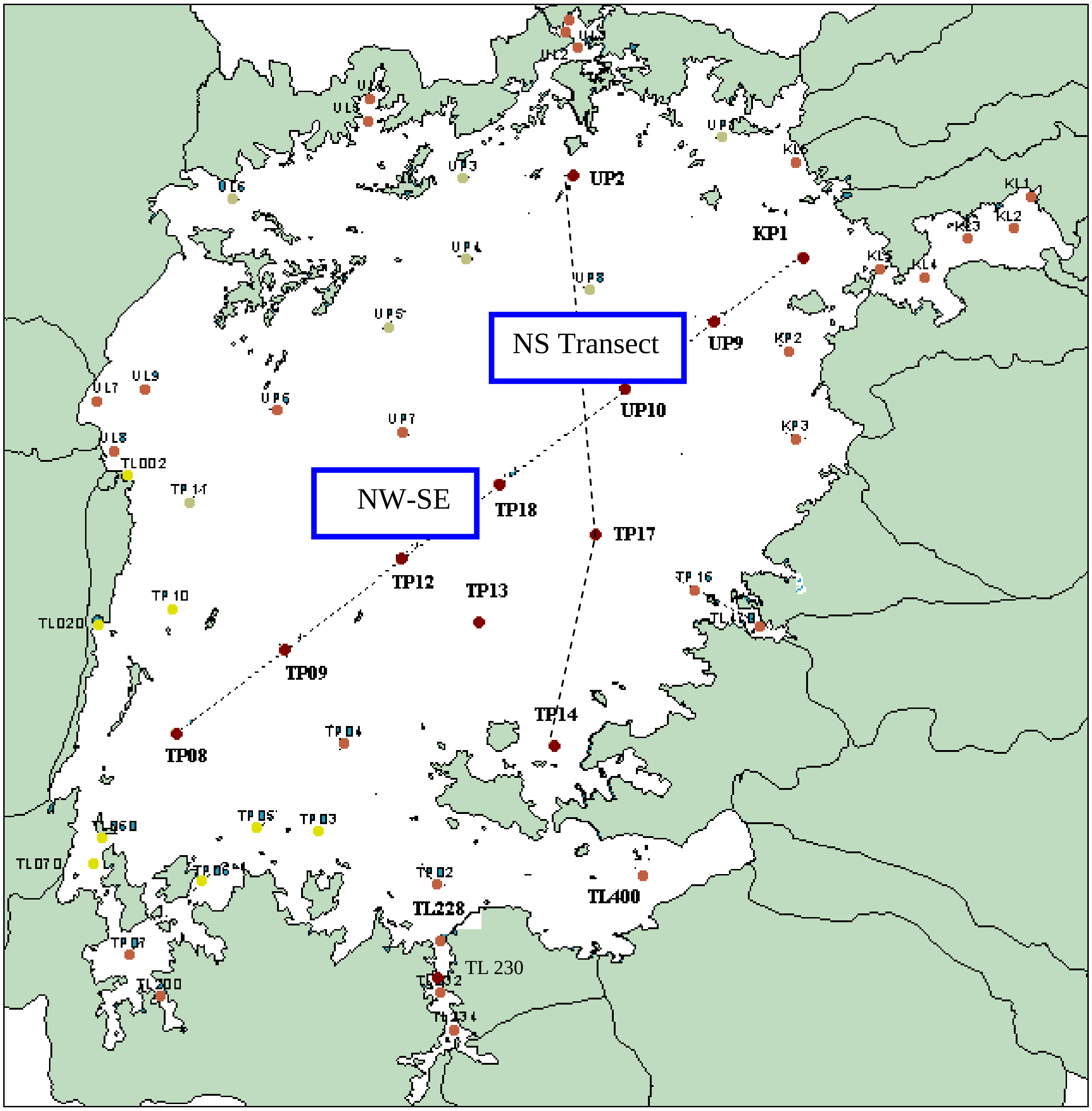

FIG. 1. ***Map of Lake Victoria showing the harmonized in-lake monitoring network and the northeast-southwest and north-south transects***.

RESULTS

Nutrients

Soluble nutrient concentrations along the northeast-southwest (NE-SW) transect (Fig. 1) are presented in Figure 2. Nitrate nitrogen (NO_3-N) and phosphate phosphorus (PO_4-P also referred to as soluble reactive phosphorus, SRP) concentrations ranged between 16.2 - 87.9 µg/l and 39.6 - 92 µg/l respectively and were both higher in the northeast. Dissolved reactive silicon (SiO_2-Si) concentrations along the transect ranged between 0.525 and 0.902 mg/l and the values were higher in the northeast and southwest part of the lake compared to mid-lake stations.

SiO_2-Si concentration showed a gradual decrease along the south-north transect (TP14, TP17, UP2 and UL1), from 0.70 to 0.29 mg/l (Fig. 3). UP2, the pelagic station near Bugaia Island, had mean SiO_2-Si, PO_4-P and NO_3-N concentrations of 0.29 mg/l, 128.2 µg/l and 51.4 µg/l respectively. Dissolved nutrients varied between the three gulfs of Mwanza, Napoleon and Nyanza (Fig. 2b). Nyanza Gulf had lower PO_4-P concentration (16.2 to 21.1 µg/l) than the Mwanza and Napoleon Gulfs (54.8 to 68.7 µg/l) but had higher SiO2-Si concentration range (4.5 to 5.2 mg/l) than the other two gulfs. NO3-N concentration in the gulfs ranged between 25 and 93 µg/l with Napoleon Gulf having higher values than the other two gulfs while also having very low SiO_2-Si.

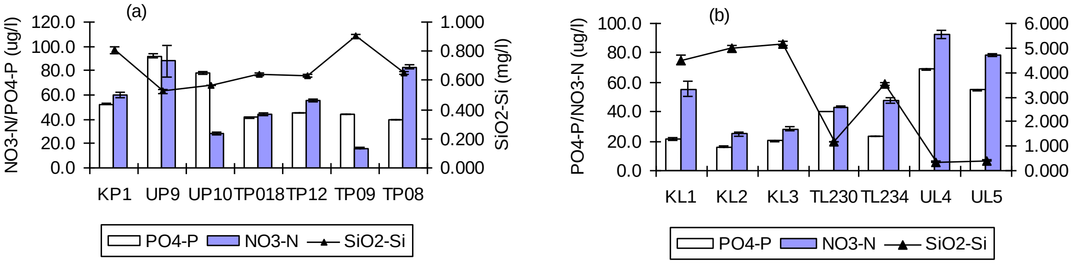

FIG. 2. Average dissolved nutrient concentrations (a) along the northeast-southwest transect in Fig.1 and (b) within the major gulfs, Winam (KL1, KL2), Mwanza (TL230,TL234) and Napoleon (UL4, UL5). Standard deviations for parameters are indicated.

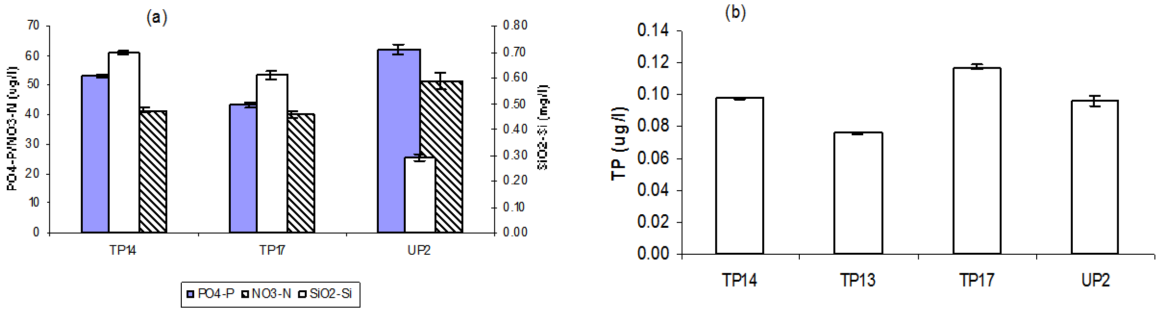

FIG. 3. Average concentration of (a) dissolved nutrients and (b) Total Phosphorus (TP) along the North-South Transect of Figure 1.

Along the north-south transect, total phosphorus (TP) ranged between 80 and 120 µg/l and along the northeast-southwest transect from 78 and 100 µg/l (TP14 and UP2 respectively) (Fig. 3b and 4a). TP values in the three gulfs (Mwanza, Napoleon and Nyanza) ranged between 52 and 100 µg/l with Nyanza Gulf having the lowest average concentration values and Mwanza Gulf having the highest average concentration values

(Fig. 4b). Total nitrogen ranged between 53 and 83 µg/l along the NE-SW transect with TP18, located in the middle of the lake, having the lowest average value.

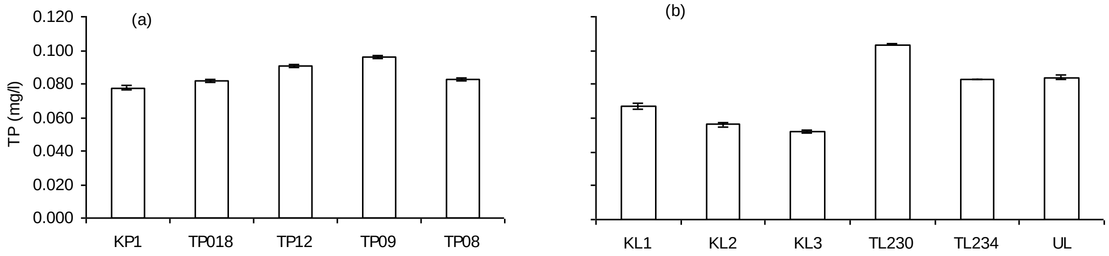

***FIG. 4. Total phosphorus concentrations along the (a) open pelagic lake zone and (b) in Mwanza, Napoleon and Nyanza Gulfs*.**

The mean TN:TP ratio (molar) in the pelagic open lake along NE-SW transect (Fig. 5a) differ from the ratios in the Mwanza and Nyanza Gulfs (Fig. 5b). The ratios show that in Mwanza Gulf either N or P can become limiting to algal growth whereas in the Nyanza Gulf P is limiting based on values in Guildford and Hecky (2000). On average, in the open pelagic lake zone, nitrogen is tending strongly to N deficiency.

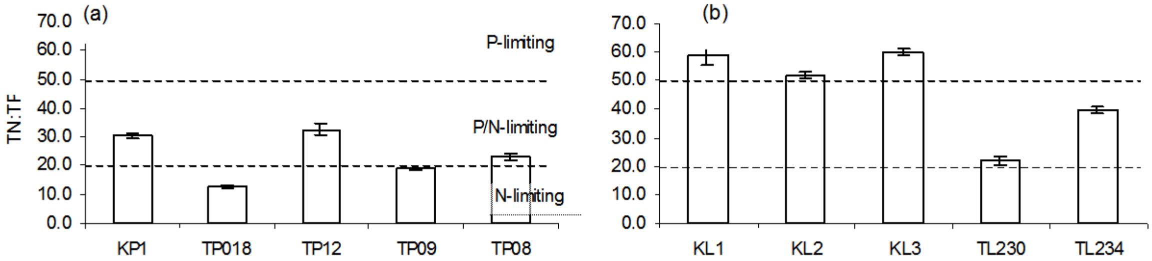

***FIG. 5 Mean TN:TP ratios for open pelagic stations (a) and Mwanza and Nyanza Gulfs (b). (Areas between the stippled lines indicate the zones where either nitrogen or phosphorus become limiting to phytoplankton growth)*.**

Phytoplankton Biomass and Species composition

Chlorophyll *a* concentrations were generally higher in the littoral areas (and Gulfs) than in the pelagic open waters (Fig. 6a and 6b). Along the NE-SW transect (Fig. 6a) the concentrations ranged between 3.6 to 11.7 µg/l and were higher on both ends of the transect, with UP10 in the middle of the lake having the lowest average concentration value (Figure 6a). The station UP2 had an average concentration of 3.2 µg/l. Water transparency (Secchi depth) in the lake, ranged between 0.4 and 7.5m. Secchi depth values were higher in the open lake stations (2 to 7.5m) compared to littoral stations (0.4 to 1.8). The graphical relationship between chlorophyll and Secchi depth is presented in Figure 7. Algal biomass (chlorophyll) controls light penetration over much of Lake Victoria with the exception of turbid Winam Gulf where resuspended mineral sediments affect light penetration (Gikuma-Njuru and Hecky 2005).

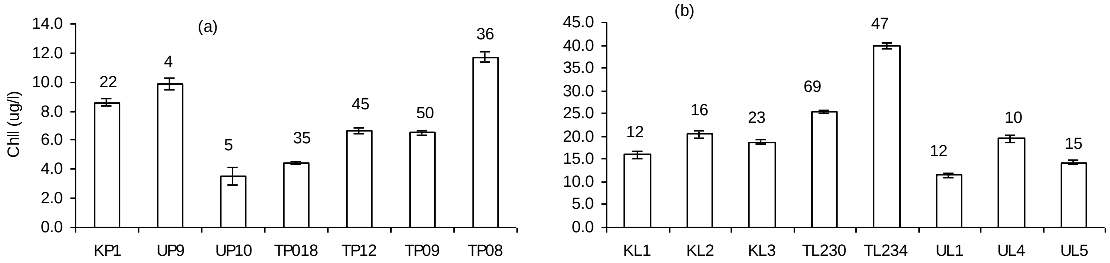

FIG. 6. Mean Chlorophyll a concentrations in the (a) open pelagic lake zone and (b) Mwanza, Napoleon and Nyanza Gulfs. Note difference in vertical scale between (a) and (b); number of samples (n) contributing to the mean are shown above the bars

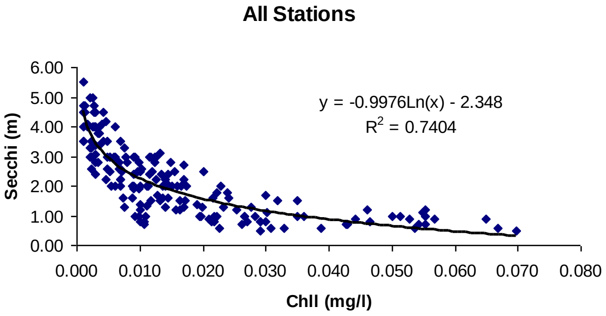

FIG. 7. Relationship between chlorophyll a and transparency (Secchi depth) in Lake Victoria for both littoral and pelagic zones.

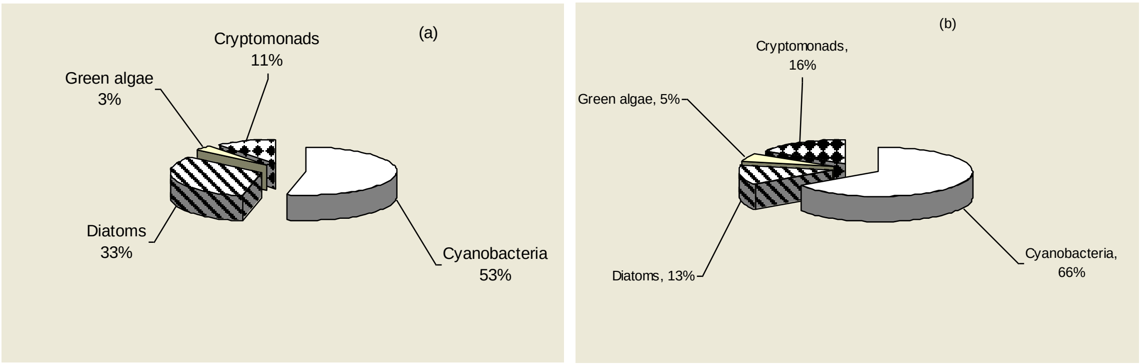

FIG. 8. Relative biomass of major phytoplankton groups in (a) Open pelagic waters and (b) in littoral areas in Lake Victoria.

The phytoplankton community in the lake was dominated by Cyanobacteria (>50%) both in the littoral and pelagic waters (Fig. 8), followed by diatoms. *Microcystis*, *Anabaena* and *Cylindrospermopsis* were the most common Cyanobacteria in the lake, whereas *Nitzchia* was the most common diatom. Higher Diatom biomass was recorded in the pelagic than in the littoral stations. *Aulacoseira* (*Melosira)*, the formally dominant diatom species (Talling 1966; Akiyama *et al* 1977) were rarely encountered in the present study. Green algae were the most diverse group in species followed by blue green algae.

Invertebrates

Species composition and distribution

Copepods, cladocerans, Rotifera, Diptera and Mollusca comprised the invertebrate community. Rotifera, Bivalvia and Gastropoda were the most diverse groups, containing several genera and numerous species. Each of the broad groups contained species that exhibited lakewide distribution while other species of the groups were rarely encountered.

Abundance

The invertebrate community was numerically dominated by copepods among the zooplankton, dipteran larvae and molluscs. Zooplankton densities indicated generally higher concentrations in the littoral compared to pelagic zones (for example Fig. 9). Cladocerans characteristically occurred at low abundance throughout the lake with their highest numbers recorded in the very shallow waters near Kisumu (KL1).

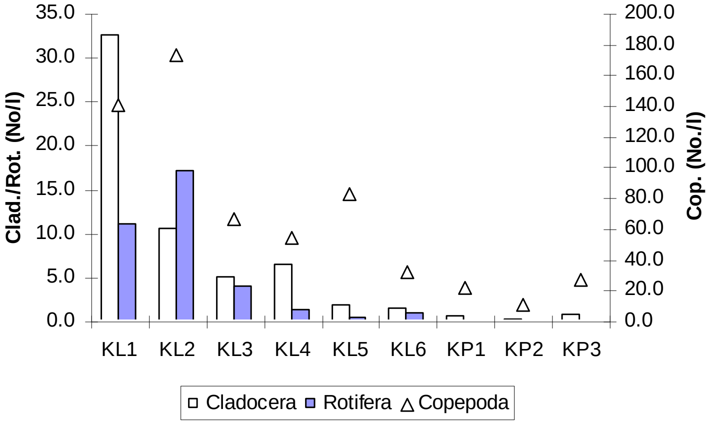

FIG. 9. Mean abundance estimates of zooplankton taxonomic groups at littoral (KL) and pelagic (KP) stations in Kenya including Winam Gulf (KL1to KL5) in Lake Victoria 2000-2005. Key: Cop.= copepoda, Clad.= Cladocera, Rot.= Rotifera.

Vertical distribution and abundance of zooplankton

Day time vertical distribution patterns in the littoral areas showed generally well dispersed zooplankton distributions over the entire water column (Fig. 10a).

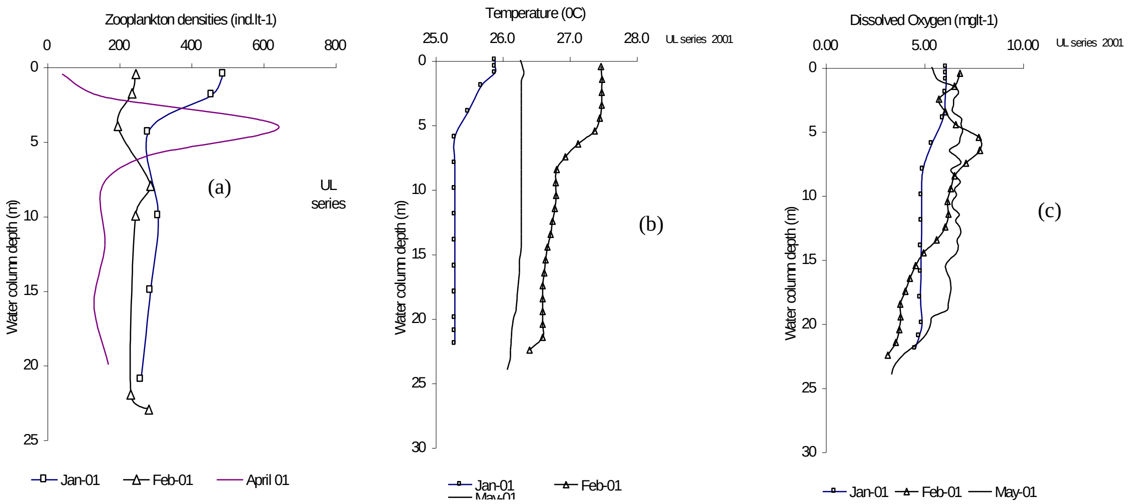

FIG. 10. Vertical profiles of zooplankton densities (a), temperature (b) and dissolved oxygen (c) at selected littoral sites, Lake Victoria 2001.

The corresponding environmental profiles also showed even distribution of temperature and dissolved oxygen throughout the water column at these littoral stations (Fig. 10). Zooplankton biomass data from TL 230 confirmed that in the littoral zones zooplankton occurred throughout the water column (Fig. 11).

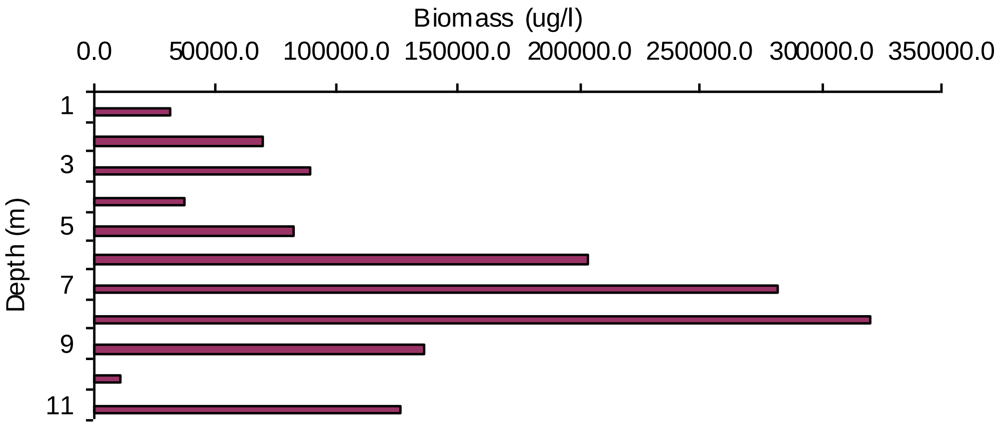

FIG. 11. Day time vertical distribution of zooplankton biomass at station TL 230, Lake Victoria, December 2000.

The vertical distribution of zooplankton at deeper open pelagic stations (UP2, UP7 and UP10) during thermal stratification showed concentration of organisms in surface and mid-waters with few or no organisms in the bottom water layers (Fig. 12).

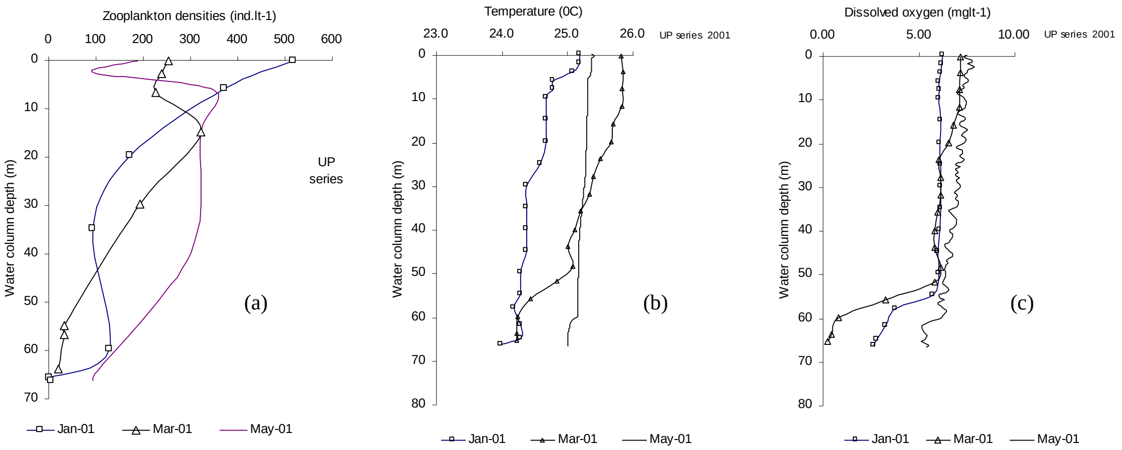

FIG. 12. Vertical profiles of zooplankton densities, temperature and dissolved oxygen at selected pelagic sites, Lake Victoria 2001.

Corresponding oxygen and temperature profiles indicated pronounced development of thermoclines and oxyclines between 50 and 70 metre depths below which the water mass was characterized by low dissolved oxygen, even $< 1.0 \text{mgO}_2 \text{ L}^{-1}$ in March 2001. Also phytoplankton primary productivity, which is grazed by the zooplankton as their food resource, is restricted to the upper 15m by penetration of light for photosynthesis (Mugidde 1993), and the availability of rapidly growing phytoplankton in the upper part of the water column accounts for the higher abundance of zooplankton in the upper water column.

DISCUSSION

Nutrient Indicators

Compared to Tallling values for SiO_2-Si concentrations of 1961, concentrations in the lake as a whole (excluding the semi-closed inshore areas) have decreased by a factor of 3, although at his primary station south of Bugaia Island (UP2), SiO_2-Si concentration has decreased by a factor of 8. PO_4-P concentration in the open pelagic waters has increased 4 to 8-fold compared to values measured by Talling in 1961. This draw down of SiO_2-Si, an essential element for diatoms, is due to eutrophication effects of high P loads into Lake Victoria. Similar depletion of dissolved SiO_2-Si also occurred during the P driven eutrophication of the Laurentian Great Lakes in North America where P loading reduction programs have led to a reversal of the eutrophication and a restoration of SiO_2-Si concentrations (Barbiero *et al*. 2002). TP concentration has shown a marked increase (4-fold), from 20 to 47 µg/l as measured by Talling in 1961, to the present 78 to 140 µg/l. The TN:TP ratio (molar) in the main lake (<20) indicate that phytoplankton growth in the lake is nitrogen deficient (Guildford & Hecky 2000). This favors the dominance of nitrogen fixing Cyanobacteria which is in line with high nitrogen fixation rates in lake reported by other researchers (Mugidde *et al* 2003). This low TN:TP ratio is associated with the increased phosphorus loading into the lake and selective loss of nitrogen through denitrification and enhanced recycling of P which is associated with increased anoxic conditions in the deep pelagic waters (Hecky 1993, Hecky *et al* 1996, LVEMP 2002).

Bio-indicators

The observed species composition of the Victoria invertebrates is consistent with the previous studies (Worthington 1931; Macdonald 1956; Rzoska 1957; Akiyama *et al*. 1977; Okedi 1990; Mavuti and Litterick 1991; Mbahinzireki 1994; Mwebaza-Ndawula 1994; Waya 2001; Waya and Mwambungu 2004; Waya 2004). This observation suggests that the community composition has remained relatively stable despite drastic changes in water quality and fish species composition save for a single cladoceran , *Simocephalus vetullus* recorded by Rzoska (1957) which has not been reported in recent studies. Bridgeman (2001) has also reported drastic decline of the cladoceran species, *Bosmina longirostris,* and chydorids from sediment core analysis. A cladoceran species, *Daphnia barbata* hitherto unrecorded in the lake has recently been reported in samples from the Nyanza Gulf. Mwebaza-Ndawula (1994) reported changes in relative abundance of the broad taxonomic groups from dominance of calanoid to cyclopoid copepods and the reduction of cladocera abundance, formerly >30% to the present 5-7%. Such changes appear to reflect ecosystem responses to the changing water quality and consumer communities.

The abundance of *Caridina nilotica*, lake fly larvae, and other invertebrates have increased in the lake with the decline of haplochromine stocks (Witte *et al* 1992). *Caridina* is now considered a keystone species for the Nile perch while the lake flies are not well utilized based on food web isotope studies (Campbell *et al* 2003). *Rastrineobola argentea* is a small zooplanktvorous fish that is most abundant in inshore areas and feeds on zooplankton. Comparison of present zooplankton density estimates with previous studies (Mavuti and Litterick 1991, Branstrator *et al.* 1996, Mwebaza-Ndawula 1998; Waya 2001) indicates no marked differences in abundance patterns over the past 15 years. This suggests a stable and dependable food resource and a sustainable zooplankton community as prey for fishes. The zooplankton community is a critical component of the diet of all larval and small juvenile fishes. However the current zooplankton community does not effectively graze the filamentous and colonial Cyanobacteria that now dominate the phytoplankton community (Lehman and Branstrattor 1993), and condequently phytoplankton biomass accumulates to high concentrations that can cause self-shading and impose light limitation restricting further algal growth (Mugidde 1993). The stability of the current invertebrate community is largely dependent on the superabundant cyclopoid copepods, the prawn, *Caridina nilotica,* dipteran larvae and mollusks which occur widely in the lake and constitute key forage items for a number of juvenile and adult fishes, and especially the major fisheries (Corbet 1961; Ogutu-Ohwayo 1990; Mwebaza-Ndawula 1998). These abundant prey species are considered to be critical in the recovery of lost haplochromines and other fishes. These invertebrate prey species were formerly heavily used by the trophically specialized haplochromines that had specific adaptations for exploiting these prey. The loss of the haplochromines relieved predation pressure on these invertebrates and that together with increased energy flow because of eutrophication has created a strong prey base that sustains the high productivity of juvenile Nile perch.

The occurrence of hypolimnetic anoxia at the thermally stratified deepwater areas (i.e. UP, KP and TP stations) has reduced habitable space as shown in the displacement of zooplankton (Fig. 12) from deep water. Among the invertebrates, *Caridina nilotica* has become a keystone species because it is resilient to low oxygen conditions (Branstrator *et al* 1996). The ability of these organisms to find refuge from fish predation by temporarily occupying hypoxic waters ensures that reproductive populations and growth potential is maintained. Recent work by Sekiranda (2005) shows progressive impoverishment of benthic and fish communities in three Ugandan bays (Murchison, Fielding and Hannington) with water quality ranging from non-polluted, nascent pollution to highly polluted conditions based on intensity of settlement and agriculture within the bays. Thus, increasing agricultural land use and the associate increased loading of sediments and nutrient is an emerging threat to invertebrates and other lake biota especially in confined embayments that restrict dispersion of the incoming loads. Occurrence of relatively high abundance of well known hypoxia-tolerant biological indicators such as larvae of the lake flies (chironomids and chaoborids), *Caridina nilotica* and rotifers in the lake is a signal of deteriorating water quality conditions although these are useful food organisms for juvenile fish. However, Ogutu-Ohwayo (1999) has documented the decline in condition of Nile perch after the depletion of the haplochromines, and Balirwa *et al* (2003) have suggested that restoration of haplochromines could lead to higher growth rates of adult Nile perch and increased yields to the fishery.

The reductions in Secchi depth are a general indicator of the loss of transparency and a reduction in the depth of the euphotic zone. Phytoplankton primary production is restricted to the euphotic zone and has become light limited because of self-shading (Mugidde 1993). The narrowing of the euphotic zone as algal biomass accumulates in a nutrient saturated system also contributes to the increase in maximum phytoplankton biomass concentrations. However, depth integrated primary production does not increase with increasing biomass in light limited systems for which chlorophyll controls light penetration. Silsbe (2004) has recently shown that as chlorophyll concentration increases above 20 μg/L integral gross primary production plateaus at a maximum value of approximately 20 g $O_2/m^2/d$. The consequence of this is that currently high chlorophyll concentrations in inshore areas can be reduced without reducing the primary productivity of the ecosystem. The currently high phytoplankton biomasses also shade out benthic algal growth which was an important component of the diet of algivorous littoral haplochromines and also supported other littoral invertebrate food webs upon which carnivorous haplochromines depended. In other species rich African Great Lakes such as Lake Malawi, benthic algal productions sustains a number of invertebrate and fish species (Bootsma et al. 1996). The loss of the littoral benthic productivity likely contributed to the loss of these specialized feeding groups as littoral benthic algal production declined.

Biodiversity Declines

Eutrophication often leads to changes in relative abundance of species as some are favored by changes in productivity while others suffer as the habitat degrades. Seehausen *et al.* (1997) concluded that the eutrophication of Lake Victoria has contributed to the decline of the endemic species flock of haplochromines because of reduced visibility (declining Secchi depths) and loss of chromaticity (color) in transmitted light. They demonstrate that species richness under present lake conditions is a function of light transmissivity at all wavelengths. The reduction of Secchi depth from historic conditions would therefore cause deterioration of haplochromine mate selection which is based on visual cues and lead to more hybridization of these closely related species. As well as loss of visibility affecting mate selection, Seehausen *et al.* (2003) further conclude that loss of visibility and color visualization will lead to increased competition among predators and favor Nile perch over endemic predators. Haplochromines have eyes that are sensitive to a broad spectral range and are effective predators in highly transparent water while Nile perch have visual capacities to adapted to low light and low color environments. Certainly the Nile perch through its direct predation effects contributed to the decline of the endemic haplochromine populations, but the eutrophication contributed to the loss of biodiversity because its effects on visibility in the system and created conditions in which Nile perch where competitively favored over native species. Restoration of haplochromine stocks and a diversified fishery will require both management of eutrophication as well as management of Nile perch stocks.

Process Indicators

The lake was found to stratify between February and April with weak stratification occurring between September and November. The lake fully mixes between June and August and partially in December to January, although inter-annual variation to these patterns has been observed. This is consistent with past observations in Lake Victoria (Talling 1965, 1966, 1969 and Mugidde 2001). Generally, Lake Victoria is now warmer and more stable than in the 1960s (Hecky 1993, Hecky et al. 1994, Lehman *et al.* 1998). Minimum water temperatures during the mixing period in June-July are 0.5 ^{o}C warmer in the 2000 to 2004 than they were in the 1960s. High water temperature due to stronger thermal stratification affects water chemistry in a number of ways. Elevated temperatures accelerate chemical reactions and microbial processes such as denitrification –nitrification (Seitzinger 1988), thus affecting nutrient cycling and availability as well as algal biomass development and oxygen availability. More stable thermal stratification makes the lake less able to mix effectively and promotes low oxygen conditions in deep waters while surface waters remain well oxygenated due to replenishment in day light by high algal photosynthetic activity and wind effected oxygenation. The stronger and more persistent thermal stratification aggravates the increased oxygen demand resulting from increased organic matter from primary production. Hypoxia also favors regeneration of soluble reactive phosphate and produces a positive feedback to maintain even higher phosphate concentrations and leads to a positive feedback and increased internal loading of phosphorus.

System Changes

Compared to values reported by Talling (1966), chlorophyll a concentration in the open pelagic waters of Lake Victoria has increased 2-3 fold. However the station near Bugaia Island (Talling's sampling station), had concentrations ranging between 1.92 and 3.84 µg/l), which are within the range reported by Talling (1966). But chlorophyll concentrations at Bugaia were apparently higher in the early to mid-1990's (Mugidde 1993; Mugidde et al 2003) when chlorophyll concentrations (mean 13.5 µg/l) were more similar to those found at other pelagic stations (Fig. 5a) in the LVEMP period of observation.

Worthington (1930) reported higher transparency values (6.0 to 8.0m) in the pelagic area compared to current values, but in the gulfs the current values are more comparable to those reported by Worthington. This decrease of water transparency in the pelagic waters is the result of increased phytoplankton biomass reported above as observed by other researchers (Mugidde, 1993; Kling et al 2001) as chlorophyll concentrations and Secchi depths are highly correlated.

Phytoplankton primary productivity was in the range 8 to 50 g O_2 m^{-2} d^{-1}, with the mean average of 18.3 g O_2 m^{-2} d^{-1} that was approximately twice higher than the values recorded in the 1960s (Mugidde 1992, 1993; Talling 1966). Overall, the algal photosynthetic efficiency is now lower as indicated by average productivity per unit biomass of 18.1 mg O_2 mg $chl^{-1}h^{-1}$ in the 1990s compared to 25 mg O_2 mg $chl^{-1}h^{-1}$ in the

1960s. This high algal primary productivity supports remarkable levels of secondary production including fish production in Lake Victoria. Currently the phytoplankton are light limited so any increase in nutrients will not lead to an increase in production although phytoplankton biomass can reach higher concentrations depending on hydrodynamic conditions. Conversely a reduction in nutrients can reduce algal biomass without affecting annual primary production significantly until chlorophyll values drop below 20 µg/L.

The very fertile conditions can support elevated algal wet biomass in the range 5 to 250 mg l^{-1} which has risen by a factor of 4 to 5 since the 1960s (Kling *et al.* 2001). High P concentrations and resulting high N-demand favour dominance of nitrogen fixing Cyanobacteria (blue-green algae), primarily speces of *Cylindrospermopsis*, *Anabaena* and *Microcystis*. Overall, there is seasonal succession in species composition of algae with increasing dominance of N-fixing blue-green algae during the early stratified period followed by non-fixers which benefit from the recycled fixed nitrogen later in the stratified period and during the deepest mixing period in June-July.

The shift in dominance from the historical algal communities dominated by diatoms such as *Aulacoseira* (formerly *Melosira*)and green algae to Cyanobacteria is in response to increased P laoding into Lake Victoria (Hecky 1993; Lipiatou *et al*. 1996; Verschuren *et al*. 2002) and increasing N-demand by phytoplanktom (Mugidde *et al*. 2003). The shift in diatom dominance away from *Aulacosiera* which formed the main food of the native commercially important tilapiine *Oreochromis esculentus* and its reduction might have affected stocks of this species. The decline in *Aulacoseira* and shift to more thinly silicified *Nitzschia* spp. is a consequence of the falling SiO_2-Si concentrations in the lake.

TABLE 1. OECD boundary values for fixed trophic classification system (extracted from Mason (1997).

Trophic	*TP*	*mean Chl*	*max Chl*	*mean Secchi*	*minimum*
Ultraoligotrophic	<4.0	<1.0	<2.5	>12.0	>6
Oligotrophic	<10.0	<2.5	<8.0	>6.0	>3.0
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

Explanation of terms:
TP = mean in-lake total phosphorus concentration (ug/l);
mean Chl = mean annual chlorophyll a concentration in surface waters (ug/l);
maximum Chl = peak annual chlorophyll a concentration in surface waters;
mean secchi = mean annual Secchi depth transparency (m)

TABLE 2. Trophic status in pelagic and littoral waters in the lake as indicated by different indicators.

	TP	*mean Chl*	*max Chl*	*mean Secchi*	*min Secchi*
Pelagic zone	100	10	40	3	1.2
	Hypertrophic	Eutrophic		Eutrophic	
Littoral zone	156	39	128	1.3	0.3
	Hypertrophic	Hypertrophic		Hypertrophic	

Trophic classification of Lake Victoria can be done using the OECD trophic classification system for lakes (Table 1) in order to appreciate how Lake Victoria compares to other global lakes. The littoral zone was found to be hypertrophic with respect to all the trophic state indicators whereas the pelagic open zone was hypertrophic with respect to TP but eutrophic with respect to other indicators (Table 2). However, considering water transparency (Secchi depth) as an indicator, some stations near the middle part of the lake (eg TP 10, with Secchi depth up to 7.5m), can be considered mesotrophic. The high TP concentrations in the lake can be as a result of enhanced external and internal phosphorus loading in to the lake coupled with less phosphorus demand by phytoplankton due to light limitation in the lake (Mugidde *et al* 2003). By comparison with the OECD the trophic status of the open pelagic waters has changed from mesotrophic (with respect to TP, chlorophyll and Secchi as reported by Worthington (1930) and Talling (1966)) to presently eutrophic status while littoral waters have changed from mesotrophic-eutrophic to hypertrophic.

Relation to fisheries

The occurrence of hypolimnetic anoxia, especially in the deep open waters, during periods of thermal stratification may result in displacement of demersal fishes and other bottom dwelling biota vertically into mid-waters and/or laterally into shallower areas. This phenomenon commonly leads to disappearance of fish from established fishing grounds such as is the case around Goziba (Nabuyongo) islands in Tanzania during February-March (as reported by local fishermen) and because of the loss of habitable space. This condition was associated with migration of fishermen from the Goziba islands to the islands of Ukerewe, Bumbire and Kerebe due to scarcity of fish in the traditional fishing area during March 2004. Under critical conditions hypoxia in the lake can result in fish kills (Ochumba 1990) when upwelling conditions occur.

Some species of cyanobacteria such as *Microcystis, Cylindrospermopsis* and *Anabaena* that commonly occur in the lake today can produce toxins that have deleterious impacts on aquatic biodiversity and other biota including humans (Hummert et al 2001; Krienitz *et al.* 2002). Phytotoxins have been reported in some inshore areas in Nyanza and Mwanza Gulf (Krienitz *et al.* 2002) and pose a risk to aquatic biota, food web functioning and potability of lake waters. Algal biomass has increased disproportionately to the increase in productivity indicating that the transfer of energy from primary producers to grazers is now less efficient than it was or could be. Decreased visibility in the system and loss of fish biodiversity may also have affected the transfer of energy between prey and predator in food chain. Low light conditions thus created also affects visual feeding and may also be associated with observed high hybridisation among tilapiine fishes (Balirwa *et al.* 2005) and contributed to loss of species diversity.

The increased nutrient concentrations, has made the lake vulnerable to invasive weeds such as the water hyacinth which at its peak during the mid and late 1990s covered large areas of sheltered bays and gulfs, leading to increased light attenuation, low dissolved oxygen concentrations and loss of fish habitats. The reported increased biomass of *Caridina niloticus* and lake flies as a result of increased eutrophication and change of food web has provided the food-base for the expansion of *Lates niloticus* and *Rastreonobola argentia* populations, which now have great economic importance to the region, but they are also indicators of deteriorating water quality.

CONCLUSIONS

1. Nutrient and phytoplankton data has confirmed earlier reports on water quality and ecosystem changes in Lake Victoria. These include increased phosphorus levels, reduced silica concentration in the water, increased phytoplankton biomass, higher primary productivity and major changes in species composition.
2. Increased phosphorus enrichment from external sources may further enhance phytoplankton biomass in inshore areas and lead to further dominance by N fixing and other Cyanobacteria, many of which are potentially toxic.
3. N fixation is an important process that makes atmospheric nitrogen available to meet the requirements of N deficient Cyanobacteria. This process accounts for 50-80% of total external nutrient loading and cannot be controlled except through reducing phosphorus loading and availability.
4. The integral phytoplankton primary productivity has increased approximately a factor of two from historic rates but the primary productivity of the system is now light limited. Further nutrient enrichment will not supply more energy from phytoplankton and will increase the risk of intense algal blooms and the invasion by floating macrophytes that are not limited by light.
5. The current ecosystem conditions are a threat to sustainable utilization of lake resources including the fishery because 1) they impose deep water anoxia limiting habitable volume for higher organisms, 2) limit fish biodiversity, 3) create the potential for algal toxins to affect food webs and human consumers and 4) favor resurgence or invasion by water hyacinth and other floating macrophytes,

6. The wide distribution and high abundance of copepods, dipteran larvae, molluscs and *Caridina nilotica* have adjusted to the new conditions and can provide a sustainable and resilient food web, but they do not control algal abundances through direct grazing and, in turn, may be inefficiently used by fish compared to former conditions. Restoring visibility in the system by reducing algal biomass would have benefits for food web efficiency, fish biodiversity and potentially growth rates of mature Nile perch if haplochromines were restored as prey of the perch.

RECOMMENDATIONS

- Integrated management of nutrient loading (mainly phosphorus) into the lake should be implemented catchment-wide to reduce over time the algal biomasses in the lake and restore aspects of the former condition of the lake especially reduced Cyanobacteria and improved visibility.
- Regular lake monitoring is a necessary part of an early warning mechanism to avert further decline in lake ecosystem health and inform the management on the impact of catchment management on the lake ecosystem.
- Together with stakeholders, responsible agencies should establish achievable water quality objectives to guide the multiple-use management of the Lake Victoria ecosystem.

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