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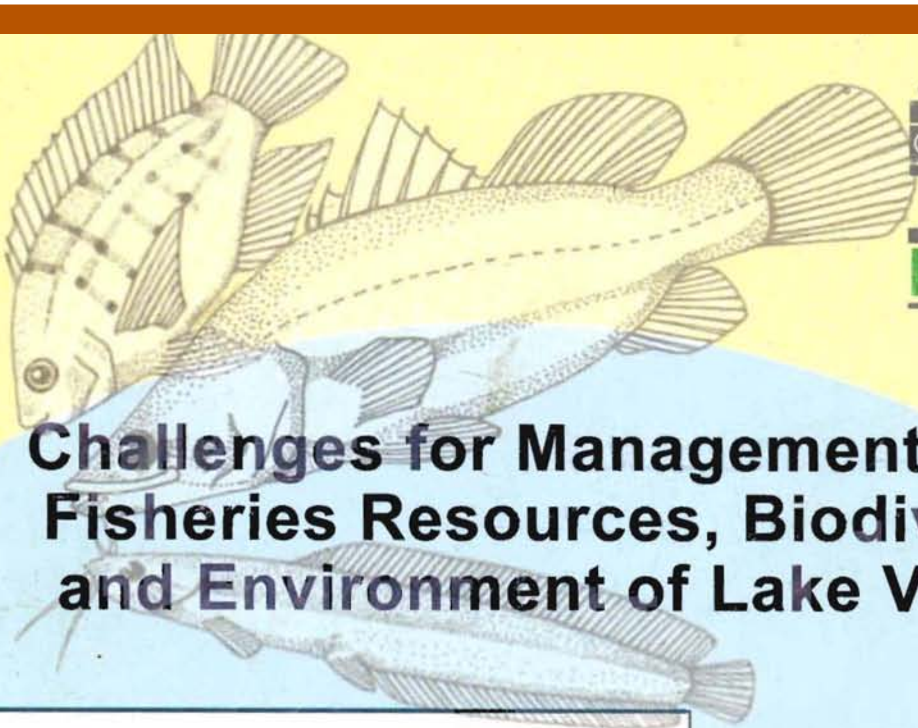

Challenges for Management of the Fisheries Resources, Biodiversity and Environment of Lake Victoria

Editors:
J. S. Balirwa,
R. Mugidde,
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Fisheries Resources Research Institute

Technical Document No. 2 First Edition - 2004

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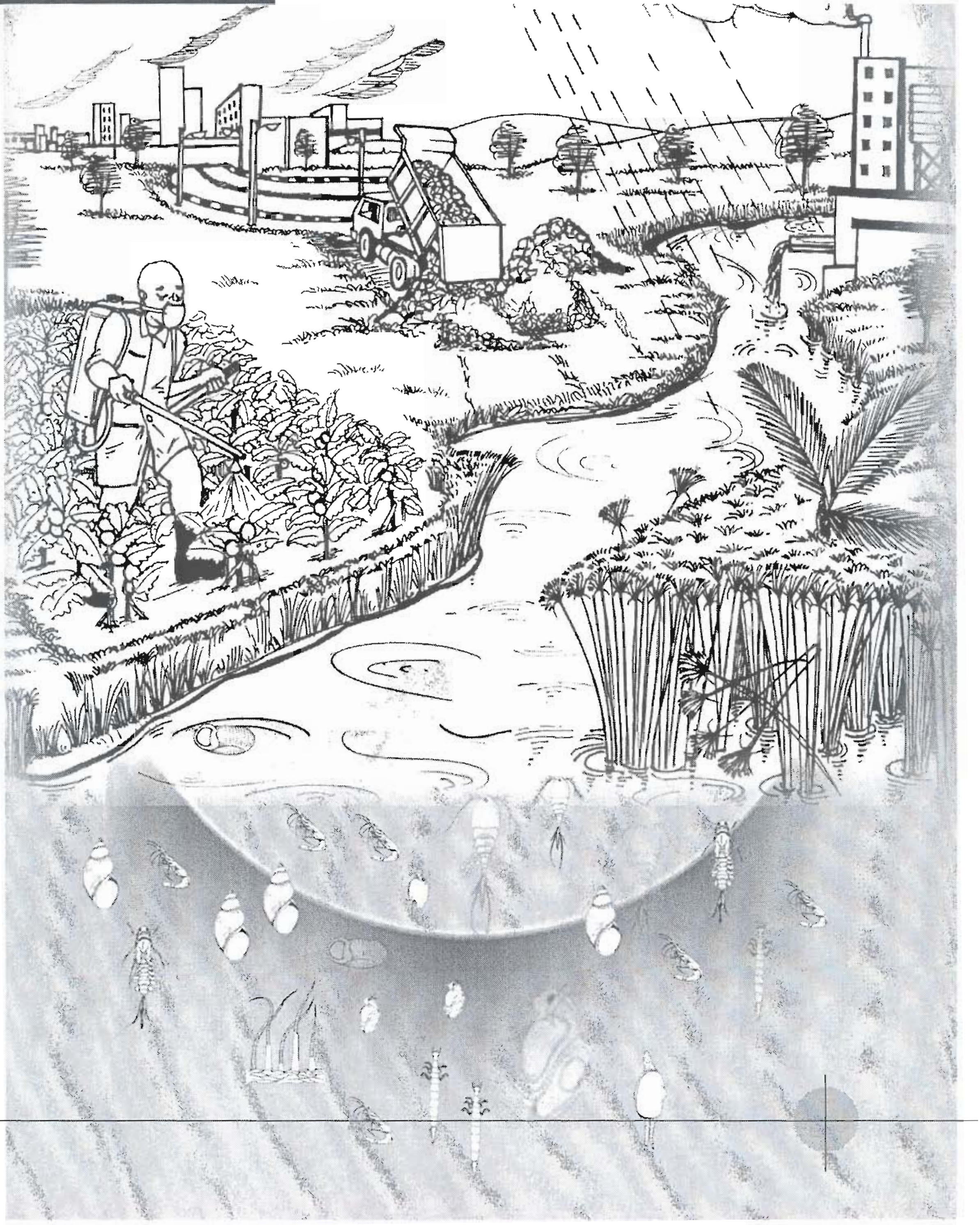

6.1. Nutrient Status and Thermal Stratification in Lake Victoria

R. Mugidde and R.E. Hecky.

Introduction

Worldwide, human activity in the watershed has been found to induce lake responses at various levels, including at population and ecosystem scale. Recently, Carignan and Steedman (2000) reported on disruptions of biogeochemical cycles in temperate lakes following watershed deforestation and /or wildfire and Carignan *et al.,* (2000 a, b) concluded that water quality and aquatic biota are strongly influenced by disturbances in the watershed. Similarly, Lake Victoria is no exception as people in its catchment have exploited it for the last hundred years or more, but have now begun to understand the extent to which they have thrown the lake into disorder and how their increasing activity in the watershed have driven some environmental changes within and around the lake.

Already, human activity including overfishing, deforestation, intense cultivation, animal husbandry and introduction of exotic fish species have contributed to the changes in the physical, chemical and biological qualities of Lake Victoria (Bugenyi and Balirwa 1989; Ogutu-Ohwayo 1990 a,b; Hecky and Bugenyi 1992; Lowe-McConnel *et al.*, 1993; Lipiatou *et al.,* 1996; Ogutu-Ohwayo *et al.,* 1996; Mugidde 2001). Prior to the 1960s, Lake Victoria seemed to have coped fairly well as ecosystem changes, especially eutrophication effects were not obvious. However, Verscheruren *et al.*, (2002), reported changes in deep water oxygen and silica concentrations as early as 1940s. Between the 1960s and 1990s, the lake underwent a limnological transition that became manifest as reduced transparency, increased algal abundance, reduced populations of endemic and native fish species, population explosion in the introduced Nile perch. Proliferation of aquatic weeds and especially Water hyacinth that thrives in the shallow eutrophic bays receiving nutrient-rich influents from rural and urban areas was characteristic of the lake. The causes of the limnological shift in Lake Victoria are multifactorial and include climate change and the successful invasion of the predacious Nile perch and ensuing food-web changes.

Certainly, heavy predation by the Nile perch contributed to the decimation of the native fish species that already were being overexploited in Lake Victoria. But eutrophication also contributed to species loss due to declining transparency (Seehausen *et al.*,1997). In addition, changes in the algal community, especially dominance of blue-green algae and loss of large diatoms types such as *Aelucoseira* (Kling *et al.*, 2001) changed the food quality of fishes that feed directly on algae and for other grazers that feed on algae, and are in turn fed on by fish.

Less visible, but a fundamental and threatening change was excessive nutrient loading from agricultural, municipal, industrial and atmospheric sources. Agriculture is a major economic activity impacting water quality via increased nutrients from increased use of fertilizers and other agrochemicals that boost crop productivity and, also from sediment yields coming from soil erosion. Excess nutrient inputs into Lake Victoria is a key environmental concern for the water and the fisheries managers in riparian countries. Several ecosystem changes that include changes in algal species, increased incidences of noxious and toxic blooms of algae, increases in incidences of water borne diseases, seasonal hypoxia and anoxia, and fish kills are a direct and/ or indirect result of eutrophication from increased nutrients inputs into Lake Victoria. All these changes pose a threat to many beneficial uses of the lake which include fish for food and for export, clean water for domestic, agriculture, transport, industrial and hydroelectric power generation uses.

Evidence from the sediment records show that increased nutrient loadings into Lake Victoria begun in the 1920s (Hecky 1993; Lipiatou *et al.*, 1996; Verschuren *et al.*, 2002) with the first settled agriculture and the movement of stock animals into areas not previously occupied. At that time, the number of people around the lake was small and their impacts to the water quality were minimal. With increasing populations and higher agriculture production, consequent land use changes led to wide spread progressive enrichment of the lake's sediment with essential nutrients phosphorus (P), nitrogen (N) and silica begun, and accelerated accumulation has occurred since the 1960s (Lipiatou *et al.,* 1996; Bootsma *et al.*, 1996; Verschuren *et al.,* 1998). Complementary evidence from the water column indicate that total phosphorus concentrations have doubled since 1960s and are now in the range 1.0 μM to 12.0 μM, average 2.7 μM.

Although eutrophication threatens the sustainability of multi-fold beneficial uses of Lake Victoria, it did result in increased algal production (Mugidde 1992; 1993) that supports increased fish yields that have risen by 4 to 5-fold since the 1950s (Ogutu-Ohwayo *et al.*, 1996). Increased fish production is a blessing as more local people have turned to the lake for their livelihood and fish exports to international markets earn foreign exchange for the riparian countries. The increased importance of higher fish yields raises concern about its dependence on nutrient loading to Lake Victoria.

Changes in thermal stratification and mixing regimes associated with changes in local meteorological conditions have often been invoked to explain nutrient availability and distribution in the African Great lakes, especially on seasonal time scales (Talling and Talling 1965; Talling1969; Hecky 1993; Lehman *et al.,* 1998; Mugidde 2001). The annual cycle of thermal stratification and mixing are some of the major physical factors responsible for seasonal changes in chemical properties and biological processes in Lake Victoria. Seasonal thermal stratification affects water chemistry because it leads to elevated temperatures that determine the rate and extent of various chemical *interactions. A stronger thermal stratification due to elevated temperatures can accelerate temperature dependent chemical reactions and microbial* processes such denitrification-nitrification and thus affecting nutrient cycling and availability as observed in Lake Victoria. In addition, thermal stratification isolates the surface waters from the bottom layers and thus limiting nutrient and dissolved oxygen exchange. In Lake Victoria, the physical movement of the water is one major force that drives the vertical and horizontal distribution of nutrients (Talling J & J. Lemoalle 1998; Talling J.F 1965, 1986, 1987; Hecky 1993; Lehman *et al.*, 1998; Mugidde 2001). The primary objective of the Lake Victoria limnological research was to determine nutrient status and understand how thermal stratification and mixing regimes affect nutrients dynamics, and ultimately shape the fisheries and function of the lake. One primary objective of the Lake Victoria limnological research was to determine nutrient status and understand how thermal stratification and mixing regimes affect nutrients dynamics, and ultimately shape the fisheries and function of Lake Victoria. Since the early 1990s, data were collected from both shallow inshore waters (≤30 m) such as Napoleon Gulf (Fig. 6.1.1 a) and deep offshore stations (≥60 m) such as Bugaia and the far station as well as along a transect (T) from the Uganda to the Tanzania waters of Lake Victoria (Fig. 6.1. 1 b, c). These data were compared with historical records of the 1930s and 1950-60s.

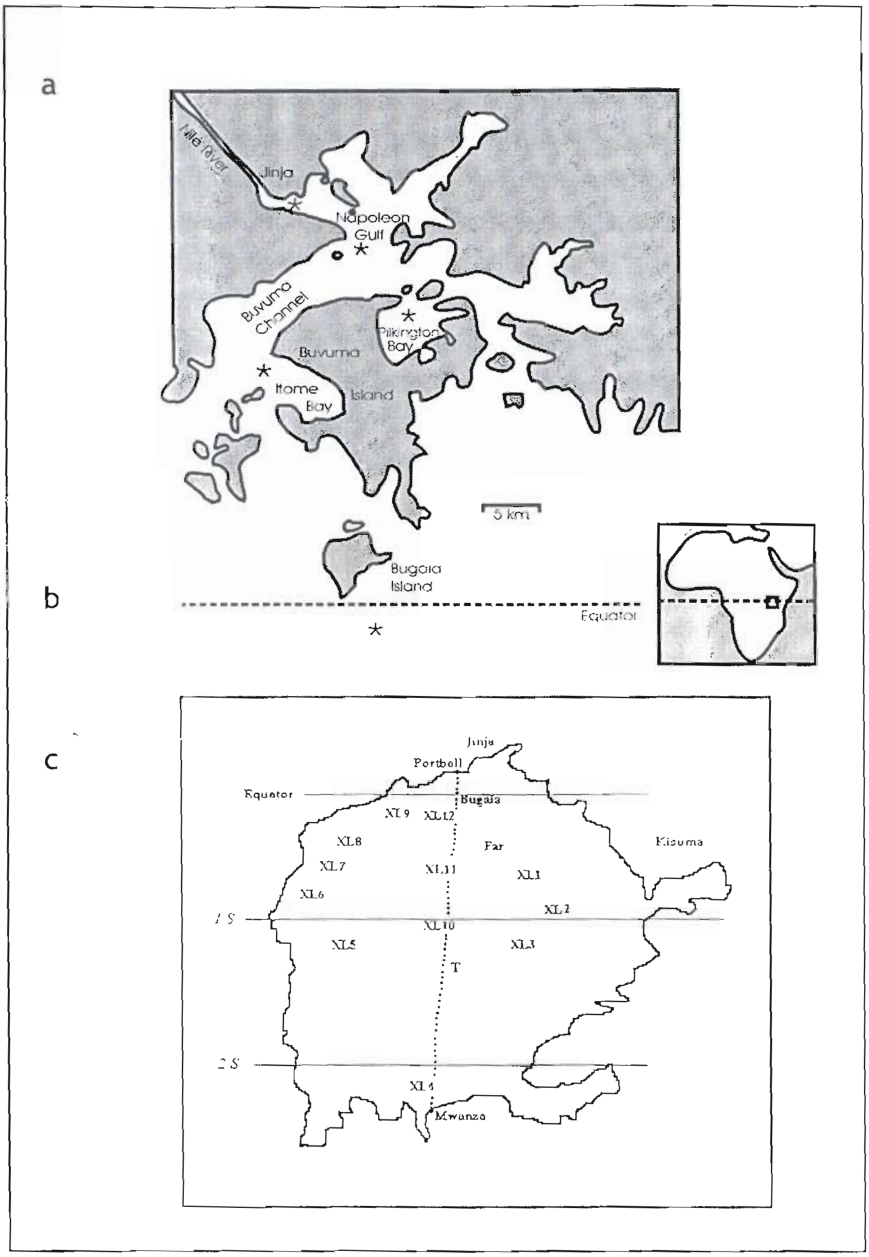

Fig. 6.1.1. (a) Lake Victoria sampling stations (a) inshore, (b) map of Africa showing location of Lake Victoria and (c) offshore and cross-lake transect (T) from Port bell (Uganda) to Mwanza (Tanzania)

Inshore to offshore trend of nutrients and chlorophyll concentrations

Lake Victoria is spatially variable with relatively higher suspended nutrients (phosphorus, carbon and nitrogen), total nitrogen and chlorophyll-a concentrations inshore shallow bays and gulfs compared to offshore regions. Average total phosphorus (TP) concentrations in surface waters generally have a narrower range of 2.3 µM to 3.1 µM (Table 6.1.1) and are not significantly different among inshore and offshore stations ($p > 0.05$). Overall total phosphorus remained fairly constant from inshore to offshore waters. However, the relative distribution of phosphorus and nitrogen between the dissolved and particulate forms are different for inshore and offshore surface waters of Lake Victoria. Dissolved inorganic phosphorus (DIP) concentrations were significantly lower inshore than offshore. Dissolved inorganic phosphorus made up a dominant fraction of the TDP (48-80%) offshore and was reduced to 30-60% of the TDP in inshore. Suspended particulate phosphorus (SP) and nitrogen (SN) were the most abundant form of phosphorus and nitrogen in surface inshore waters but not offshore. Offshore suspended phosphorus and nitrogen contributed a less fraction (< 35%) of the total phosphorus and nitrogen stock.

Table 6.1.1. Average total dissolved phosphorus (TDP) and soluble reactive phosphorus (SRP) and their standard deviation from the inshore (0-5 m) and offshore (0-10 m) surface waters of Lake Victoria.

Station/ Concentrations	Bugaia	Far station	Itome Bay	Buvuma Channel	Napoleon Gulf	Pilkington Bay
TP (µM)	3.1 ± 0.9	2.6 ±1.3	2.31 ± 1.0	3.1 ± 0.7	2.9 ± 2.1	2.3 ± 0.9
DIP (µM)	2.0 ± 0.7	1.1 ± 1.2	1.5 ± 1.5	0.8 ± 0.9	0.8 ± 1.3	0.5 ± 0.8

In Lake Victoria, total nitrogen (TN) concentrations were high and varied from 190µM to 250 µM, with concentrations always much higher in the shallow inshore regions than offshore (Table 6.1.2). Average total N was similar in magnitude in the shallow Napoleon Gulf, Pilkington Bay and Buvuma Channel but decreased from an average of 106.4 µM in inshore to 37.1µM in offshore at Bugaia. Nitrogen concentrations were low and remained relatively constant at Bugaia and other offshore stations in the lake. Overall, total nitrogen concentrations were highest at shallow (≤30 m) inshore bays and gulfs where suspended nutrients (SP, SN and SC) concentrations and chlorophyll-a were also highest. Five inshore-offshore nutrient transects made across Lake Victoria, between 1994-1998, show that Bugaia marked the beginning of deep offshore waters, while the far station and XL1-XL5 were typical offshore sites with low chlorophyll-a and suspended nutrients concentrations.

Table 6.1.2 . Average total nitrogen (TN), total dissolved inorganic nitrogen (DIN), nitrate and ammonium and their standard deviation in inshore (0-5 m) and offshore (0-10 m) surface waters of Lake Victoria

	Offshore		Inshore	
Station/ Concentrations	Bugaia	Buvuma Channel	Pilkington Bay	Napoleon Gulf
TN (µM)	37.1 ± 18.7	81.4 ± 13.0	100.2 ± 24.0	106.4 ± 28.2
DIN (µM)	4.5 ± 3.2	6.0 ± 5.7	4.7 ± 9.6	2.4 ± 1.2
Nitrate (µM)	3.0 ± 2.5	1.4 ± 1.8	0.2 ± 1.0	1.3 ± 1.7
Ammonium (µM)	1.4 ± 1.1	4.5 ± 4.9	4.5 ± 5.9	2.0 ± 3.6

Dissolved inorganic nitrogen contributes small proportions of 10% to 20% of the total dissolved N in Lake Victoria (Table 6.1.2). Nitrite as a component of the total N was negligible and was always £ 0.1 µM. Ammonia made up a larger fraction (65% to 87%) of the total dissolved inorganic N inshore but constituted only 37% to 48% offshore. Nitrate unlike ammonia constituted a larger fraction (65 to 67%) of the DIN offshore and a lesser fraction (23 to38%) inshore. Frequently, these dissolved inorganic nitrogen concentrations do not meet the algal N demand, especially in inshore shallow areas. The low dissolved inorganic nitrogen concentrations in combination with high P loads favor the persistence of blue-green algae including types such as Cylindrospermopsis and Anabaena that can fix atmospheric nitrogen Victoria.

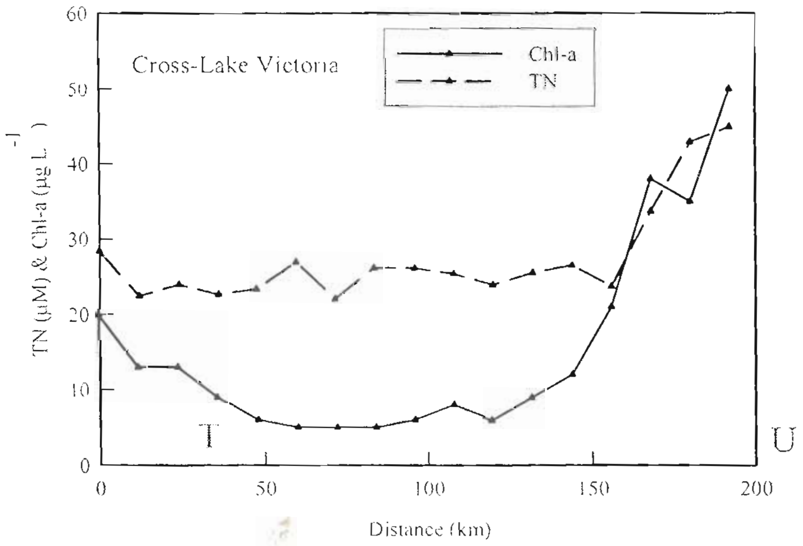

Fig. 6.1 2. Nutrient and chlorophyll-a concentrations across Lake Victoria.

Further, soluble reactive silica concentrations were much lower in the 1990s than those recorded in the 1960s. Average silica concentrations (17.3 ± 3.6 μM) have decreased by a factor of 10 since the 1960s, partly due to increased phosphorus concentrations/ loading and utilization by a two-fold higher diatom biomass in the lake in the 1990s than in the 1960s. Silica concentrations are often < 1μM, suggesting severe silica depletion comparable to that observed during the eutrophication of the Laurentian Great Lakes (Schelske *et al.,* 1975). Elevated algal biomasses and a two-fold increase in algal primary productivity (Mugidde, 1992; 1993) provide further evidence of increased nutrient enrichment of Lake Victoria in the 1990s compared to the 1960s.

Past and present water temperatures

When recent water temperatures are compared with earlier records, Lake Victoria is warmer than it used to be in the 1960s. Modern water temperatures are consistently higher compared to values reported in the 1960s (Talling, 1966; Fish, 1957) and have increased thermal stability in the lake in the 1990s (Hecky & Bugenyi, 1992; Hecky 1993; Lehman *et al.,* 1998). More stable thermal stratification than in the 1960s reduces mixing during the stratified season and enhances low oxygen conditions in bottom waters (Hecky *et al.*, 1994; Mugidde, 2001). High temperatures accelerate oxygen consuming reactions and lower solubility of oxygen. Overall, monthly mean temperatures for the whole lake are higher and minimum water temperatures during mixing in July and August are 0.5 °C warmer (Hecky, 1993; Lehman *et al.*,1998). Lehman *et al.,* (1998) suggests that increased thermal stability due to climate change may be one of the master variables enhancing eutrophication in Lake Victoria. This is possible as thermal stratification directly affects the mixed depth of the mixed layer, which in turn, affects the light availability in the water column and vertical distribution of nutrients including oxygen.

Thermal condition in inshore and offshore Lake Victoria

Despite the small changes in surface temperatures ($\leq$2.0 °C)over the annual cycle, they are adequate to stratify sufficiently deep waters ($\geq$ 30 m) and also shallow sheltered bays such as Napoleon Gulf ($Z_{max} \geq 15.0$ m) located in a low wind stress areas. Historic (1960s) and modern (1990s) records of temperature profiles (Fig. 6.1.3) and Wedderburn numbers (Mugidde, 2001) indicate that the deep (> 40-65 m) offshore waters, such as Bugaia region of Lake Victoria, undergo annual thermal stratification and destratification while the shallow inshore bays and gulfs have different temperature patterns and mix more frequently than offshore. Both inshore and offshore waters undergo diurnal stratification during which the upper 5 m are often heated by over 0.5 °C higher than the deeper layers.

The inshore shallow (≤ 30 m) waters do not often exhibit prolonged stratification except during periods of calm weather. However, sheltered inshore waters such as Napoleon Gulf do develop thermal stratification that breaks down more frequently than offshore. Despite the diurnal stratification, the shallow areas with depths ≤ 15 m, such as Pilkington Bay, mix throughout their depth all the year.

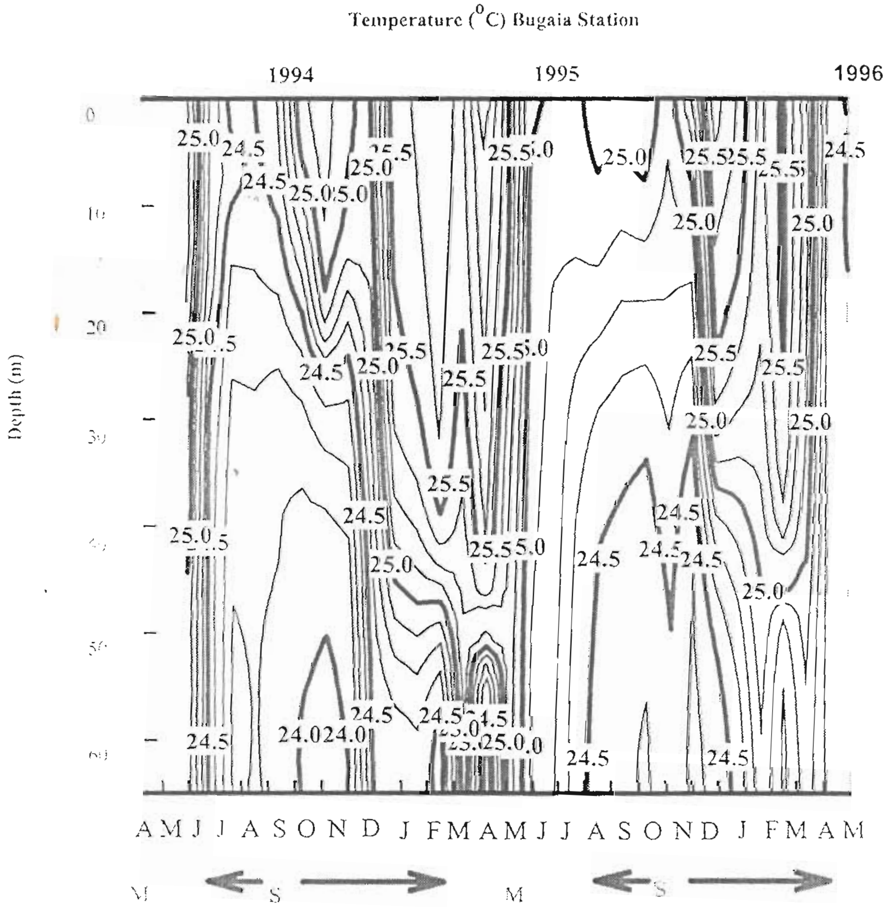

Fig. 6.1.3. Thermal stratification and mixing regimes in Lake Victoria

Destratification and complete mixing

Destratification and complete mixing occurs during periods of increased wind stress around July. This windy season is due the strong and cool south -easterly monsoon trade winds that blow towards Lake Victoria from May to July. These winds lead to a seasonal fall in air temperatures and lake-wide cooling (Newell 1960; Talling 1966; 1969). Increased evaporative cooling makes the cooler and denser surface waters descend into the hypolimnion. At this time of the year, differences in temperature between the surface and bottom waters are low or disappear and stability is lowest. When this occurs water almost have uniform characteristics throughout the depth of the lake and substantial amounts of dissolved oxygen reaches bottom water. Nutrients show almost uniform concentrations during complete mixing in July (Fig. 6.1.4). This is because nutrients, in particular P, return to surface waters during mixing. The greatest change in total P concentrations occurs between July and September corresponding to the mixing and early stratification period. At Bugaia, areal total P concentration increased 2-fold in the whole water column and 5-fold within the surface mixed waters during destratification in May to July (Table 6.1.3).

Table 6.1.3. Areal total P concentrations (μM μ2) from offshore (Bugaia) Lake Victoria during 1998

Month	Water column (0-65 m)	Surface water (0-20 m)
March	156.6	35.5
May	247.4	29.5
July	442.8	137.7
August	575.9	148.7
September	564.6	145.5
October	178.3	59.3
November	247.5	72.3
December	296.5	60.5

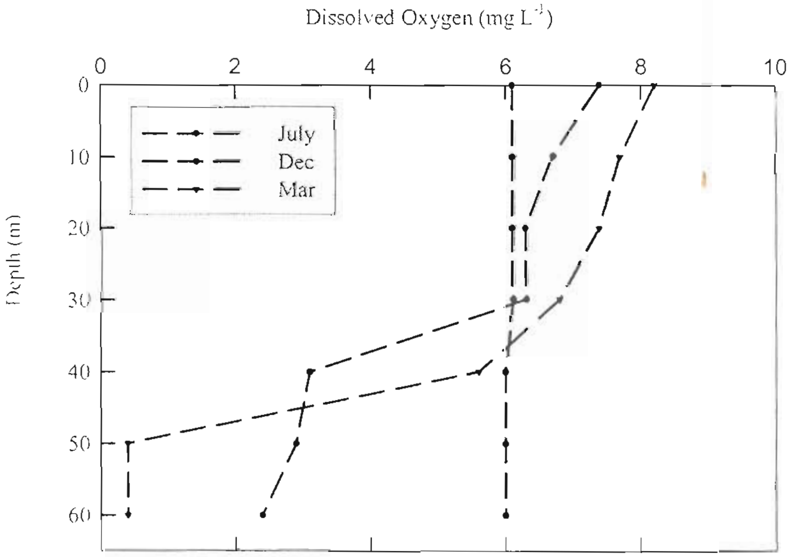

Fig. 6.1.4 . Vertical distribution of dissolved oxygen in the offshore waters (Bugaia) of Lake Victoria

Thermal stratification in Lake Victoria

The deep offshore waters of Lake Victoria experience three phases of thermal stratification and destratification (Fish 1957; Talling 1966; Hecky *et al.*, 1994, Mugidde, 2001 (Fig. 6.1.3). Deep and stronger mixing occurs around June-July and stable and more stable thermal stratification occurs between September to December and January to April respectively.

Thermal stratification allows slightly warmer surface waters to overly slightly cooler and denser waters in the hypolimnion (Fig. 6.1.3). This difference in temperature and the resulting difference in density cause resistance (stability) to mixing of the top and bottom waters. Offshore waters (Bugaia) remain thermally stable between September and April as indicated by the persistent thermoclines (Fig. 6.1.3.) and bottom water hypoxia. When the deep offshore waters of Lake Victoria are stratified, the depth of the upper warmer layer varies between 20 m to 40 m with the lower layer occupying the depth range to the maximum depth of the lake. These layers are not always level in the lake. Winds from one direction can push water towards the opposite shore. The accumulation of warm water along the downwind coast deepens the mixed layer and tilts the upper surface of the deeper layer upwards in the wind direction (Fish 1957; Talling 1966). These wind events that involve strong oscillation of water and thermocline tilts are called seiches and are important in allowing interchange of water from the deep layer with the upper layer, especially, through boundary mixing (Sally Macintyre *et al.*, 2002). Fish and Talling observed thermocline tilts due to internal waves that could bring deep waters near the surface even during periods of maximal thermal stability (Fish 1957; Talling 1966). These seiches lasted a period of 40 days and had the capability to spread their effects from offshore (Bugaia) to inshore waters (Buvuma). Seiches or episodes of incursions of cooler water are ecologically important as they permit partial return of various dissolved nutrients accumulated in deep waters to the mixed layer. Kitaka (1971) observed spikes in nutrient concentrations in surface waters during similar thermal events described by Fish (1957), and interpreted them as cyclonic upwelling. When the wind event ceases, the layers return to level position and interchange between the layers becomes small.

Thermal stratification and distribution of nutrients

In Lake Victoria, thermal stratification limits nutrient exchange between surface and bottom waters during its advanced phase (December-April). This limited exchange between the hypolimnion and the epilimnion results in a build up of sedimented and regenerated nutrients in the hypolimnion (Fig. 6.1.4). At the same time, areal total P concentration in the whole water column (0-65 m) and in surface waters (0-20 m) decreased 2 to 4-fold during the stratified period (Table 6.1.3).

However, concentrations of dissolved phosphate and inorganic fixed nitrogen (ammonia, ammonium and nitrite) are low in the epilimnion because of uptake by photosynthetic organisms and sedimentation with minimal return to surface waters as thermal stratification becomes pronounced from December to March.

Temporal variation in total nitrogen and its species are qualitatively similar to phosphorus. Total N concentrations rise to maximum concentrations in September-November and decrease remarkably during the pronounced stratified period (December -April). However, there is loss of regenerated N at the oxic-anoxic boundary in the water column (Hecky *et al.,* 1996; Mugidde, 2001). The deep offshore waters acts as sinks for nitrogen N (Hecky *et al.*,1996). This is because denitrification results in N loss resulting in a mid-water sink of dissolved inorganic N between the nitrate and ammonium maxima in Lake Victoria known to occur in other African Great Lake, lakes Malawi and Tanganyika (Hecky 1993; Bootsma & Hecky 1993).

Spatio-temporal variability of nutrient status

In Lake Victoria, knowledge of nutrient status and limitation is crucial to improvement of the conditions in the lake that has undergone remarkable nutrient enrichment. Knowledge of nutrient status and which nutrient (s) might be limiting phyto planktonic communities enables correct decisions in nutrient control measures that would result in substantial improvements in the water quality and other changes in the altered fish and algal communities. Total nitrogen (TN) to total phosphorus (TP) ratios used as indicators of nutrient status at an ecosystem indicate that phosphorus concentrations are in excess relative to nitrogen in Lake Victoria (Hecky,1993; Mugidde, 2004; Mugidde *et al.,* 2004). The epilimnetic TN: TP ratios varied with season and were in the range 4-42, overall average 15.7±9.3 (Table 6.1.4). Average and minimum TN: TP ratios inshore waters were almost double the corresponding values in offshore indicating that phosphorus was more available offshore than in inshore. The TN: TP ratios varied seasonally, with the highest ratios occurring when the lake was thermally stable and nitrogen N income via biological N-fixation quite high (Mugidde,2001). Low TN: TP ratios occurred on destratification and deep mixing when bottom waters return relatively more phosphorus than nitrogen and lowest ratios occur in the hypolimnion during stratification when TN:TP ratios can be as low as 4. Overall, TN: TP ratios are higher inshore because of N-fixation while TN:TP is lower offshore. Mugidde *et al.*, 2004 conclude that Lake Victoria is N-deficient with deficiency made up through N-fixation but incomplete due to light limitation.

Table. 6.1.4. Minimum, average and maximum total nitrogen (TN): total phosphorus (TP) molar ratios in surface waters of Lake Victoria during 1994-1998

Location	Depth (m)	Minimum	Average	Maximum
Offshore (Bugaia)	Surface (0-10)	8.1	14.5	27.2
Offshore (Bugaia)	Bottom (50-60)	4.4	8.1	11.9
Inshore (Napoleon Gulf)	Surface (0-5)	14.3	29.1	43.2

In Lake Victoria, a potential for N-limitation at an ecosystem scale was suggested by evaluations of ambient inorganic nutrient concentrations in the 1960s (Evans, 1961; Talling & Talling, 1965; Talling, 1966). Further evidence that N may limiting at a community scale in Lake Victoria came from nutrient (P & N) enrichment bioassays that were done to determine algal response to nutrient conditions (Lehman & Branstrator 1993; 1994; Lehman *et al.*, 1998) and from metabolic and compositional measures (Hecky 1993; Mugidde 2001) which give an indication of which nutrient may be limiting in the lake. Nitrogen additions were found to increase algal growth and biomass as chlorophyll-a) in Lake Victoria. The very presence of N-fixing cyanobacteria (Kling *et al.*, 2001; Mugidde 2001; Mugidde *et al.*, 2004) suggests that regeneration and re-mineralization processes alone do not meet the algal nitrogen demand in Lake Victoria. This nitrogen demand is aggravated by nitrogen loss through denitrification and increased excess phosphorus concentrations and is frequently met through biological N-fixation, by the heterocystous cyanobacteria (Mugidde, 2001; Mugidde *et al.* , 2004), as N loading from the watershed is insufficient to support the observed algal production in the lake (Lehman & Branstrator 1993).

Nutrient loading

High nutrient loads into Lake Victoria are characteristic of disturbed watershed where extensive agriculture and land clearing are common (Hecky *et al.*, 2004, Carignan *et al.*, 2000). Indeed, anthropogenic nutrient supply to Lake Victoria has increased (Hecky, 1993; Lipiatou *et al.*, 1996) and atmospheric nutrient chemistry has changed over the African Great Lakes including Lake Victoria (Bootsma *et al.*, 1994)

Recent studies indicate that atmospheric deposition is a large source of P and N to Lake Victoria (Mugidde, 2001; Tamatamah, 2002). Rainfall contributes approximately 5-kilo tonnes t per year of TP into Lake Victoria (Table 6.1.4) and rivers almost twice as much. Total N loads income through rainfall contributes approximately 83-kilo tonnes year^{-1} and half as high much entered through rivers. The magnitude of nutrient loads via precipitation is magnified because the rain contributes about 80% of water budget of Lake Victoria. In situ biological nitrogen fixation is an extremely important source of nitrogen as it brings in approximately 480 kilo tonnes per year of total nitrogen, which accounts for ≥ 60 % of the total nitrogen budget of Lake Victoria (Hecky *et al.*, 1996; Mugidde 2002; Mugidde *et al.,* 2004. High nitrogen income via biological fixation is because nitrogen supply from the hypolimnion is reduced by denitrification and nitrogen from the catchment is insufficient to support algal production (Lehman & Branstrator 1993; Lehman 1996).

Table 6.1.5. Provisional nutrient budgets for Lake Victoria based on inflowing river concentrations using annual mean concentrations, volume weighted concentration of the rain measured at Jinja, Uganda, nitrogen fixation (this assumes 10g y^1 for inshore 40% of lake area and 5g y^1 for offshore 60% of lake area), sedimentation rates and denitrification by difference.

Flux	Total nitrogen (Kt y-1)	Total phosphorus (Kt y-1)
Inputs:		
Rainfall	83[2]	4.82
Rivers	43[3]	9.83
External Total	126	14.6
N Fixation	480[4]	
Total	**606**	**14.6**
Outputs:		
Nile	25	1.8
Sedimentation[5]	78	13.9
Denitrification[6]	503	
Total	**606**	**15.7**

[1]Xin & Nicholson (1998), [2]Bootsma & Hecky, 1999, [3] based on volume weighted concentrations of rain measured at Jinja, Uganda, apportioned to total rainfall, [4]Mugidde, 2001, [5]Cornwell & Giblin (1999), [6]denitrification by difference.

Summary and recommendations

Although increased nutrient (P & N) enrichment and biotic community changes have been invoked to explain the eutrophication in Lake Victoria, the stronger thermal stability in the 1990s (Hecky 1993; Lehman *et al.*, 1998) can also be a contributing factor through its effects on the mixing depth offshore. Offshore, stratification offsets eutrophication due to increased losses through the thermocline. However, mixing can contribute to higher production offshore given that total phosphorus has increased. Inshore, mixing depth are unchanged and are set by the bottom, therefore, depth is not a factor in increases in algal biomass. Complete mixing of the lake occurs around June-July and results in almost uniform distribution of dissolved oxygen and nutrients in the water column. Around July, nutrients, in particular P, from the bottom water reservoir return to the surface layers and relax nitrogen and phosphorus deficiency. In contrast, a stable thermocline (September to April) limits exchange and supply of nutrients from the bottom into the surface waters resulting in higher nutrient concentrations in bottom than in surface waters.

Overall both P and N loads into the lake have increased and contribute to eutrophication in Lake Victoria. Consequently, reductions of P and N through appropriate watershed measures are essential in the reversal of undesirable water quality changes and eutrophication control of Lake Victoria. In particular, reductions in phosphorus loads is key to the control and reversal of eutrophication that threatens the ecosystem health as any reductions in N inputs from terrestrial sources are likely to be offset by increased N input by biological fixation. Phosphorus reduction will lead to reduced frequency of nitrogen deficiency, and reduction in blue-green algal biomass and blooms, including genera known to produce phycotoxins. Reduced biomass will improve the underwater light availability and expand the euphotic zone and also reduce organic loading to the stratified, anoxic deep waters. Reduced P will also allow relaxation of silica demand and return to larger diatoms.

Nutrient reduction into Lake Victoria requires reductions of direct and indirect anthropogenic loads that contribute to enrichment of rivers and to modification of the precipitation chemistry of Lake Victoria. Reduction of nutrient loads requires watershed management and good soil conservation practices aimed at reducing extensive vegetation clearing, soil erosion and vegetation burning. In addition, municipal and industrial effluents should be of acceptable nutrient concentrations and ratios to reduce proliferation of algal biomass and invasive weeds, such as water hyacinth.