CHAPTER SEVEN

Sedimentation in the Ugandan part of Lake Victoria

[1]Mwebembezi, L and [2]Hecky, R. E.*
[1]Water Resources Management Department,
Directorate of Water Development, P.O.Box 19, Entebbe, Uganda
[2]Department of Biology, University of Waterloo, 200 University Avenue, Waterloo, Ontario N2L-3G1, Canada

**Correspondence: mwebembezi.wrmd@dwd.co.ug*

ABSTRACT. *Sedimentation rates were determined from successive sediment trap retrievals that generated 346 samples that were analysed for nitrogen, phosphorus, carbon and silica. The samples from sediment traps were analysed for particulate nutrients, nitrogen (N), phosphorus (P), carbon (C) and silicon (Si). The results indicate that re-suspension did not bias sedimentation estimates if traps were more than 2m above the bottom. Sedimentation rates into traps were highest at littoral stations compared to pelagic stations. For pelagic stations, the settling velocities of particulate P is 0.14 m/d and particulate N is 0.18 m/d which are somewhat higher than the settling velocity of biogenic silicon (BSi), 0.09 m/d. In littoral areas, the settling velocities of P, N and BSi are higher ranging from 0.25 to 0.30 m/d. The composition of the settling material is highly organic and of algal origin. Both inshore and offshore settling velocities are relatively low for sedimentation in large lakes as a consequence of the dominance of slow sinking cyanobacteria throughout the lake. The deeper water column of the offshore sites may also allow for more regeneration of nutrients from settling material than at the shallower inshore sites thus reducing the sedimentation fluxes at pelagic locations relative to littoral fluxes. Inshore sediment cores had generally lower annual sediment burial rates than deep offshore areas of the lake. This indicates that higher rates of nutrient regeneration and resuspension occur from shallow inshore sediments with eventual transport to deeper areas of the lake that have continuous deposition below depths where storm waves can cause resuspension (>40 m). Exceptions to this occur in protected embayments sheltered from strong wave action such as inside the archipelago of islands along the Ugandan shores. Comparison of sedimentation fluxes to traps with permanent burial rates into the sediments as measured in sediment cores indicates that only 10-15% of trapped carbon and nitrogen is permanently buried on an annual basis. In contrast 40% of phosphorus settling into traps is permanently buried with the remainder being recycled into the water column and constituting the internal loading of P into Lake Victoria. The trapped amounts of biogenic silicon are insufficient to account for recent historic rates of burial, and this is consistent with the depletion of soluble reactive Si observed in lake water over the past several decades as a consequence of P enrichment causing eutrophication. Sediment cores indicate that increased loading of P began prior to 1940 and continues to the present. The increased loading of P has depleted dissolved Si in the lake's mixed layer and oxygen in the deeper waters, created a nitrogen demand by phytoplankton that can only be met through nitrogen fixation, and has created conditions where cyanobacteria now dominate sedimentation. Restoration of ecological conditions characteristic of the first half of the last century will require reductions in P loading to rates that occurred at that time.*

Key words: Lake Victoria, sedimentation rates, particulate nutrients, historical change

INTRODUCTION

The depression forming the Lake Victoria basin was a byproduct of crustal uplift associated with the forming of the Albert Rift Valley to the west and crustal doming of the Kenya highlands, also caused by rifting activity, to the east (Scholz *et al.* 1990). These earth movements led to reversal of the formerly westward flowing rivers along the lakes western margin, and the impoundment of the waters forming Lake Victoria which overflowed to a new northern outlet near Jinja, the Victoria Nile River. The basin is shallow compared to some of the deep rift valley lakes of East Africa, but it is expansive currently holding the world's second largest freshwater lake. The rivers coming to the lake and the rain and dust fall on the lake deliver materials to the basin that can be processed by biological organisms within the lake or simply settle to the lake bottom. Lake Victoria is slowly flushed as evaporation accounts for most of the water leaving the lake while the River Nile outflow is a minor portion of the water budget. Consequently only small amounts of materials entering the lake are flushed out through the River Nile and most of the incoming materials are either processed into gaseous forms (for example degradation of organic materials to carbon dioxide) or settle to the bottom of the lake.

Knowledge of the rate of loss of materials through sedimentation is critical to the determination of the mass budget of nutrients, the fate of pollutants, and the estimation of relative importance of internal loading of nutrients and pollutants relative to external loading. The sediments that eventually accumulate on the lake floor also provide an opportunity to reconstruct the past history of the lake from microfossils and other sediment indicators that are essentially archived in the lake sediments. From the study of sediment cores, it is also possible to correlate ongoing water quality changes, e.g. changes in biota that leave fossil remains, with changes in nutrient sedimentation. Dating of core sediment made possible through radioactive decay of natural radioisotopes establishes the timing of changes in sedimentation rates of nutrients elements and the microfossil changes and allows historical reconstruction of the changes in water quality.

Sedimentation is the settling of particulate matter produced in the catchment and in the lake (e.g. dead plankton, calcium carbonate, diatom shells, faecal pellets from zooplankton and fish). It includes the mud, silt and sand from rivers and shore erosion, but this is a minor part of the sedimentation on a lake-wide basis in Lake Victoria because much of the coarser material delivered by rivers is retained in deltas and wetlands. Farther away from river mouths, biological processing of nutrients within the lake produces most of the sediment that settle through the water column and is eventually permanently buried in the deeper areas of the lake.

Sedimentation in Lake Victoria has been studied under the Lake Victoria Environmental Management Project. However the studies started much later in the Project. Effort was put on measuring sedimentation rates and riverine sediment loads since equipment to carry out other detailed activities on bottom lake bottom sediments was procured too late in the project for training to be accomplished in time for this report. However, the sediments of Lake Victoria have received a great deal of study by international investigators interested, not only in the long term history of the lake and its response to climatic change (e.g. Johnson *et al.* 1996; Verschuren *et al.* 1998), but also investigating more recent changes in the lake recorded in the lake's sediments related to anthropogenic impact and climatic variation (Verschuren *et al.* 2002; Campbell *et al.* 2003). This chapter synthesizes what is known about sedimentation in Lake Victoria from all available sources.

Particulate matters in lakes are derived from import from the catchments and the atmosphere and from in-lake biological production. Particles can be inorganic, deriving from erosion of soils in the catchments and shorelines in the lake or by chemical precipitation, or they are organic particles, produced by primary production and further metabolised through the food chains in the catchments and in the lake. Particles with density higher than lake water sink to the sediment floor and can be captured by sediment traps. During sinking the organic particles can be decomposed, and the observed settling flux can decrease with the trap exposure depth in deep water columns. Decomposition can also occur within the traps. By reducing the exposure time to 1 - 2 days the decomposition of organic matter in the traps become negligible compared to the mineralisation during sinking. Close to the sediment floor the traps may also catch re-suspended particles from the bottom dependent on the shear stress from waves and currents and the cohesive forces between the sediment particles. Sediment traps work best in quiescent water columns where the presumed vertical path of settling material is best approximated. Measurements in turbulent water or water affected by currents can lead to over-harvesting of materials from water moving over the opening of the trap. Therefore traps are best deployed well below the turbulent mixed layer, and they must have sufficient length to insure a still water column within the trap. The closer to the bottom the traps are placed the more they can represent the materials actually delivered to the sediment surface; but if placed too close to the bottom, they may sample re-suspension events and overestimate downward sedimentation.

Once deposited onto the bottom surface, mineralisation continues. Dissolved nutrients are released to the pore water and come under control of sorption equilibria and molecular diffusion along concentration gradients so that the dissolved nutrients can move upwards or downwards and be further affected by bacterial uptake, redox reactions, nitrification, and denitrification. The relative importance of sedimentary processes compared to processes in the water phase increases with hydraulic residence time and decreases with water depth. Lake Victoria has a long residence time, 100 years, and has a relatively low average depth, 40 m. Consequently, sedimentary processes become very important as the primary loss term in the Lake Victoria mass balance, justifying the comprehensive sediment sub model as an important part of the Lake Victoria Water Quality Model. Pore water concentrations, labile and stable particulate nutrient fractions and diffusive fluxes are state variables and processes constituting important parts of the sediment model, but to date have received very little study in Lake Victoria.

Sediment trapping studies in Lake Victoria reported here have emphasized short term exposures of sediment traps at depths where re-suspension is expected to be negligible and the comparison of those results with long term permanent burial as estimated from sediment cores. The difference between the sedimentation flux measured in traps and the rates of permanent burial for the whole basin provide estimates of the recycling of nutrients sedimenting particles within Lake Victoria. Such estimates require experimental determination of sediment-water fluxes under aerobic and anaerobic conditions to further refine and confirm the rates and locales of recycling within Lake Victoria. These detailed laboratory studies are yet to be undertaken as necessary equipment and training were not available during LVEMP's first phase.

MATERIALS AND METHODS

Pelagic Stations-Number and Frequency

There are 10 pelagic stations in Ugandan Portion of Lake Victoria where sedimentation trap measurements were taken (UP1 – UP10) (Figure 1). Six of these stations were to be sampled on a monthly basis while all the 10 stations were to be sampled on quarterly basis. This was the original plan in accordance with the agreed regional program (LVEMP 2002). The stations over the entire lake were set up along defined grids of 20 km by 20 km. However the actual deployments and retrieval of sediment traps at these stations was much less than what had been planned due to a number of external factors. Hence the total number of successful deployments was 56.

Duplicate sediment traps with a diameter of 8.4 cm and an aspect ratio >5 were mounted on an anchored rope kept vertical with a subsurface buoy on a taut line and connected to a marking buoy. Three sets of traps were placed at each station:

- At the bottom of the photic zone (2.2 x secchi depth)
- 2 m above the sediment
- One set in between the two.

Initially, duplicate traps were exposed at depths of 0.2, 0.4, 0.6 and 0.8 m above the bottom to determine the re-suspension layer (LVEMP 2002). After 1 - 2 days of exposure the traps were retrieved and the trapped particles were sub sampled and collected on GF-C glass fibre filters (pore size 1 µm) to be analysed for filterable total suspended solids (TSS), particulate phosphorus (P), particulate (N) and particulate carbon (C), and also collected on Nucleopore membrane filter (pore size 0.45 um) to be analysed for biogenic silica (BSi) that is produced primarily by diatoms, an algal group that secretes a silica shell. The settling fluxes can then be calculated in $mg/m^2/d$ based on the trap area and exposure time and after correction for the particulate content initially in the water in the trap.

Littoral Stations-Number and Frequency

There are 9 littoral stations in Ugandan Portion of Lake Victoria where measurements were taken (UL1 to UL9). Seven of these stations were to be sampled on a monthly basis while all the 9 stations were to be sampled on quarterly basis. This was the original plan in accordance with the agreed regional program. However the actual deployments and retrieval of sediment traps at these stations was much less than what was achieved on a monthly basis due to a number of external factors. Hence the total number of total successful deployments was 72. Trap design, deployment and measurements were the same as for the pelagic traps.

Sediment cores

Sediment accumulation is not uniform over the bottom of Lake Victoria. Coarse sediments such as gravels, sands and coarser silts are retained in deltas near river mouths. Sandy and rocky bottoms are found in depths of about 40 m and beyond depending on the wave and current energies available to transport fine and coarse materials. High resolution echo-sounding and seismic reflection profiling indicate that there is little accumulation of fine sediments (organic particles, phytoplankton debris, fine silts and clays) in water depths less than 40 m because of re-suspension by wave energy at shallower depths (Kalff 2002) and transport to more quiescent deeper areas of the lake (Scholz *et al.* 1990; Scholz *et al.* 1998). Exceptions to this generalization of depth control on fine sediment accumulation are protected embayments especially in the archipelago of islands off the Ugandan mainland. Where fine sediments accumulate, it is possible to recover sediment cores with well-preserved stratigraphy that can be dated by radioisotope techniques so that rates of sediment accumulation can be measured. Several cores have been taken in Lake Victoria by international investigators and a few have been analyzed for their nutrient content as well as being dated using radioisotope techniques. These cores provide evidence of historical changes in Lake Victoria (Hecky 1993; Verschuren *et al.* 2002) as well as evidence of changes over the prehistoric period including the drying up of Lake Victoria about 12,000 years ago (Johnson *et al.* 1996). Inshore cores from Itome Bay (Campbell *et al.* 2003) taken at a depth of 25 m and Muubale Bay (Hotzman and Lehman 1998) from 23 m depth are used to characterize inshore sedimentation while Core 103 from 56 m near Kenya and various offshore locations from depths 57 to 68 m are available to characterize the offshore (Table 1).

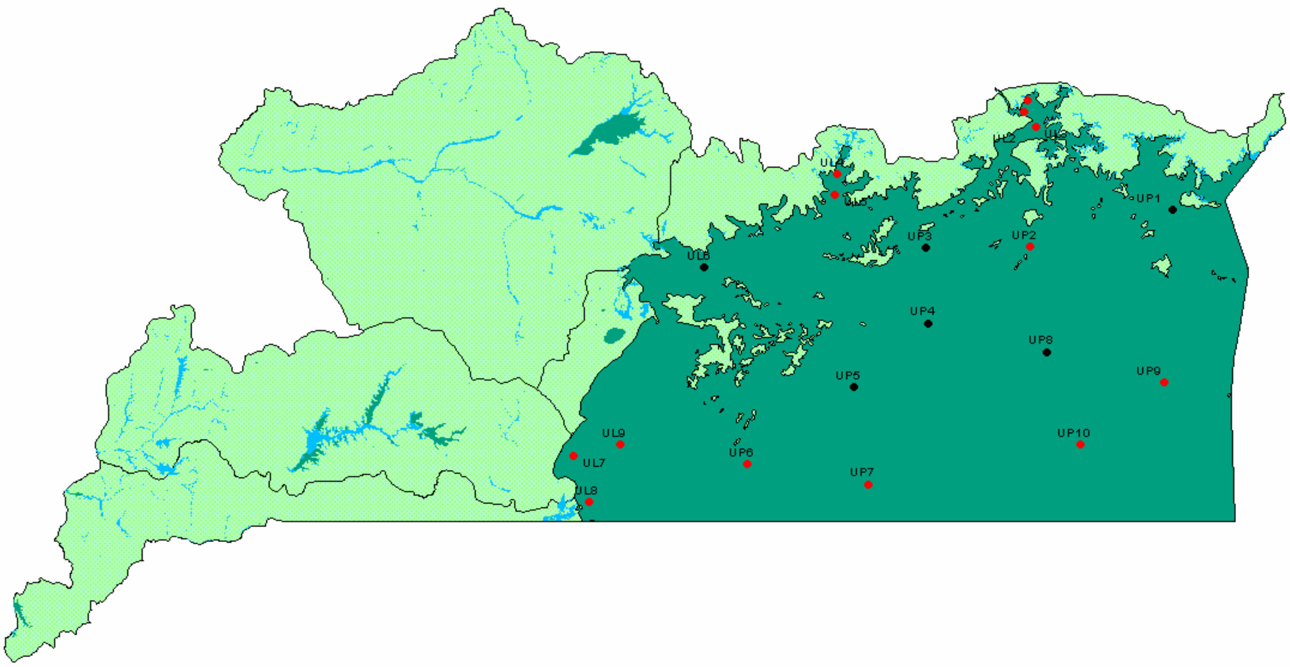

FIG. 1. Stations in Lake Victoria (Uganda Portion).

RESULTS AND DISCUSSIONS

Comparison of Pelagic and Littoral Stations

Composition of Sedimenting Materials

To determine the composition of the settling materials, regressions were performed on the data for nutrient content of sedimenting material (Figure 2.). High correlation of particulate N, P and biogenic Si with carbon (C) indicates that the sedimenting materials are of organic origin and the low intercept values of the regression lines on the y-axis indicate that there is little contribution of inorganic P compounds to the sediments. The stoichiometric relationship for pelagic settling material can be calculated as 666:91:1:5 as C:N:P:Si (molar ratio). These C:P and N:P ratios are much higher than reported by Guildford and Hecky (2001), C:N:P 149:18:1, for suspended materials in near-surface waters of Victoria where algal growth rates are high and would indicate that the dead settling material rapidly loses P back into solution during sedimentation. The low Si content suggests that settling diatoms are a very minor fraction of the settling material in these trap samples. The stoichiometry for littoral stations calculated from regression relationships yields a generally similar composition 444:61:1:4. The lower C:P and N:P ratios at littoral stations likely reflect the shallower depths of water over the traps and less time for regeneration of P from the settling material.

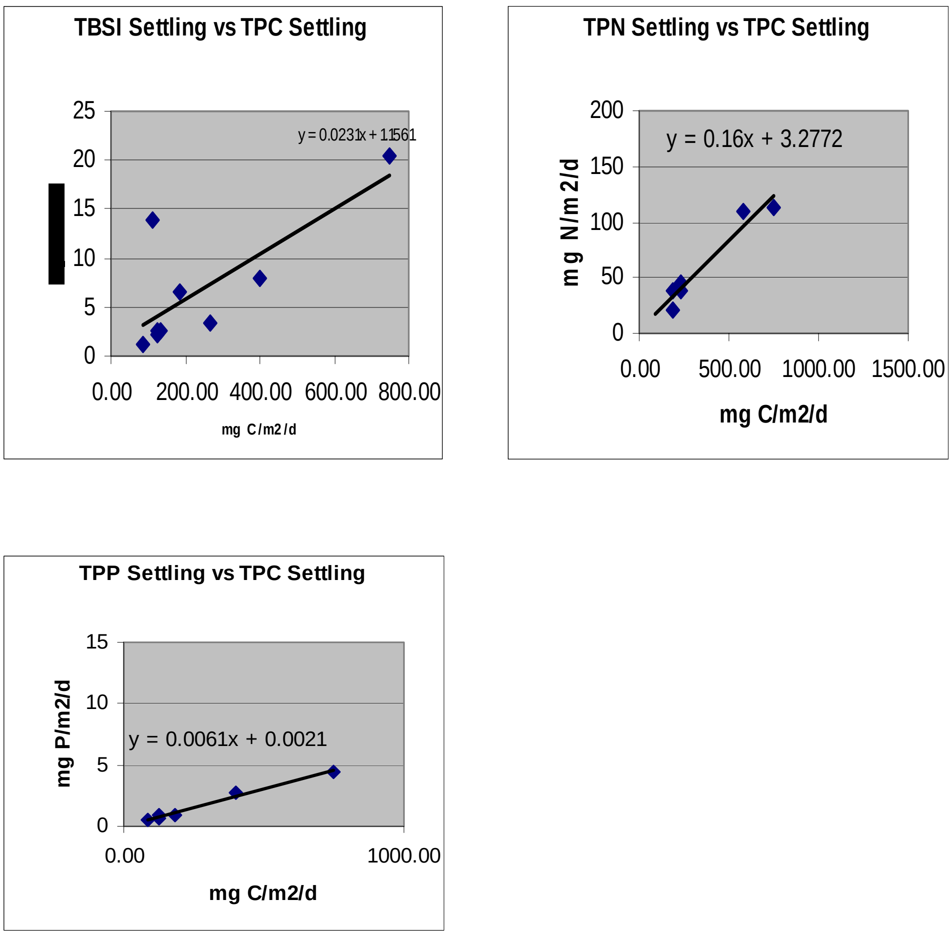

FIG. 2. Linear regressions relations for nutrient fluxes in settling material.

Areal Flux Rates

The average areal downward flux rates for sedimenting material for pelagic and littoral stations are given in Table 1. Flux rates are substantially higher on average in littoral stations. This is expected because algal growth is higher in inshore waters and consequently concentrations of biogenic particles are higher for example chlorophyll concentrations (a measure of algal biomass) on average are twice as high inshore as compared with offshore locations (Mugidde *et al.* 2003). The higher particle production near shore and the shorter water column over which decomposition can occur result in the higher sedimentation flux rates at littoral stations.

TABLE 1. Mean sedimentation flux rates for pelagic and littoral stations.

	TPP $mg/m^2/d$	TPN $mg/m^2/d$	TPC $mg/m^2/d$	TBSi $mg/m^2/d$
Pelagic Stations	1.56	41.02	283.32	7.45
Littoral Stations	5.92	78.67	777.03	20.17

Settling Velocities

The settling velocities for pelagic stations are obtained from the slope of regressions between sedimentation rates ($mg/m^2/d$) and the particle concentration at the exposure depth (mg/m^3). Although there is scatter in the data, the slopes for the individual nutrients yield similar settling velocities (m/d) (Figure 3).

The settling velocity of P is 0.14 m/d and the one of N is 0.18 m/d which are somewhat higher than the settling velocities of BSi of 0.09 m/d. This means that for pelagic stations the sedimentation of diatoms, the only phytoplankton group contributing BSi, is a relatively unimportant contributor to the settling of material at the pelagic stations.

The settling velocities of P, N and BSi at littoral stations are of the same magnitude ranging from 0.25 – 0.30 m/d but somewhat higher on average than the pelagic stations. These settling velocities are nearly double the pelagic rates despite the similarity in their elemental composition. The higher rates may imply that the settling particles are of larger linear dimension at inshore stations than at the pelagic stations. In general larger diameter particles of similar composition settle more rapidly (Kalff 2002). The settling velocities calculated for both pelagic and littoral stations are relatively low for phytoplankton communities, e.g. large heavily silicified diatoms can sink at rates of 6-10 m/d, but cyanobacteria, the dominant phytoplankton group currently in Lake Victoria are nearly neutrally buoyant so the slow velocities estimated are reasonable. However, slow settling velocities result in longer times necessary to clarify the water column if algal growth slows and this contributes to the reduced visibility reported currently in Lake Victoria as compared to earlier in the last century (Hecky 1993).

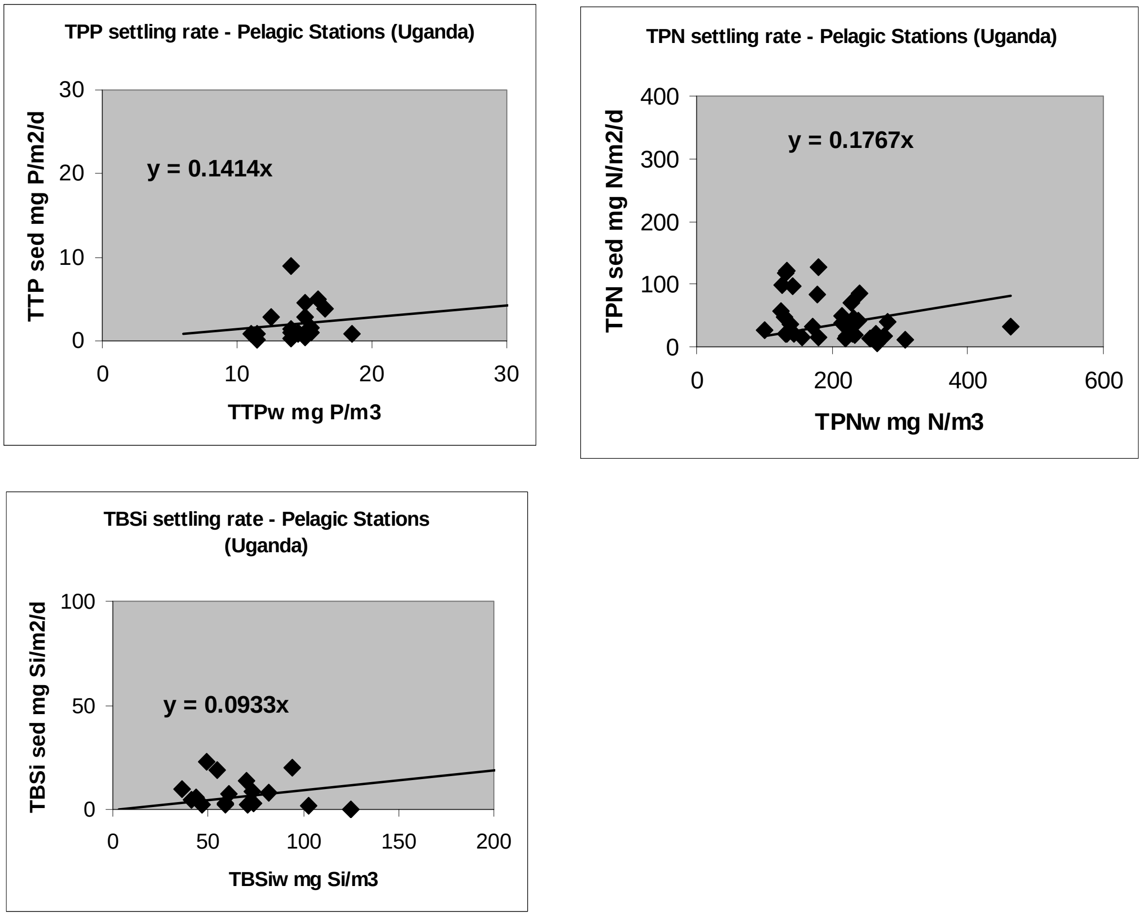

FIG. 3. Regressions of areal sedimentation fluxes for P, N and BSi on initial particulate concentrations of those elements at the depth of the trap. Slopes of regressions yield estimates of settling velocities.

Sediment accumulation rates as measured in sediment cores

Sediment accumulation rates in Lake Victoria cores that have been dated (Table 2) range from 100 g m^{-2} y^{-1} to over 300 g m^{-2} y^{-1} as dry weight accumulation. In terms of linear rates these are comparable to rates of about 0.5 to 1 mm per year. These rates are comparable to or somewhat higher than observed in other great lakes (Kalff 2002), and infilling of Lake Victoria through sedimentation is not a concern although infilling in the vicinity of deltas may be accelerating as more sediment is delivered by rivers than occurred historically. The sediment accumulation rates in cores represent longer term averages compared to the sedimentation traps. When sampling cores, a centimetre slice can represent 5-10 years of sediment accumulation in the lake. The longer time integration during sediment burial of the estimated rates allows continued decomposition to affect the sedimentation fluxes. Another limitation when comparing sediment burial rates to sediment traps is that very recent changes in sedimentation may not be apparent as they are mixed with several previous years of sediment accumulation. However, the accumulation rates measured in cores represent permanent burial of materials (below the upper few millimetres of recently deposited material). In comparison the material measured in traps is still subject to further decomposition and re-suspension prior to permanent burial. The sediment accumulation rates and the dependent nutrient accumulation rates provide an estimate of the permanent loss of these nutrients from the lake by burial.

Permanent accumulation of fine organic sediments is largely restricted to depths greater than 40 m. At depths less than 40 m (Scholz *et al*. 1998), wave and current energy is adequate to re-suspend the fine organic sediments and transport them to more quiescent waters at deeper depths. This phenomenon is referred to as sediment focussing (Kalff 2002) and occurs in all lakes.

Its affect is strong in Lake Victoria because of the shallow depths over much of the basin and the lake's large size that results in high wave energies applied to much of the lake's surface area. The area of the lake bottom with depths in excess of 40 meters where fine sediments may accumulate is 36,400 km^2 or approximately one-half of the surface area of Lake Victoria. There are some shallower basins where fine sediments accumulate in protected embayments (such as Itome and Muubale in Table 2) but these represent a small proportion of the total area of the lake. Most of the sediments settling onto the bottom at depths <40m will be re-suspended, become subject to further decomposition, and eventually be transported to greater depths before permanent burial.

The average sedimentation flux of nutrients as measured during short term exposure of traps generate much higher estimate of the downward flux of nutrients than is realized in cores when the mean daily trap rates are extended over a full year (Table 3) to be comparable to core measured rates. The accumulation rates realized in both inshore and offshore cores are similar indicating similar conditions and microbial processing during burial and the nutrient ratios in the buried sediments are more similar to each other than to the trap material (C:N:P:Si of 310:24:1:37 for littoral cores and 206:16:1:65 for pelagic cores. After sedimentation on the lake bottom and subsequent burial in the cores, C and N continue to be regenerated from the sediment while P and Si are relatively retained compared to the material settling into traps. Much of the C and N regenerated from the sediments can eventually be lost from the lake as CO2, CH4 and N2 gases because of microbial activity especially under low oxygen conditions that occur over these organic sediments and in the water column in pelagic areas.

The annual sedimentation flux of P as estimated in traps at the deeper pelagic stations where the traps are deployed deeper in the water column than in littoral stations agrees more closely with the burial rates in the deep pelagic cores. This would be consistent with the view that most of the P regeneration is accomplished within the water column. Once permanently deposited at deep stations, the P may be retained by microbial demands in these organic rich sediments (15-20% organic C).

TABLE 2. Sediment cores from Lake Victoria that have been dated using Pb-210 chronology. Data sources are:1) Delft Hydraulics 1999, 2) Verschuren et al. 1998, 3) Hecky 1993, 4) Campbell et al 2003 and 5) Holtzman and Lehman1998. Locations of cores given in Figure 1.
Cores XL1-1A and XL1-2 are from the same location. Biogenic silicon (BSi) from same sources or Hecky (unpublished). TP from Hecky (unpublished). Nutrient content on a dryweight (mg/g d.w.) basis for uppermost sediments and sedimentation rates (sed) for those nutrients. Sedimentation rates for Mubaale core are inferred from other cores and were not dated by Pb-210.Sedimentation rates for C,N,P and Si are based on composition of the most recent sediments.

Core	Depth m	Dry wt sed. G m^{-2} y^{-1}	TP Mg/g	BSi Mg/g.	TC mg/g	TN mg/g	P sed. g m^{-2} y^{-1}	C sed. g m^{-2} y^{-1}	N sed. g m^{-2} y^{-1}	BSi sed. g m^{-2} y^{-1}
Littoral										
P2K4	8	150								
NG-1	16	100								
Bill-2	23	180								
Mubaale	23	170	1.0	11	120	9.8	0.2	20	1.7	2
Itome	25	276	1.8	97	203	20.7	0.5	56	5.7	27
MEAN		**175**					**0.3**	**38**	**3.7**	**14**
Pelagic										
103	56	110	1.9	180	163	15.7	0.2	18	1.7	20
XL12	57	183	2.0		164	14.4	0.4	30	2.6	
XL10A	61	200	7.3		135	10.0	1.5	27	2.0	
95-1G	64	280	3.0	120			0.8			34
XL1-1A	66	199	1.3		164	13.9	0.3	33	2.8	
XL1-2	66	186								
96-5MC	68	320	2.7	100	200	17.3	0.9	64	5.5	32
MEAN		**211**					**0.7**	**34**	**2.9**	**28**

TABLE 3. Comparison of mean annual sediment flux rates for C, N, P and BSi in traps with accumulation rates in cores.

	C ($g\ m^{-2}\ y^{-1}$)	N	P	Si
Littoral Traps	284	28.7	2.2	7
Littoral Cores	38	3.7	0.3	14
Pelagic Traps	103	15.0	0.6	3
Pelagic Cores	34	2.9	0.7	28

The sediment flux of nutrients as caught in traps can be considered an estimate of gross output of the contained nutrients from the productive layer of the lake. The comparison of this flux on an annual basis with the permanent burial of these materials provides an estimate of the potential recycling of these nutrients back into the productive layer and an estimate of the internal loading of nutrients that can be compared with external loading rates. If the mean littoral flux (Table 3) is applied to the area of the lake within the 20 m bathymetric contour (16,300 km^2) and the pelagic sedimentation flux to traps applied to the remaining area of the lake (48,800 km^2), then a total down flux of settling material out of the productive zone of the lake can be estimated (Table 4). Considering only the area of sediments >40 m as permanently accumulating sediments then 85-90% of the sedimenting C and N is regenerated and only 10-15% of the sedimenting mass is permanently buried. In contrast, 40% of sedimenting P is buried, and there is a deficit of sedimenting biogenic Si (Table 4).

TABLE 4. Comparison of total annual downflux from traps with permanent burial of the contained nutrients for all of Lake Victoria. Areas from http://sciborg.uwaterloo.ca/research/uwaeg/maps/victoria.htm

	Area	C	N	P	Si	C	N	P	Si
	km^2	g m-2 y-1				kilotonnes/year			
Littoral Zone <20m	16,910	284	28.7	2.2	7	4,796	486	37	124
Pelagic Zone >20 m	48,800	103	15.0	0.6	3	5,046	731	28	133
Total sedimentation flux	65,710					9,842	1,216	64	257
Permanent Burial >40m	36,400	34	2.9	0.7	28	1,249	107	24	1,036
Internal Loading						8,593	1,109	40	-779

Hecky (1993) compared historic dissolved Si concentrations with recent data and demonstrated a substantial drawdown of dissolved Si concentrations over the last 50 years. Burial rates of biogenic Si in the past have exceeded the amounts of Si entering Lake Victoria, and the apparent current deficit in sedimenting BSi is consistent with the depletion of BSi in the lake. Current rates of BSi sedimentation, as measured in the sediment traps, are much lower than the recent rates of burial. The declining soluble Si concentrations have caused changes in the diatom community (Kling *et al.* 2001) with a shift toward thinly silicified species that have slow sedimentation rates.

Historical changes documented in sediment cores

The rates of accumulation in sediment cores given in Table 2 are recent rates determined from the composition of the most recent sediments and the sedimentation rates of the cores. There is yet no evidence that the rate of accumulation of sediments in Lake Victoria have changed over the last few decades in response to eutrophication. Campbell *et al.* (2003) discuss this possibility in regard to the Itome core and the 96-5MC cores (Table 2) and concludes that the changes may be too recent to detect with the radioisotope dating methods used as these methods necessarily integrate multiple years in the dating process. However, the nutrient content of Lake Victoria sediments has changed over time with very significant changes over the last 50 years. Hecky (1993) first reported on these changes from core 103 from Kenya waters. The rise in biogenic Si in this core was consistent with the decline in dissolved Si compared to 1960’s and the rise in the P content of the core also was of the same magnitude as he reported for total phosphorus concentrations in lake water. These changes were consistent with classical changes reported in other large lakes in response to nutrient enrichment (Hecky 1993).

Since that first report on recent changes recorded in Lake Victoria core, other sediment cores have been taken and analyzed in Ugandan waters. The first inshore core for which a record of change in sediment composition is available comes from Itome bay in Uganda. This core shows the same increase in BSi and P concentration, and the increases are of similar magnitude and timing as in the 103 core. Offshore changes in sedimentation of P in core 96-5MC are somewhat delayed compared to the inshore location but the increases are subsequently more dramatic. Verschuren *et al*. (2002) reported that significant increases in biogenic Si concentrations became evident in the 1940’s in the 96-5MC core and that deoxygenation at the coring site is detectable by the change in animal microfossils in the core as early as the 1960’s which would be concurrent with the increases in P. All these cores indicate that sedimentation of P and Si have increased over the last half of the past century and continue at historically maximally high rates. Although soluble Si concentrations have decreased since 1960 as sedimentation exceeded supply, the total phosphorus concentrations in Lake Victoria waters have actually risen, approximately doubling in that period. These changes in nutrient availability have caused changes in the algal communities (Kling *et al.* 2001) as large rapidly sinking diatoms of the genus *Aulacoseira* (formerly *Melosira*) have been replaced by the thinly silicified forms of slow sinking *Nitzschia* in Lake Victoria’s accumulating sediments. This change in diatom community has been accompanied by the increase in cyanobactera taxa (*Anabaena, Cylindrospermopsis, Microcystis and Planktolyngbya*) that now dominate the algal biomass. These cyanobacteria do not leave recognizable microfossils in the sediments, but Kling *et al.* (2001) documents the dramatic increase in abundance of these cyanobacteria since the 1960’s. These cyanobacteria are inefficiently used by aquatic biota and can also be toxic to animals including humans. Their increase is also used globally as an indicator of eutrophication.

CONCLUSIONS AND RECOMMENDATIONS

The results obtained from this study show that sedimentation flux rates in the water column are higher at littoral stations compared to pelagic stations. Settling velocities are also higher at littoral stations probably because settling particles are larger since they are compositionally similar to pelagic settling material. The higher biomasses of cyanobacteria and their detritus in shallow waters is responsible for this pattern. The high abundances in shallow waters is a result of the shallower mixing depths that relieve the light limitation present in more deeply mixed offshore waters. Better light conditions allow biological nitrogen fixation by some species of cyanobacteria to relieve nitrogen limitation in the phytoplankton community. Despite higher sedimentation fluxes in the shallower areas of the lake, highest rates of sediment permanent accumulation occur in the deepest areas of the lake >40 m. Eighty to ninety per cent of the sedimenting C and N to the bottom is returned to the water column as dissolved nutrients, but only sixty percent of the sedimenting P is similarly regenerated on a lake wide basis. Current sedimentation flux for BSi is less than the longer term estimates of BSi accumulation measured in sediment cores indicating the Si depletion remains severe and may limit diatom production.

The recent enrichment of the lake by P is evident in sediment cores from both shallow and deep waters. This enrichment caused increased deposition of biogenic Si in sediments and depleted the dissolved Si in the lake. The diatom community response to these changes over the last 50 years is evident in the change in microfossils deposited in the sediments. Away from riverine deltas (not investigated by this study), sedimentation in the lake is now determined by the productivity of the slow settling cyanobacteria. To restore the lake to earlier ecological conditions of the past century it will be necessary to reduce phosphorus loading to rates that occurred at that time.

References

Campbell, L.M., Hecky, R. E., Mugidde, R., Dixon, D. G. and Ramlal, P. S. 2003. Variation and distribution of total mercury in water, sediment and soil from northern Lake Victoria, East Africa. Biogeochemistry 65:195-211.

LVEMP. 2002. Integrated Water Quality and Limnology Study of Lake Victoria – Final Report. COWI Planning and Consulting Engineers- LVEMP Entebbe. 258 pp.

Delft Hydraulics, IHE Delft and Hydroqual. 1999. Preparation of a Preliminary Lake Victoria Physical Processes and Water Quality Model. Final Report to World Bank.

Guildford, S.J. and Hecky, R.E. 2000. Total nitrogen, total phosphorus and nutrient limitation in lakes and oceans: is there a common relationship? Limnol. Oceanogr. 45:1213-1223.

Hecky, R.E. 1993. The eutrophication of Lake Victoria. Verh. Internat. Verein. Limnol. 25: 39-48.

Holtzman, J. and Lehman, J.T. 1998. Role of apatite weathering in the eutrophication of Lake Victoria, pp. 89-98. In Lehman, J.T. (ed.) Environmental change and response in East Africa lakes. Kluwer, Netherlands.

Johnson, T.C., Scholz, C.A., Talbot, M.R. Kelts, K., Ricketts, R., Ngobi, G., Beuning, K. Ssemmanda, I. and McGill. J.A. 1996. Late Pleistocene desiccation of Lake Victoria and rapid evolution of cichlid fishes. Science 273:1091-1093.

Kalff, J. 2002. Limnology - Inland Water Ecosystems. Prentice Hall, New Jersey.

Kling, H.J., Mugidde, R. and Hecky, R.E. 2001. Recent changes in the phytoplankton community of Lake Victoria in response to eutrophication, p.47-66. In Munawar, M. and Hecky, R.E. (eds.). Great Lakes of the World: Food webs, health and integrity. Backhuys, Leiden.

Mugidde, R., Hecky, R.E., Hendzel, L. and Taylor, W.D. 2003. Pelagic nitrogen fixation in Lake Victoria, Uganda. Journal of Great Lakes Research 29(2):76-88.

Scholz, C.A., Johnson, T.C. Cattaneo, P., Malinga, H, and Shana, S. 1998. Initial results of 1995 IDEAL Seismic reflection survey of Lake Victoria, Uganda and Tanzania, pp. 47-57. In Lehman, J.T. (ed.) Environmental change and response in East Africa lakes. Kluwer, Netherlands.

Scholz, C.A., Rosendahl, B.R., Versfelt, J. and Rach. N. 1990. Results of high-resolution echo-sounding of Lake Victoria. J. African Earth Sci. 11:25-32.

Verschuren, D., Edgington, D.N. Kling, H.J. and. Johnson, T.C. 1998. Silica depletion in Lake Victoria: Sedimentary signals at offshore stations. J. Great Lakes Res. 24:118-130.

Verschuren, D., Johnson, T.C., Kling, H.J., Edgington, D.N., Leavitt, P.R., Brown, E.T., Talbot, M.R., and Hecky. R.H. 2002. The chronology of human impact on Lake Victoria, East Africa. Proc. R. Soc. Lond B 269: 289-294.