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Lake Basin Management Initiative
Thematic Paper

African Lake Management Initiatives: The Global Connection

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1. Introduction

All African lakes, large and small, have great significance to their riparian populations and the nations in which they lay for providing protein from fisheries, water for agricultural, domestic and drinking use, transportation for commerce, and recreational use. The three largest lakes in Africa, Victoria, Tanganyika, and Malawi/Nyasa (hereafter referred to as Malawi) offer similar benefits, and their very size certainly amplifies the numbers of people and the number of countries that depend upon them for their beneficial uses. The Victoria catchment is shared by approximately 30 million people living in five countries, and it exports critical quantities of water downstream to the Nile and fishes to a global market. The other two lakes are shared by three (Malawi) and five (Tanganyika) countries and are headwater lakes to the Zambesi and the Congo Rivers whose outflows sustain downstream benefits to many other users outside their catchments. These three great lakes in addition have evolved remarkable endemic biodiversity with nearly 10% of all the planet's freshwater fish species occurring within them making them globally significant gene banks. The multi-national distribution of benefits, and the potential losses of such benefits if the lakes are degraded, places these lakes in a class of their own with regard to management challenges. Lakes everywhere come under stress as human populations in their catchments increase, demands for natural resource extraction grow and industrialization impacts spread through economic development, and this is equally true on these great lakes. In recognition of the international scope of the management challenge posed by these great lakes and the global benefits they provide, the Global Environmental Facility (GEF) and its national and international funding partners have funded extensive studies and analysis of these lake ecosystems through the mid to late 1990's extending up to the present.

The achievements and shortcomings of those GEF projects are reviewed in case studies presented at this workshop. In aggregate, those studies and other studies around the world have revealed that some of the challenges to successful management of these great lakes extend beyond their catchments and that regional or even global action will be necessary to maintain or restore many of the lakes' beneficial uses. Smaller lakes are likely also being impacted by these regional and global scale threats although other more immediate impacts may be of greater concern at present. The thesis of this paper is that there is a global dimension to lake management in Africa, and elsewhere, that will require concerted action by, not only individual riparian states, but also regional, continental and global communities. Current threats arise from global climate change, land degradation and contaminants, and they share the common feature that the atmosphere is the vector that spreads their impact over large areas and to many lakes.

2. Hydrologic sensitivities

The African Great Lakes occupy a large proportion of their catchments, and their huge surface area allows precipitation (P) directly on their water surface and evaporation (E) from their surface to dominate the gains and losses of their water budget (Table 1). This is as true of the deep rift valley lakes as in the shallow Victoria that occupies a depression between uplifted sides of the rift valleys on either side. However, unlike Victoria, the deeper lakes are permanently stratified which results in the accumulation of high concentrations of nutrients in the deep waters (Bootsma and Hecky 1993). In all three lakes direct rainfall accounts for well over 50% of all inputs, with Victoria being the most extreme because inflowing rivers (I) account for only 15% of total water input. In terms of the water budget, E is the greatest water loss with river outflow (O) accounting for 15% or less of total water loss. However, the maintenance of the lake levels as open drainage basins is dependent on river inputs as the P/E balance over the lake surface area is negative for the two deep lakes or just in balance for Victoria.

Rainfall in eastern Africa is relatively low over most of the terrestrial catchments of these lakes, although the lakes themselves generate higher rainfall over the lakes than the average over the catchment (Nicholson and Yin 2002). Evaporation is highly sensitive to over-lake wind regimes that are still poorly known. Most recent estimates of evaporation over the lake are higher than published values, largely as a result of better definition of diurnal and offshore wind regimes (Hamblin et al 2002; Verburg and Hecky 2003). The water level history of these lakes as recorded for the past century (Fig. 1) and inferred from historical accounts over the previous century indicates how dynamic the water balance of the lakes can be. Lake Malawi was a closed basin from 1915-1930 (and nearly again in the late 1990's), Tanganyika was closed when the Lukuga outlet was first observed by Europeans and Victoria had its highest documented stand at about the same time in the early 1880's (Nicholson 1998). Over longer periods, the variability of lake levels is even more dramatic, with Lake Victoria desiccating around 12,000 years ago (Johnson et al. 1996) when Tanganyika (Haberyan and Hecky 1987) had much lower levels and many smaller lakes in eastern Africa had low water stands or were also desiccated. Grove (1996) has previously commented on two apparent synchronies in the level records of these three large lakes: 1) the very high stands of the early 1960's (a period of record high rainfall in eastern Africa) and 2) declining levels (and associated river discharges) since the 1980's. Both Tanganyika and Malawi have returned to their pre-1960's water level, but Victoria has not. The persistence of Victoria at higher than 1960 levels is still anomalous although it has engendered optimism that the lake has found a new long term level that can be harvested as increased hydroelectric generation at the Owen Falls generating stations at its outlet. Let us hope the optimism is well-founded.

3. Climate Change

The water level records of the three lakes over decades, centuries and millennia indicate that the lakes do respond sensitively to changes in rainfall and evaporation. Even in their modern condition, they are barely open lakes with flushing times of over 100 years for Victoria to over 7000 years for Tanganyika (Bootsma and Hecky 1993). When they fall below their outlet, they will fall to a level where evaporative losses are balanced by water inputs making the lakes very sensitive recorders of P/E over geologic time. However, the lakes can also be affected by changes in their surface heat budget even when levels are relatively constant. Verburg et al (2003) have recently shown that Tanganyika has been warming through the last century and warming at relatively high rates since 1980 in response to globally (and regionally) rising air temperatures. Density change per degree of warming increases rapidly as temperatures rise, therefore small changes in temperatures in tropical lakes can result in significant changes in the stability of thermal stratification (Hecky 2000). Because the Tanganyika does not mix throughout its depths annually its upper waters have warmed more rapidly than the deep waters with the result that the density stratification of the lake has been strengthened and interchange with the deeper metalimnion and hypolimnion has been slowed. This has resulted in reduced internal nutrient loading from the deeper waters and falling primary productivity in the lake. O'Reilly et al (2003) suggest that this may have resulted in reduced fish production in Tanganyika.

Vollmer (2002) has also documented rising temperatures over the last 60 years in Malawi as well as measuring reduced ventilation of the deep waters since 1980 (Vollmer et al. 2002). Because internal nutrient loading of nutrients is a significant source of Si and P, two critical plant nutrients, Malawi would have reduced internal loading of these nutrients over the past 20 years. Victoria also has warmer deep water temperatures in its seasonal hypolimnion in the 1990's relative to those temperatures in the 1960's (Hecky et al. 1994). Its more stable stratification now compared to 1960 (Hecky 1993) may in part be a consequence of warmer air temperatures and reduced nocturnal cooling; however, changing wind strengths might also affect Victoria which still mixes throughout its depths in July and August. Many of the inflowing rivers entering the northern Malawi plunge below the warm epilimnion because they are cooler and more turbid than the mixed layer. The river plumes plunge to depths determined by their densities (Bootsma et al 2003) and can potentially plunge below the depth of annual mixing (approx. 110 m) and disperse into the large volumes of the deep metalimnion and hypolimnion. These deeper layers slowly exchange with upper layers and incoming nutrient loads may not affect the mixed layer for decades (Vollmer et al 2002). The load of sediments and nutrients carried by these rivers can therefore bypass the mixed layer with little effect. In southern Malawi, plunging is confined by the shallower bottom depths and therefore remains above the depth of annual mixing and the fluvially transported loads are available to affect surface waters during annual mixing. Similarly in shallow Lake Victoria, riverine loads enter into shallow water, and the lake mixes throughout its depth annually, so incoming loads do affect water quality of the whole lake annually.

A warming climate such as has occurred over the past century will warm rivers more rapidly than the deep waters of Tanganyika and Malawi and may have reduced the cooling effect from these plunging rivers and contributed to the warming trends in the lakes' hypolimnions. The potential climatic effects on lake behaviour including the distribution of incoming nutrient loads is complex and cannot be adequately modeled at present due to lack of data. However, the lakes are warming, and the full consequences are as yet undefined. Reduced internal circulation as measured in Malawi, and inferred for Tanganyika, could reduce internal nutrient loading and offset increases in external loading from rivers and the atmosphere. This would be a positive benefit ameliorating cultural eutrophication, but it can also mask evolving problems in the catchments if they are adding more nutrients. A future reduction in the warming trend would allow deep water temperatures to increase relative to the mixed layer and eventually result in rapidly increasing nutrient loading if cultural eutrophication is neglected. Due to the slow response rates of these lakes to changes in heat flux and nutrient inputs, it is important that we understand the implications of these changes before their impacts are fully manifest, because the lakes' response rates to mitigation may also be slow. Managing the nutrient loading of these large systems is only partially controllable through managing external loading. Global climate change and dependent changes in internal loading can certainly delay the response of the lake to catchment management and potentially it could overwhelm and reverse positive trends in external nutrient loading. The challenge is aggravated by current projections that climate warming over the next century in the tropics will be three to five times greater than over the last century (Hulme et al. 2001).

4. Nutrient loading

In eastern Africa increasing populations require increased agricultural production and increasingly this production comes from marginal land and increased elevations and slopes. The transformation of land from forest or natural continuous savanna to grazed grasslands and tilled agriculture has been well recognized to increase to water and sediment yields from the land surface into waterways (Sundborg and Rapp 1986). Basin scale estimates of the impact of land clearance and changing land use are less common. Hecky et al (2003) compared forested catchments with extensively cultivated catchments and concluded that nutrient yields increased 6 to 9 fold and sediment yield from 10 to 40 fold depending on catchment slopes. Land use, topography, soils and hydrology interact to determine watershed export and these aspects can be modeled to allow predictions about future changes in land use or to guide restoration of landscapes to reduce nutrient loading (e.g. Lam et al. 2002). The sediment and nutrient yields at the basin scale represents costly depletions of natural soil capital that ultimately reduce farmers' yields. This negative effect at the farm scale can provide motivation to lake basin management initiatives to improve farming practices and maintain soil fertility and crop productivity.

Tropical Africa has the highest rate of biomass burning in the world with burning especially high in savanna areas (Hao and Liu 1994). Agricultural practice in Africa is very dependent on fire to clear the land, regenerate nutrients from agricultural debris and on grazing lands, and control pests; but fire is also heavily used for domestic warmth and cooking. Fire mobilizes fine ash and volatile elements into the atmosphere where these materials can travel widely. Recent studies suggest transport over hundreds and even thousands of miles (Jickells et al. 1998) is possible, although highest deposition rates in wild fires and windstorms may be closer to the source fire as coarser ash will be removed more rapidly from the atmosphere. In the planting season, the soil surface is exposed, after clearing and tilling, to wind erosion; and exposed soils are a source of fine soil and ash particles to the atmosphere until a vegetation cover is reestablished after the rains begin (Bootsma et al 1996). Measurements in eastern Africa on Lake Malawi and around Lake Victoria indicate phosphorus, P, deposition rates in rain and dry fall are among the highest that have been measured (Table 2), but not exceptionally high for tropical areas undergoing land clearance. Because of the large surface area of the lakes available to receive dry fall and the dominance of rain in the water budget of the great lakes, atmospheric deposition of P is an important external source of P to Lake Malawi (Fig. 1) and may be the dominant source of external P loading to Lake Victoria (Table 3). Phosphorus is not the only nutrient mobilized, but others such as sulfur, nitrogen, iron and potassium (Crutzen and Andreae 1990) are also transported through the atmosphere. Atmospherically borne N and P have been documented to enrich oligotrophic lakes far from the origins of the atmospheric nutrients (Lewis 1981, Jassby et al. 1994, Sickman et al. 2003) and to be transported long distances (Jickells et al. 1998, Brunner and Bachofen 1998).

The similarity of atmospheric phosphorus deposition rates between stations on Malawi and around Lake Victoria (including stations with dominant winds offshore and dominant winds onshore from the lake) and in the protected area of Serengeti National Park are consistent with widespread and relatively uniform atmospheric concentrations of P. Bootsma et al. (1999) compared deposition rates of nutrients at three locations in Malawi and found that deposition rates of most nutrients were similar at all stations, although particulate C, N and P deposition was greater at an inland location. Areas of higher rainfall tend to have higher wet deposition rates and lower dryfall deposition and the same is true when comparing rainy season deposition rates with dry season rates (Tamatamah et al. in review) with the result that annual deposition rates are remarkably similar throughout East and Southern Africa, despite quite different climatic conditions and land uses at the monitoring stations.

Despite the apparently similar and high rates of P deposition around southern Africa, the number of monitored stations and the geographic distribution of stations are still quite limited. What is needed is a regional monitoring network to define spatial and temporal trends and significant source areas. Also extrapolation of these rates over large areas, such as the surface area of Lake Victoria requires confirmation by monitoring on the lake itself before full confidence can be given to estimates such as those in Table 3. The atmospheric and ecological consequences of biomass burning in the tropics and the potential for disrupting nutrient cycles and productivity of the burned terrestrial systems has been identified for some time (Crutzen and Andreae 1990). Less appreciated is the possible effect of these mobilized nutrients on lakes. In terms of atmospheric transport and deposition, lakes are receiving systems and effective sinks for the mobilized nutrients. Except for very conservative ions such as chloride, whatever comes to the great African lakes will remain in the lakes. Nutrients such as S, N, Si and P are very highly retained in these poorly flushed systems, even compared to Lake Superior that has the longest flushing time of the Laurentian Great Lakes (Hecky 2000). Such high retention means that any pollutant entering these lakes will remain in the water or sediment of the lakes with potentially prolonged effects on the aquatic systems (Bootsma and Hecky 1993). As flushing times decrease in smaller lakes and reservoirs, the importance of atmospheric deposition in nutrient budgets should decline, but nutrient management in the great lakes will require addressing atmospheric deposition; and that in turn will require a regional approach to maintaining or restoring air quality. Biomass burning also produces other atmospheric hazards such as ground level ozone that can reduce plant productivity (Maggs et al 1995; Ashmore et al. 1994) and cause respiratory problems. For farmers to change their current practices, benefits will have to accrue at the farm scale as well as the basin scale. Lake managers will have to work closely with their partners in land use and agricultural management to bring about such change.

5. Contaminants

The atmosphere can also be a transport medium for volatile contaminants such as organochlorines (OC's e.g. DDT, PCB's), mercury and other semi-volatile and dust borne toxic compounds such as polynuclear aromatic hydrocarbons (PAHs). The organochlorines have caused serious biotic degradation of Laurentian Great Lakes especially affecting the fish eating birds because of bioaccumulation of OC's in food webs. The banning of manufacture and use of the most persistent and toxic organochlorines such as DDT and PCB's has led to a slow downward trend in the concentrations of these compounds from high concentrations in Laurentian Great Lakes biota in the late 1970's. However, even after thirty years PCB concentrations in some fish remain above levels acceptable for consumption (Lamon et al. 1999). Mercury (Hg) is also toxic particularly as its methylated species, methyl Hg (CH_3Hg^+), that bioaccumulates in food webs and can exceed acceptable concentrations in piscivorous fish when concentrations in water are at sub-nanogram per liter concentrations. The lucrative Lake Erie fishery was closed in the early 1970's because concentrations of Hg in predatory fishes exceeded market acceptability. Removal of Hg from industrial point sources allowed rapid recovery and reopening of the commercial Lake Erie fishery. However, Hg concentrations remain high enough yet in the Laurentian Great Lakes to cause fish consumption advisory statements urging people to limit consumption of many of the predatory species. Atmospheric concentrations of Hg have risen through the past century and deposition of Hg even into remote lakes has increased by approximately a factor of two all over the globe. Recognition of this historic contamination of the atmosphere and aquatic ecosystems has led to international efforts to further reduce or eliminate the economic use of Hg in industrial processing and in manufactured products. Similarly organochlorine concentrations have been rising in remote northern lakes and coastal marine systems because of atmospheric transport from lower latitudes where historic use was high or remains high. The volatility of these organochlorine compounds leads to a grasshopper effect moving the compounds from warmer ecosystems to colder ecosystems and eventually to accumulation in continuously cold aquatic food webs at high latitudes (Wania and Mackay 1993). The transboundary dimension of this problem has led to recent global protocols for reduction and elimination of organochlorines, and it should encourage developed countries in higher latitudes to assist tropical and subtropical developing countries to find alternatives to the use of persistent toxic organochlorine compounds.

Organochlorines and especially DDT are still in use in tropical countries. They are detectable in the air at stations in Uganda (Fig. 2) and in air, water and aquatic biota of Malawi (Karlsson et al. 2000, Kidd et al 2001) at concentrations well above those found at higher latitudes. Fortunately, volatilization (and perhaps degradation) of these compounds keeps their concentrations low in tropical waters and biota (Kidd et al 2001) and well below concentrations that would be of concern for fish consumers. However, the trend over time as recorded in a sediment core from Lake Victoria (Lipiatou et al. 1996) is for increasing concentrations in sediment, and careful monitoring and eventually elimination of the use of these persistent organic pollutants will be the only way to eliminate risk of contamination of aquatic organisms while they are still in use. Use of pesticides has been limited by the economic conditions in Africa, but wise use of such pesticides may be necessary to boost agricultural production, especially of valuable export crops, as well as to control health risks such as disease bearing insects.

Eliminating Hg from the atmosphere of eastern Africa and its lakes will not be possible. Hg is a naturally occurring element; it is everywhere and in every environmental media. Metallic or inorganic Hg itself can be toxic but is rarely so at environmental concentrations. Inorganic Hg compounds can be excreted by the kidney of higher organisms and so do not bioaccumulate to any significant degree. However, the formation of methyl Hg by bacteria in the environment can lead to efficient bioaccumulation and biomagnification in food webs, often by a factor of over one million above water concentrations, and can cause potentially unacceptable concentrations in top predators (Campbell et al.2003a). Surveys of African fisheries have found generally acceptable Hg concentrations for marketing and frequent human consumption except in very large piscivorous Nile perch in Lake Victoria or as a result of long food chains such as in Lake Albert, Uganda (Fig. 4; Campbell et al. 2002). This positive outlook is tempered by the recognition that Hg deposition to the lake has increased over time in Lake Victoria (Fig.5) and that the capacity of bacteria to methylate Hg can be modified both by the addition of more Hg to an ecosystem and by enhanced rates of bacterial methylation (Hecky et al. 1992). Concentrations of total Hg are actually higher in Lake Victoria waters (Campbell et al. 2003b) than they are in the Laurentian Great Lakes, but the fishes in the African lakes have lower concentrations of methyl Hg in their flesh than temperate great lake fishes (Fig.6) for reasons that currently beg explanation. Biomass burning is likely the greatest source of Hg to Lake Victoria (Campbell et al 2003a), and its reduction would reduce Hg loading to the lakes. More problematic is what controls rates of bacterial methylation of Hg. Any increase in Hg methylation could drive Hg concentrations in top predatory fish to unacceptable levels for frequent consumption or even export. Research is needed to address this issue for tropical ecosystems. Sulfate-reducing bacteria are often implicated in elevated rates of bacterial methylation, and the low concentrations of sulfur compounds in the African Great Lakes may be limiting methylation rates. Biomass burning will also increase the sulfur loading to the lakes (Crutzen and Andreae 1990) and could act synergistically with increased Hg loading to increase methyl mercury production over time.

Careful monitoring of Hg and OC concentrations in fish can protect fish consumers as well as the international market place for fish products from the African lakes, and hopefully it would detect any upward trend before Hg concentrations in fishes becomes unacceptable. If upward trends are detected, it will likely require regional action to reverse those trends in these great lakes and their fisheries.

6. Conclusion

Many environmental risks to African lakes arise within their catchments and can be addressed by riparian states or lakes in the catchment through appropriate basin management initiatives with adequate funding. However, other risks that arise from atmospheric change can affect lakes over broad areas and will require regional or even global action to address. There is now evidence coming from the great African lakes that climate change, intensifying land use (mobilizing nutrients) and toxic substances are increasingly affecting the atmosphere over the African Great lakes. The Great Lakes are particularly sensitive to these changes because of their enormous surface areas; slow flushing rates and the importance of direct rainfall in their water budgets. Their response times may be slow to yield a detectable change, and unfortunately recovery times may also be slow. It is possible for atmospheric effects to act antagonistically to impacts of catchment change, e.g. evidence for lower productivity in Lake Tanganyika despite ongoing catchment degradation, but antagonistic effects may become synergistic (e.g. the positive effect that increasing atmospheric S deposition might have on mercury methylation) in the future. Improved understanding of the physical dynamics of these lakes, and models to link their physical and biogeochemical behaviour to regional, mesoscale climate models will be necessary to guide lake managers.

The inherent hydrologic sensitivity of the African Great Lakes and the attention they have received from GEF sponsored studies, as international waters requiring cooperative management among riparian states, have now made the risks inherent in atmospheric change evident; but the scale of the risks, the rates of change and, most importantly, the regional and global management response is yet to be defined. The Global Environmental Facility programmatic focal areas are: international waters, biodiversity, climate change, ozone depletion, land degradation, and persistent organic pollutants. Clearly the issues on the African Great Lakes are appropriate for further GEF action. However, the states of eastern Africa that enjoy benefits from these lakes will increasingly have to collaborate to engender a regional or possibly even continental approaches to resolve many of these issues. Climate change, in particular, will have to be addressed at a global scale in order to safeguard the African Great Lakes. The challenge to lake management will be to unravel the causation of undesirable changes to determine whether local, catchment impacts are the main cause of change or whether atmospherically mediated and/or climatically driven changes are responsible. The scale of response and the possibility of effective management require resolution of that challenge for all the lakes of Africa.

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Table 1. Morphometric and hydrological data for Africa's three largest lakes (after Bootsma and Hecky 1993).

	Malawi	**Tanganyika**	**Victoria**
Catchment Area	100,500	220,000	195,000
Lake Area	28,000	32,600	68,800
Maximum Depth	700	1470	70
Mean Depth	292	580	40
Volume	8,400	18,900	2,760
Outflow (O)	11	2.7	20
Inflow (I)	29	14	20
Precipitation (P)	39	29	100
Evaporation (E)	55	44	100
Flushing Time (V/O)	750	7000	140
Residence Time (V/(P+I)	140	440	23

Table 2. Summary of total phosphorus loading rates from selected global sites sites (kg/ha/yr) relevant to tropical lakes (Tamatamah submitted).

	WET	DRY	WET +DRY	Source
Mwanza, L. Victoria	0.5	2.2	2.7	Tamatamah 2002
Bukoba, L. Victoria	0.6	1.3	1.9	Tamatamah 2002
Seronera, L. Victoria	0.3	1.5	1.8	Tamatamah 2002
Duma, L.Victoria	-	1.8	-	Tamatamah 2002
Jinja, L. Victoria	0.7	-	-	Lindenschmidt et al. (1998)
West Coast of Africa	1.2	-	-	Thornton (1965)
Lake-Valencia, Venezuela	-	-	1.68	Lewis (1981)
Lake Malawi, Africa	0.3	2.1	2.5	Bootsma et al. (1999) *
Ontario Shield, ELA	-	-	0.32	Schindler et al. (1976)
Colorado Mountains USA	-	-	0.26	Grant and Lewis (1979)

*Wet and dry deposition collected separately; wet samples taken on event basis

Table 3. A provisional nutrient budget for total nitrogen (TN) and total Phosphorus (TP) for Lake Victoria. Precipitation data from Tamatamah (2002) and nitrogen fixation from Mugidde et al. (2003). River data extrapolated from Linthipe River (Malawi; Hecky et al. 2003).

Flux	Water	TN	TP
	mm/y	kilotonnes/y	
Rainfall	1790	83	4.8
Dryfall		110	13
Rivers	338	43	9.8
External Total		236	27.6
Nitrogen Fixation		480	
Total Inputs		716	27.6

List of figures

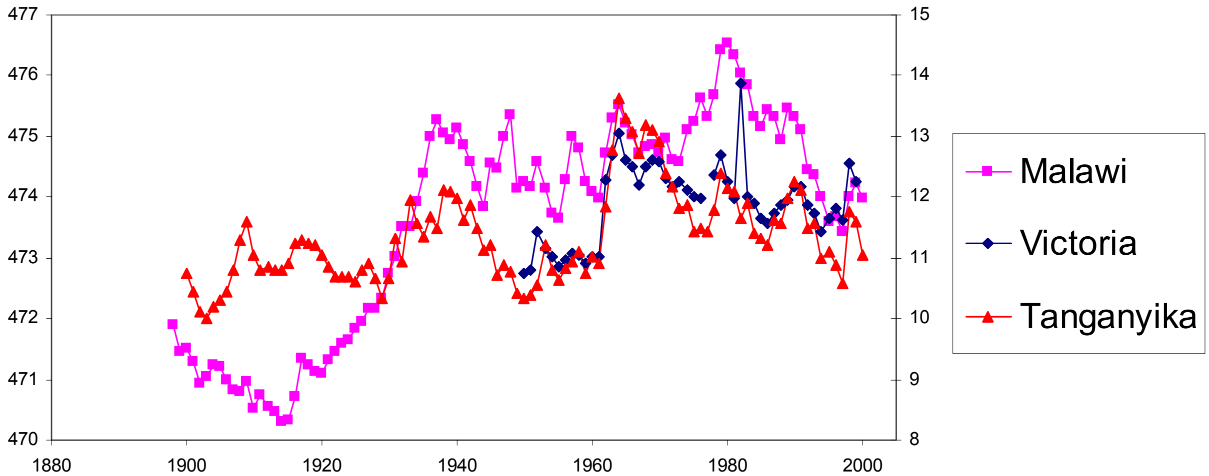
Figure 1. Annual mean water levels for the African Great Lakes placed on a common datum for comparison.

Figure 2. Fluxes of total P to and from Lake Malawi. Numerical units are mmol m^{-2} m y^{-1}. Ranges are given for fluxes based on high and low estimates for the rivers based on different approaches to extrapolation to unmonitored terrestrial catchments (Bootsma and Hecky 1999). Riverine inputs are split depending on the density of the inflowing stream into fluxes to the mixed layer and fluxes to the metalimnion.

Figure 3. Concentrations of selected pesticides and some of their degradation products in air for two monitoring stations in eastern Africa (Kakira, Uganda and Senga Bay, Malawi) compared to a remote monitoring station in the high Arctic (Alert, Canada). Data from Wejjuli et al. (2002).

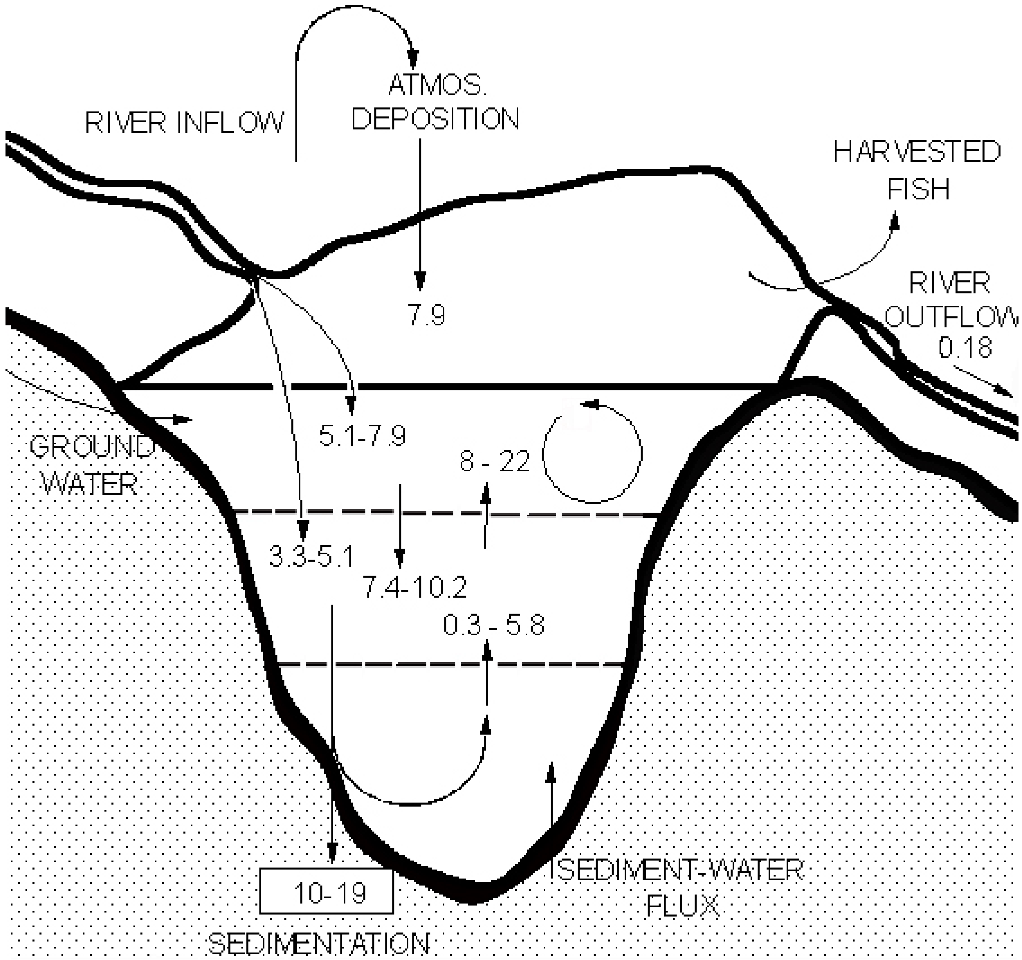
Figure 4. Concentrations of Hg in top predator fishes (solid bars) and in herbivorous/detritivorous fishes (light bars) in African lakes. Note logarithmic scale. From Campbell et al. (2002). I.M.L. refers to acceptable level of Hg for marketing fish internationally. W.H.O. is the guideline concentration for frequent fish consumption by sensitive groups e.g. nursing mothers and children.
Figure 5. Concentrations of THg in two sediment cores (offshore and inshore) in Lake Victoria. Pore water THg concentrations are given by dashed line in inshore core. From Campbell et al. (2003b)

Figure 1.



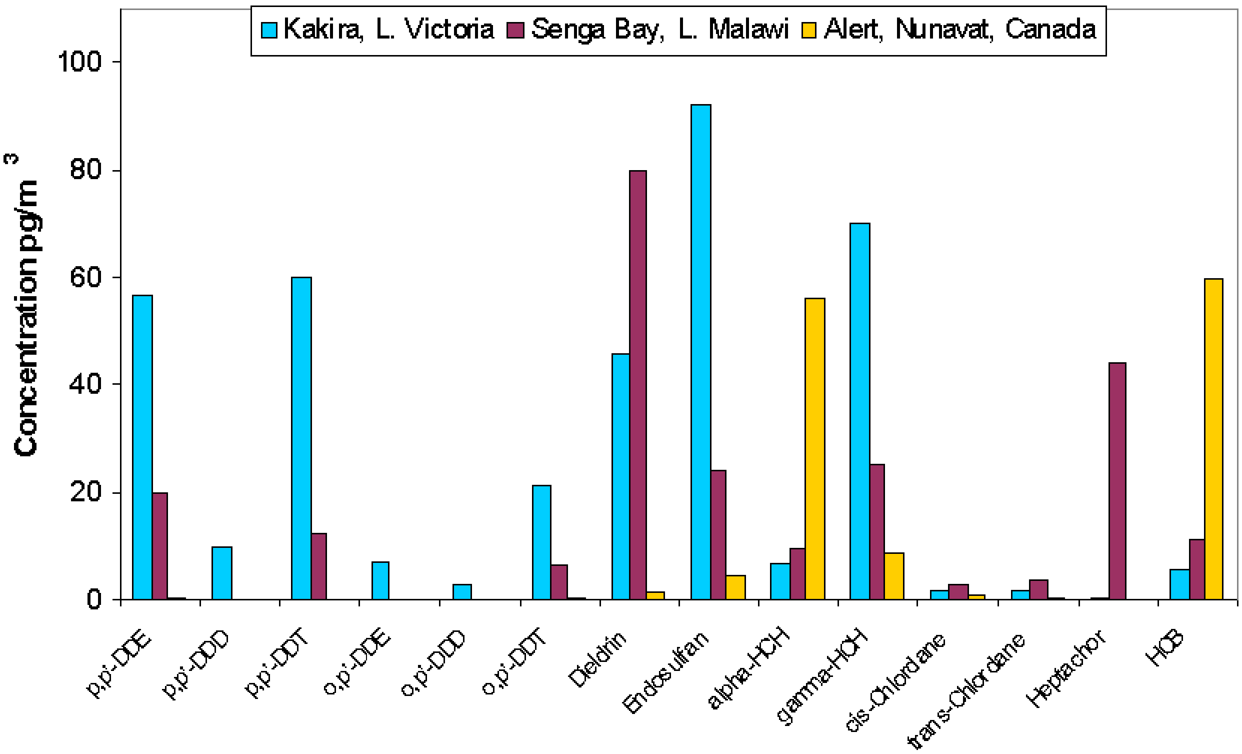
477
476
475
474
473
472
471
470
15
14
13
12
11
10
9
8
1880
1900
1920
1940
1960
1980
2000
Malawi
Victoria
Tanganyika

Figure 2.



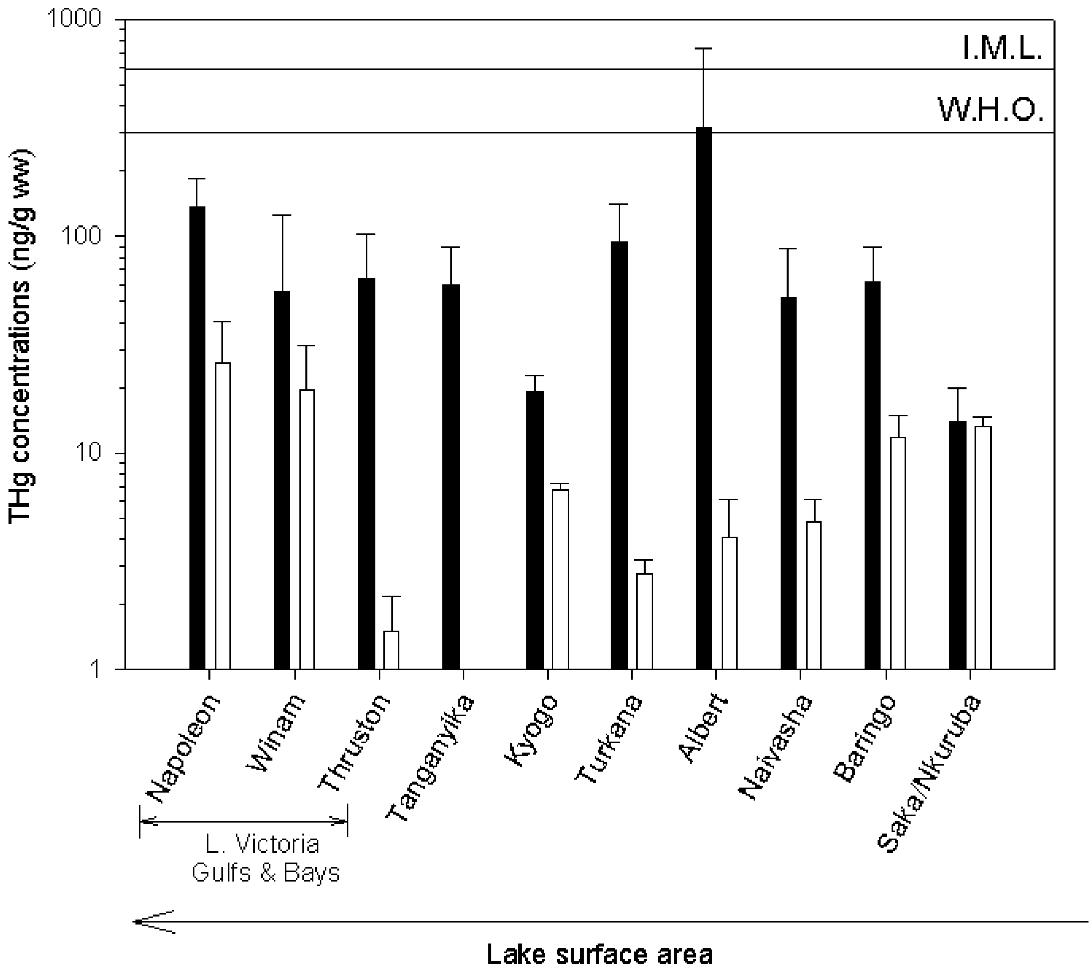
RIVER INFLOW
ATMOS. DEPOSITION
HARVESTED FISH
7.9
RIVER OUTFLOW
0.18
5.1-7.9
8 - 22
GROUND WATER
3.3-5.1
7.4-10.2
0.3 - 5.8
10-19
SEDIMENTATION
SEDIMENT-WATER FLUX

Figure 3



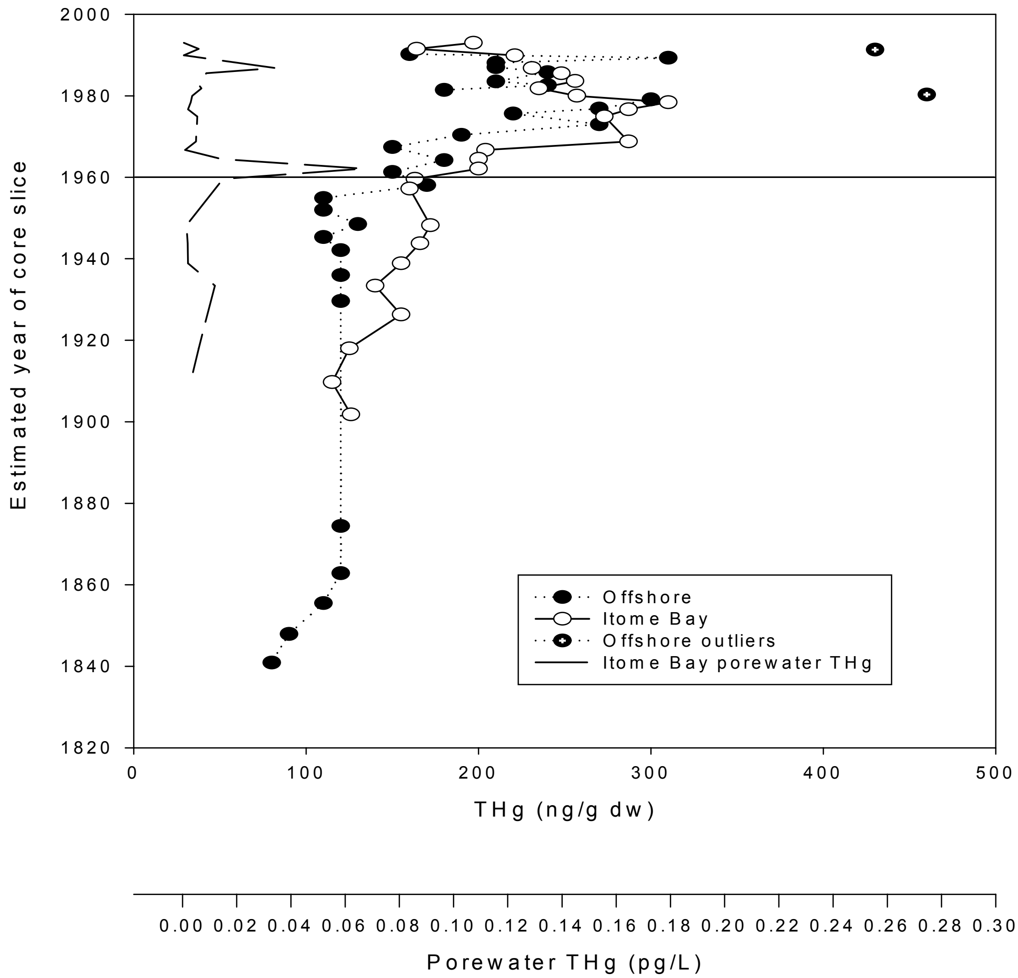
Kakira, L. Victoria
Senga Bay, L. Malawi
Alert, Nunavat, Canada
Concentration pg/m 3
100
80
60
40
20
0
p,p'-DDE
p,p'-DDD
p,p'-DDT
o,p'-DDE
o,p'-DDD
o,p'-DDT
Dieldrin
Endosulfan
alpha-HCH
gamma-HCH
cis-Chlordane
trans-Chlordane
Heptachor
HCB

Figure 4.



1000
100
10
1
THg concentrations (ng/g ww)
I.M.L.
W.H.O.
Napoleon
Winam
Thruston
Tanganyika
Kyogo
Turkana
Albert
Naivasha
Baringo
Saka/Nkuruba
L. Victoria
Gulfs & Bays
Lake surface area

Figure 5.



Estimated year of core slice
2000
1980
1960
1940
1920
1900
1880
1860
1840
1820
0
100
200
300
400
500
THg (ng/g dw)
0.00 0.02 0.04 0.06 0.08 0.10 0.12 0.14 0.16 0.18 0.20 0.22 0.24 0.26 0.28 0.30
Porewater THg (pg/L)
Offshore
Itome Bay
Offshore outliers
Itome Bay porewater THg