Biogeochemistry (2005) 73: 325–344
DOI 10.1007/s10533-004-0196-9

The atmospheric deposition of phosphorus in Lake Victoria (East Africa)

RASHID A. TAMATAMAH[1,*], ROBERT E. HECKY[2] and HAMISH C. DUTHIE[2]

*[1]Department of Fisheries Science and Aquaculture, University of Dar es Salaam, P.O. Box 35064, Dar es Salaam, Tanzania; [2]Department of Biology, University of Waterloo, Waterloo, Ont., Canada N2L 3G1; *Author for correspondence (e-mail: rtamah@cc.udsm.ac.tz; Phone: + 1-255-22-2410-462; fax: + 1-255-22-2410-038)*

Received 6 November 2002; accepted in revised form 27 April 2004

Key words: Atmospheric deposition, Dry deposition, Lake Victoria, Phosphorus, Watershed, Wet deposition

Abstract. Wet and dry atmospheric fluxes of total phosphorus (TP) and soluble reactive phosphorus (SRP) measured at four sites over a 12-month period were used to estimate lake-wide atmospheric phosphorus (P) deposition to Lake Victoria, East Africa. Atmospheric samples were collected in plastic buckets with top diameter of 25.5 cm by 30 cm deep. The highest P loading rates of 2.7 (TP) and 0.8 (SRP) kg ha^{-2} $year^{-1}$ were measured at Mwanza compared to less than 1.9 (TP) and 0.65 (SRP) kg ha^{-2} $year^{-1}$ measured in other three sites. By applying these loading rates to the lake surface, it was estimated that 13.5 ktons (13.5×10^3 kg) of TP were deposited annually into the lake from the atmosphere. Thirty-two percent of the total was found to be in the SRP form. Dryfall, a component ignored in previous studies exceeded wet deposition by contributing 75% of the total P input. However, materials deposited by dryfall made a lesser contribution to soluble form of phosphorus, as SRP concentrations in the wet samples were 2–3 times higher than SRP concentrations in dry samples. The annual fluxes of phosphorus measured on the south and western shores of Lake Victoria (1.8–2.7 kg ha^{-2} $year^{-1}$) are near the upper range of similar fluxes measured in the tropics. In comparison with the existing estimates of municipal and runoff P inputs from other studies, it is estimated that atmospheric deposition represent 55% of the total phosphorus input to the Lake Victoria. The four sampling sites were fairly clustered and wet and dry P deposition data were collected from shore/land stations and applied to open lake areas to estimate lake-wide P deposition. In this regard, the estimates determined here should be viewed as a first order approximation of actual P load deposited into the lake.

Introduction

The importance of atmospheric deposition as a nutrient source to aquatic ecosystems has been well documented (Schindler et al. 1976; Lewis 1981; Cole et al. 1990; Jassby et al. 1994). This is partly because important intersystem exchange of various nutrients such as N and S occurs via the atmosphere and partly because human activities release pollutants to the atmosphere in amounts that are comparable to, or even exceed, the natural (preindustrial) rates of mobilization (Likens and Butler 1981; Crutzen and Andreae 1990).

For example, while the effects of human activities such as vegetation burning on C, N, and S cycles are most obvious (Crutzen and Andreae 1990), several

studies have reported savannah fires associated with shifting agriculture to be a major source of P to the atmosphere. Artaxo et al. (2000) found that 56% of the aerosol mass (including that of P) measured in the Amazon tropical forest was associated with biomass burning.

More recently, there has been keen interest in the deposition and composition of P in rainfall and air around Lake Victoria. This is largely due to concern about the large scale deforestation and biomass burning occurring in the region (Delmas et al. 1991; Hao and Liu 1994) which could influence P deposition. In the lake where water input by rainfall exceeds river inflow by a greater ratio (6:1), direct atmospheric deposition of P on the lake may be significant. Furthermore, the post-1960s increase in P concentrations in the sediment microfossil and water (Hecky 1993) has been associated with dramatic shifts in the algal community (Kling et al. 2001) and anoxic conditions in the hypolimnetic waters of Lake Victoria (Hecky et al. 1994). Concentrations of TP in the lake now are 2.5 μmol l^{-1}, on average (Guildford and Hecky 2000), more than double the TP concentrations reported by Talling (1966) in the early 1960s. Nitrogen-fixing cyanobacteria (*Anabaena* and *Cylindrospermopsis*) now dominate the phytoplanktonic biomass along with the non-fixing *Microcystis* and *Planktolyngbya*. These species which currently have a competitive advantage at the low TN:TP ratios of the lake were either not present or only minor elements of the phytoplankton in the 1960s.

There is a substantial seasonality of rainfall and large spatial differences in the average rainfall around Lake Victoria, with more rain recorded on the north-west coast and decreasing towards the south (Yin and Nicholson 1998). Such temporal and spatial climatic differences are likely to influence both wet and dry P deposition in the lake. Previous studies of P precipitation in Lake Victoria were limited in sampling spatially with only one lakeshore location in the north (i.e. Jinja) being analyzed, and only the wet component of the atmospheric deposition being measured (R. Mugidde, Fisheries Research Institute of Uganda, unpublished data). Dryfall remained unmeasured in Lake Victoria until the present study. Also, in a different study employing a Rapid Assessment method, Scheren et al. (2000) used areal P loading rates from wet deposition only measured for Lake Malawi (0.53 kg ha^{-2} $year^{-1}$) and applied them to the surface area of Lake Victoria to calculate lake-wide atmospheric P loading.

The present work attempts to utilize data of both wet and dry atmospheric P collected at four land stations to estimate lake-wide atmospheric P input in Lake Victoria. These are the first estimates to include the contribution of dryfall to the P precipitation in this large tropical lake.

Materials and methods

Site description

Victoria is the second largest lake by area in the world, with surface area of 68,800 km^2. The lake receives inflows from 17 tributaries, which contribute less

Table 1. Characteristics of the sampling sites

Station	Latitude	Longitude	Elevation (m asl)	Annual precipitation* (mm) (1995–2000)	Climate	Surrounding land use
Bukoba	−1.333	31.817	1140	2000	Wet tropical climate	Urban
Mwanza	−2.520	32.900	1140	1050	Warm tropical Savannah climate	Urban
Duma/Sayaka	−2.571	33.530	1222	1000	Warm tropical Savannah climate	Cultivation and free range grazing
Seronera	−2.333	34.917	1345	800	Warm tropical Savannah climate	National park (Wildlife)

*Source: Tanzania Meteorological Agency.

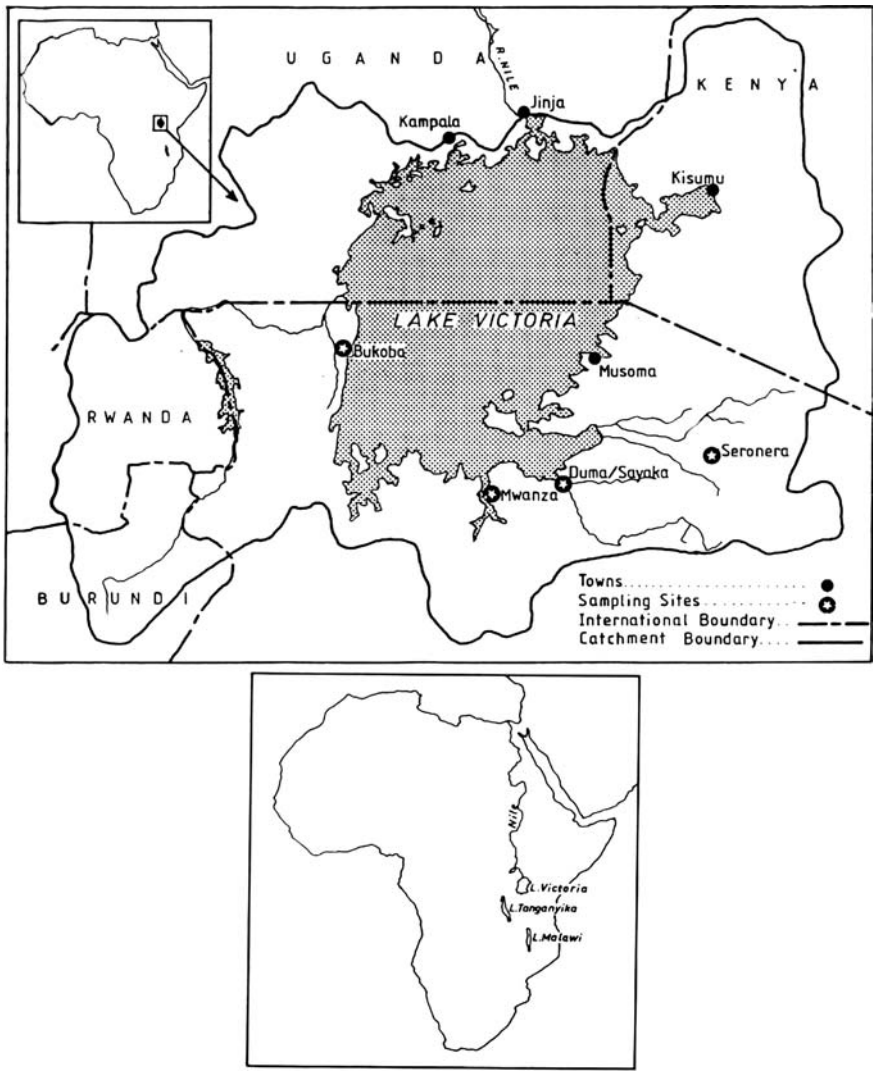

Figure 1. The Lake Victoria catchment, showing sites sampled for atmospheric deposition and the relative locations of other African Great Lakes.

than 20% of the water entering the lake, the rest being provided by rainfall (Yin and Nicholson 1998). The water exits by a single outlet, the River Nile on the north end of the lake. Rainfall over the lake surface is not only the biggest component of its water balance, it is also the most variable (Crul 1993; Yin and Nicholson 1998). Wind and rainfall patterns in the region are associated with an atmospheric belt of low pressure, the intertropical convergence zone (ITCZ). The prevailing winds blow predominantly southerly and southeasterly

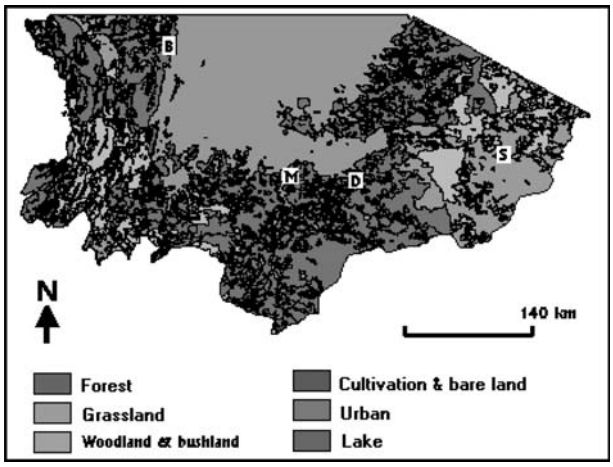

Figure 2. Landuse coverage on the Tanzanian part of Lake Victoria catchmet. Study sites are B, Bukoba; M, Mwanza; D, Duma-Sayaka; and S, Seronera.

with heavy rains falling in the period March–May and short "vuli" rains in November–December (EAMD 1975) when the ITCZ migrates back south.

Atmospheric precipitation samples were collected from four sites on the south and western shores of Lake Victoria (Table 1 and Figure 1) in Tanzania. The study area spans a wide range of land use typically found in the lake's watershed (Figure 2). Agricultural and rangeland management practices in the region typically include annual burning of the savannah vegetation to simulate natural burning cycles but avoid highly destructive fires. Burning occurs through the dry season and gradually declines as the short rains begin in November.

Sampling procedures

Wet and dry atmospheric samples were collected as discrete events/intervals using plastic buckets with top diameter of 25.5 cm by 30 cm deep deployed at the beginning of a rain or at regular intervals for dry deposition. This is in contrast to the commonly used bulk collection method whereby the collector is continually open to the atmosphere, which results in measurement of dry fallout, occurring during dry spells, as part of the input on the first rainfall event (Galloway and Likens 1978). Dry deposition samples were collected on a 2-week interval and wet deposition sampling on a storm event basis. While samples were collected for the period of 12 months (August 1, 1999–July 31, 2000) at Mwanza, Duma-Sayaka and Seronera in the south, logistical problems allowed only a 6 months (early June to early December 2000) sampling at

Bukoba. Due to lack of functional meteorological instruments at Duma-Sayaka, wet precipitation samples were not collected at this station.

At the beginning of a rainfall event, the collectors were placed on a stand 2 m above the ground and removed as soon as possible after the storm (usually within an hour, but occasionally as long as 12 h when rain fell at night). The water volumes in the buckets were measured after each storm.

On a dry sampling day three buckets were set out in an attempt to insure at least one collection without visible contamination by insects or bird droppings. Samples with obvious particulate contamination were always discarded. After each sampling event the buckets were thoroughly cleaned with phosphorus-free detergent (CONTRAD), copiously rinsed with distilled water, and kept covered until the next sampling. Occasionally, distilled water used in the rinsing procedures was treated as a sample to verify that the collector buckets were clean, and not sources of contamination. The collectors were filled with 1 l of distilled water to simulate the collecting properties of a wet lake surface (Jassby et al. 1994). The collectors were then left on top of a 2 m stand for the period of 24 h, after which the final water volumes were measured. Dry precipitation samples were discarded when rain fell during the 24-h exposure of sample collection buckets.

Sample treatment and chemical analyses

Total phosphorus (TP) and soluble reactive phosphorus (SRP) are the two forms of P that were measured in this study. TP, which incorporates the total of all filterable and particulate P forms was analyzed because of its close association with a wide variety of limnological variables (Peters 1986), and the link between TP loading estimates and P content found in many lake studies. SRP consist largely of the inorganic orthophosphate (PO_4) form of P and constitutes an index of the amount of phosphorus immediately available for algal growth (Nürnberg and Peters 1984).

Immediately following collection an aliquot of precipitation samples was filtered through pre-combusted Whatman GF/C filters ($\sim$1 μm nominal pore size) for SRP analyses. TP was analyzed from unfiltered samples. Samples collected at Mwanza were immediately analyzed for SRP and TP at the water quality laboratory in Mwanza. For the remaining stations samples were stored in 10% hydrochloric acid-washed polypropylene bottles, frozen and delivered to the Mwanza water quality laboratory for analysis in a period ranging from 1 day to 2 weeks. TP was analyzed after digestion of unfiltered water samples for 30 min with potassium persulfate under pressure (15 lbs in^{-2}). This was followed by a colorimetric determination of P at 885 nm by the ascorbic acid method (Parsons et al. 1984) using benchtop Novaspec II spectrophotometer. SRP was analyzed from filtered and undigested samples by the same method.

Calculations and statistical analyses

P was quantified in terms of concentration (μmol l^{-1} per event or day) of the mass sampled and later converted to deposition rate (μmol m^{-2} day^{-1} or μmol m^{-2} $event^{-1}$) by dividing by the surface area of the opening of the bucket (0.05 m^2). For dry precipitation, on average, between 5% and 15% of distilled water in the buckets was lost by evaporation during the 24-h exposure. A correction factor, which takes into account the final and initial sample/water volumes, was used to compensate for the concentrating effect of evaporation as follows:

$$C_2 = \alpha C_1 \qquad \alpha = V_f / V_0 \tag{1}$$

where C_2 is the final P concentration corrected for evaporation (μmol l^{-1}); α, the correction factor; C_1, the measured P concentration (μmol l^{-1}); V_f, the final sample volume; V_0, the initial sample volume.

To normalize the averages between light rains, which have relatively high concentrations and heavy rains, in which the samples may be more dilute, wet P deposition concentrations were expressed as volume-weighted mean (VWM) concentrations (i.e. weighted by the amount of precipitation collected). VWM concentration was calculated as follows:

$$\mathrm{WM} = \frac{\sum_{i=1}^{n} V_i P_i}{\sum_{i=1}^{n} V_i} \tag{2}$$

where WM is the volume weighted mean concentration (μmol l^{-1}); V, the rainfall volume (ml); P, the phosphorus concentration (μmol l^{-1}); n, the number of measured rainfall events.

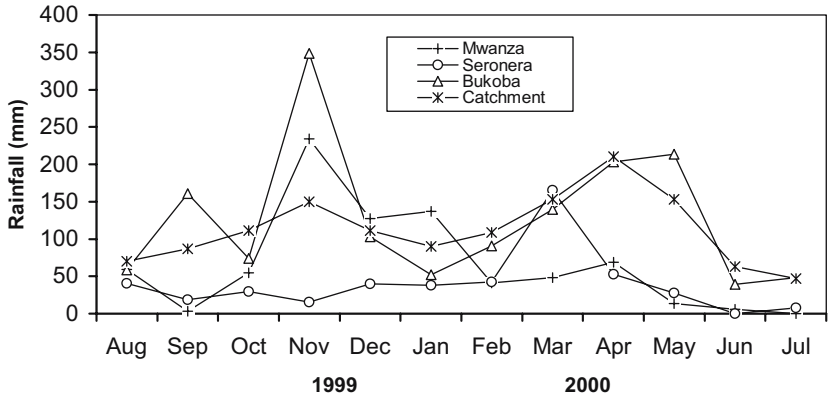

Figure 3. Comparison of mean monthly rainfall (mm) at sampling sites (1999–2000) and entire Lake Victoria catchment (1956–1978).

Also, measured event concentrations were assigned to individual storm categories (5 mm interval) in order to assess the relative contribution of different sized storms to P deposition around the lake.

P deposition to the lake was computed using the following formula:

$$P_{\text{dep}} = 31 * D_{\text{mean}} * d * A \tag{3}$$

where P_{dep} is the phosphorus deposition (tons year^{-1}); 31, the molecular weight of P (to convert μmol l^{-1} to μg l^{-1}); D_{mean}, the mean deposition (μmol m^{-2} day^{-1} or μmol m^{-2} event^{-1}); d, the number of dry/wet days in a year; A, the surface area of the lake under consideration.

For comparison, two types of procedures were used to estimate P deposition to Lake Victoria by using Equation (3) above. First, dry and wet atmospheric P deposition rates measured at each of the four sites were applied across the lake to calculate several possible annual lake wide P depositions. The final estimate (ktons P year^{-1}) was computed by averaging P depositions recorded at Bukoba, Duma-Sayaka and Seronera. Atmospheric deposition rates measured at

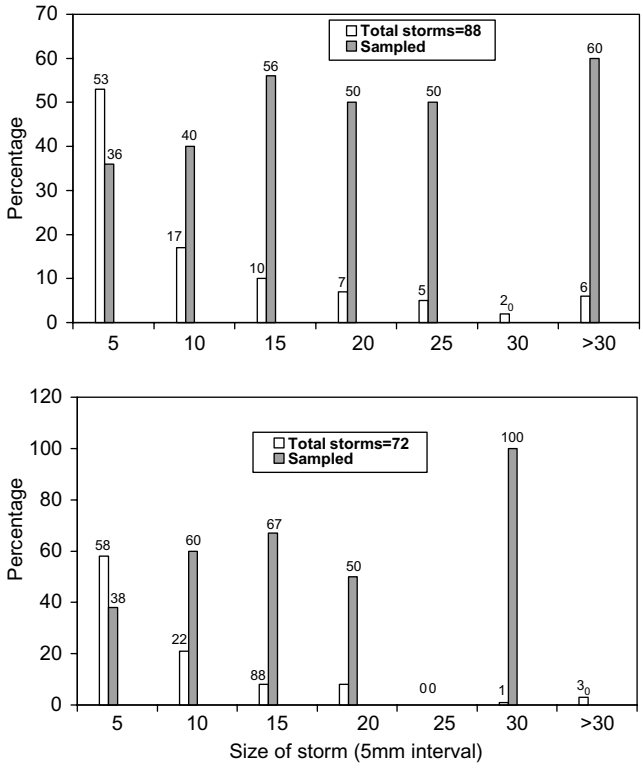

Figure 4. Distribution of the storms as a function of their size and frequency of sampling at Mwanza (top) and Seronera (below).

Mwanza were excluded from the final estimate because of more frequent contamination of samples with dust from unpaved city roads near the collection site. During the study year there were 150, 88, and 72 rain events (of greater than 0.5 mm) at Bukoba, Mwanza and Seronera, respectively. For dry deposition, there were 215 dry days at Bukoba, 277 days at Mwanza and Duma Sayaka, and 293 days at Seronera.

The second procedure involved dividing the lake into five sections based on observed rainfall regimes, and area weighted deposition rates from sampling sites closest to the particular lake section to estimate areal P depositions. Wet deposition rates measured at Jinja (reported by Lindenschmidt et al. 1998) were also included in this procedure. The number of dry/wet days used for each of the five lake sections were found by averaging 5-year (1996–2000) rainfall data, and their annual mean differ slightly from that used in the first procedure.

Analyses of variance (ANOVAs) were performed using the SYSTAT statistical package to assess if site and seasonal variations in the quantities of TP and SRP carried by rainfall and dryfall were significantly different. Where ANOVA gave significantly different results, a *post-hoc* test was conducted via

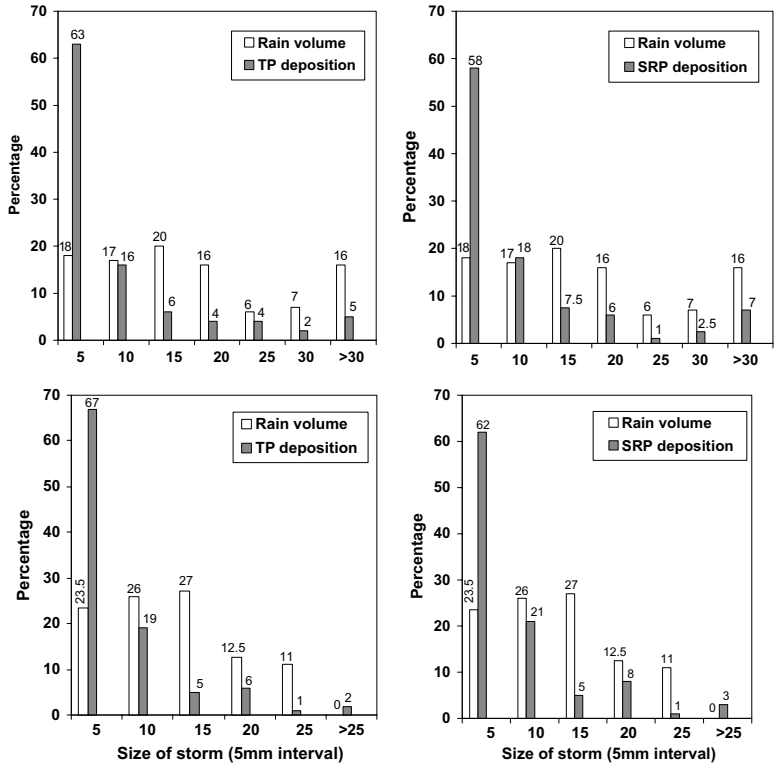

Figure 5. Comparison of the rainfall volume (mm) and phosphorus deposition (μmol m^{-2} $event^{-1}$) for storms of different size sampled at Mwanza (top) and Seronera (below).

Table 2. (a) Measured mean dry phosphorus deposition at four sites around Lake Victoria (this study) and that of Lake Malawi/Nyassa (Bootsma et al. 1999). Mean values sharing a superscript are not significantly different (Anova test; $p > 0.05$). (b) Measured mean wet phosphorus deposition at three sites around Lake Victoria (this study) and that of Lake Malawi/Nyassa (Bootsma et al. 1999). Mean values sharing a superscript are not significantly different (Anova test; $p > 0.05$)

Site	TP (μmol m^{-2} day^{-1} ± s.e.)	SRP (μmol m^{-2} day^{-1} ± s.e.)	*n*
Panel A			
Bukoba	20.4 ± 2.18[a]	5.2 ± 0.73[a]	12
Mwanza	26.2 ± 2.25[ab]	8.2 ± 0.75[b]	24
Seronera	17.4 ± 1.76[ac]	3.8 ± 0.58[a]	21
Duma-Sayaka	21.6 ± 2.12[a]	5.4 ± 0.43[a]	23
Lake Malawi/Nyassa	24.7		
Panel B			
Bukoba	13.2 ± 1.12[a]	8.0 ± 0.60[a]	35
Mwanza	16.2 ± 1.31[ab]	7.6 ± 0.35[b]	60
Seronera	12.4 ± 0.88[ac]	7.0 ± 0.38[a]	48
Lake Malawi/Nyassa	14.2	4.53	

Panel A: *n* = dry days sampled.
Panel B: *n* = wet days sampled.

the least significant difference (LSD) procedures to identify the sites or periods that were significantly different in terms of TP and SRP depositions.

Results

Rainfall

During the study period (August 1999–July 2000) 793 mm of rainfall were recorded at Mwanza, 478 mm at Seronera, and 1531 mm Bukoba. Rainfall

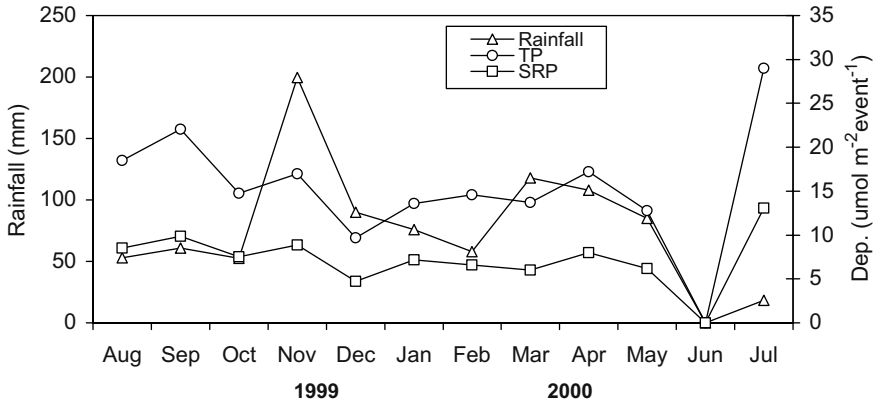

Figure 6. Seasonality of mean rainfall (mm) and mean phosphorus deposition (μmol m^{-2} $event^{-1}$) for the three sites (Bukoba, Mwanza, and Seronera) around Lake Victoria.

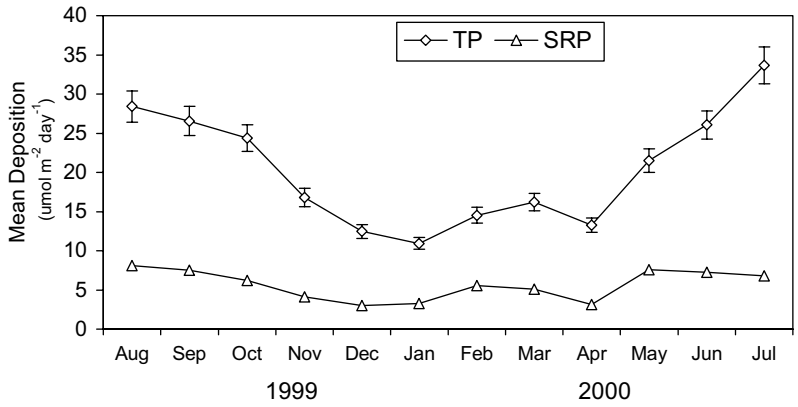

Figure 7. Seasonality of mean dry phosphorus deposition for four sites around Lake Victoria. Error bars indicate ±standard error (SE) of the mean.

amounts recorded at each of the three stations are lower than the estimate of rain falling directly on the lake made by Yin and Nicholson (1998), who estimated average annual rainfall to be 1791 mm. Figure 3 illustrates the seasonality of rainfall around Lake Victoria and compares the mean rainfall over the entire lake catchment (Yin and Nicholson 1998) with that of the three sampling sites during the study period.

During the study period 88 storms of more than 0.5 mm of rain occurred at Mwanza, 72 storms at Seronera, and 150 storms at Bukoba. Figure 4 shows the frequency distribution of storms ranging in size from 1 to 52 mm for Mwanza and Seronera. The category of high-frequency storms of low magnitude (< 5 mm) was somewhat inadequately sampled relative to larger storms. Despite their possible under-representation in the sampling, these frequently occurring small volume storms, which accounted for only 20% of the rain volume at Mwanza and Seronera, deposited approximately two-thirds of the TP and SRP observed at the two sites (Figure 5).

Spatial atmospheric P deposition

Mean wet and dry phosphorus deposition measured at four sites around Lake Victoria are given in Table 2(a and b). For wet samples, mean SRP deposition rates were relatively similar at the three sites with no statistically significant spatial differences ($p < 0.39$). A weak but significant spatial heterogeneity existed in wet TP deposition, with Mwanza having significantly greater TP deposition than Seronera ($p < 0.02$). Wet TP deposition rates measured at the three sites (12.4–16.2 μmol m^{-2} $event^{-1}$) are relatively similar to the deposition rate of 14.2 μmol m^{-2} $event^{-1}$ reported by Bootsma et al. (1999) for Lake

Table 3. Summary of wet and dry phosphorus deposition measured at Lake Victoria

	Bukoba		Mwanza		Seronera		Duma	
	TP	SRP	TP	SRP	TP	SRP	TP	SRP
Wet								
V.W.M. Concentration ($p > 0.05$ mol l^{-1})	0.66 ± 0.08	0.4 ± 0.05	0.81 ± 0.07	0.38 ± 0.03	0.62 ± 0.06	0.35 ± 0.03		
Mean Deposition ($p > 0.05$ mol m^{-2} $event^{-1}$)	13.1 ± 1.65	8.0 ± 1.05	16.2 ± 1.39	7.2 ± 0.53	12.4 ± 1.25	7.0 ± 0.61		
Lakewide Deposition (ktons $year^{-1}$)	4.20	2.50	3.60	1.30	2.20	1.10		
Dry								
Mean concentration ($p > 0.05$ μmol l^{-1})	1.02 ± 0.11	0.26 ± 0.04	1.31 ± 0.11	0.41 ± 0.04	0.87 ± 0.09	0.19 ± 0.03	1.08 ± 0.10	0.27 ± 0.02
Mean deposition ($p > 0.05$ μmol m^{-2} day^{-1})	20.4 ± 2.18	5.20 ± 0.73	26.2 ± 3.25	8.20 ± 0.75	17.4 ± 1.76	3.80 ± 0.58	21.6 ± 1.12	5.40 ± 0.43
Lakewide deposition (ktons $year^{-1}$)	9.30	2.30	15.40	4.80	10.80	2.30	12.90	3.20
Total annual deposition to the lake (ktons $year^{-1}$)	13.50	4.80	19.00	6.10	13.00	3.40		
Loading rate (kg ha^{-1} $year^{-1}$)	1.90		2.70		1.80			

Measured concentration and deposition values are mean ± SD. (For Mwanza, Duma and Seronera the annual deposition estimates are for the period August 1, 1999 to July 31, 2000; and for Bukoba are for the period June 1 to December 1, 2000). Lake surface area = 68,800 km^2. Lake loading rates assume deposition rates to the lake are the same as those measured at land stations.
Lakewide P deposition (ktons $year^{-1}$) estimated from Equation (3).

Table 4. Estimates of wet and dry phosphorus deposition to Lake Victoria by dividing the lake into five sections of relatively similar rainfall regimes and area weighting P deposition values measured from nearest sampling sites (Lakewide P load estimated from Equation (3))

Lake section	1	2	3	4	5	Total
Surface area (km^2)	6880	17,200	18,576	13,074	13,070	68,800
Mean annual rainfall (mm)	1800	2400	1200	2600	1000	
Mean deposition						
$\mu mol\ m^{-2}\ day^{-1}$	20.4	20.4	17.4	20.4	21.6	
$\mu mol\ m^{-2}\ event^{-1}$	13.8*	13.1	12.4	13.8*	16.2	
Mean dry days per annum	200	205	240	190	250	
Mean wet days per annum	165	160	125	175	115	
Annual deposition (tons $year^{-1}$)						
Dry deposition	870.2	2229.8	2404.7	1570.9	2187.9	9263.5 (69%)
Wet deposition	485.6	1117.6	892.6	978.8	754.8	4229.4 (31%)
Total deposition [Dry + Wet (tons $year^{-1}$)]	1355.8	3347.4	3297.3	2549.7	2942.7	13,492.9

*Wet deposition rates measured at Jinja (reported in Lindenschmidt et al. (1998)).

Table 5. Summary of selected tropical and temperate TP loading rates (kg ha^{-1} $year^{-1}$)

	Wet	Dry	Wet + Dry	Source
Tropical				
Mwanza, L. Victoria	0.5	2.2	2.7	This study*
Bukoba, L. Victoria	0.6	1.3	1.9	This study*
Seronera, L. Victoria	0.3	1.5	1.8	This study*
Duma, L.Victoria	–	1.8	–	This study
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)*
Temperate				
Ontario Shield, ELA	–	–	0.32	Schindler et al. (1976)
Colorado Mountains (USA)	–	–	0.20	Grant and Lewis (1982)

*Wet and dry samples collected separately, and wet samples measured on event basis.

Malawi. In this study SRP constituted one half (47–60%) of the TP in wet samples that were analyzed. This was considerably higher than for rain samples measured at Lake Malawi whereby SRP comprised 30% of the wet TP deposition (Bootsma et al. 1999).

For dry precipitation, measured TP deposition rates were significantly greater at Mwanza than Seronera ($p < 0.03$). The SRP deposition rate was 1.5–2.2 times greater at Mwanza than Duma-Sayaka, Bukoba and Seronera ($p < 0.00$). As with wet phosphorus deposition, mean dry deposition rates measured in this study (17.4–26.2 $\mu mol\ m^{-2}\ day^{-1}$) compare favourably with the dry deposition rates measured at Lake Malawi (24.7 $\mu mol\ m^{-2}\ day^{-1}$, Bootsma et al. 1999).

Temporal atmospheric P deposition

When phosphorus concentrations from measured rain events were averaged by month and across the three sites, there were strong temporal variations in wet phosphorus deposition with significantly greater mean monthly TP ($p < 0.02$) and SRP ($p < 0.04$) deposition rates measured in July and September (Figure 6). Mean wet TP deposition measured in July was three times greater than that measured in January and December. Mean SRP deposition was 2.7 times greater in July than in December. This was possibly due in part to low rainfall recorded during the dry season when the dryfall deposition was large relative to rainfall events.

Enormous temporal variability in the amount of TP in the dry samples was also measured at the sites, with significantly greater concentrations measured in July, June, August, September, October and May ($p < 0.04$) (Figure 7). The measured TP dry flux ranged from the highest daily mean deposition rates of 26.0–33.6 μmol m^{-2} day^{-1} in June through September to the lowest daily means of 11.0–13.2 μmol m^{-2} day^{-1} in January, December and April. Dry TP deposition measured in July was three times greater than that measured in January and December. Unlike TP, dry atmospheric deposition of SRP followed no apparent seasonal trend and accounted for only 20–30% of the TP in measured samples. The low percent composition of SRP in dry samples suggests that dry deposition contained a high proportion of refractory large-particle size fallout (>0.45 μm).

Atmospheric phosphorus deposition to Lake Victoria

A summary of the calculations of wet and dry P deposition to Lake Victoria are presented in Tables 3 (procedure no. 1) and Table 4 (procedure no. 2). The results show that, on average, 13.5 ktons of P are deposited annually on the lake from the atmosphere, representing a loading rate of 1.9 kg P ha^{-2} $year^{-1}$. Thirty-two percent of the total P input (4.2 ktons) was in a bio-available form (SRP) and possibly immediately linked to the on-going process of eutrophication in the lake. Dry deposition, a component ignored in previous studies, exceeded wet deposition by contributing between 70% and 75% of the atmospheric P input. The ratios of dry to wet P deposition were 2:1 at Bukoba, 5:1 at Mwanza, and 6:1 at Seronera. Similarly, wet P load measured at Bukoba (4.2 ktons) was comparable to that of the previous measurements made at Jinja (4.8 ktons; Lindenschmidt et al. 1998). Bukoba and Jinja experience a wet tropical climate as opposed to tropical savannah climate typical of much of the south and eastern parts of Lake Victoria.

In comparison with other studies the annual atmospheric fluxes of P measured around Lake Victoria are near the upper values in the range of loading rates reported elsewhere (Table 5). Using P input estimate of 9.8 ktons from runoff (Mugidde et al. 2003) and 1.1 ktons from municipal wastes (5% annual

increase from 0.92 ktons in 1997) (Scheren et al. 2000), the present estimates of atmospheric deposition would represent 55% of the total phosphorus input to the lake.

Discussion

The atmospheric phosphorus fluxes measured around Lake Victoria are comparable to those reported for the nearby Lake Malawi, but the values are high compared to measurements made in other deposition studies conducted in South and North America. Because phosphorus is generally a non-volatile element, its deposition has been attributed to gravitational settling of atmospheric particulate phosphorus from localized sources (Hendry et al. 1984). Thus, while the cause of high phosphorus deposition rates in the Lake Victoria catchment remains uncertain, soil particulates, dust, and fires are likely sources of elevated fluxes due to the intensity of deforestation and biomass burning.

The seasonal pattern that emerged from the data was both predictable and enlightening. Greater P deposition rates were measured during the dry season. This may be due to the tendency of atmospheric aerosol and dust plumes to be suppressed during periods of frequent rain. Also both average and maximum concentrations in each event peaked in July through September. Higher values during these months were not surprising because at this time of the year, the majority of the annual seasonal burning of vegetation occurs between July and September. In addition, the dry season coincided with the period of maximum exposure of soil following harvest of most crops. Elevated concentrations of P observed during this period are likely attributable to a combination of these activities and the infrequent occurrence of rainfall.

The significantly lower dry P deposition measured at Seronera relative to other sites possibly reflects less input from local soil particles because the surrounding park area is vegetated for most of the year by native plant communities. In contrast, Mwanza and Bukoba are urbanized and deforestation caused by shifting cultivation is significant around Duma-Sayaka. Several suggestions for high P deposition include soil exposure from deforestation and open field agriculture (Bootsma and Hecky 1993), and ash released from vegetation burning (Lewis 1981; Artaxo et al. 2000).

It remains unclear as to why there was no statistically significant spatial difference in wet SRP deposition in the current study. SRP in rain samples measured at the three sites may have been transported from distant areas, thus representing a regional phenomenon. While this is an oversimplication, it may have some validity. The depositional velocity of terrestrial particles injected into the atmosphere is related to mass, which is, in turn, related to particle size. According to Murphy (1974), large atmospheric particles that have a short residence time are a major contributor to dry fallout and are chiefly of local origin. However, small particles with relatively long atmospheric residence times are removed chiefly by precipitation scavenging and can be of local or

very distant origin. If this was the case during the study period, dominant airflow over the region would normally place the sampling sites beneath the plume of dust constantly generated in a more semi-arid region south of the Lake Victoria catchment. Thus, in addition to locally generated anthropogenic inputs the regional weather pattern may have had a modifying influence on the final concentration of solutes measured at the sampling sites and that SRP being scavenged by precipitation at these sites may very likely be of distant origin.

The influence of meteorological factors on the measured atmospheric fluxes was also demonstrated by low annual dry TP load (tons $year^{-1}$) deposited at Bukoba despite high P concentrations measured at this site compared to Seronera. The low annual dry TP load for Bukoba was the result of the large amount of rainfall and large number of rain days per annum compared to Seronera.

A combination of long atmospheric residence time of small, potentially more reactive, particles and the importance of moisture for effective stripping of major soluble substances from the atmosphere is the most likely explanation for elevated levels of SRP in wet precipitation compared to dry precipitation. In this study SRP was analyzed from filtered (0.45 μm) samples. Similar greater concentrations of SRP were reported in precipitation samples measured in Lake Tahoe, Nevada (Jassby et al. 1994) and Central Alberta, Canada (Caiazza et al. 1977). Lewis et al. (1985) suspected long-distance transport of phosphorus containing particles in filtered atmospheric water samples collected in the montane region of Colorado, USA.

For dry precipitation the theory of depositional velocities would imply that dry fallout should be dominated by local inputs of large particles, which are probably the most representative of depositional trends in the immediate area. Greater TP:SRP ratios measured in dry samples especially for drier sampling sites in the south, and statistically significant site differences in both TP and SRP deposition in the dry samples, illustrate a possible linkage between dry precipitation and locally generated inputs. Around Lake Victoria, there is a higher contribution of dryfall to the total atmospheric deposition of P and a greater TP:SRP ratio in dry deposition samples measured in this study compared with the results obtained by Bootsma et al. (1999) in one of the few available studies of atmospheric P deposition in the Great Lakes region of Africa. Esser and Kohlmaier (1991) have also shown that a lack of gaseous P phase should imply that very little (10–25%) of the total atmospheric P emitted from anthropogenic sources will reach land and freshwater systems as wet deposition, since essentially all the P is in particulate form, to be delivered predominantly as dry deposition.

There remain some inherent difficulties in the efforts to extrapolate how far particulate plumes from land stations would travel to the central area of the lake. However, the fact that the dominant south east trade winds system in the region place the four sampling sites upwind relative to the lake, would make estimates derived from these stations more reasonable to Lake Victoria than

estimates derived from Jinja, which is downwind relative to the lake. Similarly, while it may be true that the average transport distances of particulate materials in dry deposition are shorter than those associated with wet deposition, Prospero (1979) demonstrated long distance movement of large amounts of dust from North Africa to the Caribbean.

The present estimates of atmospheric P deposition differ from those reported in earlier studies by rapid assessment method (Scheren et al. 2000) where percent contributions of 55, 36 and 9 were assigned for runoff, atmosphere, and municipal wastes, respectively. Different sampling and analysis protocols used to estimates atmospheric P inputs explain the observed differences between this study and data reported in the literature. In their rapid assessment study, Scheren et al. (2000) used areal P loading rates from wet deposition only measured for Lake Malawi (0.53 kg ha^{-2} $year^{-1}$ as reported by Bootsma et al. 1996) and applied them to the surface area of Lake Victoria to calculate atmospheric P loading. Inclusion of dry deposition in our estimates greatly increases the relative importance of atmospheric P loading.

The Victoria ecosystem has been affected by an increase in P concentrations and P loading. Concentrations of TP in the lake now are 2.5 μmol l^{-1}, on average (Guildford and Hecky 2000), more than double the TP concentrations reported in the early 1960s. Hecky (1993) reported that P concentrations in the sediment record (assumed proportional to total P loading) began to notably rise by 1960 and was accompanied by dramatic shifts in the algal microfossils. Kling et al. (2001) compared the algal community in Victoria in the 1990s with earlier records and found a profound change. Nitrogen-fixing cyanobacteria (*Anabaena* and *Cylindrospermopsis*) now dominate the phytoplanktonic biomass and nitrogen fixation accounts for over 70% of the total nitrogen loading to the lake (Mugidde et al. 2003). The nitrogen-fixing species have a competitive advantage at the low TN:TP ratios of the lake that are among the lowest reported in the literature at an average of 13.6 molar and are observed as low as 7.5, well below Redfield proportions (Guildford and Hecky 2000).

Study limitations

The major limitation of this study is that rain and dry deposition data were collected from land stations and then applied to open lake areas to estimate lake-wide phosphorus deposition. Unlike on a wet lake surface, it is possible for major solutes deposited on land by dryfall to be recycled from land to atmosphere and back to land, thus falsely inflating net input of land stations. Therefore, it is difficult to know how well measurements made on land would adequately represent phosphorus deposition over the open lake areas.

Also, there is a possible error caused by the small sample size of rains used in wet deposition measurements. Given the frequency and variability of storms in the study sites a relatively large sample size would be needed to reduce the

expected error associated with event-based estimates of the true VWM concentration of solute measured in wet precipitation. For example, 6 months data at Bukoba may not be representative of the annual population of storms.

Conclusions

Atmospheric precipitation fluxes measured in this study provide insights into identifying trends and assessing variability of P precipitation in the region where there are few data on atmospheric deposition. The data allows, for the first time, inclusion of the contribution of dry atmospheric precipitation in the phosphorus budget of Lake Victoria. Dry precipitation, a component ignored in previous studies, provides particularly important amounts of phosphorus in drier areas around the lake.

Circumstantial evidence gathered from flux rates measured at the four sites allows for the general conclusion that land use was the primary factor influencing the observed spatial differences in atmospheric P deposition around Lake Victoria. As land use became more intensive (e.g. for human settlement, agriculture, animal husbandry, etc.), measured P deposition rates also increased, possibly as a result of increased atmospheric input of terrestrially derived material such as blown soil, dust and ash. Meteorological factors such as amount of precipitation and wind patterns were found to have a modifying influence on the spatio-temporal deposition of atmospheric phosphorus.

The concurrence of rates of wet deposition among studies on the Great African lakes and dry deposition among locations in this study and Malawi indicate that atmospheric P deposition is an important source of P loading that must be considered in future management of the nutrient inputs to these lakes. The measurement of very similar rates of wet and dry P deposition at such widely separated locations as Tanzania and Malawi suggests that our results are likely representative of high deposition rates throughout the tropics as a consequence of human activities.

Acknowledgements

The work upon which this paper is based was supported by the Lake Victoria Environment Management Project (LVEMP) through its Support to Riparian Universities component in Tanzania. The field research was also supported, in part, by the Rockefeller African Dissertation Internship Award (ADIA) RF 97034 # 796. It is a pleasure to acknowledge the assistance of the Ministry of Water and Livestock in Tanzania for permission to use Mwanza and Bukoba labs and facilitating sampling access, Mr. G.T. Mgwatu for assisting in sample collection and analyses, and four anonymous reviewers for helpful comments on the manuscript.

References

Artaxo P., de Campos R.C., Fernandes E.T., Martins J.V., Xiao Z., Lindqvist O., Fernandes-Jimenez M.T. and Maenhaut W. 2000. Large scale mercury and trace element measurements in the Amazon basin. Atmos. Environ. 34: 4085–4096.

Bootsma H.A. and Hecky R.E. 1993. Conservation of the African Great Lakes: a limnological perspective. Conserv. Biol. 7: 644–656.

Bootsma H.A., Bootsma M.A. and Hecky R.E. 1996. The chemical composition of precipitation and its significance to the nutrient budget of Lake Malawi. In: Johnson T.C. and Odada E. (eds) The Limnology Climatology and Paleoclimatology of the East African Lakes. Gordon and Breach Publishers, pp. 251–265.

Bootsma H.A., Mwita J., Mwichande B., Hecky R.E., Kihedu J. and Mwambungu J. 1999. The atmospheric deposition of nutrients on Lake Malawi/Nyasa. In: Bootsma H.A. and Hecky R.E. (eds) Water Quality Report. Lake Malawi/Nyasa Biodiversity Conservation Project, pp. 85–111.

Caiazza R., Hage K.D. and Gallup D. 1977. Wet and dry deposition of nutrients in Central Alberta. Water Air Soil Pollut. 9: 309–314.

Cole J.J., Caraco N.F. and Likens G.E. 1990. Short-range atmospheric transport: a significant source of phosphorus to an oligotrophic lake. Limnol. Oceanogr. 35(6): 1230–1237.

Crul R.C.M. 1993. Limnology and hydrology of Lake Victoria. Comprehensive and comparative study of Great Lakes. Unesco/IHP-IV Project M-5.1.

Crutzen P.J. and Andreae M.O. 1990. Biomass burning in the tropics: impact on atmospheric chemistry and biogeochemical cycles. Science 250: 1669–1678.

Delmas R.A., Loudjani P., Podaire A. and Menaut J. 1991. Biomass burning in Africa. In: Levine J.S. (ed.) Global Biomass Burning. Atmospheric, Climatic and Biospheric Implications. The MIT Press, Cambridge, pp. 126–132.

EAMD. 1975. East African meteorological department climatological statistics for East Africa. Part III. Tanzania, Nairobi, E.A. Meteorological Department, 92 p.

Esser G. and Kohlmaier G.H. 1991. Modelling terrestrial sources of nitrogen, phosphorus, sulphur and organic carbon to rivers. In: Degens E. et al. (eds) Biogeochemistry of Major World Rivers SCOPE 42. John Wiley and Sons, pp. 297–322.

Galloway J.N. and Likens G.E. 1978. The collection of precipitation for chemical analysis. Tellus 30: 71–82.

Grant M.C. and Lewis W.M. 1982. Chemical loading rates from precipitation in the Colorado Rockies. Tellus 34: 74–88.

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.

Hao W.M. and Liu M.H. 1994. Spatial and temporal distribution of tropical biomass burning. Global Biogeochem. Cycles 8: 495–503.

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

Hecky R.E., Bugenyi F.W.B., Ochumba P., Talling J.F., Mugidde R., Gophen M. and Kaufman L. 1994. Deoxygenation of the deep water of Lake Victoria. Limnol. Oceanogr. 39: 1476–1480.

Hendry C.D., Berish C.W. and Edgerton E.S. 1984. Precipitation chemistry at Turrialba, Costa Rica. Water Resour. Res. 20: 1677–1684.

Kling H.J., Mugidde R. and Hecky R.E. 2001. Recent changes in the phytoplankton community of Lake Victoria in response to eutrophication. In: Munawar M. and Hecky R.E. (eds) Great Lakes of the World: Food Webs, Health and Integrity. Backhuys, Leiden, pp. 47–66.

Jassby A.D., Reuter J.E., Axler R.P., Goldman C.R. and Hackley S.H. 1994. Atmospheric deposition of Nitrogen and Phosphorus in the annual load of Lake Tahoe (California–Nevada). Water Resour. Res. 30(7): 2207–2216.

Lewis W.M. Jr. 1981. Precipitation chemistry and nutrient loading by precipitation in a tropical watershed. Water Resour. Res. 17(1): 169–181.

Lewis W.M. Jr., Grant M.C. and Hamilton S.K. 1985. Evidence that filterable phosphorus is a significant atmospheric link in the phosphorus cycle. Oikos 45: 428–432.

Likens G.E. and Butler T.J. 1981. Recent acidification of precipitation in North America. Biogeochem. Forested Ecosyst. 15: 1103.

Lindenschmidt K.E., Suhr M., Magumba M.K., Hecky R.E. and Bugenyi F.W.B. 1998. Loading of solutes and suspended solids from rural catchment areas flowing into Lake Victoria in Uganda. Water Res. 32: 2776–2786.

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

Murphy T.J. 1974. Sources of phosphorus inputs from the atmosphere and their significance to oligotrophic lakes. University of Illinois Water Resources Centre (UILU-WRC-74-0092). Research Report No. 92. 45 p.

Nürnberg G. and Peters P.H. 1984. Biological availability of soluble reactive phosphorus in anoxic and oxic freshwaters. Can. J. Fish. Aquat. Sci. 41: 757–765.

Parsons T.R., Maita Y. and Lalli C.M. 1984. A Manual of Chemical and Biological Methods of Seawater Analysis. Pergamon, Oxford, England.

Peters R.H. 1986. The role of prediction in limnology. Limnol. Oceanogr. 31: 1143–1159.

Prospero J.M. 1979. Mineral and seal salt aerosol concentrations in various ocean regions. J. Geophys. Res. 84: 725–731.

Scheren P.A., Zanting H.A. and Lemmens A.M. 2000. Estimation of water pollution sources in Lake Victoria, East Africa: application and elaboration of the rapid assessment methodology. J. Environ. Manage. 58: 235–248.

Schindler D.W., Newbury R.W., Beaty K.G. and Campbell P. 1976. Natural water and chemical budgets for a small Precambrian lake basin in Central Canada. J. Fisheries Res. Board Canada 33: 2526–2543.

Thornton I. 1965. Nutrient content of rainwater on the Gambia. Nature 205: 1025.

Yin X. and Nicholson S.E. 1998. The water balance of Lake Victoria. Hydr. Sci. J. 43(5): 789–811.