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Phosphorus inputs to Lake Naivasha, Kenya, from its catchment and the trophic state of the lake

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Abstract

The main river supplying Lake Naivasha, Kenya, the Malewa, drains a catchment given over to largely subsistence cultivation and animal husbandry. The lake itself is the focus for an intensive horticultural industry based upon irrigation from the lake. The Malewa, however, is relatively independent of the impact of industry, and so its contribution to eutrophication of the lake was evaluated. Two periods of study, a very wet-dry and a 'normal' wet-dry season showed that the river contribution of phosphorus led to a total phosphorus loading of 1.4 g m^{-2} lake surface ann^{-1} in the very wet period compared to 0.2 in the 'normal'. Chlorophyll '*a*' in the open water of the lake was significantly related to soluble reactive phosphorus. The lake is now eutrophic by normal limnological criteria.

Introduction

Eutrophication in tropical lakes is not as well understood than it is in the temperate zone. In general tropical/sub-tropical systems appear to tolerate higher phosphorus loads for similar algal biomass and, of course, experience a more uniform light climate but a more dramatic wet/dry hydrological regime (Talling, 2001). Total phosphorus concentration of 50–60 μg l^{-1} has been suggested as the boundary between mesotrophic and eutrophic for Lake Chivero (formerly Lake Mcllwaine) in Zimbabwe (Thornton & Nduku, 1982), similar to the concentration reported for Australian water bodies (McDougall & Ho, 1991) and higher than that of the temperate zone. Ryding & Rast (1989) suggest that tropical systems often develop low N/P ratios, thereby favouring the dominance of nitrogen-fixing cyanobacteria. Toerien (1975) suggests that these are more dominant in tropical lakes, but a change in phytoplankton either from diatom to cyanobacteria dominance and *vice versa*, induced by wind regime, has been observed in lakes Naivasha (Kalff & Brumelis, 1993), Volta (Biswas, 1972; Talling, 1986), Tanganyika, Malawi (Talling, 1966), Victoria (Hecky, 1993; Lehman, 1996) and Kariba (Cronberg, 1997) as a result of seasonal water mixing.

Generally low levels of industrialization in Africa, means that eutrophication does not present the same problems as it does in temperate countries. The leading causes of environmental degradation in Africa are over-cultivation, overgrazing, and deforestation. Deforestation takes place as a result of clearing agricultural land, wood for fuel (about 90% of the population use fuel wood), building material and a source of income (UNEP-IETC, 1999). Elsewhere in the tropics, construction of new reservoirs and increase in uses of natural lakes for water supply combined with settlement in the catchments has resulted in extensive problems following accelerated nutrient inputs (Thornton, 1987a). Nutrient runoff and sedimentation may become serious problems and widespread in future if they are not properly addressed now.

Many lakes,reservoirs and rivers studied within the tropical region have shown an increase in eutrophication, for example in southern Africa (Twinch, 1986; Thornton, 1987b) although the benefits of deliberate eutrophication to increase edible fish yield from ponds fertilized with human wastes has been enjoyed for centuries in Asia (Payne, 1984). According to UNEP-IETC (1999), Lake Malawi has already given an early warning of degradation in water quality using Eccles's (1974) and Bootsma's (1993) data. Subsequent surveys a decade later including Malawi, noted a marked reduction in water quality in the region (ILEC, 1994).

In Lake Kariba (the world's largest man-made lake by storage), the levels of total phosphorus in some parts are approaching thresholds with respect to future eutrophication (Cronberg, 1997). Lake Chivero became hypereutrophic in the 1960s with phytoplankton species *Anabaena* and *Microcystis* dominating. After installation of a Biological Nutrient Removal (BNR) sewage treatment plant in 1974, the lake showed a recovery (Thornton, 1982), but due to further increase in population within the surrounding area, it reverted to hypereutrophic status in the mid 1980s (Moyo, 1997) up to the present day (UNEP-IETC, 1999) which currently has chronic water hyacinth problems and repeated fish kills.

Naivasha in the past was more phosphorus limited than nitrogen, (Talling & Talling, 1965; Kalff, 1983). There is no study undertaken on the trophic state of the rivers flowing into Lake Naivasha and although phosphorus is generally low in Kenyan soils (Hinga, 1973; Nyandat, 1981), erosion which follows ploughing or over-grazing may bring sediment-bound phosphorus into the lake in higher quantities.

The ecological stability of Lake Naivasha is threatened by the impact of both internal and external factors. Internal factors are exotic species' introductions and accidental arrival. External factors are the impact of an intensive horticultural industry, which has grown up on the shores over the last 15 years, based upon lake water for irrigation. The impact is believed to be both runoff of pesticides, effluents and nutrients and the pressure of tens of thousands of people who have migrated into the area for work. The catchment, however, is given over to mainly subsistence cultivation and animal husbandry.

This study examines the sources and quantity of phosphorus entering the lake from the Malewa. It was carried out from September 1997, when heavy rains fell over the country, believed to be a consequence of the 'El Niño' earlier in that year in the southern Atlantic, to March 1998, after Naivasha lake level had risen by 2 vertical metres (Fig. 1). This period was then compared with a more 'normal' period, between 1998 and 1999.

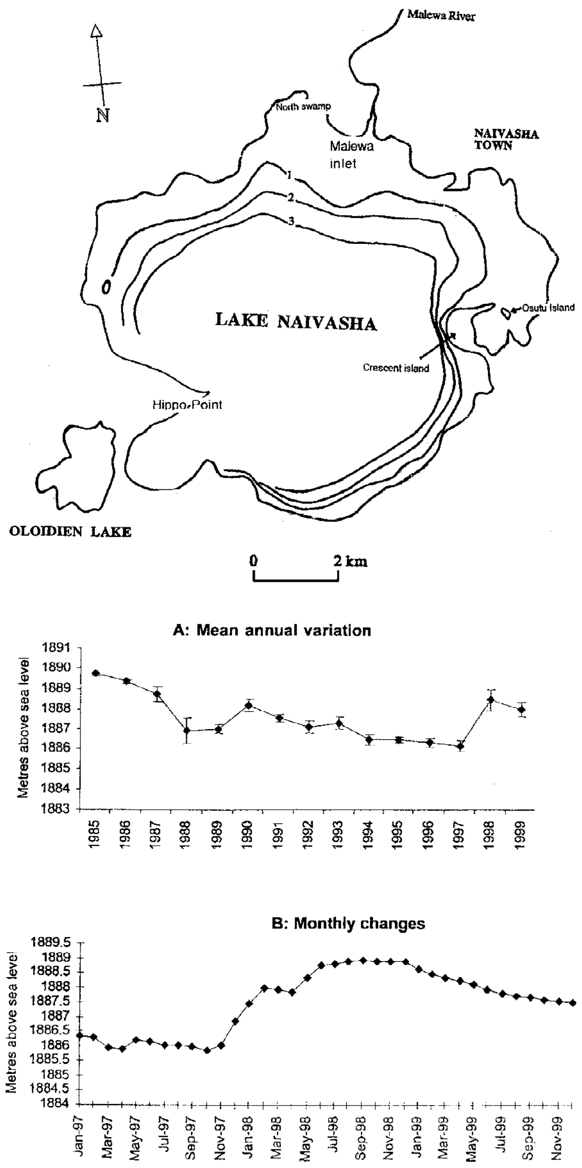

Figure 1. Location of Lake Naivasha, Kenya and its lake level change, 1985–99 & 1997–99. The depth contours on the map refer to 1991 (Hickley et al., 2002).

Methods

In the field, weekly samples were taken along a transect from the river inlet to the open water of the lake, 8.5 km to the south. Five stations were sampled – at the inlet, then 100 m, 500 m, 5 km and 8.5 km south. Secchi disc transparency and water conductivity were recorded directly from a boat (conductivity using YSI conductivity meter). Water samples were collected just below the surface of the lake using a

1.5 l messenger-closed plastic sample bottle (Institute of Oceanographic Sciences, Surrey). Water was transferred into acid-washed polythene 1 l bottles and a portion immediately filtered using an acid-washed 60 ml disposable syringe to push the water through a pre-weighed GF/C glass fibre filter (Whatman, U.K.). Both filtered and unfiltered samples were transported in a cool-box and analysed within 1–3 h on return to a lake-side laboratory; a further unfiltered sample was transported in the same way for chlorophyll '*a*' analysis.

In the laboratory, chlorophyll *a* as a measure of phytoplankton biomass was analysed using 90% ethanol as solvent and biomass calculated from absorbancies of the extract before and after acidification with HCl. Soluble reactive phosphorus was determined in filtered water samples using the molybdenum blue technique after Mackereth et al. (1979). Total phosphorus (TP) and total dissolved phosphorus (TDP) were obtained by measuring P after digestion of 20 ml unfiltered and filtered water samples respectively with 0.5 g potassium persulphate and 1.2 ml of 10N sulphuric acid. Particulate phosphorus (PP) was calculated as the difference between TP and TDP; dissolved organic phosphorus as the difference between TDP and SRP (Lennox et al., 1997). The filer papers were oven dried and re-weighed to give total suspended solids (TSS).

Data were analysed using Minitab. Phosphorus input from the catchment was calculated from the river inlet site and expressed as loading per unit area of lake surface. The loading rates were related to mean depth of the lake to estimate its trophic status (Vollenweider, 1968). Internal loading was estimated from Cooke et al. (1993) following a phosphorus sedimentation calculation, to arrive at a predicted TP concentration.

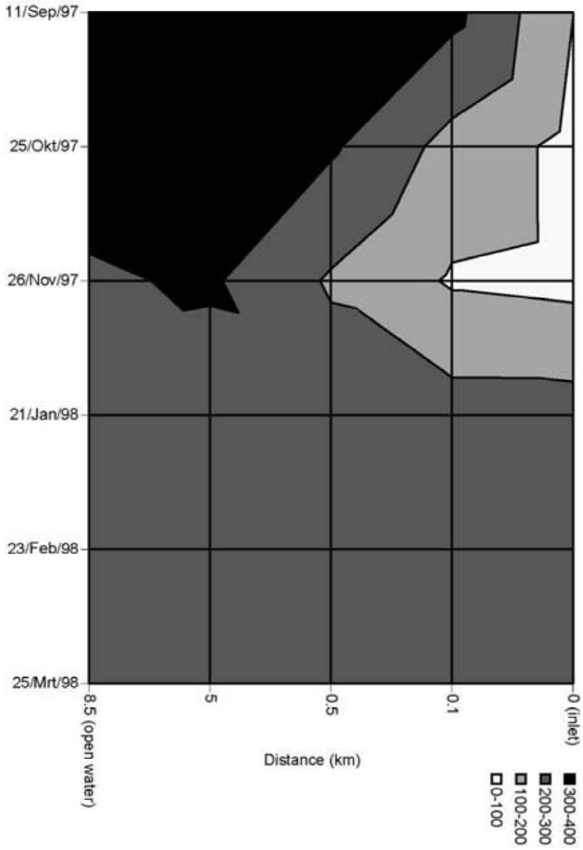

Figure 2. Spatial variation of conductivity, μS cm^{-1}, on a transect from the Malewa inlet SE to Hippo Point (vertical axis) over time (horizontal axis). Note the scale changes on the axes.

Results

The chemical influence of the river Malewa on the lake was most pronounced at the beginning of the heavy rainy season between October and November 1997 for up to 0.5 km into the lake, shown by the spatial variation in conductivity (Fig. 2), Secchi transparency (Fig. 3), and chlorophyll *a* (Fig. 4).

The effect of the rain on the lake was not apparent until January 1998, (see Fig. 1) when the river inlet was almost 2.5 km further north of its normal position as the water rose. This dramatically changed the riverine conductivity characteristics of the inlet September–November 1997 into lake conditions in January 1998 (Fig. 5).

A significant negative correlation between Secchi tranparency and TSS (Fig. 6) occurred both in the inlet and the open water, but the much steeper relationship in the inlet demonstrates the effect here of inorganic silt, the major contributor to TSS. A strong negative correlation between chlorophyll *a* and Secchi depth in the open water (compared to no relationship at the inlet; Fig. 7) shows that transparency in the open water is caused by variations in phytoplankton biomass, Phytoplankton are of course part of the lacustrine TSS (a strong significant positive correlation between TSS and chlorophyll *a* (R = 0.871, R^2 = 0.758, $n = 20$ $p < 0.0001$)), which is why TSS influenced transparency more significantly (R^2 = 0.67, $p < 0.0001$) in the open water than did chlorophyll *a* (R^2 = 0.003, $p > 0.05$).

Mean TP concentrations of 83.9 +/- 33.2 and 52.2 +/- 18 occurred at the inlet and the open water respect-

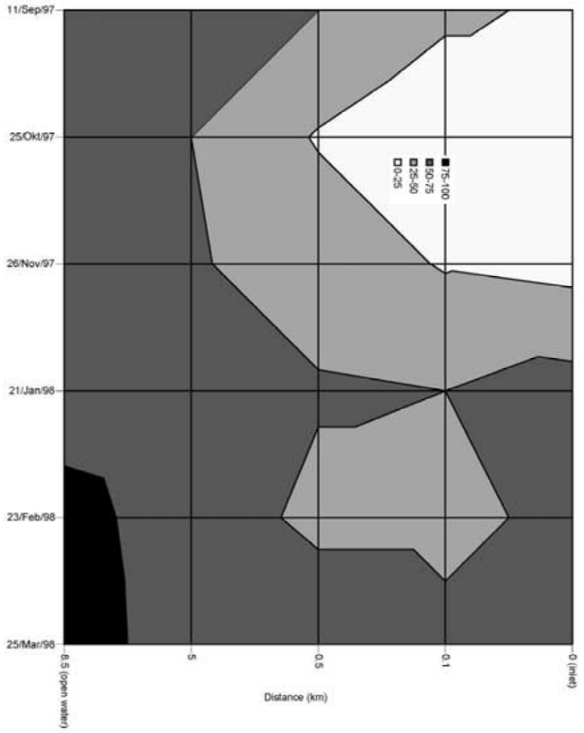

Figure 3. Spatial variation of Secchi disc transparency, cm, on a transect from the Malewa inlet SE to Hippo Point (vertical axis) over time (horizontal axis). Note the scale changes on the axes.

ively. In both locations the means hide an early peak from the river at the time of the rains but before the volume increase (Fig. 8). There was a much stronger positive correlation between TSS and TP at the inlet ($R = 0.92$, $R^2 = 0.84$, $n = 20$, $p < 0.001$) than in the open water ($R = 0.62$, $R^2 = 0.38$, $n = 20$, $p < 0.05$), which indicates the phosphorus is entering the lake bound to the sediment particles. Once in the lake, PP is reduced by sedimentation but also transformed as SRP is turned into phytoplankton P. In both periods chlorophyll *a* increased in proportion to TP – 8 fold during the very wet period, 2-fold during the 'normal' (Table 1). Chlorophyll *a* was correlated most strongly with TP and PP in the open water (Chl $a = 0.226\text{TP} + 10.3$ $R = 0.67$, $R^2 = 0.44$, $n = 18$, $p < 0.005$) and with nothing at the inlet.

The TP in the open water predicted from Cooke et al. (1993) matches its measured mean concentration, but the estimated lake loading derived from these figures do not agree, with the predicted figures 2–3 fold lower (Table 2). When chlorophyll *a* was predicted from the many north-temperate lake models, reasonable concentrations were obtained in the open water

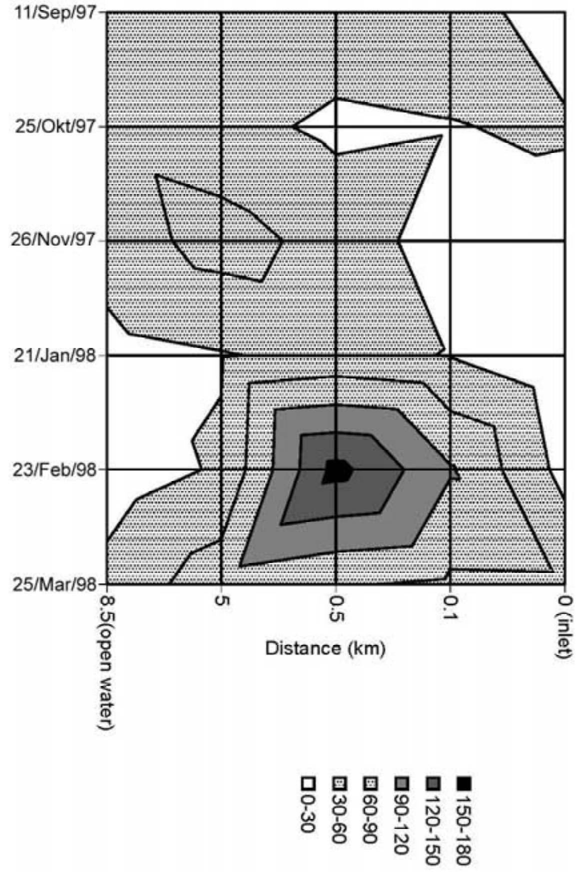

Figure 4. Spatial variation of chlorophyll *a* concentration, μg L^{-1} on a transect from the Malewa inlet SE to Hippo Point (vertical axis) over time (horizontal axis). Note the scale changes on the axes.

but higher predictions in the inlet. This is not surprising considering the light restriction that the suspended sediment caused despite the TP value. Only two models seriously under- (OECD, 1982) or over- (Schindler et al., 1978) estimated chlorophyll (Table 3), which considering the major difference of an endorrheic lake in an 'enless summer' climate (Kilham & Kilham, 1990) is encouraging.

Discussion

Temperate analogues are often necessary for understanding tropical waters when an inadequate data base exists (Kalff & Watson, 1986). Temperate trophic status classification of Lake Naivasha, estimated for the heavy rain period and the normal period, is eu-polytrophic and meso-eutrophic, respectively, using Vollenweider's five-class tentative classification (Vol-

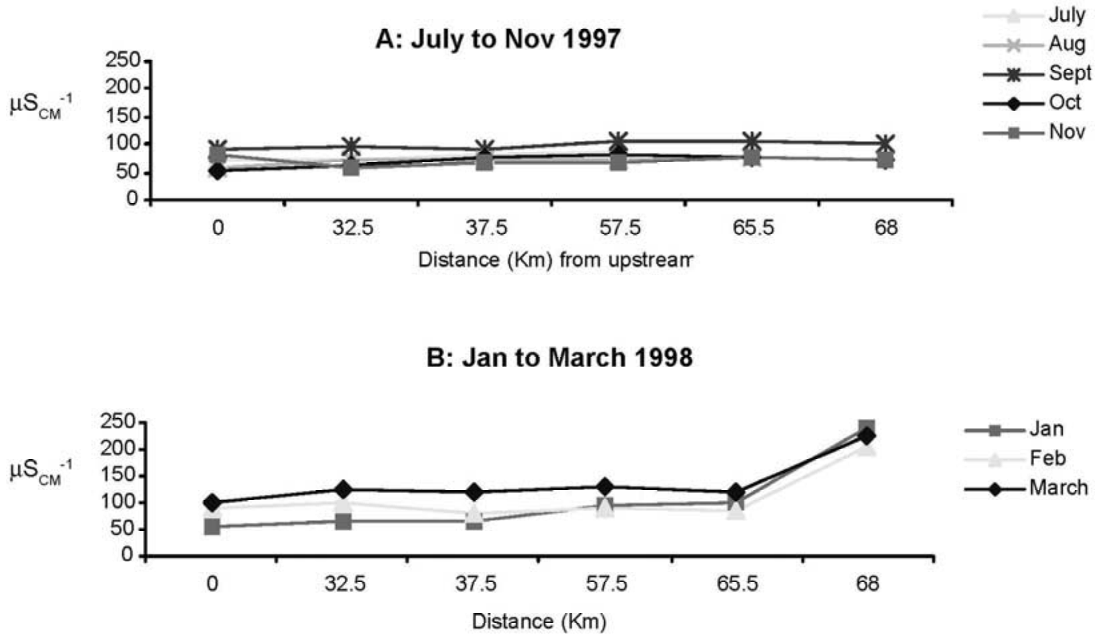

Figure 5. Longitudinal pattern of conductivity in the river Malewa during the very heavy wet season (upper) and following dry season when river discharge increased (lower) when the 'inlet site' (distance 68 km from source) became influenced by lake conditions.

Table 1. Comparison of different phosphorus fractions and ratios between the inlet and the open water

Station	PP%	SRP/TP	TP/Chla
September 1997–March 1998			
Malewa inlet	62.1 ± 7.8	0.38 ± 0.1	16.2 ± 7.4
Open water (Hippo point)	54.0 ± 10.5	0.30 ± 0.1	2.2 ± 0.5
November 1998–September 1999			
Malewa inlet	66.1 ± 7.0	0.11 ±0.02	5.3 ± 0.8
Open Water (Hippo point)	59.7 ± 7.1	0.12 ±0.02	2.7 ± 0.4

Table 2. The observed and predicted TP concentrations and lake loadings for Naivasha

	1997–8	1998–9	Overall mean
Measured TP mg l^{-1}	45.9	37.2	52.2
Measured TP mg l^{-1}	45.0	37.7	51.2
Estimated lake loading g m^{-2} ann^{-1}	1.41	0.21	0.6
Predicted lake loading g m^{-2} ann^{-1}	0.39	0.14	0.23

lenweider, 1968). Plotting the quotient between in-lake phosphorus and mean inflow phosphorus concentration P/P_1 against P_1 on a logarithmic scale and extrapolated using Ahlgren et al. (1988), Lake Naivasha is also eutrophic (Fig. 9).

TP concentrations in a water body should not be considered as the only indicator of water quality without considering the consequences for algae (Jones & Lee, 1982). Naivasha is eutrophic with chlorophyll *a* concentration >10 μg/l^{-1}, Secchi depth <1.7 m and TP concentration of >40 μg/l^{-1} using the Lee et al. (1980) and Jones & Lee (1982) categories. The lake is further classified into various categories according to the OECD 'open boundary' system (OECD, 1982) summarised in Table 4. An alternative classification of Carlson (1977) used the calculation of a 'Trophic State Index' (TSI) was also considered and using Kratzer & Brezonik's (1981) index scale, Naivasha was approaching hyper-eutrophic status during the heavy rainy season with TSI scale values range of 58–66.

Lake Naivasha is now a eutrophic lake; a condition which was probably reached in the late 1970s although the recorded evidence is sparse (Hubble & Harper, 2001). It appears to have had a high transparency (several metres) up until the mid 1970s (Melack, 1976) but

Table 3. The trophic state of Lake Naivasha calculated on OECD and TSI indices at two different periods of heavy rainfall and normal rainfall based on three parameters

	TP (μg l^{-1})	Chlorophyll *a* (μg l^{-1})	Secchi depth (m)
Heavy rainfall (Oct 97–Feb 98)			
Measured value in the lake	54.75	31.32	0.57
OECD	eutrophic	hyper-trophic	hyper-trophic
TSI index	59.3	58.04	65.6
Normal rainfall (Sept 98–Feb 99)			
Measured value in the lake	46.93	11.5	1.26
OECD	eutrophic	eutrophic	eutrophic
TSI index	59.2	56.1	57.7

KEY
TSI scale
< 20 ultra-oligotrophic,
30–40 oligotrophic,
45–50 meso-trophic,
50–60 eutrophic
and above 70 hyper-trophic (Kratzer & Brezonik, 1981).

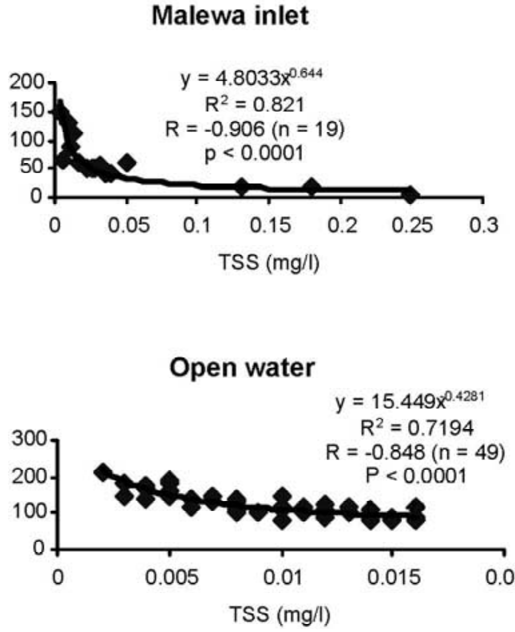

Figure 6. Correlation relationships between Secchi transparency and TSS at the inlet site and the open water site.

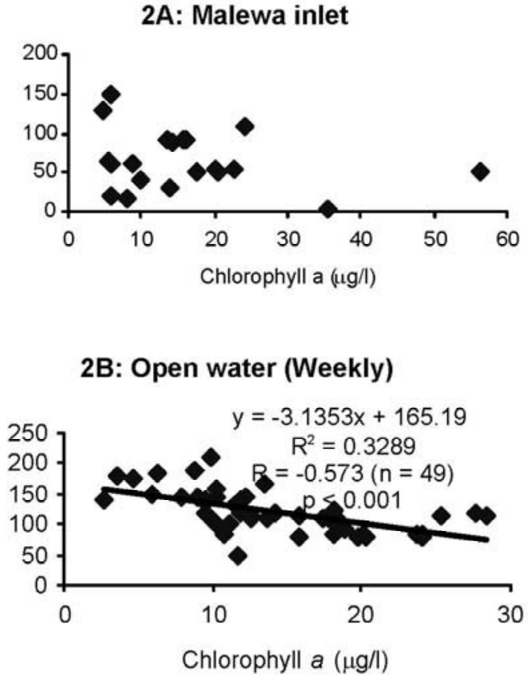

Figure 7. Correlation relationship between Secchi transparency and chlorophyll *a* at the inlet site and the open water site.

not always (Jenkin, 1936). It is tempting to suggest that its current eutrophic state has been accelerated by the loss of any natural buffering of the *Cyperus papyrus* fringe (Gaudet, 1979) following the decline of the area covered by the north swamp (Boar et al., 1999), but there is no direct evidence for this. Equally, there is no evidence of the earlier condition of the suspended sediment or the phosphorus in the rivers; only the certainty that the river did not run directly into the lake when the 'North Swamp' was intact. Evidence from the Malewa input is adequate to explain the increased trophic state of the lake without citing any

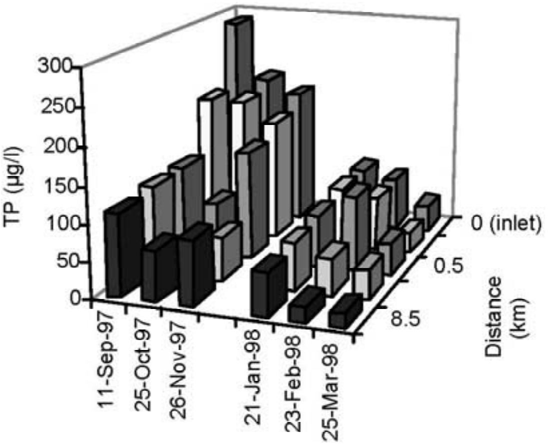

Figure 8. Spatial and temporal change in TP concentrations along the transect from the Malewa inlet (0 km) to open water at Hippo Point (8.5 km).

additional nutrient inputs from urban or horticultural sources.

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