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Chemical characteristics, with particular reference to phosphorus, of the rivers draining into Lake Naivasha, Kenya

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Abstract

The loss of phosphorus from the catchment of Lake Naivasha, Kenya, was 0.2 kg ha^{-1} ann^{-1}, 76% of it particulate in a 'normal' year of wet and dry periods. It rose to a mean of 1.8 kg ha^{-1} ann^{-1}, 90% of which was particulate, in the months following the extreme rainfall which followed the 1997–1998 El Niño event in the Southern Atlantic. Total and particulate phosphorus were positively correlated with suspended solids and with discharge, and conductivity was negatively correlated with discharge. The magnitude of losses pose both threats to the water quality of Lake Naivasha and to the sustainable soils resources of the catchment.

Introduction

The extent of soil degradation, the losses of potential agricultural production (Dregne, 1990) and the decrease in water quality (Calamari, 1987; Dejoux, 1988) are relatively poorly known for Africa. Yet its human population growth makes the necessity for an agricultural production increase essential (Fardeau & Frossard, 1991). Knowledge of the negative consequences of this, then becomes paramount.

In many regions of the tropics, a sustainable level of food production is possible only by achieving better agricultural yields with the current land resources and not by extending cultivation on marginal lands (Dregne, loc.cit.; Downing et al., 1990). This means that for a large part of Africa, an increase in agricultural output is possible only if pathways of phosphorus cycling are changed by a greater P uptake by crops (Fardeau & Frossard, loc.cit). Phosphorus is low in Kenyan soils and is commonly the primary limiting nutrient (Hinga, 1973; Nyandat, 1981). It is lost from cultivated land mainly in particulate form, where the phosphate adsorption capacity is dependent on particles' surface area and on their content of hydrated metal compounds (Fe, Al, Mn); most particles with these characteristics are clays (Viner, 1987). Their iron content depends on particle size and a strong relationship exists between available P, Fe content and the size of different clay fractions (Viner, loc. cit.). Organic matter also plays a significant role in the transport of particulate phosphorus. Organic particulates transport a larger fraction of adsorbed P than inorganic particulates (Sharpley & Smith, 1990). Conditions of intensive weathering in the tropics are associated with the leaching of Ca (Uriyo & Singh, 1978) and correlates with high abundance of amorphous Fe and Al (Wolf et al., 1985).

Total phosphorus and suspended solids (SS) generally increase in parallel during rain events when erosional processes in the catchment and in the channel are active. Discharge is initially positively correlated to TP and SS concentrations. Most of the particulate matter is mobilised during the rising limb of the hydrograph. Its concentration may decrease before the peak in discharge is reached. Alternatively peaks of SS and TP concentration can be observed during the falling limb of the hydrograph when the mobilisation of sediments continues after the peak in discharge. The concentration of TP generally correlates with the concentration of sediments (Pacini & Harper, 1999).

P export is maximal in storm events as the P carried by high discharge during periods of increased surface runoff represents the highest losses of total and dissolved phosphorus (TP and DP). Once in the river, dissolved and adsorbed P forms behave differently in relation to discharge. The concentration of DP is often reported to be higher in baseflow and to decrease during storms as a consequence of dilution by high water levels. Some studies have shown the opposite: higher DP export during surface runoff has been observed and explained as a reduction in contact time between the percolating water and the soil constituents which results in less P adsorption of the DP carried by surface waters (Sharpley & Syers, 1976).

The irregular flow regimes of tropical rivers are related to the particular rainfall pattern characterized by short rainy seasons with intense peaks, which generate a very high response in runoff (Jones, 1979; Viner, 1981). In the Orange river (South Africa) as much as 90% of the suspended and dissolved yearly load is mobilized during one rainy season. In Morocco, short-term monitoring revealed that four hours of flood could yield 98% and 74% of the annual TP and TN loads, respectively (Viner, 1981). These examples point out the challenge represented by attempts to monitor sediment and TP in tropical catchments. Roseboom & Lotriet (1993) found, after a detailed analysis of sediment export studies in South Africa, that a minimum of 8 years of continuous monitoring would be necessary to obtain reasonable estimates of suspended sediment export from a single catchment. A recent sediment yield map for South Africa was still based on simplifying assumptions defining broad regions of similar SS export potential, however, despite several decades of sediment monitoring and a detailed survey of reservoir sedimentation across the country, (Roseboom & Lotriet, 1993).

In Kenya, information on the physical and biological processes characterizing the cycle of phosphorus is scarce and fragmentary. Data are periodically collected by soil scientists (Hinga, 1973; Nyandat, 1981), by limnologists (Talling & Talling, 1965; Kilham, 1972; Gaudet, 1976, 1977, 1979; Melack, 1976, Peters & McIntyre, 1976; Melack et al., 1982; Njuguna, 1988; Melack & McIntyre, 1993; Hecky, 1993) and by agriculturists (Smaling & Bouma, 1992). There have been no surveys, however that would integrate different compartments of the P cycle and no quantitative estimates of annual P losses through runoff. Melack & McIntyre (1991) reviewed the available data on P in surface waters in tropical Africa and its potential for the limitation of aquatic ecosystems. A large part of their data concerns lakes and rivers in Kenya. In their analysis, they stressed the diversity of chemical composition of surface waters in the country and the lack of data on P in rivers during a full hydrological cycle.

A study of the major sources and sinks of P and other nutrients in different agro-ecological zones in Kenya (Smaling, 1993) suggested that human intervention in nutrient cycles in modern tropical Africa may be a cause of excessive enrichment in surface waters. This is supported by reports of on-going eutrophication in Lake Victoria (Hecky, 1993) and by concern expressed about the impact of increasing intensive agricultural land use around Lake Naivasha (Harper et al., 1993).

This study examines the sources and quantity of phosphorus in the rivers of the Lake Naivasha catchment, particularly the river which carries the main input, the Malewa. It was carried out from September 1997 to March 1998, when heavy rains fell over the country, believed to be a consequence of 'El Niño' in the southern Atlantic, and this period was then compared with a more 'normal' period, between 1998 and 1999.

Methods

Sampling stations were established on a range of headwater rivers and streams and the three major rivers flowing into lake Naivasha; the Malewa, Gilgil and Karati (Fig. 1). The positions of the sampling stations were on road access to the river, in most cases, below bridges.

Instantaneous river discharge at the time of sampling was estimated using a mechanical flow meter of General Oceanics, model 2030R to give mean column velocity at 60% water depth, at 1 m interval in stations with more than 10 m width and 0.5 m intervals in stations with less than 10 m width. Discharge was calculated by the velocity area method. In the lower reaches and in rainy seasons, the meter could not be safely used; water velocity was estimated by timing an orange flowing through a known distance from a bridge or vantage point. The values obtained during low flows were calibrated using graduated gauges positioned at the riverbank and in the middle of the river

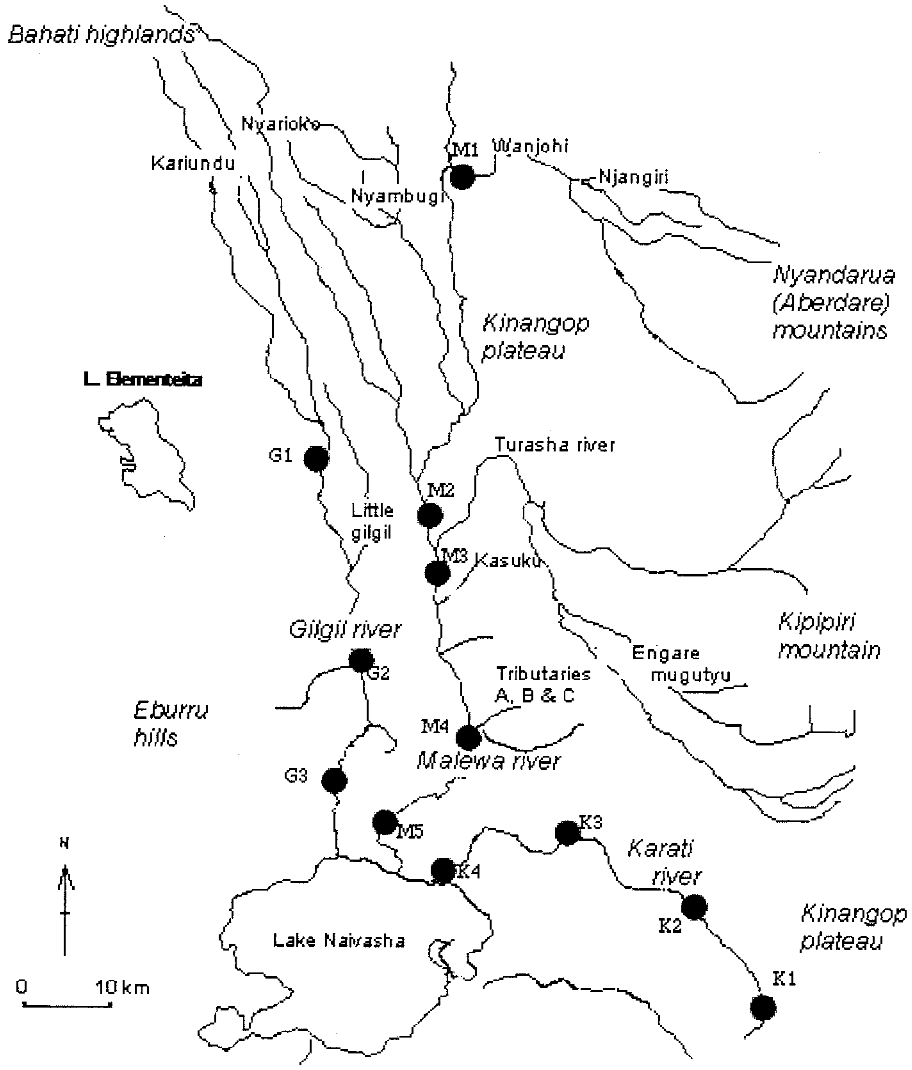


Figure 1. The lake Naivasha catchment showing sample stations.

channel by the Kenyan Ministry of Water at the lower, M_4 and G_2 stations. The gauge height values (GHT) were calibrated using Åse et al. (1986).

Water samples were collected by dipping an acid-washed polyethylene bottle a few centimetres below the water surface in the middle of the river channel. During high water level, samples were collected by lowering down an acid-washed plastic bucket tied on a rope from the bridge to the middle of the river. The water was then transferred into an acid-washed polyethylene sample bottle. The samples for dissolved nutrients were filtered immediately after collection in the field using an acid-washed 60 ml syringe and a Swinnex filter holder with a GF/C glass microfibre filter. The samples were transported in a cool box to the laboratory for analysis. The water samples were analysed the same day of collection or, were stored in the refrigerator for analyses the following day. During the sample visit, conductivity, total dissolved solids (TDS) and temperature were measured by probe using a portable Hach Conductivity/TDS meter whilst pH measurement was determined using an Orion SA 250 model pH meter.

The alkalinity was determined by titrating a 50 ml sample in the field using a Hach Digital Titrator model 16900, with a 0.16N H_2SO_4 titration cartridge

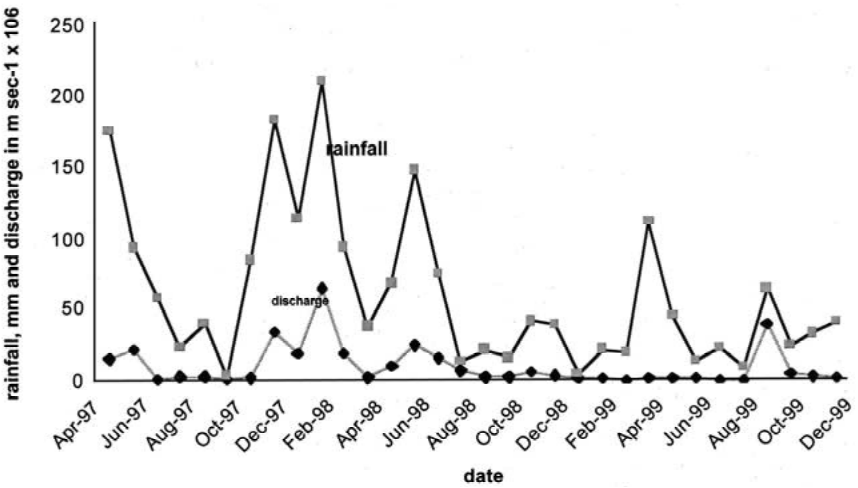


Figure 2. The average rainfall and Malewa river discharge between 1997 and 1999. Source: R. Becht, pers. comm.

and phenolphthalein and bromocresol green powder pillows as indicators.

On arrival in the laboratory, total hardness (TH) and calcium hardness (CH) were determined using the Hach calorimetric version procedure of the traditional Solochrome Black method using the EDTA titration technique with Manver 2 and Hardness solution 1 with Calver 2 indicators, respectively.

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).

Total suspended solids (TSS) were determined by filtering a known volume of water sample on arrival in the laboratory through a pre-weighed, oven dried GF/C glass microfibre filter. The amount of water filtered depended on turbidity of the water samples. The filters were then dried in the oven at 100 °C for 24 h before re-weighing them. The re-weighed filter papers were then ignited at 500 °C in a muffle furnace for 2 h to determine the loss on ignition (Dean, 1974).

River sediment was analysed in the same way after oven drying for 24 h. Total phosphorus (TP) in the sediment was analysed by heating 10 gm of sediment after LOI determination in a volumetric flask with 10 ml of 1N HCl to dryness in a hot plate at 100 °C. After cooling the flask, 20 ml of 50% HCl was added slowly until the residue dissolved. The flask was covered with a self-sealing Nescofilm and left for 36 h to extract. After extraction, phosphorus concentration was determined using the molybdenum blue method as above. Iron-bound phosphorus was extracted by adding 25 ml of bicarbonate buffered solution of sodium dithionite (BD-reagents) to a known weight of sediment sample in a screw capped polypropylene bottle. The bottles were then incubated at 40 °C for 30 min in a water bath with a shaker. After centrifuging at 5000 rpm for 10 min, the phosphorus content of the supernatant was analysed using the molybdenum blue method after 30 min aeration of each sample to oxidise the dithionite, which is known to interfere with the phosphorus analysis (Nürnberg, 1988).

Data were analysed using Microsft Excel and Minitab.

Results

The patterns of rainfall and river discharge in the major river, the Malewa, are shown in Figure 2. They do not indicate a true relationship, because the rainfall gauging is predominantly at the lower altitudes of the catchment, below 3000 m, whereas the disharge is generated by the high-altitude rainfall, which is not gauged reliably. For this reason, the rains in early 1999 did not produce a corresponding increase in discharge because they reflected the more local situation on the floor of the Rift Valley, whereas those in 1997–1998 did, because they were a reflection of the region-wide

Table 1. The characteristics of the Naivasha headwaters

Name of tributary	Drainage region	Altitude m.a.s.l	Catchment area km^2	Stream order	Temp °C	Condy $\mu s\ cm^{-1}$	pH	Total hardness $mg\ l^{-1}$ as $CaCO_3$	Ca hardness $mg;^{-1}$ as $CaCO_3$	Alkalinity $ms\ l^{-1}$ as $CaCO_3$
Nyambugi	Bahati hills	2320–260	17	1	20.9	81	7.8	47	19	11
Nyairoko	Bahati hills	2160–2760	35	2	22.2	92	7.7	40	20	12
Njangiri	Nyandarua ranges	2360–3620	10.5	2	16.6	72	7.4	33	28	22
Wanjohi	Nyandarua ranges	2340–3800	137.5	3	13.2	76	8.2	58	30	22
Engare Mugutyu	Kipipiri	2469–2620	8	2	20.5	103	7.6	57	40	28
Turasha	Kipipiri	2000–2906	133.5	4	20.4	80	7.5	56	33	23
Kasuku	Kinangop plateau	2012–2316	<1	1	18.2	372	7.6	189	58	43
Unnamed A	Kinangop plateau	2012–2316	<1	1	20.1	384	8.0	213	40	36
Unnamed B	Kinangop plateau	2012–2316	<1	1	19.9	500	8.2	288	44	40
Unnamed C	Kinangop plateau	2012–2316	<1	1	19.7	462	8.1	218	54	48

heavy rains following the 1997 El Niño event in the Southern Atlantic.

The chemical characteristics of the headwaters streams are shown in Table 1. The streams on the north eastern part of the catchment draining the Bahati highlands and the Nyandarua mountain ranges were the most dilute, with conductivity below 100, slightly alkaline with low alkalinities. The small streams draining the southern part – the Kinangop plateau – were approximately 4 times richer and harder. This is an area of older underlying rocks, with regosol, calcareous, deep loam soils.

Total phosphorus was generally below 100 $\mu g\ l^{-1}$ (Fig. 3) with the three exceptions, which were either influenced by cattle (Njangiri, evidenced by high ammonium, Table 2 and Kitaka, pers. obs.) or at lower altitude and so more agricultural (Little gilgil) or urban (Gilgil, below the town of the same name). Nitrate was generally low. The general chemical characteristics of the main rivers were otherwise similar (Tables 3–5).

Table 2. The nutrient chemistry of the Naivasha headwaters

Tributary	SRP/TP ratio	PP% of TP	Mean NH_4-N $\mu g\ l^{-1}$	Mean NO_3-N $\mu g\ l^{-1}$
Nyambugi	0.4	59.2	82.9 ± 35	0.1 ± 0.03
Nyairoko	0.2	75.7	8.6 ± 3	0.04 ± 0.01
Njangiri	0.1	89.6	604.3 ± 34	0.04 ± 0.01
Wanjohi	0.5	47.5	50 ± 2	0.11 ± 0.03
Engare Mugutyu	0.4	59.6	68.1 ± 9	0.56 ± 0.3
Turasha	0.6	50.1	40.8 ± 7	0.58 ± 0.1
Unnamed A	0.5	54.9	11.9 ± 3	0.13 ± 0.02
Unnamed B	0.5	49.7	36.6 ± 7	0.11 ± 0.03
Unnamed C	0.7	34.6	21.2 ± 4	0.17 ± 0.01
Kariundu	0.2	80.3	< detection	0.63 ± 0.2
Little Gilgil	0.6	63.7	26.5 ± 14	0.44 ± 0.07

The means hid considerable seasonal changes. The TP of three headwater streams show (Fig. 4) that two of them – the Little gilgil and the Turasha, had elevated levels three times higher than the means at the beginning of the heavy rainy season (see Fig. 1) but less as the season progressed. The wet season brought a higher proportion of particulate phosphorus, as a consequence of soil erosion and sediment transport. The regressions of TP and PP against TSS were strong for the Little gilgil (TP R^2 0.97, $p < 0.0001$; PP R^2 0.98, $p < 0.001$), not significant at the Turasha (TP R^2 0.15, n.s.; PP R^2 0.27, n.s.), and non-existent for the Nyambugi (Fig. 5), most likely because of high values of phosphorus at low discharges.

The effect of seasonal fluctuation of discharge on chemical composition is more clearly seen in the main rivers. In the Malewa, suspended sediment increased with discharge (Fig. 6). Most phosphorus was bound into the TSS (Fig. 7), because most of the phosphorus is particulate (Fig. 8).

The TSS was mostly organic in all the three of the main rivers, with higher values at the start of the rainy season than at its middle to end (Figs 9–11), There was an indication of higher organic content percentages in the upper and the middle-course stations in all the three rivers. (The Karati in September and October 1997 and the Gilgil in October were dry with pools in places).

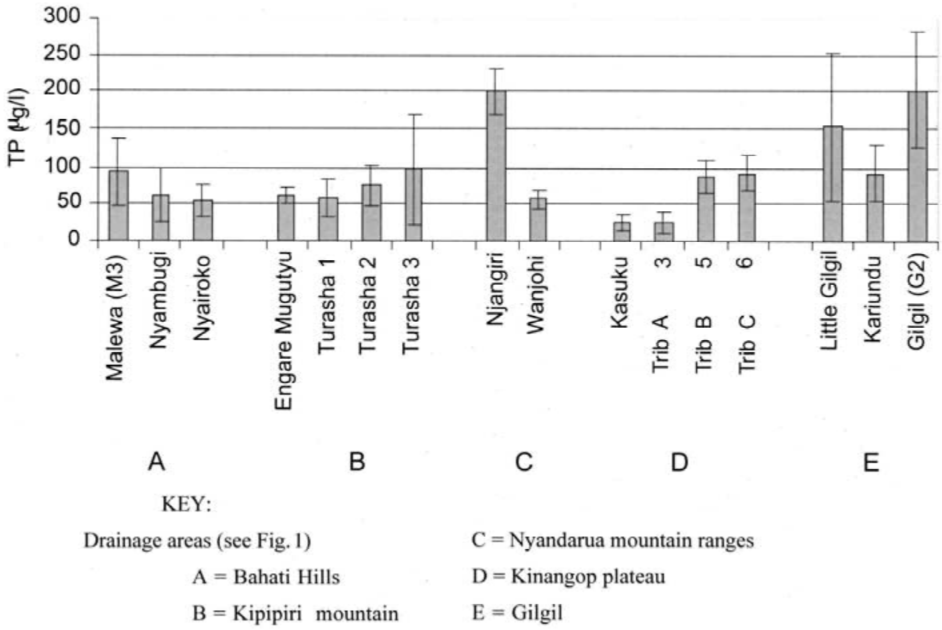


Figure 3. Mean total phosphorus (TP) concentrations in the Naivasha headwater streams, together with the Malewa (M3) and Gilgil (G2) for comparison.

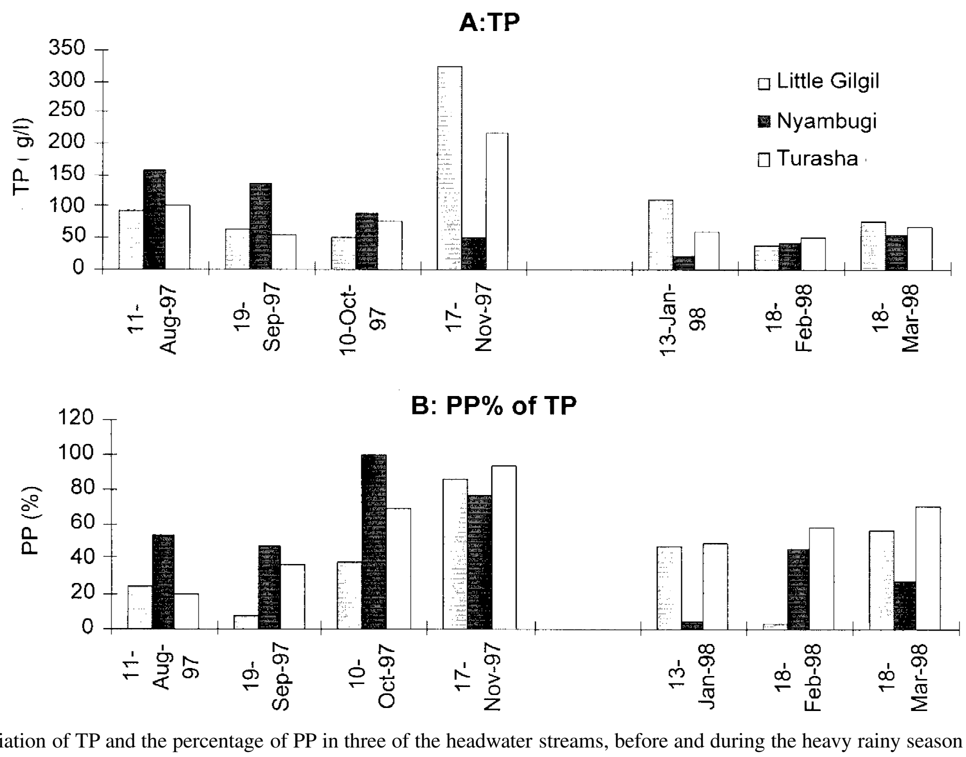


Figure 4. Variation of TP and the percentage of PP in three of the headwater streams, before and during the heavy rainy season of 1997–1998.

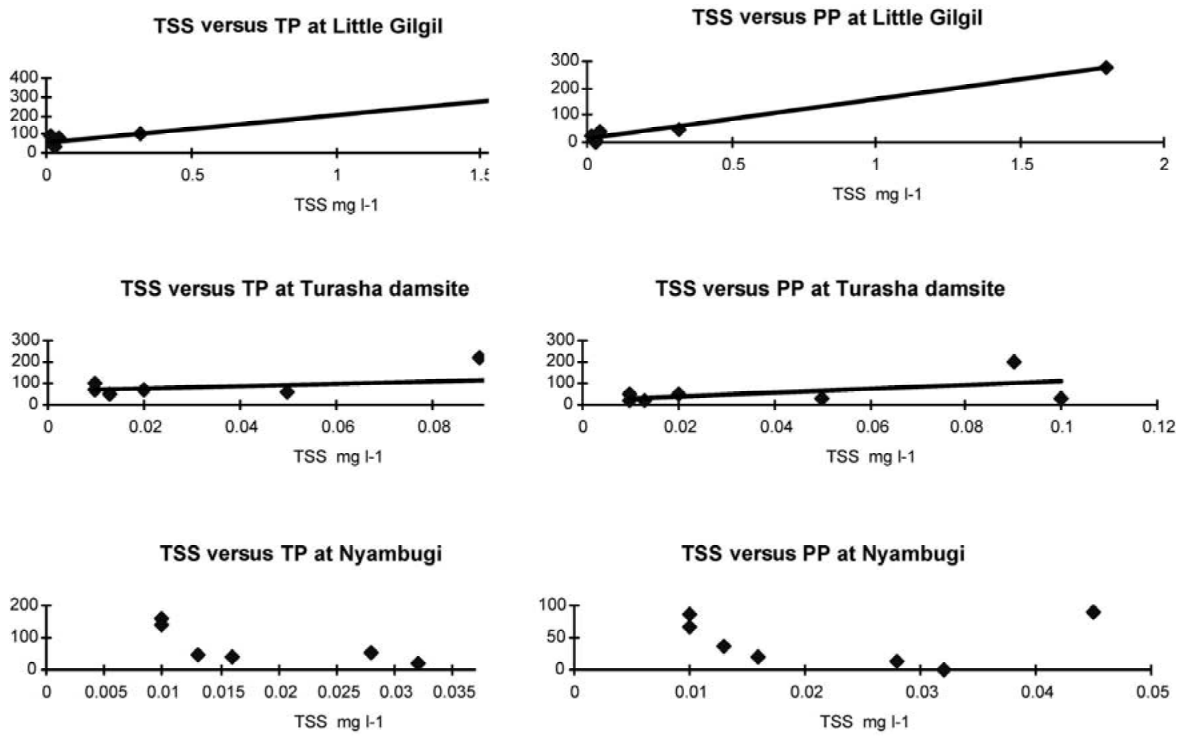


Figure 5. Regressions between forms of phosphorus and suspended solids in three upper catchment streams.

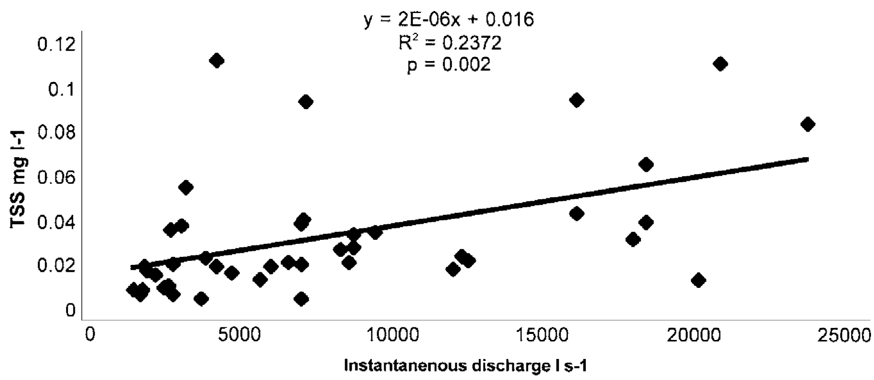


Figure 6. The relationship between instantaneous discharge and TSS in the river Malewa.

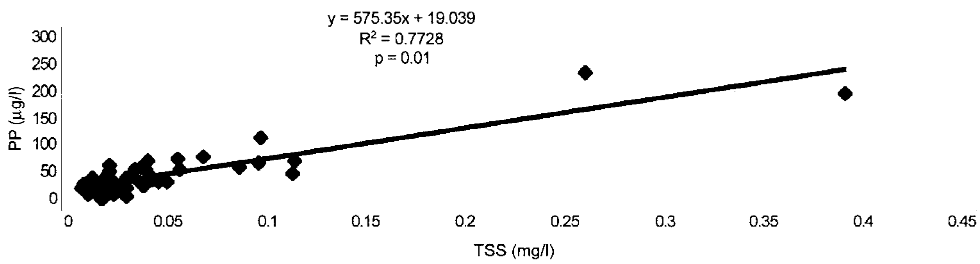


Figure 7. The correlation of suspended solids (TSS) and PP in the river Malewa.

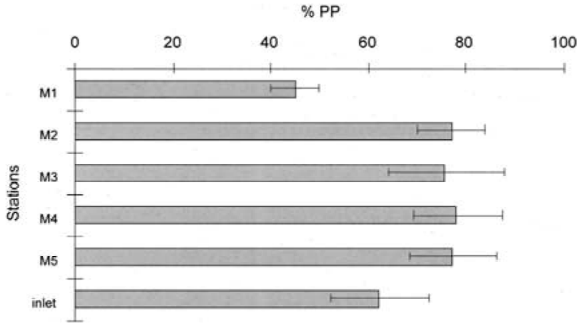


Figure 8. Mean particulate phosphorus (PP) content (%) along the river Malewa.

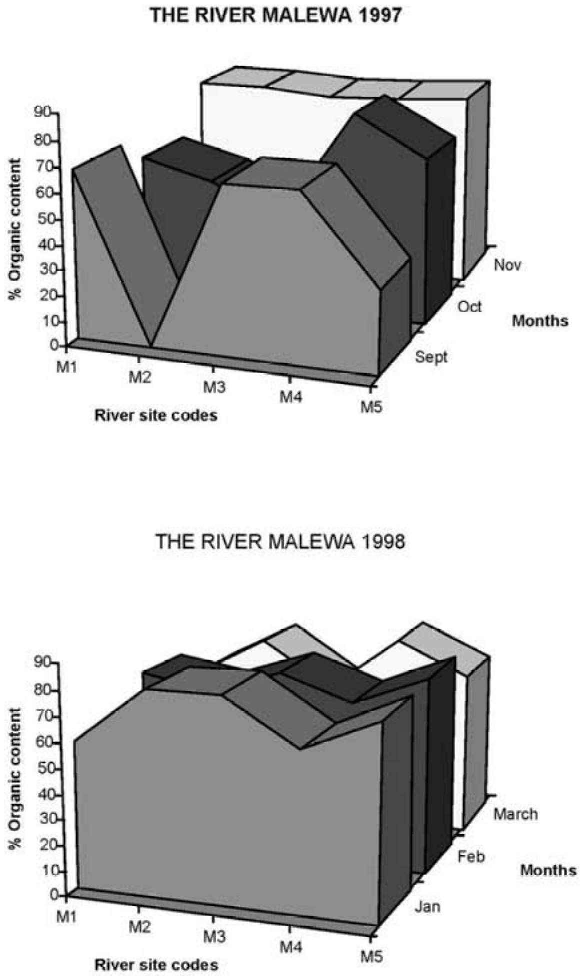


Figure 9. The percentage organic matter of the suspended sediment in the river Malewa just before (September & October 1997) at the start of (November 1997) and during (January–March 1998) the heavy wet season following the 'El Nino rains'.

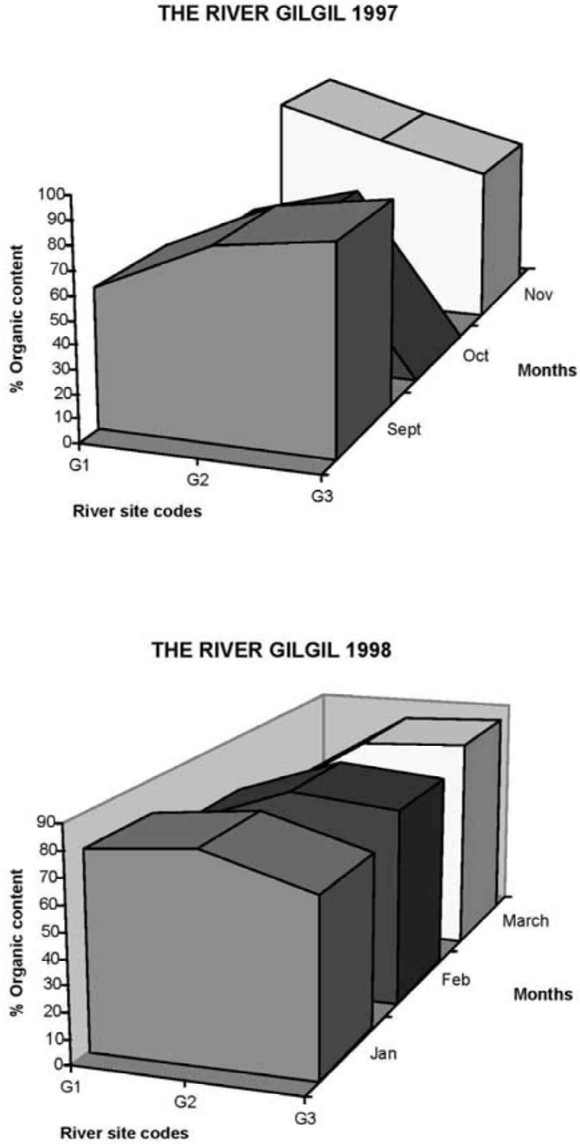


Figure 10. The percentage organic matter of the suspended sediment in the river Gilgil just before (September & October 1997) at the start of (November 1997) and during (January–March 1998) the heavy wet season following the 'El Nino rains'.

An increase in discharge resulted in dilution of soluble constituents, which are shown by significant negative correlations between instantaneous discharge and conductivity in both the Malewa and Gilgil (Fig. 12). The seasonal changes are shown for 13 months 1998–1999, which reflect a more 'usual' pattern, with dry season conductivities which are over twice the wet season ones, a mirror image of the seasonal pattern of TSS (Fig. 13). At high flow conditions, the rivers approached the proportional con-

Table 3. Chemical characteristics of the Malewa river

Station code	Location	Distance km from lake	Altitude (m.a.s.l.)	pH	Alkalinity mg l^{-1} as $CaCO_3$	Total hardness mg l^{-1} as $CaCO_3$	Ca hardness mg l^{-1} as $CaCO_3$
M1	Upstream Ol Kalou	68	2360	7.98 ± 0.4	46 ± 10	26.2 ± 3.99	17.7 ± 2.7
M2	Gilgil pump house	35.5	2222	7.67 ± 0.3	49.8 ± 6.5	26.8 ± 2.6	18.1 ± 1.8
M3	Turasha ridge settlement	30.5	2012	7.69 ± 0.3	48.4 ± 4.7	27.4 ± 2.4	17.4 ± 1.9
M4	Naivasha-Nakuru road bge	10.5	1903	7.44 ± 0.2	57.8 ± 9.9	27.6 ± 2.1	19.0 ± 2.5
M5	Marula	2.5	1890	7.69 ± 0.2	50.6 ± 6.2	27.4 ± 2.0	19.2 ± 2.5

Mean ± standard error ($n = 16$).

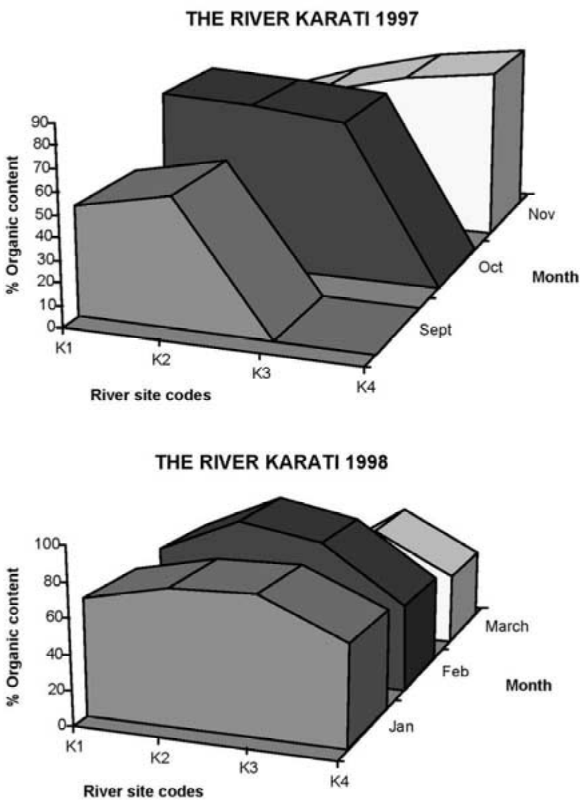


Figure 11. The percentage organic matter of the suspended sediment in the river Karati just before (September & October 1997) at the start of (November 1997) and during (January–March 1998) the heavy wet season following the 'El Nino rains'.

centration of the upper catchment streams; about 4–5 times the concentration of rainwater in the catchment (mean conductivity 10.6 μS cm^{-1}, $n = 8$).

The patterns of the phosphorus forms in the two rivers were dissimilar (Fig. 14). Total phosphorus more closely followed the rainfall pattern (see Fig. 1) than discharge, with dissolved phosphorus more often the predominant form in low flows and particulate in high flows.

The daily loss of TP from the catchment reached over 4×10^3 kg day^{-1} at the beginning of the heavy rainy season in late 1997 (Fig. 15) and, although strongly correlated with discharge (Fig. 16), fell tenfold in the later part of the season in early 1998. At its height in 1997, this phosphorus loss was 75–95% particulate, but in the more normal discharges of 1998–1999 the loss of soluble and particulate was almost equal (mean 41 and 42 kg day^{-1}), respectively (Fig. 17). These gave an annual phosphorus loss of 1.8 kg ha^{-1} ann^{-1}, 90% particulate, in the 'El Niño' year and 0.2 kg ha^{-1} ann^{-1}, 76% particulate in the 'normal' year.

Sediment phosphorus, from 8 headwater streams, averaged 0.47 TP mg g^{-1} dry wt sediment and iron content 51.3 mg g^{-1} dry wt., giving a mean ratio of 109 Fe:P.

Discussion

The calculated catchment losses are derived from regular samplings. They spanned a heavy rainfall period by chance, but the sample frequency must be borne in mind when considering the annual loss estimate. Pacini (1994) found, from intensive study of a catchment draining eastwards from the Nyandarua, that a single day exported 10% of the annual TP loss and about 75% of the TP and SS losses occurred during the rainy events.

The background composition of the river water matches the scenario described for rivers draining mature, leached tropical soils (Viner, 1975; Faniran

Table 4. Chemical characteristics of the Gilgil river

Station code	Location	Distance km from lake	Altitude (m.a.s.l.)	pH	Alkalinity mg l^{-1} as $CaCO_3$	Total hardness mg l^{-1} as $CaCO_3$	Ca hardness mg l^{-1} as $CaCO_3$
G1	Gilgil	3.0 (0)	2012	7.96 ± 0.2	38.7 ± 7.2	17.68 ± 2.0	11.05 ± 1.4
G2	North lake road	15.0 (15.0)	1950	7.54 ± 0.2	47.3 ± 5.4	21.85 ± 3.3	15.35 ± 3.4
G3	Marula	2.0 (28.0)	1890	7.48 ± 0.2	55.1 ± 3.3	24.44 ± 2.6	14.97 ± 1.4

Mean ± standard error ($n = 16$).

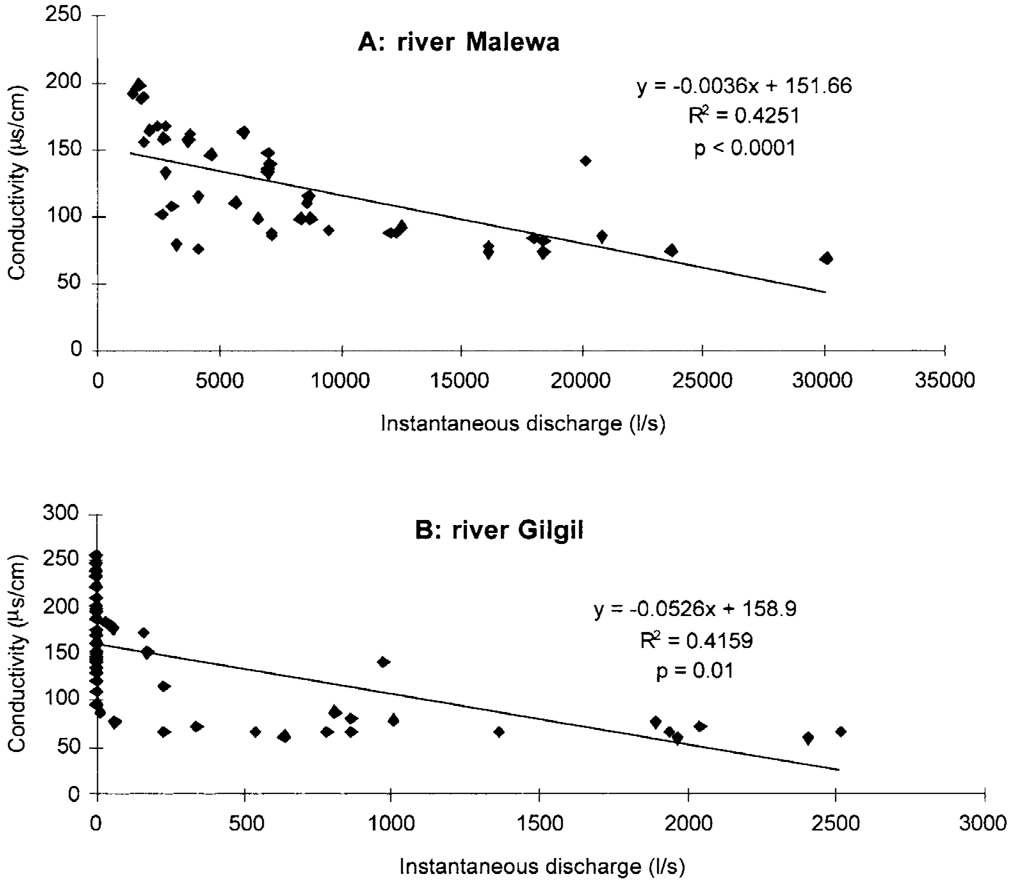


Figure 12. The relationship between instantaneous discharge and conductivity in the rivers Malewa (A) and Gilgil (B).

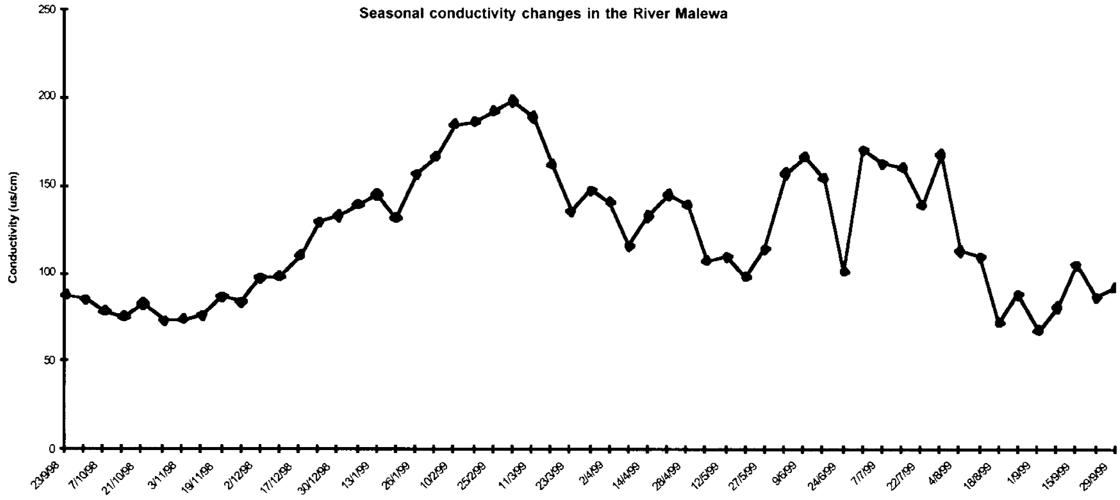
& Areola, 1978). The catchment lies in a volcanic area consisting of trachytes, alkaline basalt and phonolites with acid to alkaline soils (Odingo, 1971) and the drainage chemistry similar to Kilham's 'common' African rivers (Kilham, 1972) in contrast with more 'rain-dominated' catchments such as found in the Amazon basin (Gibbs, 1970).

The Naivasha rivers and streams have more phosphorus concentration than the 10 μg l^{-1} (SRP) or 25 μg l^{-1} (TDP) calculated by Meybeck (1982) from unpolluted rivers world-wide. Phosphorus in the

Table 5. Chemical characteristics of the Karati river

Station code	Location	Distance km from lake	Altitude (m a.s.l.)	pH	Alkalinity mg l^{-1} as $CaCO_3$	Total hardness mg l^{-1} as $CaCO_3$	Ca hardness mg l^{-1} as $CaCO_3$	Mg mg l^{-1}	Ca mg l^{-1}
K1	Karati Mission	33.5 (0)	2745	7.00 ± 0.3	85.5 ± 15.1	39.4 ± 5.5	25.5 ± 5.1	10.5 ± 2.1	15.2
K2	Karati centre	15 (18.5)	2134	6.69 ± 0.4	96.8 ± 4.5	44.3 ± 6.8	33.3 ± 8.7	11.0 ± 1.7	17.8
K3	Nakuru road	5.5 (28.0)	1903	7.27 ± 0.3	104.2 ± 13.5	48.9 ± 5.5	35.8 ± 5.8	10.6 ± 2.1	19.6
K4	Delamere	0.5 (33.0)	1890	7.49 ± 0.4	140.2 ± 18.9	48.9 ± 8.2	35.8 ± 8.2	18.5 ± 3.6	19.6

Mean ± standard error (n = 16).



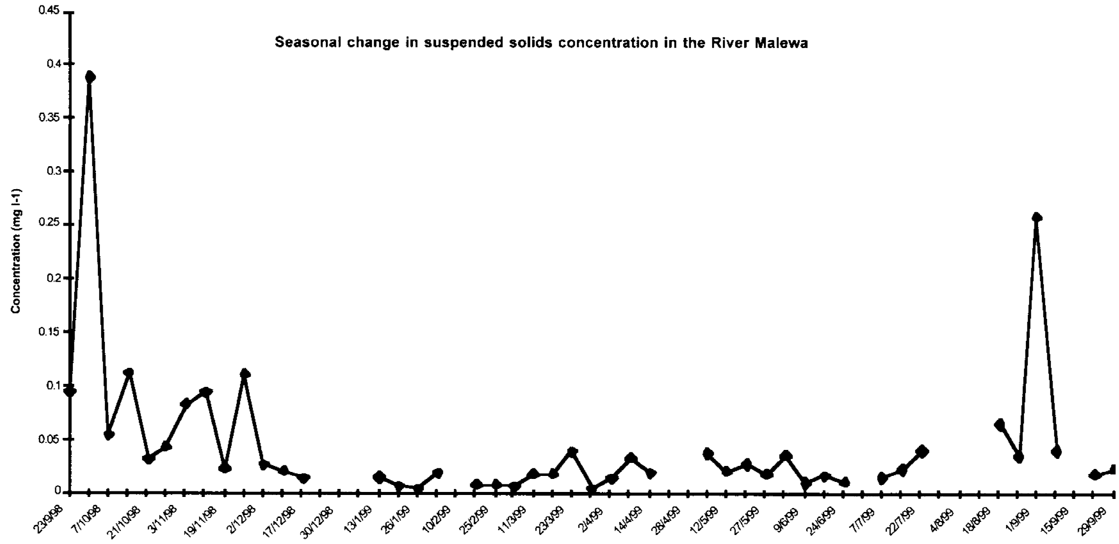


Figure 13. The seasonal pattern of conductivity and TSS in the river Malewa, between 1998 and 1999. The rainy season and high discharges were at the beginning (the heavy rains) and end of this period ('normal' rains), the low discharge in the middle (see Fig. 1).

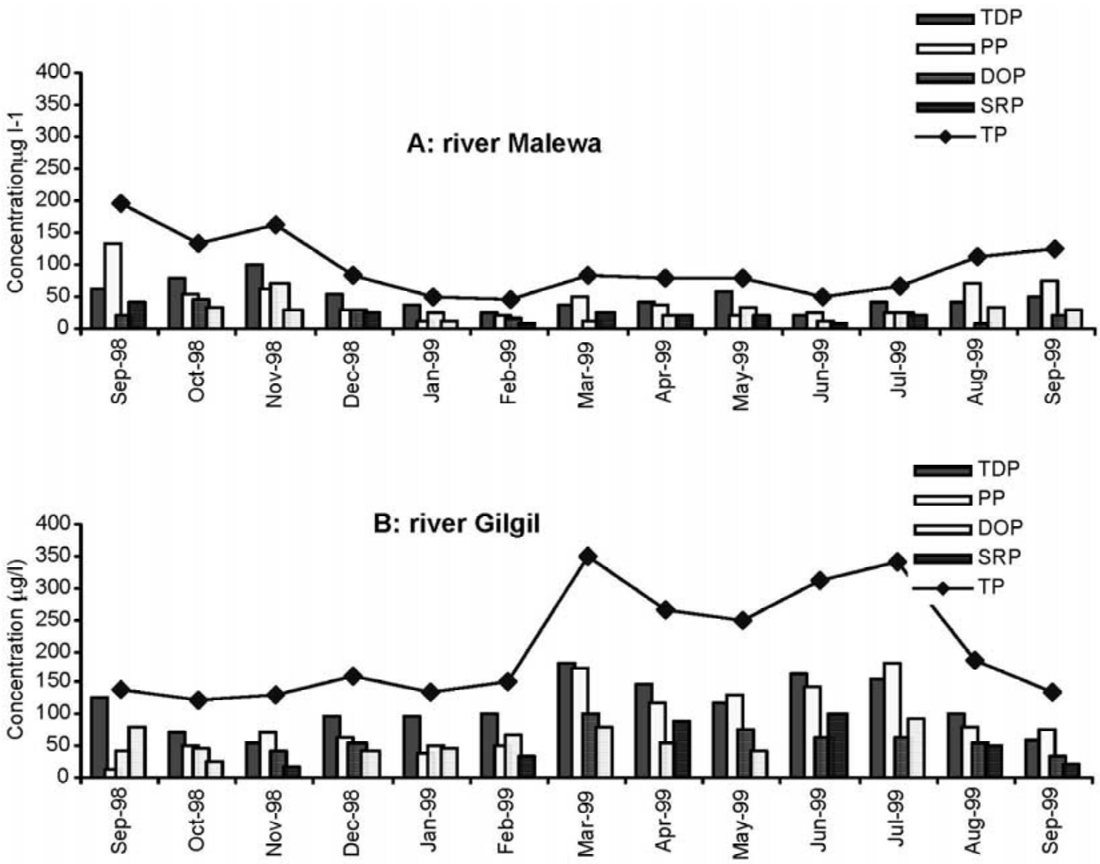


Figure 14. Seasonal pattern of TP and the different forms of phosphorus in the rivers Malewa and Gilgil (lower sites), 1998–99.

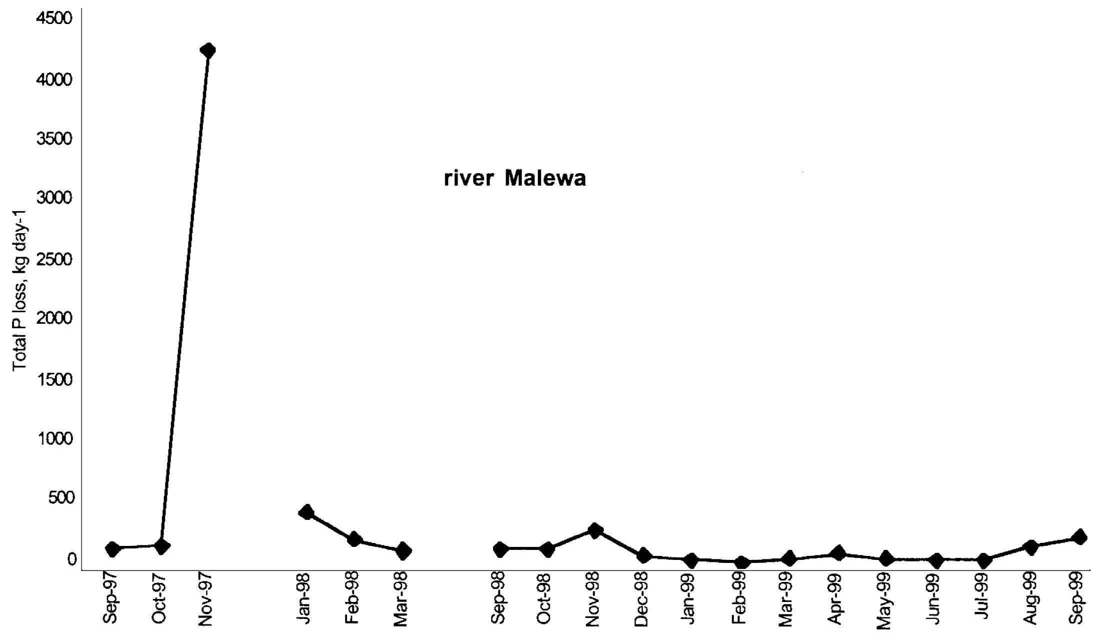


Figure 15. Daily losses of TP in kg, from the Malewa catchment, calculated for all days on which samples were analysed from the lower site, M5.

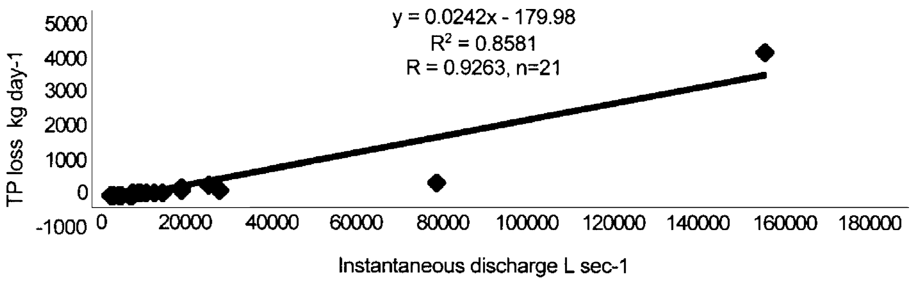


Figure 16. Correlation of daily TP with instantaneous discharge for the river Malewa.

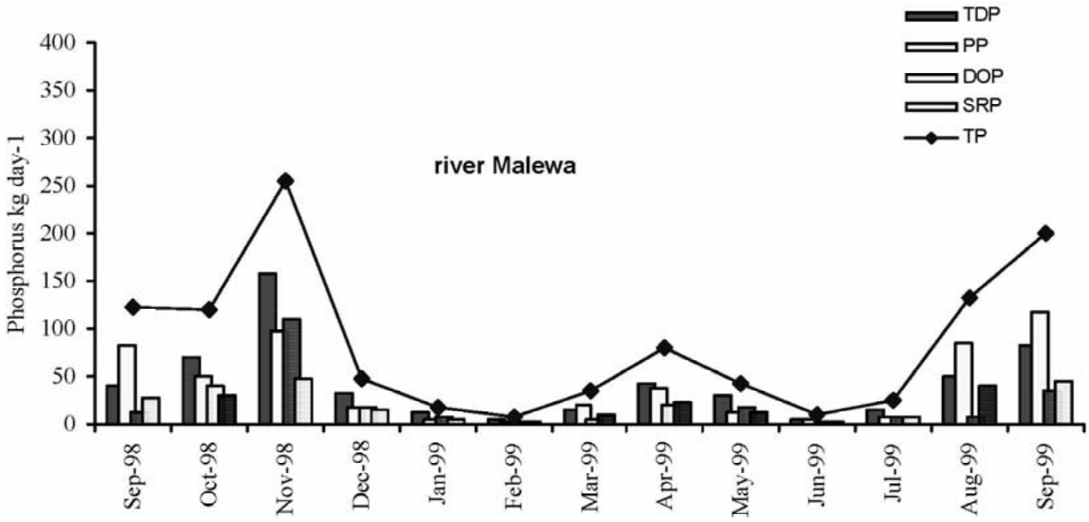


Figure 17. Transport of the different forms of phosphorus in the river Malewa, kg day^{-1} 1998–99.

Naivasha catchment has not previously been studied and so comparisons are barely possible. Gaudet (1979) had measured the concentration of TP and PO_4-P of the lower Malewa, as part of a large study of the chemical budget of the erstwhile *C. papyrus* North swamp, through which the river waters entered lake Naivasha. In 1975, his mean TP values were 40 μg l^{-1}, soluble 3 μg l^{-1}. His study spanned a period of moderate river discharges (maximum monthly mean 24 m^3 s^{-1}) more comparable with 1998–1999, when annual mean TP was 3x Gaudet's and SRP 6 $\times$ Gaudet's PO_4-P.

The rapid increase of TP at the start of the 1997 rains yet decline during equally high discharge a month or two later, suggests a phosphorus flush into the rivers and streams as a result of surface erosion. Three quarters of the land in the catchment is cultivated, intensively up to and even down the riverbanks. High surface runoff results in a rate of surface erosion increased tenfold. The significant linear relationship obtained between PP and TSS, as found elsewhere (Burwell et al., 1977; Nelson et al., 1979; Kronvang et al., 1996), supports this. The importance of vegetation cover for reducing soil mobilization is indicated by the lower TP and higher proportion of SRP in higher catchment streams, which compare with 62% SRP from grass watersheds on the southern plains area of Oklahoma and Texas (Sharply & Smith, 1990). In the Kinangop plateau, only 1/4 of the land is pasture, carrying livestock with a density estimated at 0.62 cows per hectare, which is heavy (Simpson, pers. comm.). The lower catchment has a slightly lighter stocking density.

The TP export for the heavy rains (1997–1998) are at the upper end of figures produced for temperate agricultural land (Reckhow & Chapra, 1983) while the normal year (1998–1999) gave more acceptable losses.

The catchment presently lies outside the designated RAMSAR site of the lake, and outside any present land use management policies other than Kenya government advice to small farmers, which has minimal environmental component. The future needs of the lake basin can only be met if sustainable use of the catchment's soil resource is an integral part of its management; the future needs of the rural population can only be met if they receive environmental as well as economic advice for maintaining their agricultural resource base. The two are identical and should be tackled together.

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References

Åse, L-E., K. Sernbo & P. Syren, 1986. Studies of Lake Naivasha, Kenya and its Drainage Area. Forkningsrapporter 63, Stockholms Universitet Naturgeografiska Institutionen, Stockholm: 75 pp.

Burwell, R. E., G. E. Schuman, H. G. Heinemann & R. G. Spomer, 1977. Nitrogen and phosphorus movement from the agricultural watersheds. J. Soil Wat. Conserv. 32: 226–230.

Calamari, D., 1987. Water quality problems in Africa: a brief report. Int. J. Environ. Studies 29: 3–8.

Dean, W. E., 1974. Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition. Comparison with other methods. Journal of Sedimentary Petrology 44: 242–248.

Dejoux, C., 1988. La Pollution des Eaux Continentales Africaines. Éditions de l'ORSTOM, Collection Travaux et documents no 213, Paris: 513 pp.

Downing, T. E., S. Lezberg, C. Williams & L. Berry, 1990. Population change and environment in central and eastern Kenya. Environ. Conserv. 17 (2): 123–133.

Dregne, H. E., 1990. Erosion and soil productivity in Africa. J. Soil Wat. Conserv. 45 (4): 431–436.

Faniran, A. & O. Areola, 1978. Essentials of Soil Study (with special reference to tropical areas). Heinemann, London: 278 pp.

Fardeau, J. C. & E. Frossard, 1991. Processus de transformations du phosphore dans les sols de l'Afrique de l'ouest semi-aride: application du phosphore assimilable. In Tiessen H. & Frossard (eds), Phosphorus Cycling in Terrestrial and Aquatic Ecosystems, Proceedings of a SCOPE/UNEP Workshop (Nairobi 18–22 March 1991). Vol. 4 Africa: 108–128.

Gaudet, J. J., 1976. Nutrient relationships in the detritus of a tropical swamp. Archiv. Hybrobiol. 78: 213–239.

Gaudet, J. J., 1977. Natural draw-down of Lake Naivasha, Kenya and the origin of papyrus swamps. Aquat. Bot. 3: 1–17.

Gaudet, J. J., 1979. Seasonal changes in nutrients in tropical swamp water. J. Ecol. 67: 953–981.

Gibbs, R., 1970. Mechanisms controlling world water chemistry. Science 170: 1088–1090.

Harper, D. M., G. Phillips, A. Clivers, N. Kitaka & K. M. Mavuti, 1993. Eutrophication prognosis for Lake Naivasha, Kenya. Verh. int. Ver. für Theor. Ang. Limnol. 14: 192–195.

Hecky, R. E., 1993. The eutrophication of lake Victoria. Verh. int. Ver. für Theor. Ang. Limnol. 25: 39–48.

Hinga, G., 1973. Phosphate sorption capacity in relation to properties of several types of Kenyan soil. East African Agricultural and Forestry Journal 38: 400–404.

Jones, M. E., 1979. Rainfall intensities of East African storms. East African Agriculture and Forestry Journal 43: 261–264.

Kilham, P., 1972. Biogeochemistry of African Lakes and Rivers. PhD thesis, Duke University, Durham, North Carolina: 199 pp.

Kronvang, B., A. Laubel & R. Grant, 1996. Transport of sediment and phosphorus in the Aarable Gelbaæk catchment, Denmark. In Proceeding of Sediment and Phosphorus Workshop in Denmark. N.E.R.I Technical Report 178: 89–92.

Lennox, S. D., R. H. Foy, R. V. Smith & C. Jordan, 1997. Estimating the contribution from agriculture to the phosphorus load in surface water. In Tunney, H. O. T. Caton, P. C. Brookes & A. E. Johnston (eds), Phosphorus Loss from Soil to Water. CAB International: 55–75.

Mackereth, F. J. H., J. Heron & J. F. Talling, 1989. Water Analysis. Freshwater Biological Association, Windermere, U.K.: 120 pp.

Melack, J. M., 1976. Limnology and Dynamics of Phytoplankton in Equatorial African Lakes. PhD thesis, Duke University, Durham: 453 pp.

Melack, J. M., P. Kilham & T. R Fisher, 1982. Responses of phytoplankton to experimental fertilization with ammonium and phosphate in an African soda lake. Oecologia 52: 321–326.

Melack, J. M. & S. MacIntyre, 1991. Phosphorus concentrations, supply and limitation in tropical african lakes and rivers in Phosphorus cycling in terrestrial and aquatic ecosystems. In Tissen, H. & H. Frossard (eds), Proceedings of a SCOPE/UNEP Workshop (Nairobi 18–22 March 1991). Vol. 4 (Africa): 1–17.

Meybeck, M., 1982. Carbon, nitrogen & phosphorus transport by world rivers. Am. J. Sci. 282: 401–450.

Nelson, D. W., E. J. Monke, A. D. Bottcher & L. E. Sommers, 1979. Sediment and nutrient contributions to the Maumee River from an agricultural watershed. In: Loehr, R. G., D. A. Haith, M. F. Walter & C. S. Martin (eds), Best Management Practises of Agriculture and Salviculture. Ann. Abor. New York: 491–505.

Njuguna, S. G., 1982. Nutrient-Productivity Relationship in Tropical Naivasha Basin Lakes, Kenya. PhD thesis, University of Nairobi: 300 pp.

Nürnberg, G. K., 1988. Prediction of phosphorus release rates from total and reductant-soluble phosphorus in anoxic lake sediments. Can. J. Fish. aquat. Sci. 45: 453–462.

Nyandat, N., 1981. The primary minerals in some Kenya's topsoil and their significance to inherent soil fertility. East Africa Agriculture and Forestry Journal 46: 71–76.

Odingo, R. S., 1971. The Kenya Highlands: Land-use and Agricultural Development. East Africa Publishers House, Nairobi: 226 pp.

Pacini, N., 1994. Coupling of Land and Water; Phosphorus Fluxes in the Upper Tana RiverCatchment, Kenya. Ph.D. Thesis. University of Leicester. U.K.: 176 pp.

Pacini, N. & D. M. Harper, 1999. Phosphorus transport from a tropical catchment and implications for sustainable catchment management. In Harper, D. M. & A. G. Brown (eds), The Sustainable Management of Tropical Catchments. Wiley, Chichester: 61–76

Peters, R. H. & S. MacIntyre 1976. Orthophosphate turnover in East African lakes. Oecologia (Berl) 25: 313–319.

Reckhow, K. H. & S. C. Chapra 1983. Engineering Approaches for Lake Management: Vol.1. Data Analysis and Empirical Modeling, Butterworth Publishers, Boston.

Roseboom & Lotriet, 1993 A new sediment yield map for southern Africa, erosion and transport monitoring programmes in river basins. Proceedings of the Oslo Symposium, August 1992, IAHS Publ. No. 210: 527–538.

Sharpley, A. N. & S. J. Smith, 1990. Phosphorus transport in agricultural runoff. The role of erosion. In Bardman, J., I. D. L. Foster & J. A. Dearing (eds), Soil Erosion on Agricultural Land. J. Wiley and Sons Ltd: 352–366.

Sharpley, A. N. & Syers, 1979. Phosphorus inputs into a stream draining an agricultural watershed. Wat. Air Soil Poll. 11: 417–428.

Smaling, E. M. A., 1993. An Agro-ecological Framework for Integrated Nutrient Management with Special Reference to Kenya. Ph.D. Thesis, Agricultural University of Wageningen, Netherlands.

Smaling, E. M. A. & J. Bouma, 1982. Bypass flow and leaching of nitrogen in a Kenyan vertisol at the onset of the growing season. Soil Use and Management 8: 44–48.

Talling, J. F. & I. B. Talling, 1965. The chemical composition of African Lakes waters. Int. Rev. ges. Hydrobiol. 50: 421–463.

Viner, A. B., 1975. The supply of minerals to tropical rivers and lakes (Uganda). In Hasler, A. D. (ed.), Coupling of Land and water systems. Springer Verlag, New York, Ecological Studies 10: 227–261.

Viner, A. B., 1987. Nutrients transported on silt in rivers. Archiv. Hydrobiol. Beih. (Ergebnisse der Limnologie) 28: 63–71.

Wolf, A. M., D. E. Baker, H. B. Pionke & H. M. Kunishi, 1985. Soil tests for estimating labile, soluble, and algae-available phosphorus in agricultural soils. J. Environ. Qual. 14 (3): 341–348.