PHOSPHORUS SUPPLY TO A SHALLOW TROPICAL LAKE AND ITS CONSEQUENCES - LAKE NAIVASHA, KENYA

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by

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DEDICATION

To my son, Solomon Kitaka

and

my parents;

The late Samuel Kitaka and Ruth Kitaka

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ABSTRACT

Phosphorus supply to a shallow tropical lake and its consequences- Lake Naivasha , Kenya.

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The ecological stability of lake Naivasha is unpredictable, as it lies in an endorrheic basin situated in an intensive agricultural region with diversified climatic conditions. The situation is getting worse as increase in agricultural activities and hence human population continues, consequently resulting in an increase in water demand and abstractions.

An investigation in phosphorus dynamics, interactions and possible sources was carried out both in the inflowing waters and the lake. During the "El Niňo" rains approximately 9 times more TP was transported into the lake from the catchment mainly in particulate form (PP). The river Malewa transported almost 30 times more total phosphorus (TP) than the other two rivers. Most of the TP input arose from the middle course of the river, mainly in PP form bound in suspended solids. Watering of the livestock in the river was found to elevate the concentration of TP, PP and total suspended solids (TSS), although its influence downstream depended on discharge, intensity and frequency of disturbance.

The phosphorus lake loading to the lake varied significantly between the two hydrological phases encountered with 1.41 and 0.21 g m^{-2} yr^{-1} for the "extremely" wet and "normal" wet years respectively classifying the lake as eutrophic. However the overall quotient between the mean in-lake phosphorus (P) and the inflow phosphorus (Pi) concentration from the river Malewa portrayed an equilibrium state with an overall P/Pi ratio of 0.62.

The Naivasha sediments are poorly sorted with inorganic phosphorus dominance. The lake sediment has low phosphorus buffering capacity as portrayed by a low phosphorus sorption index (PSI), indicating a phosphorus source rather than sink.

ABBREVIATIONS

TP = Total phosphorus

TDP = Total dissolved phosphorus

PP = Particulate phosphorus

SRP = Soluble reactive phosphorus

DOP = Dissolved organic phosphorus

TIP = Total inorganic phosphorus

IP = Inorganic phosphorus

NAIP = Non apatite inorganic phosphorus

P_i = mean inflow phosphorus concentration

P = Mean phosphorus inlake concentration

R_P = Phosphorus retention coefficient

σ = Phosphorus sedimentation rate coefficient

ECP_O = Zero equilibrium phosphorus concentration

PSI = Phosphorus sorption index

TSS = Total suspended solids

M_Z = Mean grain size

SD = Inclusive standard deviation

SK = Sorting coefficient

SK_1 = Inclusive graphic skewness

KG' = Transformed or normalised kurtosis

Chl.a = Chlorophyll *a*

TSI = Trophic state index

T_w = water residence time

P_w = Lake flushing rate

Z = Lake mean depth

Loading terminologies

Transport (kg/g) = Amount of phosphorus transported by the river into the lake per day.

Areal yield or Export coefficient (kg $ha^{-1}yr^{-1}$) = Total mount of phosphorus transported in relation to its catchment area per year.

Lake loading (g m^{-2} yr^{-1}) = The Areal yield from the catchment in relation to the lake surface area

CHAPTER 1: INTRODUCTION

EUTROPHICATION IN FRESHWATERS

1.1 What is eutrophication?

Eutrophication or nutrient enrichment in the broadest sense describes the biological effects of the elevation in the supply of plant nutrients in natural waters either as solutes or bound to organic and inorganic particles, resulting to reduction in water quality (UNEP-IETC 1999). Cooke *et al.* (1993) gave a holistic definition of eutrophication, which includes, organic matter input into lakes and reservoirs leading to loss of volume. This subsequently result to release of nutrients through mineralization or from the sediment when the organic matter stimulates respiration and dissolved oxygen is depleted. However there is a difference between eutrophication and natural aging process of a lakes and reservoirs (Phillips pers. Comm.) with the latter reflecting the cumulative impacts of all the water and materials flowing into the lake. The lake fills slowly with soils and other materials, either carried by the inflowing waters or organic material from in-lake production and eventually becomes a marsh and ultimately, a terrestrial system. This process takes hundreds of thousands of years. Unlike eutrophication, water systems undergoing natural aging process have good water quality and exhibit a diverse biological community throughout most of their existence (Harper 1992a, Ryding & Rast 1989).

In the early 20th century, nutrient enrichment in water bodies started to be seen as a problem, as a consequence of human settlement in the drainage basin, associated with clearing of the forests (Ryding & Rast 1989), development of urban societies, with consequent disposal of industrial and agricultural wastes (Harper 1992a). All these activities, change the natural eutrophication process in a dramatic way by accelerating runoff of materials from land to water body, with a consequent increase in plant nutrients (mainly nitrogen and phosphorus). Consequently this stimulates algal and aquatic plant growth, which in turn stimulates the growth of fish and other higher trophic levels in the aquatic food chain. In this context the lake undergoes what has been termed as "man-made" or "artificial" or "anthropogenic" (Harper 1992a, Ryding & Rast 1989) or even "cultural" eutrophication (Ryding & Rast 1989).

Water bodies are classified into different trophic categories. The categories generally used today either denote the nutrient "status", or describe the effects of the nutrients on the general water quality and/or trophic conditions of a water body. However, attempts have been made to relate descriptive trophic terms to specific "boundary" values for certain water quality parameters, as illustrated in Table 1.1. Strict boundaries are often difficult to apply because of regional variations in ranges of limnological factors. However Ryding & Rast (1989) suggest that trophic characteristics are basically similar between tropical/sub-tropical and temperate regions with differences only in the magnitude and/or timing rather than the substances (Thornton 1987b).

Table 1.1 OECD boundary values for fixed trophic classification system (adopted from OECD 1982)

Trophic Category	**TP**	**Mean chl.*a***	**Maximum chl.*a***	**Mean Secchi**	**Minimum Secchi**
Ultra-oligotrophic	<4.0	<1.0	<2.5	>120	>6.0
Oligotrophic	<10.0	<2.5	<8.0	>6	>3.0
Mesotrophic	10 - 35	2.5 - 8	8 - 25	6 - 3	3 - 1.5
Eutrophic	35 - 100	8 - 25	25 - 75	3 - 1.5	1.5 - 0.7
Hypertrophic	>100	>25	>75	<1.5	<0.7

KEY

TP = mean annual in-lake total phosphorus concentration in μg/l
Mean chl.*a* = mean annual chlorophyll *a* concentration in surface waters (μg/l)
Maximum chl.*a* = peak annual chlorophyll *a* concentration in surface waters (μg/l)
Mean Secchi = mean annual secchi depth transparency (m)
Minimum Secchi = minimum annual secchi depth transparency (m)

1.2 What causes eutrophication?

Liebig first invented the nutrient-limiting concept, in 1840 (Liebig 1872). He found that, the materials needed by the crop in minute quantities often limited the yield of terrestrial crops. He further found that the ultimate yield of any crop was limited by one essential nutrient, which was most scarce in the environment in relation to the specific needs of the crop (Odum 1971, Welch 1980). Despite some minor misuse of this concept (Wetzel 1983), it has been applied to phytoplankton growth in water systems ever since. Therefore a limiting nutrient(s) in water systems is the nutrient(s) available most closely in amounts below the critical minimum required by the sum of phytoplankton species, thus regulating the algal biomass, hence eutrophication. Tilman *et al.* (1982) suggested that one should not refer to a lake as either "phosphorus" or "nitrogen" limited, but rather recognize that individual algal species "not lakes" are the ones limited by a particular nutrient.

The ratio at which these nutrients are taken up and used by the algae, reflect the composition of these elements in their cellular materials. Redfield (1934) determined the cellular content and produced the "Redfield Ratio" of 106C: 16N: 1P. This ratio has become a standard reference in Limnology, although Tilman *et al.* (1982) suggest that, different algal species can assimilate nutrients in different quantities and at different rates, on the basis of "resource competition". He further provided support of his idea by noting that diatoms grow better under low phosphorus concentration, which indicates that they are superior competitors for phosphorus. Lang & Brown (1981) reported that some cyanobacteria were more efficient in phosphorus uptake, while Smith & Kalff (1982) showed that the small algal cells are more efficient than the large cells during nutrient-deficit conditions.

High concentrations of nitrogen and phosphorus and occasionally, carbon, have been associated with eutrophication in lakes for over a century. Carbon rarely limits algal growth because of its large reservoir in the atmosphere, coupled with its ready solubility in water. Carbon limitation to algal production can only occur at the height of photosynthesis in low alkalinity waters with enhanced levels of nitrogen and phosphorus (Goldman *et al.* 1972). Even in the unusual situation where carbon limitation has been reported, Shapiro (1973) has shown that it will only affect the types, rather than quantity, of algae occurring in the water body. Phosphorus and nitrogen being important constituents of cell protoplasm with an important role in enzymatic and energy transport systems within cells would make them potential limiting nutrients (Reynolds 1984). However, phosphorus is more likely to be a limiting nutrient than any other nutrient because of its major role in biological metabolism and its relatively small amount available in the biosphere (Vollenweider 1968, Hutchinson 1975, Wetzel 1983). Gibson (1997) described phosphorus as a potent agent of change in aquatic systems although its name is derived from the Greek word meaning "bearer of light" its effects have been disastrous rather than illuminating.

There are several reasons why phosphorus is of particular significance in freshwater systems. First it is commonly thought to be a limiting nutrient for algal production. Phosphorus was limiting in 200 lakes studied by the Organization of Economic Co-operation and Development Programme (OECD 1982). A study of 479 lakes in the United States showed that 90% were phosphorus limited (USEPA 1974). Indications of phosphorus-limitation have been reported in several lakes and reservoirs in Africa (Viner 1973, Melack *et al.* 1982 and Thornton 1987b). However low levels of nitrogen compared to phosphorus reported in variety of East African freshwaters especially nitrate by Talling & Talling (1965) and Moss (1969) could indicate nitrogen limitation as well. The second reason for phosphorus significance is, very low concentrations are required for biomass production. With the Redfield ratio of 106:16:1 C:N:P implies that one atom of phosphorus can support the production of 16 atoms of nitrogen and 106 atoms of carbon, meaning that adding phosphorus has a much greater effect than nitrogen and carbon. Rigler (1973) and Gibson (1997) identified increase in phosphorus input to water systems as a key factor accelerating eutrophication.

1.3 Phosphorus in freshwaters

1.3.1 Sources

The main natural origin of phosphorus in water systems is through weathering and dissolution of geological deposits and surface soils (Pettersson *et al.* 1988, Gibson 1997) and mineralization of organic matter (Steén 1997). The solid crust of the earth has an estimate of 10^{25} g (10^{19} tones) of phosphate mostly in apatite form (Golterman 1975). Nutrient sources in water systems are either external (allochthonous) or internal (autochthonous). The major external sources are effluent discharges from domestic and industrial sources, diffuse (or non-point) sources such as land runoff, as well as deposition from the atmosphere (Thorstein 1980, Logan 1982, Ryding & Rast 1989). Internal sources are nutrients regenerated from the bottom sediments.

The amount of nutrient released into water systems from diffuse sources depends on the natural nutrient content of the soil, soil type (mineral or organic), soil texture, chemistry, and physiography (Brooks *et al.* 1997). Soil texture seems to be the most important characteristic in many regions (Sharpley & Rekolainen 1997). Land management controls, on land use and form, on method and timing of fertilizer application as well as on presence and absence of grazing animals are critical factors. Use of fertilizers with high phosphorus and nitrogen content can increase the nutrient load of the land runoff. Improper practices which do not properly incorporate inorganic fertilizers to the soil or which involve the application of fertilizers at excess rates can cause short-term elevated nutrient concentration in runoffs (Sharpley & Smith 1990, Ryding & Rast 1989). Phosphorus inputs into water bodies have increased with time worldwide, probably due to increase in use of phosphorus- based fertilizers that consequently led to accumulation of phosphorus in the soil. However, the magnitude of agricultural contribution varies among regions (Steén 1997). For example, agriculture contributes 40% of total external phosphorus loading of surface waters in UK (Withers 1994). Heathwaite (1997) cautions that there will be an increase in importance of non-point agricultural sources in future.

In dilute lakes in remote igneous rock areas, atmospheric input may be significant and it is likely that humans have direct influence on its magnitude (Gibson 1997). The atmospheric input found in literature varies from 5 to 100 kg P km^{-2} $year^{-1}$ (Gibson 1997). Holten *et al.* (1988) obtained an average as low as 430 g/ha/year (0.43g km^{-2} $year^{-1}$) of total phosphorus for 16 lakes in North America and Europe with the lowest amount of 50 g/ha/year in remote areas. Ahl (1988), Jordan (1987) and Gibson & Wu (1995) obtained lowest amounts of atmospheric phosphorus in areas remote from civilization in Sweden and Ireland. However as Gibson (1997) suggested, the importance of this source might depend on the ratio of lake surface to catchment's area, the retention of phosphorus in the catchment and the scale of other phosphorus sources.

Phosphorus in the sediment is partly from settled particulate phosphorus (of allochthonous or autochthonous origin). The allochthonous phosphorus contribution to the sediment is mainly through the organic matter, produced in the drainage area and transported to the lake. The amount and form of phosphorus brought into the sediment will depend on the chemistry and the mineralogy of the soils in the drainage area (Logan 1982). The autochthonous phosphorus comes from the settling materials consisting of dead or living planktonic organisms, excretion products, organic detritus and precipitated humic substances. These substances once they reach the sediment are transformed into final sediment component by diagenetic processes through biological activities (Holten *et al.* 1988).

1.3.2 Forms (fractions)

In the aquatic environment phosphorus is present mainly in organic form, both in living and dead materials, and inorganic form especially in the sediments (Brown *et al.* 1978, Holten *et al.* 1988, Grobbelaar & House 1995). The principal components of organic phosphorus are labile phospholids, nucleic acids, humic acids, as well as unidentified sugar phosphates generated from organic matter and biomass residues. However according to Van-Wazer (1958), phosphorus occurs in nature almost exclusively as phosphate; orthophosphate, polyphosphate, and metaphosphate, although the complex or the condensed forms are mostly unstable in water and are slowly hydrolyzed to orthophosphate (Holten *et al.* 1988).

From the analytical point of view, phosphorus occurs either as soluble or insoluble form. The soluble or orthophosphate consists of soluble reactive phosphorus (dissolved inorganic phosphorus) and soluble unreactive phosphorus (soluble organic phosphorus). The soluble reactive phosphorus is known to be biologically available (Golterman 1989, Brown *et al.* 1978). Logan (1982) found that 90% of soluble reactive phosphorus was bioavailable, while the soluble unreactive phosphorus was only biologically available through enzymatic hydrolysis. This indicates that presence of high concentration of soluble organic phosphorus would provide a long-term phosphorus source in the lake. Since particulate matter in streams and lakes are detrital, the term particulate phosphorus is less misleading and will be referred to in this study.

Phosphorus in the sediment exists in many forms, and the definitions of the terms used to describe different forms are usually experimentally derived and consequently reports are highly variable from different authors (Pettersson *et al.* 1988). Methods used to measure phosphorus in sediment, and the interpretations made on phosphorus analyzed using different extraction procedures have caused confusion to many scientists, such as the proper meaning of terms used in describing different forms of phosphorus. There is a comprehensive literature present today, on problems encountered in phosphorus fractionation, and the interpretation of results obtained using different methods (Van Eck 1982, Henning & Thamdrup 1993, Jensen *et al.* 1995). The first attempts to develop a working analytical technique to separate phosphorus compounds in sediment were made by modification of sequential extraction technique in soils by Chang & Jackson (1957), by Williams and co-workers (Williams *et al.* 1967, 1971b). Syres *et al.* (1973) has given a review of modes of combination of phosphorus in sediments, and their analytical procedures. Williams *et al.* (1976), Hieltjes & Lijklema (1980), Van Eck (1982), Golterman (1977, 1982, 1996) and Nürnberg (1984, 1988) have developed other modifications.

A workshop on sediment phosphorus in Austria 1986 (Henning & Thumdrup 1993) recommended the use of a five-step scheme. Pettersson *et al.* (1988) recommended the same. However, still the most popular extraction scheme is a simplified scheme proposed by Hieltjes & Lijklema (1980). This scheme separates sediment phosphorus into labile or loosely-bound phosphorus, iron- and aluminum-bound phosphorus, calcium-bound or apatite phosphorus and residual phosphorus, which consists of organic and inert phosphorus. Williams *et al.* (1976) subdivided sediment phosphorus into three categories; apatite, non-apatite inorganic (NAIP) and organic phosphorus. The first category consists of orthophosphate present in the crystal lattices of apatite grains, while NAIP consists of all remaining orthophosphate ions. It is assumed that non-orthophosphate forms of inorganic phosphorus, in particular pyrophosphate and other polyphosphate ions, are absent in sediments or else present in minor amounts. The NAIP also includes soluble orthophosphate ion in the sediment pore waters. The last category embraces all phosphorus with carbon atoms via C-O-P or C-P bonds. It also includes organic phosphorus compounds in pore waters. This three category classification resembles the one proposed for phosphorus in terrestrial soils by Williams & Walker (1969), except that there is no distinction attempted here between different forms of NAIP.

Sediment phosphorus fractions are also characterized by use of their bioavailability or their ability to exchange especially in mathematical models that focus on phosphorus exchange across the sediment-water interface. These models predict presence of functional pools during diagenetic processes in the sediment (Jorgensen *et al.* 1975, Kamp-Nielson 1976). These functional pools divide the sediment phosphorus into three groups; the non-exchangeable, the exchangeable and the interstitial phosphorus. There is an analytical pitfall to these divisions, since the definition of these pools are not comparable with the chemically or mineralogically analyzable fractions

Sediment phosphorus can also be categorized as being of detrital or non-detrital origin (Williams *et al.* 1976). "Detrital" is used here in its geological sense, which essentially is the same chemical and mineralogical phosphorus forms in the rocks, soils and unconsolidated surface deposits from which the sediment was derived. On the other hand non-detrital phosphorus in sediments includes all forms in which the phosphorus was at some earlier stage in solution form and subsequently converted into particulate form. The non-detrital category also includes the "diagenetic phosphorus". This consists of phosphorus present in new modes of combination created within the sediment column itself (Williams *et al.* 1976).

1.3.3 Loss and transport in catchment systems

Phosphorus has limited solubility, as it is retained by the components of soils and sediment thus restricting its movements. Retention of phosphorus normally does not occur at the same degree in all soils because of the difference in phosphorus buffering capacity among different soil types (Sharpley & Rekolainen 1997). Soils with high clay content have a greater phosphorus retention capacity (Meyer 1979, Brady 1990), because phosphorus adsorption is mainly through chemical binding onto positively charged edges of clay and metal oxides (aluminium and iron) or by substitution of phosphate for silicate in clay structure (Lee 1973). Soils without inorganic colloids retain very little phosphorus and the same applies to those that are predominantly sandy in nature (Humphreys & Pritchett 1971). The effect of organic matter on phosphorus retention is difficult to assess. But, soils with high iron and aluminium hydroxyhumic complexes have shown that they are capable of absorbing phosphorus (Wild 1950). The rate of adsorption will depend on the soil pH. Phosphorus adsorption is at its maximum at the pH range of 4 - 4.7 and minimal at pH 6 - 6.5 (Morgan 1997). Above and below pH 4 - 7.5 calcium, aluminium and iron complexes are more important (Heathwaite 1997). In addition elevated soil temperature (Beaton *et al* 1965) and presence of kaolinite and calcite (Tisdale *et al.* 1985) are also known to increase phosphorus retention in soils.

The pathway between the phosphorus on land and the recipient water body is not always a simple and a direct phenomenon (Pionke *et al.* 1997), because potential loss of phosphorus from land into water systems is highly site-specific and quite a dynamic process (Morgan 1997). To a large extent soil texture determines the hydrological properties of soils, which indirectly controls phosphorus loss rates (Rekolainen *et al.* 1997). For example the coarser the soil, the higher is its permeability, resulting in low water holding capacity with high potential to release phosphorus.

Other natural factors that will influence rate of phosphorus loss are slope, vegetation cover, overall balance between phosphorus input and output, amount, form and availability of phosphorus in the soils. Presence or absence of surface and sub-surface runoff in the catchment's area is relatively important (Sharpley & Rekolainen 1997).

Potential phosphorus loss from agricultural areas is highly spatially and temporally variable due to variability in soil types, land use and management, and climate variation (Lennox *et al.* 1997). Sonzogoni *et al.* (1980) found that phosphorus loss rates were greater from soils with arable crops than grassland areas within the Great lakes of America catchment's. But phosphorus loss rate could also be high in grassland catchments especially if there are grazing animals within the riparian land due to their proximity to watering sites. Sonzogoni *et al.* (1980) highlighted that variability of phosphorus loss rates does not only vary between different land use categories but also within a particular land use. Withers (1994) found that cereal crops had a better phosphorus balance than root crops. Management practice in the catchment is also important in influencing the amount and form of phosphorus lost in agricultural areas. Timing of ploughing and related operations, type, amount and timing of fertilizer application especially before the rains, extent of crop cover and root activity are good examples (Heathwaite 1993, Sharpley & Rekolainen 1997).

The major control of phosphorus loss and export in the catchments is the source areas of surface runoff and erosion (Sharpley & Rekolainen 1997). Clearly without runoff neither form of eroded phosphorus can be exported to water bodies. Surface runoff is generated by excess precipitation which occurs when rainfall rate exceeds soil infiltration capacity (Smith & Williams 1980) or when the potential soil water storage is filled (Pionke *et al.* 1997). As the rainwater flows overland as surface runoff or storm flow, it picks up phosphorus from the soil either in water-soluble and/or in particulate form (Brooks *et al.* 1997). Although storm flow moves quite rapidly across or through the upper soils, they are still quite rich in phosphorus despite the limited contact time (Johnson 1979, Stevens & Smith 1978). However, the depth of the soil involved in phosphorus exchange is difficult to quantify in the field in most cases, but phosphorus loss increases drastically during flood events. Sharpley et *al.* (1986) obtained a highly significant linear relationship between phosphorus concentration in runoff and phosphorus content of surface soils in Arkansas, Oklahoma and Texas, similarly to Schreiber (1988) working in 17 Mississippi catchments (R^2 = 0.61) and Romkens & Nelson (1974) in Illinois (R^2 = 0.81). But, the actual mechanisms by which phosphorus reaches the drainage network, together with the mechanisms that release phosphorus to surface runoff during low intensity events are poorly understood (Haygarth & Jarvis 1997).

Historically surface runoff and associated erosion process were viewed as the dominant mode of phosphorus loss, but Ryden *et al.* (1973), Brooks *at al.* (1997) & Heathwaite (1997) have shown that this may not always be the case. Grassland catchments where erosion is limited by the groundcover, still lose phosphorus (Sharpley & Rekolainen 1997). The loss pathway is mainly subsurface through leaching, although the link between land use and phosphorus export through subsurface is less defined than that for surface runoff (Heathwaite 1997). In this situation, phosphorus is picked up by water that enters the soil profiles and moves through the soil to streams or rivers without reaching the main water table (Ryden *et al.* 1973, Brooks *et al.* 1997). Sub-surface phosphorus loss is highly significant especially in sandy soils, which have limited phosphorus retention capacity. Until the 1980's phosphorus leaching from soil to water was generally not considered important (Mason 1996). While this is certainly true, the concentration of phosphorus required to trigger eutrophication in freshwaters is extremely small, as low as 0.02 - 0.035 µg/l (Vollenweider 1975), meaning that however small is the quantity of phosphorus entering any water body, it is a potential eutrophication risk.

Lastly phosphorus is lost through groundwater flow. This happens when phosphorus is picked by water as soluble and/or particulate form and it is passed to the water table either by infiltration (Morgan 1997), or by water moving through fissures (Øygarden *et al.* 1996) which subsequently will be discharged to streams, rivers and lakes through seepage.

Regardless of the origin of the phosphorus that enters the streams and rivers, the transfer from the catchments to the lake is either a continuous or a discontinuous series of in stream processes (Sharpley & Rekolainen 1997). Transportation processes include a series of alternate period of deposition and re-suspension of sediment-bound phosphorus, chemical and biological phosphorus-sorption and release from the river sediment, which either concentrate or dilute the phosphorus content of flowing water (Meyer 1979, House & Casey 1988). However a number of uncertainties still exist to a full understanding of these processes. It is still not clear to what extent a particular phosphorus fraction, once mobilized is modified before reaching the stream. Also the extent to which the subsequent transportation of re-mobilised sediment bound phosphorus is continuous or discontinuous; is it likely to reach the basin outlet or will it be re-deposited and subjected to further re-mobilisation, transport and deposition? The relative importance of sedimentation of particulate phosphorus versus adsorption of dissolved phosphorus by sediment deposits (Walling 1996) is also not clear.

The relative importance of these processes is highly dependant on hydrology and the size of the catchment (Sharpley *et al.* 1986, Sharpley & Rekolainen 1997). For example during base flow most of the phosphorus entering the rivers is retained within the system temporarily until the flow rates are higher (Heathwaite 1997). Reduction of flow enhances sedimentation of particulate phosphorus originating from the sediment or from coagulation processes and precipitation of soluble phosphorus in presence of high calcium ion concentration (Dorioz 1996, Pommel & Dorioz 1997). Dissolved phosphorus contained in the interstitial water is also trapped in the sediment. Low flow in rivers also activates growth of periphyton, phytoplankton, macrophytes and riverbank vegetation, which automatically increases the biological uptake of dissolved phosphorus in the flowing water. All these processes affect not only the transport of total phosphorus in the river but also the speciation of phosphorus and its bioavailability. Phosphorus is transported in dissolved and particulate form. During phosphorus transport, transformation of soluble to particulate form and vice versa continuously does occur, as a result of stream processes. The direction and extent of these transformations will depend on the rate of flow, the amount of soluble phosphorus present in the water and the adsorption capacity of the suspended solids and the sediment (Sharpley & Rekolainen 1997). Co-precipitation of phosphorus after oxidation of Fe^{2+} to Fe^{3+} is an important process, in transporting phosphorus to the sediment surface and governs the exchange of phosphorus between water and sediment (Fleisher 1986). Granelli & Solander (1988) also suggested that submergent and emergent macrophytes serve as an intermediate link in the transport of phosphorus from the sediment to the water column.

1.3.4 Transformation in lakes

1.3.4.1 In the water column and water- sediment interaction

Once phosphorus arrives at the receiving lake, further exchanges in the water column and between water and sediment, determine the amount available for biological activities. According to Golterman (1975) a distinction can be made between the "internal" or "metabolic" and the "geochemical" phosphorus cycles. The metabolic pathway involves biological aspects, mainly in days, although sometimes animals may use a small fraction of phosphate for a longer period. Thomas (1968) demonstrated the quantitative importance of phosphorus removal from the water by algae for growth in readily available inorganic form. Most algae are able to store phosphate in their cells in the form of microscopically-visible poly-phosphate granules, which under conditions of phosphorus deficiency are mobilized and used to form normal cell constituents (Stewart & Alexander 1971). Following the death of the algae most of the phosphorus is released through mineralisation by bacteria action back into the water. Goldman (1960) found that 50% of the particulate phosphorus was returned into solution as PO_4-P a few hours after the onset of autolysis. Most of this phosphorus remains in the upper water layer. There is considerable evidence indicating that mineralisation of dead plankton cells takes place mainly in the epilimnion with a high turnover rate (Rodhe 1965), although Golterman (1975) pointed out that direct demonstration of this phenomenon is extremely difficult.

Anderson *et al.* (1988) showed that herbivorous zooplankton contribute significantly to the regeneration rate of phosphorus in the open water and might be the most important phosphorus source for pelagic algae during stagnant conditions. Pelagic invertebrates not only transform phosphorus, they can also translocate or distribute the recycled phosphorus within the system especially through vertical migration (Hutchinson 1967) or horizontal diel migration pattern.

Not much is known about the biological availability of certain dissolved organic phosphate compounds released into the water during autolysis, especially at low temperatures (Golterman 1960). Some of these compounds are rapidly available for algal growth, for example, glycerophosphate (Miller & Fogg 1957). Johannes (1964) and Berman (1990) demonstrated that bacteria and extra-cellular alkaline phosphatases would hydrolyse organic phosphate compounds unavailable for algal metabolism. This occurs only when phosphate is not susceptible, even to bacterial decomposition, such as when humic-iron-phosphate complexes are withdrawn from the water column.

1.3.4.2 The role of sediment in phosphorus dynamics and the budget of lakes

Sediment may act as a phosphorus sink or source (Hesse 1973). The lake sediments play an important role in phosphorus uptake and regeneration. Any changes in the characteristics of the sediment-water interface has the potential to influence the role of sediment in the nutrient budget of the lake, especially phosphorus since it has been identified as a key element in eutrophication (Syers *et al.* 1973, Twinch & Breen 1982). Phosphorus sinking to and regeneration from the sediment depends on a great variety of physical, chemical and biological processes. The effectiveness of these environmental variables on the phosphorus sink or release from the sediment has been widely studied.

The sediment's retention capacity for phosphorus depends on the sediment's chemical binding potential and the phosphorus concentration gradient between water and the sediment. Holten *et al.* (1988) suggested that a great part of the phosphorus in sediment is adsorbed to the sediment particles or incorporated into the organic matter derived from soil. But many scientists have shown that mineralogy and chemical properties of the sediment play an important role in phosphorus adsorption. Solids such as ferric and, aluminium oxyhydroxides, calcium compounds and clay minerals have a high affinity for phosphorus (Cole *et al.* 1953, Golterman 1977, Twinch & Breen 1982, Holten *et al.* 1988). Increase in iron and calcium ions in the system results in an increase in the ability of the mineral deposits to absorb phosphorus and a decrease in ability of organic deposits to release phosphorus (Golachowska 1967). The reason for this is simply, because the organic matter cannot bind phosphorus, and adsorption of phosphorus is entirely dependent on the amount of mineral, which serves as phosphorus adsorption sites in the sediments (Boström *et al.* 1988). Holten *et al.* (1988) argue that the phosphorus adsorptive capacity in the sediment largely depends on the clay fraction by virtue of its large adsorptive area.

Increase in pH caused by high primary production rates especially, in moderate to high eutrophic lakes, acts as an important stimulant to phosphorus release (Rippey 1977, Boström *et al.* 1982). On the other hand, redox potential has been widely recognised to stimulate phosphorus release from the sediment ever since the studies of Einsele (1936, 1938) reviewed by Boström *et al.* (1988), and those of Mortimer (1941, 1942). Oxygen concentration in the sediment-water interface is the key driving force of these reactions. Under oxidised conditions phosphorus is adsorbed and co-precipitated with amorphous ferric oxyhydroxides, while under anoxic or reduced conditions there is dissolution of the ferric oxyhydroxides phosphate complexes resulting to mobilization of ferrous iron and phosphate (Syers *et al.* 1973, Ryding 1985). However, Golterman (1996) argues that higher release of phosphorus in anaerobic conditions is probably caused by mineralisation of organic matter containing phosphate and not by reduction of ferric oxides as is usually believed. Kamp-Nielsen (1976), Holdren & Armstrong (1980), Ryding (1985) among others, demonstrated that phosphorus release rates in the sediment increase with temperature. Change in temperature is known to influence mass diffusion rates and microbial activities, which in turn influences the redox potential of the sediment (Grobbelaar & House 1995).

Phillips & Jackson (1989) concluded that bioturbation particularly of 4^{th} instar *Chironomus plumosus* larvae, has a significant effect on sediment phosphorus release, which stimulates microbial decomposition of organic matter. According to Granéli (1979), their pumping action could enhance phosphorus release by moving phosphorus from the interstitial water into the overlying lake water. The influence of the interstitial water and submerged macrophytes in the littoral zone to phosphorus fluxes are also important in budgets and dynamics of the lake sediment phosphorus.

However in most of these studies, only a single environmental variable is investigated under well-defined laboratory microcosms. The extrapolations of these results to field conditions becomes very questionable and probably unreliable, because effects of different environmental variables *in situ* may be counteracting and synergistic. As of today, details of individual processes controlling phosphorus fluxes in the sediment-water interface are well understood, but their application to complex natural systems is still limiting.

1.3.4.3. Influence of interstitial water on sediment phosphorus fluxes

Surface sediments usually have a high water content of 95-99% in freshwater ecosystems (Magnus & Lofgren 1988). Only a minor part of this water is bound to solid chemical substances, the rest constitutes mobile liquid that surrounds the sediment particles. This mobile water fraction is the interstitial or the pore-water and it is an important transition medium in movement of solutes across the sediment-water interface. The composition of the interstitial water is controlled by complex interactions between the groundwater recharge system, mineralogical dissolution and precipitation, biological activities and the physical interactions between sediment and water (Harris 1977).

Interstitial water is very important in phosphorus dynamics in sediment-water interface because it is very sensitive to environmental conditions (Syers *et al.* 1973). Phosphorus concentration and dynamics in the interstitial water is a better tool for predicting the trophic state of a lake, than information of the sediment total phosphorus concentration. Magnus & Lofgren (1988) showed that there is a difference in the interstitial water phosphorus concentration between oligotrophic, mesotrophic and eutrophic lakes, although the temporal and spatial variation within the lakes is large.

Phosphorus fluxes in interstitial water can be quite complicated, especially if redox potential shifts from reduced to oxidised conditions, where the adsorption characteristics of phosphorus changes drastically (Davison 1982). Boström *et al.* (1982) state that, for sediment phosphorus to be released there has to be simultaneous mobilization of loosely bound phosphorus to the pore-water and then transportation to the overlying water body. This is known to happen during anaerobic conditions in the sediment, which causes dissolution of ferric phosphate complexes resulting in high concentration of dissolved phosphorus in the pore water. This increases the diffusive gradient between the pore-water and the overlying water column, creating a driving force for a diffusive flux from the interstitial water to the overlying water. Magnus & Lofgren (1988) suggested that there is a possibility of a direct release of particulate phosphorus into the pore-water especially those bound to iron oxyhydroxides, although there is no evidence of this in the literature.

Despite the important role played by the interstitial water in phosphorus fluxes within the sediment-water interface there is still very limited information available on the levels and forms of phosphorus in the interstitial waters. There are several reasons for this, but problems in methods of separating pore-water or substances dissolved in it from the sediment forms the biggest challenge. The sensitivity of the environment conducive for pore-water separation from the sediment and its analysis is difficult to attain with the techniques in use today, and that's why only a few investigators have tried to analyse different phosphorus fractions present in pore-water as compared to studies done on the water column and the sediment. Most of the pore-water studies have only been focusing on the analysis of total inorganic phosphorus, with the main reason being probably the restricted pore-water volume available.

1.3.4.4 Effects of aquatic macrophytes on phosphorus content in the sediment and water

Aquatic macrophytes often dominate the littoral zone of lakes and may form a large standing crop. However the effects of macrophytes on nutrient cycling in lakes are less well understood compared to nutrient cycling in the pelagic and sediment systems. There seem to be two apparently conflicting theories about the effect of macrophytes in nutrient cycling; the "sink theory" and the "pump theory" (Graneli & Solander 1988). The "sink theory" advocates that the littoral plant communities function as a net sink of nutrients. This theory supports Gaudet's (1977) finding, that nutrients entering the papyrus swamps are trapped in the swamp basin as sludge. He concluded that swamps, particularly of *Cyperus papyrus*, should be visualised as large "holding tanks" rather than producers and filters of autochthonous nutrients and organic matter. On the other hand the "pump theory" advocates that macrophytes, especially the rooted submerged ones, mediate a net transport of nutrients from the sediment to the overlying water (Carignan 1982). However, both emergent and submerged macrophytes can serve as an important intermediate link in the transportation of nutrients. Carignan (1982) showed that nutrient uptake by submerged plants takes place both from the water via leaves, and from the substrate via roots. While Gaudet (1978) and Gaudet & Muthuri (1981) suggested that the major export of nutrients from a papyrus swamp is mainly through the detritus cycles rather than through-flow systems. Carignan (1985) observed a high concentration of dissolved reactive phosphorus in weed bed sediment. But, sometimes the amount of phosphorus bound within the decaying tissues of macrophytes may not be biologically available especially when the decaying plants get buried deep into the sediment. However, not many nutrients are released by dying emergent macrophytes, because when an emergent perennial macrophyte falls into the water, its nutrient content is already low due to translocation of nutrients and early leaching (Graneli & Solander 1988).

Macrophytes do affect the chemical environment of the sediment and water. Roots and rhizomes of the macrophytes obtain oxygen from the shoots and some of this oxygen diffuses out to the surrounding substrate. This changes the redox potential, which in turn affects the mineral ion concentration including phosphorus fractions in the sediment (Wium-Andersen & Andersen 1972, Carpenter *et al.* 1983). Macrophytes also affect the chemical environment of the sediment by increasing the lake water pH through photosynthesis. Change in pH will influence the pH-dependent phosphorus release from the sediment especially aluminium and iron-bound phosphorus (Boström *et al.* 1982). Carignan (1984) proposed a way in which macrophytes enhance sediment phosphorus retention rather than release. He suggested that under oxidised conditions calcite, originating from marl formation on the macrophytes, triggers the carbonate/apatite precipitation of the insoluble phosphate. This results in high concentration of unavailable inorganic phosphorus in the sediment-water interface. Therefore the phosphate regenerated in the interstitial water within the sediment can no longer diffuse out to the overlying water since its concentration gradient across the sediment-water interface becomes negligible or even negative. Thus, different wetlands should be treated as an entity and there should be no generalisation on their impact in different water bodies (Brown *et al.* 1978).

1.4 Consequences of eutrophication

Problems associated with eutrophication are more recently experienced in tropical countries as opposed to temperate where they have a century's history (Harper 1992a). Eutrophication in temperate countries has led up to deaths of wildlife, livestock and sickness in humans, from water contaminated with extensive toxic algal blooms (Codd *et al.* 1992, Caraco 1995). Increase in growth of undesirable aquatic weeds has also occured as a result of nutrient enrichment in some water systems (Sharpley & Smith 1990). Algal problems associated with eutrophication are caused by biomass increase in water-bodies at a given time. The algal biomass is a static measure of eutrophication symptoms, while the rate of algal production is a dynamic process and defines the rate at which algal biomass is produced. Ryding & Rast (1989) note that increase in the primary production rates in a water body may be a better eutrophication indicator than elevated algal biomass. However, the resultant algal blooms and excessive growth of aquatic plants are visible and can interfere significantly with the uses and aesthetic quality of a water body. The consequences of the excessive growth on human and domestic animal health have been well elaborated by Harper (1992a), Ryding & Rast (1989), UNEP-IETC (1999). Other potential health effects especially in tropical regions are related to parasitic diseases; Schistosomiasis, Onchocercosis, and Malaria, all can be aggravated by artificial eutrophication through the enhancement of suitable habitats of their hosts. Excessive algal growth can cause off-flavors and odor problems in drinking water even after treatment, which makes water treatment more expensive and time consuming. In addition, as the algae and aquatic macrophytes increase, high concentration of dissolved organic carbon (DOC) is generated. When drinking water with a high DOC is chlorinated potentially carcinogenic mutagenic trihalomethanes are formed (UNEP-IETC 1999) which can be very detrimental. As the organic matter decomposes, oxygen concentration in the bottom waters is reduced to levels that are too low to support fish, resulting in fish kills. Moreover, under such oxygen-deficient situation the levels of iron, manganese, ammonium and hydrogen sulphide increase and these can interfere with drinking water treatment, while phosphate and ammonium are released back into the water from the anoxic sediment further enriching the lake (Harper 1992a).

1.5 Are tropical lakes different in the response to nutrient than temperate lakes ?

Thornton (1987b) stated that "eutrophication symptoms" observed in temperate zone waters do not necessarily all show in the tropical/sub-tropical waters. This does not mean that eutrophication is influenced by different factors in the tropical systems, but rather that the eutrophication indicators in these systems may not be of the same water quality and trophic conditions as in the temperate zone. The reasons for this could be many. For example Lindmark (1979) suggested that algal growth is continuous in the tropical systems, since light and temperature are mostly above levels that would limit their growth. This means that phytoplankton blooms can occur at any time of the year without following an annual cycle. Lack of climatic seasonality in the tropics had not been considered as an important feature until recently when distinct seasonality was noted in most tropical lakes and reservoir systems (Thornton 1987b), with one or two months delay in maximum algal growth after the rainy season. This would imply that lack of nutrients could be a major factor controlling seasonal patterns of algal growth within the tropics (Lindmark (1979). But, Talling & Lemoalle (1998) review on ecological dynamics of tropical waters clearly shows the importance of stratification and mixing in the higher temperatures of the tropics upon algal dominance and type. According to Harper (1992a) tropical/sub-tropical lakes behave differently to temperate ones in response to nutrients due to high turbidities caused by erratic rainfall and easily exposed soil to erosion, such that predicted plant growth is not realized. However, Melack & Fisher's (1990) review shows that flooding of nutrient-richer water causes a dense phytoplankton growth in numerous small reservoirs surveyed by Tundisi (1983,1994) in South East Brazil, lake Xolotlán in Nicaragua (Hooker *et al* 1991), Chapala in Mexico (Limón *et al.* 1989, lind *et al.* 1992). But an increase in phytoplankton density in the lake can strip inorganic phosphorus and nitrogen from the water through biological uptake (Forsberg *et al.* (1988) resulting in reduction in their biomass and species diversity. Schindler & Fee (1974) Hecky & Kling

(1981,1987) and Kalff & Watson (1986) stressed the importance of rates of supply rather than the nutrient concentration and light in controlling algal growth and production in tropical waters.

In general tropical/sub-tropical systems appear to tolerate higher phosphorus loads than the temperate zone. Total phosphorus concentration of 50-60 μg/l has been suggested as the boundary between mesotrophic and eutrophic for Lake Mcllwaine (presently known as Lake Chivero) in Zimbabwe (Thornton & Nduku 1982), similar to the concentration reported for Australian water bodies (McDougall & Ho 1991). This concentration range is much higher than that of the temperate zone (Table 1.2). By contrast nitrogen concentration boundary values are lower in the tropics/sub-tropical than in temperate waters (Table 1.2). This is indicative of nitrogen limitation (Toerien *et al.* 1975). Ryding & Rast (1989) further suggest that tropical systems often develop extremely low N/P ratios, thereby favoring the dominance of blue-green, nitrogen fixing bacteria. However, although Toerien (1975) indicates that cyanobacteria are more dominant in tropical lakes, the change in phytoplankton either from diatom to blue-green 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.

Table 1.2 Comparison of temperate and tropical boundary values between oligotrophic and eutrophic lakes. (Adopted from Ryding & Rast 1989)

Trophic indicator	Temperate lakes	Tropical lakes	Original References
Nutrient limitation often by	Phosphorus	Nitrogen	Toerien *et al.* 1975
Total phosphorus (μg P/l)	30	50-60	Thornton & Nduku (1982)
Total nitrogen (μg N/l)	50-100	20-100	Wood (1975)
Chlorophyll a (μg/l)	10-15	10-15	Walmsley & Butty (1980)
Dominant algal types	Diatoms	Cyanobacteria	Toerien *et al.* (1975)
Mean primary productivity ($gC/m^2/day$)	1.0	2-3	Robarts *et al.* (1982)
Photosynthetic efficiency	<1%	>2-3%	Wetzel (1983)

1.6 Extent of eutrophication in tropical waters

Generally low levels of industrialization in Africa would mean that eutrophication does not present the same problems as it does in temperate countries, however there are familiar contexts of eutrophication in both areas. The major concern of limnologists today relating to eutrophication, particularly in Africa, pertains to the traditions of land use in the watershed of the water bodies. 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.

Reviews of eutrophication have shown 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) and South America (Tundisi 1994, Tundisi *et al.* 1998), 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). The African Great Lakes are unique in their own way. Lake Victoria, belonging to the Nile River system, is a recent culprit of environmental degradation showing evidence of eutrophication, indicated by species reduction, fish mortality, algal blooms and currently intensive water hyacinth invasion, although the cause(s) remain complex (Hecky 1993, Mugidde 1993 & Lehman 1996). Lakes Malawi and Tanganyika are among the ancient lakes in the world, dating to 20 million and 2 million years BP respectively. Lake Tanganyika, although still oligotrophic (Hecky & Kling 1981), is threatened by sewage discharges, industrial waste, riparian agriculture and oil prospects (Coulter 1991, Cohen *et al.* 1996). 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. All these three lakes provide a unique habitat and collectively play a critical role in the socio-economic welfare of their riparian populations. Surveys conducted in 1970 in Kenya, Tanzania, Uganda and Zambia concluded that water pollution was not yet a problem, but would soon become one (UNEP-IETC 1999). 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.

Surface waters in South America are already in an adverse state with respect to eutrophication (Tundisi 1981, Serruya & Pollinger 1983, Mouchet 1984). Toxic blooms occurred in reservoirs and ponds in 12 provinces in Argentina between 1989 and 1993, with *Microcystis aeruginosa* and *Anabaena spp* being the main components of the phytoplankton. Several reservoirs in Brazil are already nutrient rich. A good example is lake Parano, which was constructed in 1959 for recreation and hydroelectric power production (Tundisi 1981). The lake is highly eutrophic because of sewage discharge into the lake, with blooms of cyanobactera such as *Microcystis aeroginosa* (Tundisi 1994, Tundisi *et al.* 1998). Lake Valencia has experienced detrimental changes such as increase in total dissolved solids and nutrients over this century (Serruya & Pollinger 1983, Lewis 1986) as a result of artificial lowering of the lake level and the catchment's deforestation.

1.7 Eutrophication evidence at lake Naivasha

The future ecological stability of lake Naivasha is unpredictable. This is due to diversified climatic conditions in the area (Odingo 1971), which consequently affect the inflow rates. The intensive agricultural and human activities along the lake and its catchment might have contributed to basic changes in the lake (Harper *et al.* 1993). Increases in water demand and abstractions continue. The existing Olkaria geothermal power station, producing 45 Megawatts (15% of national electric power requirement), using lake water to cool its turbines, is currently being expanded to yield an additional 64 Megawatts. This is a cheap source of energy for Kenya, and the geothermal power source is planned to increase to 28% of the country's demand in the next 20 years (Abiya 1996). In the last few years, there has been a tremendous increase in horticultural farming of flowers and vegetables for export along the lakeshore. This not only puts pressure on the lake through consumption for irrigation, but is a potential source of nutrients into the lake. The local availability of cheap labour required in these farms has resulted in the development of several villages and recreational facilities along the southern shores of the lake. Most of these facilities do not have sewage systems. The riparian vegetation is particularly under serious threat from burning and cutting (Harper *et al.* 1995).

With all these changes taking place in the surroundings, lake Naivasha is under risk of eutrophication, and the consequences would be serious since it lies in an endorrheic basin. To date major changes in species composition and distribution of macrophytes (Harper 1992b) and phytoplankton biomass (Kitaka 1991, Harper *et al.* 1993, Hubble 2000), which are good indicators of eutrophication progression elsewhere, have already occurred in the lake. Lakeside residents have implicated water level fluctuation and heavy agricultural practices within the catchment's area as the main sources of nutrient input into the lake and biological changes. These biological changes could have occurred as a consequence of alien species introductions (Harper *et al.* 1990). Recently the fishery has declined except, after the "El Niño" effect rains. To date there are few licensed and unlicensed fishermen on the lake (Kundu pers. comm.). The Lake Naivasha Riparian Association (LNRA) has already prepared a management plan for the lake and its lower catchment (LRNA 1999). This was officially released in February 1999. Due to LNRA efforts in conjunction with Kenya Wildlife Services (KWS), lake Naivasha was designated as a Ramsar site in April 1995 because of its special ecological value in Kenya. The lake and its surrounding area supports birds species which make it an important area for ornithological tourism in the region; with at least about 350 bird species reported. In addition the lake supports intensive irrigation agriculture, Olkaria geothermal power station and a thriving tourist industry. Therefore if lake Naivasha is to survive as a freshwater body, and maintain its past-glory with high diversity of aquatic fauna and flora, there is a great need to understand the nutrient dynamics in the lake and the internal and external sources.

This study was set up with the assumption that phosphorus was limiting algal biomass in lake Naivasha. Evidence does exist which shows that lake Naivasha is more phosphorus limited than nitrogen, despite that tropical lakes are known to be nitrogen limited (Talling & Talling 1965) elsewhere. Kalff (1983) obtained a relationship between chlorophyll *a* and TP for lake Naivasha similar to those of phosphorus-limitation, in temperate lakes in summer. Njuguna (1982) and Kitaka (1991) found high ratios of N/P indicating phosphorus deficiency.

There is no study undertaken on the trophic conditions of the streams and rivers flowing into lake Naivasha. Mineralogical research, fertiliser trials and greenhouse tests have proved that phosphorus is low in Kenyan soils (Hinga 1973, Nyandat 1981), although lake Naivasha lies in a volcanic soil region, which is known to be rich in phosphorus (Nyandat 1981, Pacini 1994). However, to sustain the increase in agricultural activities especially horticulture, there must be intensive use of phosphorus-based inorganic fertilisers or organic manure to enrich the soils for maximum agricultural production. This poses a risk of phosphorus loss into the lake either directly or indirectly. An ideal solution would be to asses the actual situation continuously by monitoring the drainage water system and the soils for phosphorus loss. However an extended sampling programme can be expensive in terms of both service and laboratory costs. As a result of the lake management plan, the LRNA, with some of the horticultural companies and the KenGen Olkaria power station have started a monitoring scheme of the lake and the lower catchment.

The impact of lake sediments as a phosphorus source to lake Naivasha has not been previously studied and, it might be an internal source that may or may not have a strong influence on the phosphorus budget of the lake. Hopefully the results of this study will provide a new perspective on nutrient control and management of the lake and its catchment's area to make the new "Lake Naivasha Management Plan" ecologically sound, for sustaining agricultural production and yet retain environmental quality.

1.8 Aims, hypotheses and predictions of the study

1.8.1 Aims

There is very little intensive work done in lake Naivasha on phosphorus dynamics in the catchment and interactions in sediment-water interface. This study addressed 4 questions

a) Do the human activities within the catchment's area of the lake have any influence on the lake's phosphorus dynamics and budget and if to so what extent?

b) Do the sediments have any impact on the phosphorus budget of lake Naivasha ? If so, how, and to what extent?

c) Are recently observed increases in phosphorus concentration in the lake associated with changes in phosphorus loading or changes in the lake volume?

d) What are the main sources of phosphorus in the catchment area ?

1.8.2 Hypotheses and predictions

To be able to answer the above questions, several hypotheses and predictions were established.

1. Lake Naivasha's phosphorus supply is from diffuse sources in its catchment, rather than from point sources

   Predictions;

   a. Total phosphorus runoff is linked to rainfall and discharge.

   b. Total phosphorus concentration in rivers is sediment-associated.

   c. Lake sediment sources are not significant.

   d. Lake riparian sources are not significant.

   e. Point source of phosphorus is not significant.

   f. Lake phosphorus concentrations reflect inflow changes rather than lake processes.

   g. Urbanisation does not result in significant sources.

2. Agriculture rather than geology is the major contributor.

   Predictions;

   a. Phosphorus concentration downstream of intensive agricultural/ horticulture will be greater than upstream.

   b. Phosphorus concentration downstream of livestock watering sites will be higher than upstream

   c. Phosphorus concentration in the headwaters will be sediment-associated.

3. Phosphorus supply to the lake is by surface water inflow.

Predictions;

a. During normal weather conditions, phosphorus remains soil-bound.

b. Phosphorus concentration in ground water is lower than in river water.

c. During storm events, surface overland flows contribute to lake phosphorus concentration.

d. A total budget for the lake will show balance between measured sources and quantity residing in lake and sediments.

CHAPTER 2

THE STUDY AREA: The Naivasha ecosystem

2.1 Geophysical characteristics

2.1.1 Geographical position

Lake Naivasha is situated in the eastern rift valley of Kenya at 0^0 45'N, 36^0 20'E and 10'S at an elevation of 1890 metres above sea level. The width of the valley around this area is between 45 to 70 Km (Stuttard *et al.* 1995). The Naivasha basin contains four morphometrically distinct water bodies that are different in their history, chemistry and biology. These are Naivasha main lake, Crescent Island lake, Oloidien lake and Sonachi crater lake.

The basin has tectonic faulting and volcanic-oriented boundaries associated with rift valley formation (Figure 2.1). The basin is bordered to the east by Nyandarua ranges (3960 m) previously known as the Aberdare ranges and the Kinangop plateau (2483 m). The Kinangop plateau is a broad flat escarpment ranging in height from 2379 m to maximum elevation of 2740 m above mean sea level. This forms a broad step between the Nyandarua ranges and the valley floor. Mount Longonot (3000 m) with its lava sheets and associated volcanic cones forms a barrier to the south that is breached by the Njorawa Gorge (Hells Gate). This is the former outlet of the Pleistocene Nakuran Lake, which once occupied the Naivasha-Elementaita-Nakuru basin (Richardson & Richardson 1972). The Mau escarpment forms the western boundary with a maximum elevation of 3080 m a.s.l. at some localities and over 3000 m a.s.l, stretching 36 km long and decreasing in height both north and south. The Eburu hills (2668 m a.s.l.) to the north separate the Naivasha basin from lakes Nakuru and Elementaita (Figure 2.1).

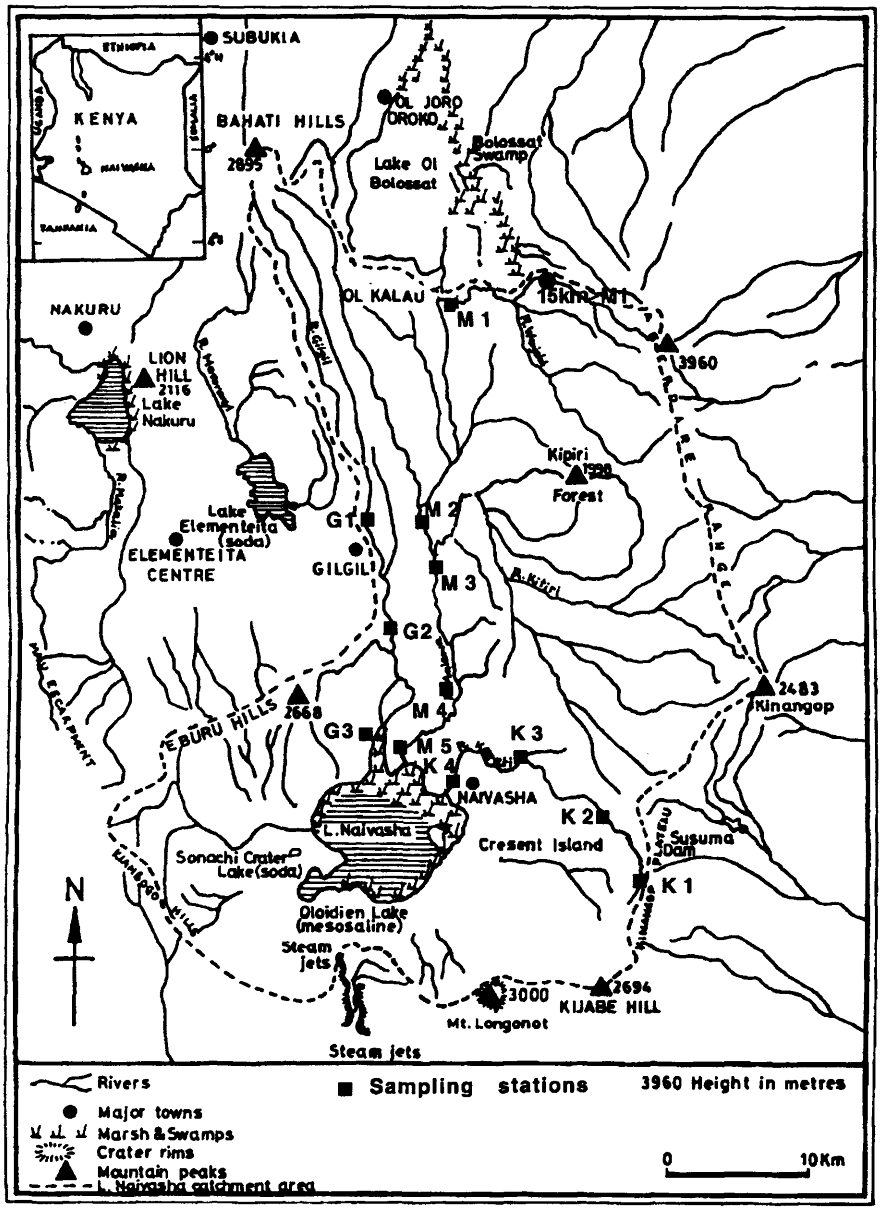


Figure 2.1 Geographical position of lake Naivasha and its catchment showing the bounderies and the sampling stations of the main rivers (M_1-M_5 for Malewa, G_1-G_3 for Gilgil and K_1-K_4 for Karati) (Modified from Mavuti 1983)

2.1.2: Geology and soils

The geology of the lake Naivasha basin and its surrounding area was described by Gregory (1921), Thompson & Dodson (1963) and reviewed by Richardson & Richardson (1972). The region is geolocally very young, with all rocks and structures having formed during the past 4

Ma (Trottman 1998) with four major volcanic and faulting activity periods as shown in Table 2.1. The catchment is covered with tertiary and quaternary deposits (Figure. 2.2), mainly pyroclastic (tuffs) and lacustrine in origin (Shackleton 1945, King & Chapman 1972, Åse *et al.* 1986). The lake basin region is covered by extensive and still active volcanic areas of recent geological origin (<1 Ma); Eburu volcanic area to the north, Longonot volcano to the south and the Olkaria complex to the southwest. The volcanic rocks in the area consists of basalts, tephrites, trachytes, phonolites, ashes, tuffs, agglomerates and the acid lavas, rhyolites, comendite, and obsidian (Thompson 1958). Basalts-lava flows are composed of slightly vesicular basalt with fairly abundant small plagioclase phenocrysts.

Table 2.1 Major volcanic and deformation episodes (adopted from Trottman 1998)

EPISODE		ACTIVITY	AGE RANGE
V_4		Late quaternary to recent salic volcanoes	0.4 - 0 Ma
	F_4	Extensive minor faulting of rift floor	0.8 - 0.4 Ma
V_3		Quaternary flood lavas of rift floor	1.65 - 0.9 Ma
	F_3	Renewed faulting of rifts margins	1.7 Ma
V_2		Early quaternary flood trachytes	2.0 - 1.8 Ma
	F_2	Formation of step faults (narrowing of graben)	3 - 2 Ma
V_1		Pliocene ash flows	3.7 - 3.4 Ma
	F_1	Major faulting of eastern rift margin	4 - 3 Ma

KEY
V_1 - V_4 = Volcanic activity periods
F_1 - F_4 = Faulting periods
Ma = Million of years

The Mau escarpment to the east and Nyandarua ranges (part of the Kikuyu escarpment) consists of older rocks (>1.5 Ma), mainly basalts. The Mau escarpment is composed largely of soft, porous volcanic ashes and tuffs, with rare outcrops of agglomerates and lavas (Thompson & Dodson 1963). The plateau is downfaulted with fault scarps up to 300 m a.s.l. separating it from valley floor. The eastern margin has more faults and fractures than the western margin. The north-eastern part of the upper Malewa catchment is the only one with a different geology which is represented mainly by basalts of the Nyandarua ranges and the agglomerates especially trachytes of the Kipipiri plateau (Åse *et al.* 1986). The trachytes range in age from middle Pleistocene to the recent lavas of less than 200 years old (Tarras-Wahlberg 1998). Also phonolytic trachytes (Sodic trachytes) occur in this area.

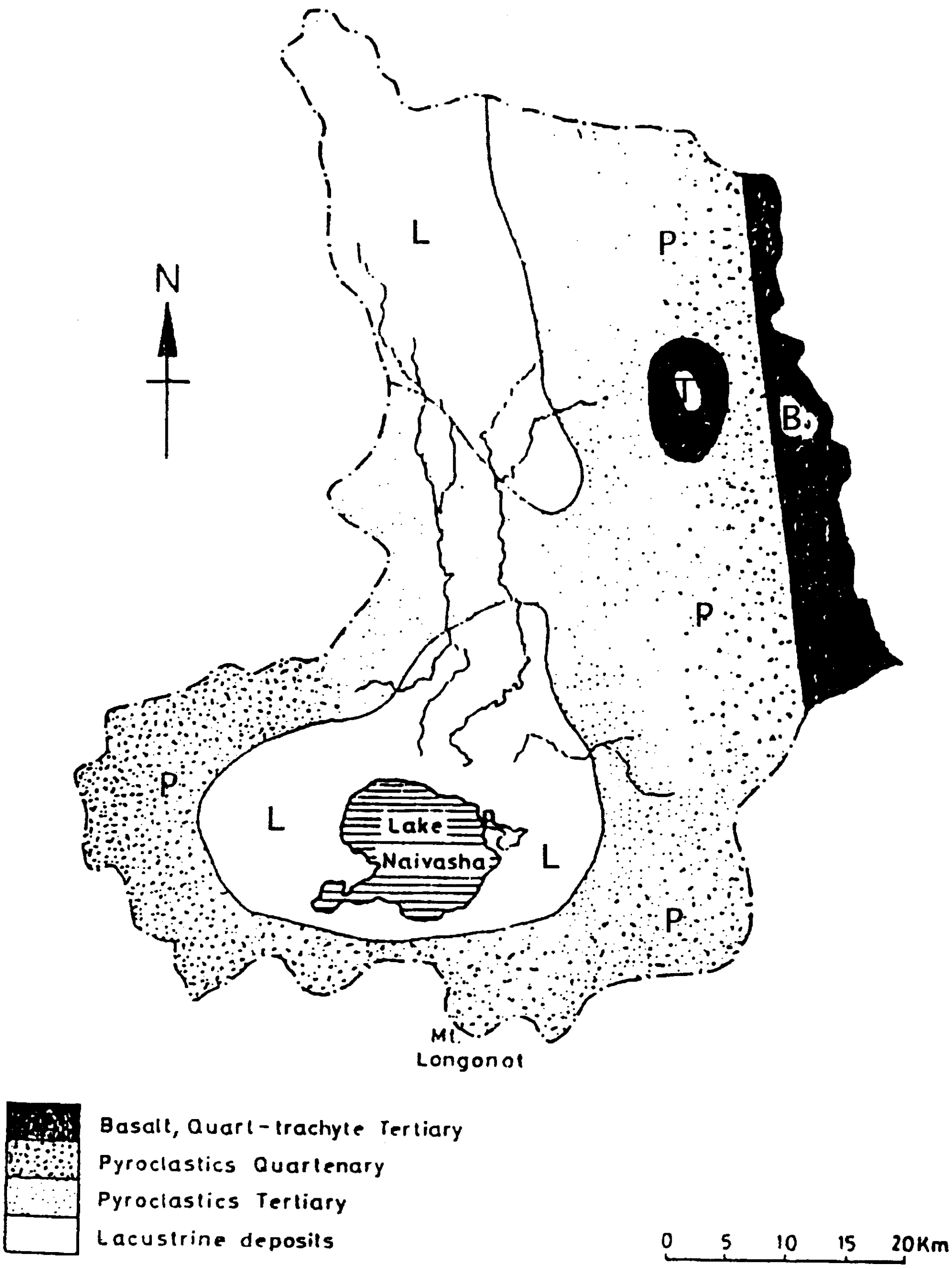


Figure 2.2 The geology of lake Naivasha catchment area
(modified from Åse *et al.* 1986)

The Naivasha basin is largely covered with sediments derived from erosion of the surrounding volcanic rocks of the rift margins. These sediments were deposited in a lacustrine environment during the Gamblian stage of the Pleistocene period, and are commonly referred to as "Gamblian lake sediment" (Trottman 1998). Despite their extensive distribution, the lake sediments are not thick, and rarely exceed 30m (Thompson & Dodson 1963). Volcanic rocks underlay the lake sediments. The lake sediments consist of sand and pebble beds, and gravel which comprises of rounded pumice clasts (Studdard *et al.* 1995). Quaternary alluvial sediments also form a minor part of the Naivasha basin cover (Thompson 1958).

The distribution of soils in the rift valley is quite complex, due to the influence of extensive factors, such as climate, volcanic activities and underlying rocks (Siderius 1980). Ongweny (1973) described the soils occupying the floor of the rift valley as an assemblage of acidic and basic lavas of gray or brown to pinkish non-calcareous soils. Naivasha basin soils are young and poorly developed, grayish-black to black acid loams seasonally inundated with pH 5.2 - 5.5 (Odingo 1971). The upper part of the catchment in the Nyandarua ranges and Kinangop plateau consists of black and red soils, predominantly montmorillonite clays (Kilham 1972, Rachillo 1977). This type of soil is typical for areas with basalts, phenolites and trachytic tuffs, compared with soil colour elsewhere in Kenya highlands which depends on the slope controlling drainage and consequently oxygenation rather than the nature of the bedrock (Shackleton 1945).

In the high mountainous areas (Nyandarua and Eburu) and major scarps (Mau and Kinangop) with a slope greater than 30%, soils consist of "regosols" and "andosols" (Hamududu 1998). The regosols are excessively drained, deep, dark brown soils in colour and slightly smeary, but strong calcareous, stony to gravel clay loam, while the andosols are well drained soils developed on older ashes of volcanoes. Nyandarua and Eburu have humic topsoils (Hamadudu 1998). The two upper plateaus situated above 2060 m a.s.l. are covered by an andoluviac phaeozem, well drained deep, dark brown and friable to slightly smeary soils (Jaetzold & Schmidt 1983). These soils are commonly known as "prairie soils" consisting of clay-loam and clay with high agricultural fertility, good workability and good water holding capacity (Hamududu 1998). The other plateaus and higher plains with an average slope 8% have soils developed on ashes from recent volcanoes, mainly planosols and phaeozems (Hamadudu 1998). The planosols are not well drained as they are made of mottled clay under a silty loam layer.

The soils of the lower catchment around the lake are mainly deep and firm, dark grayish brown to dark brown, saline, sodic and slightly calcaric known as solonetz (Hamududu 1998). They consist of silt loam and clay and are easily waterlogged. These soils have a low agricultural fertility and poor workability, although they give a high yield if well managed. According to Kwacha (1998) the lower Naivasha catchment soils are very rich in potassium with a high supply of phosphorus, calcium and magnesium, while nitrogen and carbon are low. In some areas the soils have developed on sediments from lacustrine deposits, especially in the plains. The soils along the northern shore of the lake are generally high in exchangeable Na^+ and K^+ (Makin 1967), while silts, clay and recent lacustrine deposits are found along the north-eastern shore of the main lake. Soils of the south-eastern shore are composed of diatomite, whereas those on the littoral zone are less alkaline and more liable to cracking (Gaudet 1977).

2.1.3 Vegetation cover

The upper section of the catchment area comprises indigenous hardwood natural forest (the Aberdare forest). The rest of the Naivasha catchment area is mostly grassland, with *Themeda triandra* (red oat grass) and *Cynodon dactylon* (common star grass) common in wet areas and *Cynodon plectostachyum* (Naivasha star grass) in the drier areas. In the lake basin the vegetation is characterized by leleshwa bushes, while *Tarchonanthus camphoratus*, *Acacia draponolobia* and *Themeda triandra* grassland form a good basis for ranching. The lake littoral zone consists of *Acacia xanthophyla* woodland savanna vegetation (zone IV of Pratt *et al.* 1966) typical for semi-arid climate areas with moisture indices of -30 to -40

2.2 Climate

The Naivasha catchment experiences two types of climatic conditions. These are the semi-arid climate of the rift floor and the wet conditions of the upper catchment areas of Nyandarua ranges and the surrounding area.

2.2.1 Rainfall

Rainfall rather than temperature is the crucial element in controlling agricultural activities in this region. The rainfall varies in the amount received and its intensity and mostly, erosive with major floods at the beginning of the rain season. The rainfall pattern in this area is very seasonal and bimodal with peaks during the "long rains" in March-May and "short rains" in October-December. The two rainy seasons are separated by a dry period of 2 - 6 months. This is clearly shown by the Naivasha Water Development Department meteorological station (WDD) in 1997 with the two peaks in April and November, although there is seasonal variation over the three years rainfall (Figure 2.3). These variations may be as a result of rainfall regime trends, exhibited by the difference in total amount of rainfall received over years at the WDD station (Figure 2.4). The years 1989,1990,1997 and 1998 can be considered as wet years with > 760 mm rainfall around the lake as opposed to 1984, 1991 and 1999 with <500 mm.

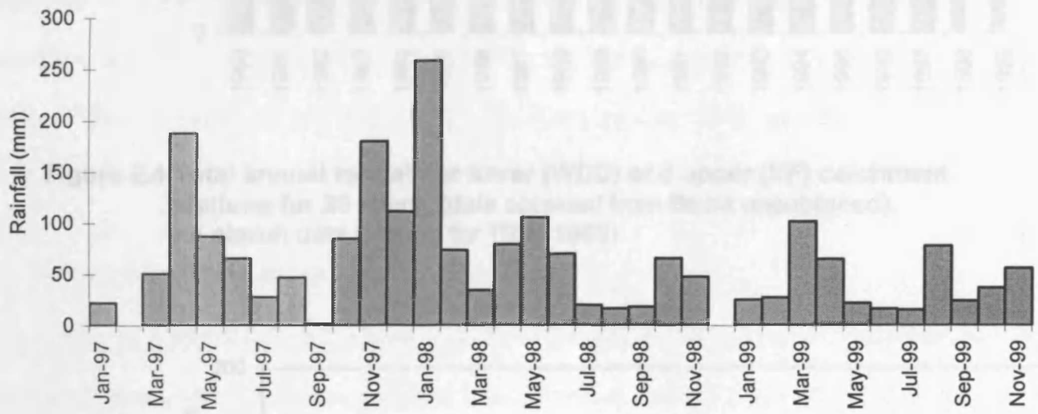


Figure 2.3 Monthly variation of rainfall at the Water Development Department (WDD) station in 1997-1999

The relationship between altitude and rainfall in this area is documented as a general increase with altitude up to 2450 m a.s.l. (Odingo 1971). The Kinangop Forest Station (KF) at an elevation of 2630 m a.s.l. had more annual total rainfall than the WDD situated at 1935 m a.s.l. (Figure 2.4) The Kinangop Forest station has an average rainfall of 1146 mm (Trottman 1998), 1129.8 mm (Hubble 2000) and 1525 mm (Hamududu 1998) while at the same period, the WDD at 1935 m a.s.l. had a significantly lower annual average of 600-637 mm (Trottman 1968) and 643.1 (Hubble

2000). The percentage increase of rainfall with altitude from 1980 to 1997 illustrates that there was >100% increase of rainfall in upper KF station in 1983-85, 1988 and 1994 than the lower WDD station (Figure 2.5). The years 1996 and 1997 had the lowest rainfall difference between the two stations with only 26% more rainfall in the upper station (Figure 2.5). This gives a general rainfall increment between these two stations with altitude of 82% more in the upstream with 45.9% coefficient of variation over the years in 1980-1997.

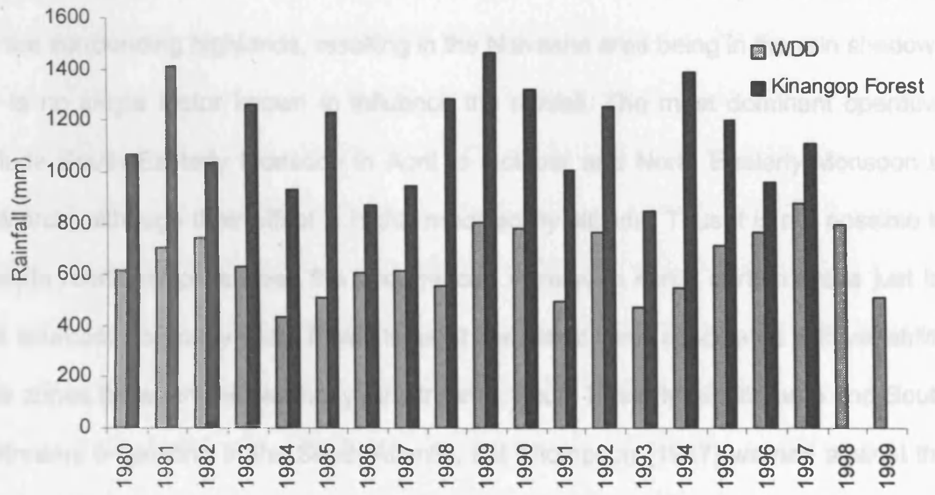


Figure 2.4 Total annual rainfall for lower (WDD) and upper (KF) catchment stations for 20 years. (data obtained from Becht unpublished). KF station data missing for 1998-1999)

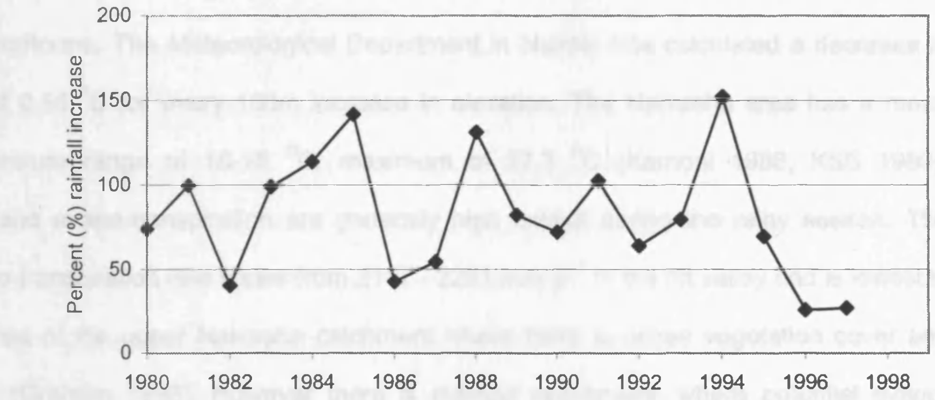


Figure 2.5 Annual variation of rainfall increase (%) with altitude at KF station in comparison to WDD station

However Hamadudu (1998) cautions that, while some stations in the Naivasha catchment, located at high altitude receive high rainfall, others at the same altitude do not receive as much rainfall, as they are located on rainy shadow slopes. Kitaka (1991) indicated a great variation in the amount of rainfall received in different stations within the lake Naivasha catchment area, with more rainfall recorded on the eastern side of the lake. Vershuren (1996) stated that, low rainfall is typical of the Naivasha area, as much of the rainfall directed towards the central rift valley from the east is intercepted by the surrounding highlands, resulting in the Naivasha area being in the rain shadow.

There is no single factor known to influence the rainfall. The most dominant operative influences include South Easterly Monsoon in April to October and North Easterly Monsoon in November to March, although their effect is highly modified by altitude. Thus it is not possible to establish a simple relationship between the occurrences of rains in some certain areas just by referring to the sources. For many years it was thought that rainfall was associated with variability in convergence zones between the Northerly Air Streams, South Easterly Air Streams and South Westerly Air Streams originating in the South Atlantic, but Thompson (1957) warned against the dangers of the simplicity of this explanation. Recently greater emphasis has been laid on the shallow low-pressure areas (troughs) that form in the upper air over the equatorial regions.

2.2.2 Temperature and evapotranspiration

There is a temperature gradient over the Naivasha catchment area due to differences in altitude and landforms. The Meteorological Department in Nairobi has calculated a decrease in temperature of 0.56 ^{0}C for every 100m increase in elevation. The Naivasha area has a mean annual temperature range of 16-18 ^{O}C, maximum of 27.3 ^{O}C (Kamoni 1988, KSS 1980). Temperature and evapo-transpiration are generally high except during the rainy season. The potential evapo-transpiration rate varies from 2117 - 2251 mm yr^{-1} in the rift valley and is lowest in the eastern area of the upper Naivasha catchment where there is dense vegetation cover and higher rainfall (Graham 1998). However there is marked seasonality, where potential evapo-transpiration is highest during dry periods and lowest during the rainy season. This is expected as rainy periods are characterized by high relative humidity. Trottman (1998) suggested that a wet year has a potential evapo-transpiration of 1320 mm, 1472 mm for average wet years and 1600 mm for a dry year. According to Åse *at al.* (1986), the Naivasha region has an annual potential of evapo-transpiration of 1500-1900 mm yr^{-1} as a result of low relative humidity with a high average temperature of about 24 ^{0}C. This value is far in excess of rainfall received in the lake area resulting in a strong negative hydrological balance.

2.2.3 Hydrology

The lake Naivasha is the largest freshwater lake in the rift valley of Kenya, with marginal woodland fringed with papyrus swamp. Due to the lake shallowness and the gently sloping sides, its surface area and that of the fringing papyrus including the littoral lagoons are very variable.

Although the lake lies in a topographically closed basin, it is hydrologically a seepage lake. Baker (1958), Thompson & Dodson (1963) referred to the lake as a "hydrographic window" because water can pass freely through the porous rocks in the catchment area. The seepage rate is related to the amount of rainfall in the catchment area (Gaudet & Melack 1981).

Most of the water in the lake comes from the Nyandarua ranges and Kinangop plateau, through the river Malewa contributes 80% of the inflowing water. The river Malewa with a catchment area of 1730 km^2 has an estimated annual average flow of 153 x 10^6 m^3 (Åse *et al.* 1986), although Becht (in press) estimated a much higher annual value of 213.9 x 10^6 m^3 for the period of 1935-1981. The river Gilgil (420 km^2 catchment), which has the second largest inflow has 24 x 10^6 m^3 average annual flow (Åse *et al.* 1986). The river Karati and other streams flowing from the Mau escarpment and Eburu hills (1240 km^2) are either dry or flow intermittently during the dry season. Despite the changes in flow rates of these rivers they contribute significantly to the lake hydrological equilibrium through seepage inflows (Gaudet 1977, Becht in press). Other sources of water input into the lake include rainfall that occurs directly over the lake surface and the underground water movement from the catchment (Table 2.2).

The water output includes direct evaporation from the lake surface, transpiration from the swamp area and other aquatic vegetation, underground seepage out and increasingly abstraction from human activities. Becht (in press) estimated 4.7 x 10^6 $m^{-3}month^{-1}$ as the rate of water loss through groundwater flows and evapo-transpiration for the pre-abstraction period between 1935-1981 and water abstraction of more than 60 x 10^6 $m^{-3}month^{-1}$ at present.

Table 2.2 Lake Naivasha water input and output for the pre-abstraction period in 1935-1981 (using Becht in press values)

Pathways	**Volume of water input** (m^3year^{-1})	**Volume of water output** (m^3year^{-1})
Surface water inflow	2.174 x 10^8	
Rainfall	9.39 x 10^7	
Evaporation		2.56 x 10^8
Water loss (seepage and evapo-transpiration)		5.64 x 10^7

A total water budget sum error of 1.36 x 10^5 was estimated.

2.3 Land use and population distribution

The Naivasha catchment area is mainly rural apart from the town of Naivasha with an estimated population of 55,000 by 1997 (Fig 2.7). Most of the inhabitants of the Naivasha catchment are small scale mixed farmers in the upper catchment. They keep cows, goats and sheep, and grow a mixture of rain-fed cash crop and subsistence crops including pyrethrum, wheat, maize and vegetables. Extensive or range livestock production is mainly practised in the drier parts of the catchment while intensive livestock production is commonly practiced around the lake. As late as the 18^{th}century the Maasai pastoralists occupied the lower Naivasha catchment where they grazed the land and watered their livestock in the lake (Harper *et al.* 1990). After the arrival of the white settlers considerable changes in land use occurred; they introduced beef and dairy farming, irrigated agriculture and within the last decade, the intensive horticultural crops and flower cultivation started around the lake. Lake Naivasha and its periphery have become economically significant as a consequence of development of flower and horticultural production as well as increase in importance of tourism. The horticultural production and flower farms, employ more than 30,000 people directly and indirectly (Goldson 1993). The Olkaria geothermal power station is currently under major expansion with more employees and their dependants moving into the region. All these activities have coincided with continuous increase in population around the lake (Figure 2.6). Between 1989 and 1997 the Naivasha division population increased by almost 57% (Figure 2.6), with almost equal number between the females and the males. Unfortunately detailed demographic information for the upper catchment was not available for comparison. Goldson (1993) estimated a population of 233,302 people, with 43,197 households in 1979 for Nyandarua district (Kinangop and Ol kalau) consisting most of the upper catchment. With an estimate of 5.36 persons per household, Goldson (1993) estimated a population density of 66 persons per km^2. An estimate of 2.5 families per hectare could be ideal for 1997-1999.

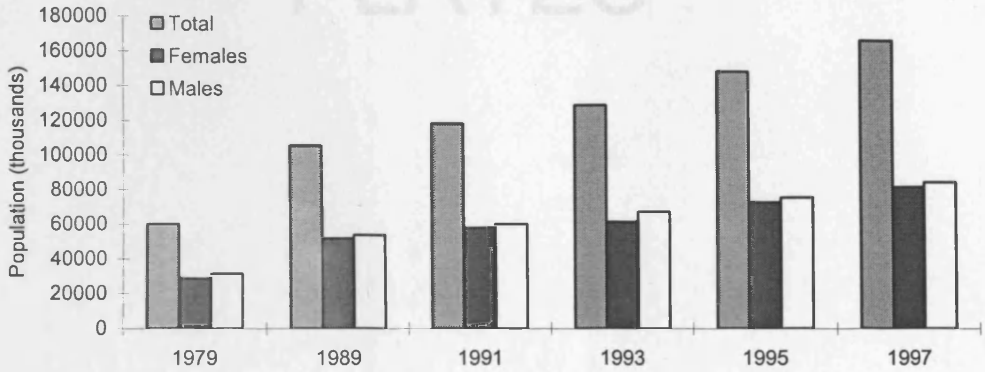


Figure 2.6 The population growth trend for Naivasha division
(Data from the Naivasha Division Officers (DO) office)

The population of the Naivasha town did not increase in proportion to the increase in the division (Figure 2.7). Out of the total Naivasha division population, only about 30% live in the urban Naivasha town, the rest 70% of the population live in the rural townships and their peripheries.

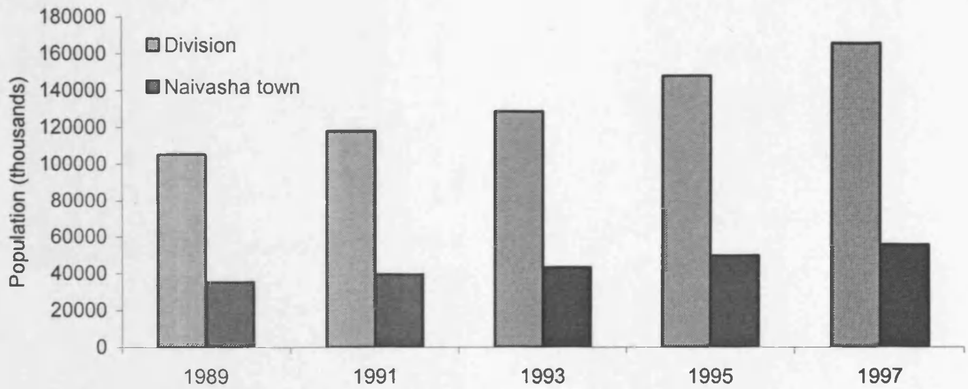


Figure 2.7 The total population of Naivasha town in relation to the whole division
(Data from the Naivasha Division Officers (DO) office)

PLATES

1. Turasha dam on the river Malewa main tributary showing the cultivated steep slope. (Photography taken from the valley edge)

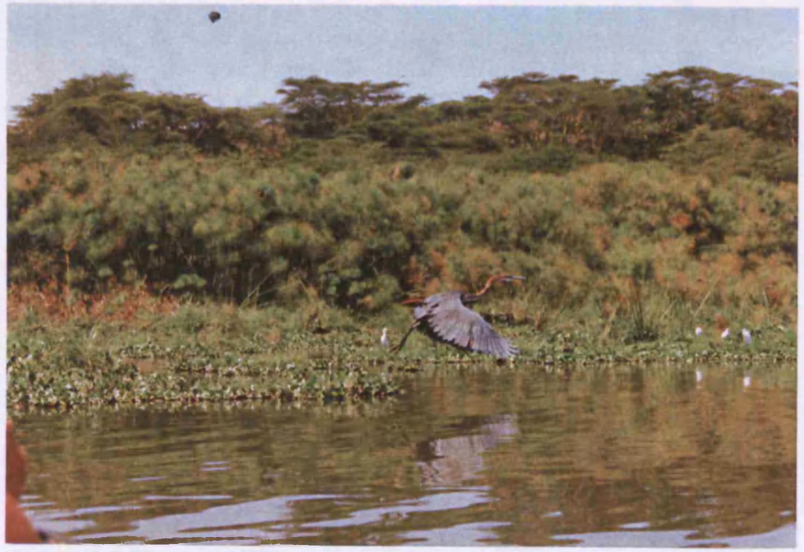
2. The river Malewa meandering through the middle course of the river channel. (Note that most of the natural vegetation has been cleared for farming or grazing with only a small strip left along the river channel)

3. A closer view of the river Malewa at M_4 station showing the small strip of riverine vegetation surrounded by maize and vegetable small-scale farms. (Note the turbid river water)

4. Livestock watering at the upper course (M_1 station) of the river Malewa. (Note the eroded riverbank at the entry point)

5. Aerial view of the delta in the lower course of the river Malewa through the *Cyperus papyrus* wetland on the northern part of the lake (northswamp).

6. One of the river Malewa channels flowing into the lake below M_5 Marula station. (Note the turbid river water)



7. The fringing vegetation surrounding the lake Naivasha with waterfowl. (*Acacia xanthophyla* trees (furthest), *Cyperus papyrus* (emergent) and floating water hyacinth (*Eichhornia crassipes*) next to the water).

8. Horticultural farming of flowers, vegetables and fruits (both indoor and outdoor) near the lake edge

CHAPTER 3

METHODS

3.1: Sampling stations

The sampling stations established along the three major rivers flowing into lake Naivasha; Malewa, Karati and Gilgil are shown in Figure 2.1, while headwater, rivers and streams sampled and their sampling stations are illustrated in Figure 3.1. The actual positions of the sampling stations depended on road accessibility into the river. In most cases, the stations were situated below bridges and extended through the whole course of the three main rivers. The physical and chemical characteristics of these stations and human disturbance estimated on 0-5 rating category are discussed in Chapter 4

Two water sampling transects running from the rivers Malewa and Karati inlets into the open water are illustrated in Figure 3.2, together with the weekly sampling stations off Hippo point and monthly sampling station at the river Malewa inlet (MI). The lake sediment samples were collected from three major parts of the lake; the delta front, central lake and southwest at Elsamere bay (Figure 3.2, Table 3.1).

Table 3.1 UTM coordinates of sediment core samples in the lake

	Replicates	UTM North	UTM East	Water depth range (m)
Malewa inlet (Delta front) (MI)	1	9919364	205273	1.5 – 3.0
	2	9918504	206390	
	3	9919272	206273	
	4	9918684	205394	
Open water (OP) (Central part of the lake)	1	9914343	199756	4.5 – 5.5
	2	9914055	203682	
	3	9914500	202000	
Off Elsamere (Southwest) (FS)	1	9910500	205000	4.0 – 5.0
	2	9910481	200425	
	3	9910496	203634	

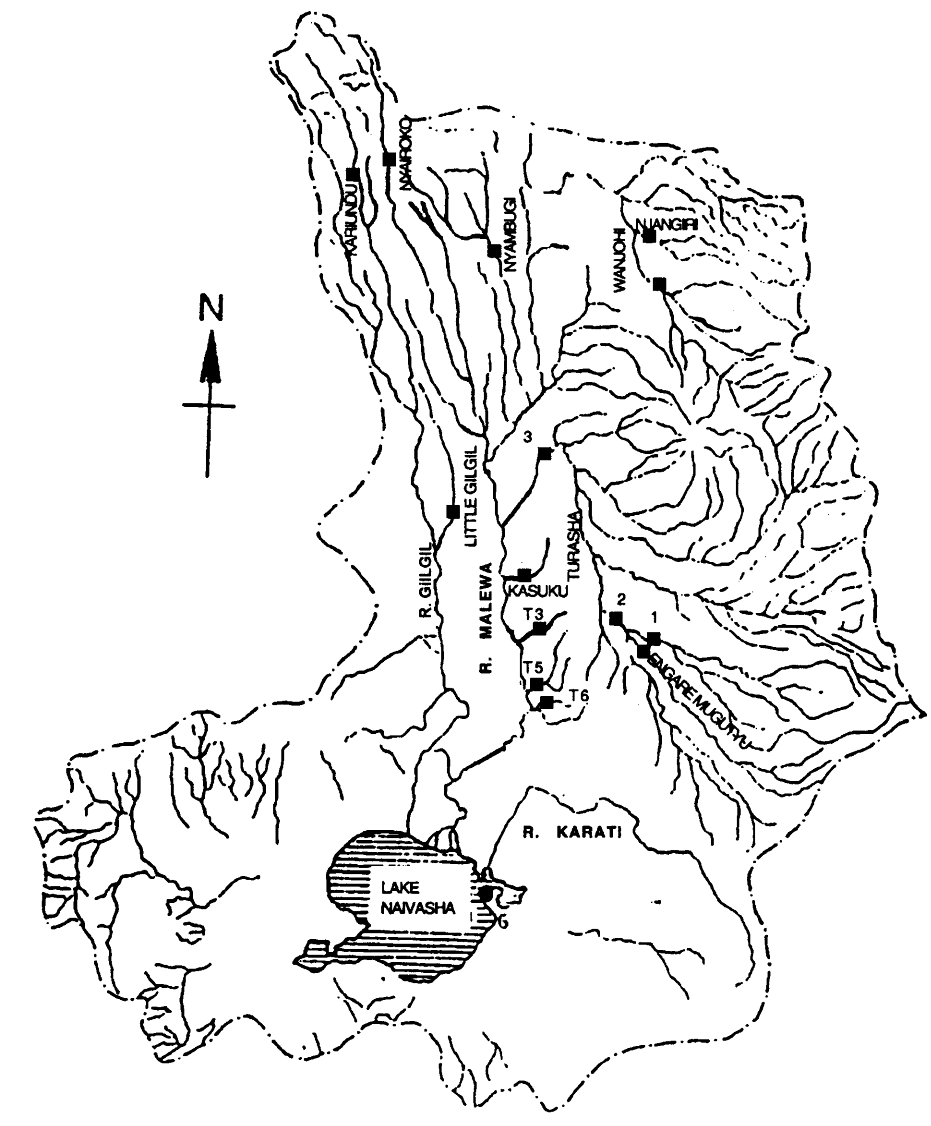


Figure 3.1 Naivasha catchment map showing the sampling stations of the river Malewa and Gilgil tributaries studied (1, 2 & 3 represents the three stations sampled in Turasha while, T3, T5 & T6 are tributaries 3, 5 & 6 respectively)

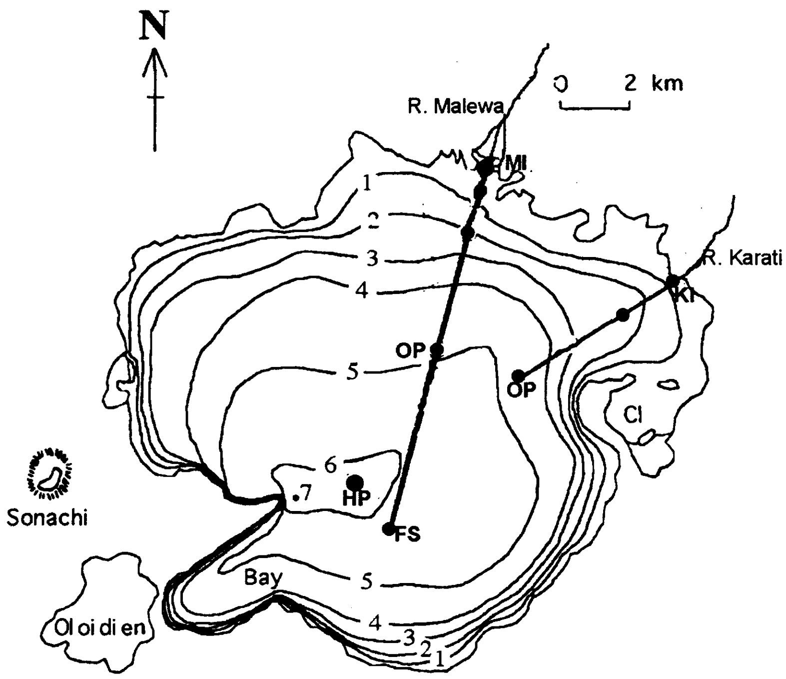


Figure 3.2 Bathymetric map of lake Naivasha showing the transects running from the Malewa (MI) **and Karati** (KI) **inlets into the open water** (OP) **with the sampling stations** (HP = off Hippo point, FS = Further south at Elsamere bay)

3.2: The study time scale

3.2.1: Phase 1: Variation of phosphorus from the catchment into the lake.

This part of the study was carried out between July 1997 and March 1998. During this part of the study there was more emphasis on spatial distribution of different forms of phosphorus and other chemical and physical parameters along the rivers into the lake. It consisted of monthly sampling in the catchment area, where a total of 24 samples were collected in 8 different sessions in each station of the three main rivers (Figure 2.1). The main components studied in this phase were:-

1. Phosphorus concentration and fluxes in the main rivers draining into lake Naivasha. Phosphorus fractions analysed in the water were TP, PP and SRP.

2. Naivasha catchment headwaters

3. Phosphorus dynamics in the lake water column and other chemical characteristics

4. Mineralogical content including phosphorus and the grain-structure of the river-bed and lake sediment.

3.2.2: Phase 2: Seasonal variation of different forms of phosphorus in the rivers and the lake, and the interaction between water and sediment

This part of the study was carried out between September 1998 and March 1999, with more emphasis on time variation (hours, weeks and months) rather than the general overview in phase 1.

1. To monitor seasonality of phosphorus fluxes from the catchment into the lake, an intensive weekly sampling on the lower courses of the three rivers was carried out for a full year starting from September 1998. Two stations studied were situated along Nakuru road at 10.5 km (M_4), 15.0 km (G_2) from lake edge in the rivers Malewa and Gilgil respectively. Phosphorus was fractionated into TP, TDP, PP, SRP and DOP in the flowing river water. The river Karati was dry throughout this phase.

2. Phosphorus sources in the Naivasha catchment:- rain water, ground water springs, and surface runoff samples were taken throughout the study in different parts of the catchment.

3. To detect the influence of livestock watering in the river, diurnal hourly water sampling at three sites at M_3 was undertaken

4. Phosphorus fluxes between the sediment and the overlying water using laboratory microcosms and the effect of equilibration time, pH and temperature to adsorption – desorption rates were studied.

3.3: Sampling

3.3.1 Water sampling

3.3.1.1 Rivers and streams

In the first phase of the study, three water samples were taken at each station (Figure 2.1) at under, a short distance above, and below the bridge, in the three main rivers at monthly intervals from July 1997 to March 1998. Three tributaries that were easier to access especially during the rainy season (Nyambugi, Little Gilgil and Turasha (T3) at the entry of the dam) were also sampled at monthly intervals during the period July 1997 to March 1998. Other headwater rivers and streams were sampled occasionally when the roads were passable; with at least each station sampled 3 different times over the study period. In the second phase of the study water samples were collected in the rivers Malewa at M_4 and Gilgil at G_2 weekly (every Wednesday) from September 1998 to September 1999. The river Karati was dry throughout this period. The influence of livestock disturbance on nutrients fluxes was studied at station M_3 (37.5 km from lake edge) in the middle course of the river Malewa. Water samples were taken hourly from 6.00 AM to 7.00 PM (diurnal) at 50 m above the impact site (A), the impact site (B) and 500 m below the impact site (C). The number and frequency of livestock watering in the river were counted throughout the day. This was repeated 6 times over the study period.

The method used to collect the water samples depended on the size, flow rate, and discharge of the river. In small, slow flowing rivers, 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 the high water level, samples were collected by lowering down an acid-washed plastic bucket tied on a rope from each side of the bridge to the middle of the river. The water was then transferred into an acid-washed polyethylene sample bottle. Sometimes in the large rivers when the water was not flowing too fast, samples were taken using a messenger activated tube sampler (IOS) giving a well-mixed representative sample of the whole water column. 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 each sampling session, conductivity, total dissolved solids (TDS) and temperature were measured by probe using a portable Hach Conductivity/TDS meter whilst pH measurement was determined using a portable Hach or Orion SA 250 model pH meters. The river discharges were estimated every month in phase 1 and every week in phase 2 on the lower river courses at M_4, G_2 and K_3 for the rivers Malewa, Gilgil and Karati respectively. In addition the river Malewa discharge was also estimated during the diurnal sampling at M_3 using the methods discussed below. The alkalinity was determined by titrating a 50 ml sample in the field using a Hach Digital Titrator model 16900, with 0.16N H_2SO_4 titration cartridge and phenolphthalein together with bromocresol green powder pillows as indicators.

3.3.1.2 The measurement of river discharge

The method used to determine water velocity depended on the site, size and flow rate. In small, slow flowing rivers, velocity was determined using a mechanical flow meter, General Oceanics, model 2030R. The commonly used mean column velocity at 60% water depth (from the water surface) relies on the existence of a logarithmic flow profile (Bretschko pers.comm.). This flow profile is found in straight, uniform river channels with low bed roughness but may be broken down by bed-irregularities, and bends (Padmore 1997). To test if the mean column velocity depth of 60% was a good representation of the flow in the Naivasha catchment rivers, a preliminary study was carried out in July 1997. The flow meter was positioned at 20, 60 and 80% water depths in three stations randomly chosen (Table 3.2). At each depth the water velocity was determined across the river channel at 1 metre interval in stations with more than 10 metres diameter and 0.5 metre intervals in stations with less than 10 metres diameter. The discharge was then calculated as follows:-

1. Distance (m) = (Counts x Rotar constant (26873))/999999
2. Speed (cm-1sec.) = (Distance (m) x 100)/time (s)
   Where 26873, 999999 and 100 are manufacturer's constants
3. The discharge was then calculated by the velocity area method (discussed below).

The results obtained are represented in Table 3.2 and showed no significant difference between the three water depths using one-way ANOVA ($F_{0.05}$ (2,8) =1.66 < 5.14). Thus, the commonly used 60% water depth was adopted for this study whenever discharge was determined using the mechanical oceanic flow meter.

Table 3.2 Discharge (l/s) in different water depths using a mechanical flowmeter

Station (Km) From lake edge	**20 % water depth**	**60 % water depth**	**80 % water depth**
Malewa Turasha ridge (30.5)	39770	31366	20999
Morendat Gilgil (30.0)	3993	3739	3124
Gilgil north lake road (15.0)	4248	2939	2327

In large fast flowing rivers were the meter could not be used; discharge was estimated by velocity area method using an orange (Bretschko pers.com.). The water velocity (m/s) was estimated by timing an orange flowing through a known distance, while the area of the cross-section of the river (m^2) was calculated as area under the curve by plotting the water depths across the channel, and discharge (l/s) was estimated as:-

Discharge (l/s) = (Area (m^2) x Velocity (m/s))x 1000

The values obtained were calibrated using the graduated gauges positioned at the riverbank and in the middle of the river channel by the Kenyan Ministry of Water at M_4 and G_2 stations respectively. The gauge height values (GHT) were calibrated using the Åse *et al.* (1986) (appendix figure 1 and Table 7) discharge rating curve. The seasonality discharge of the rivers was estimated using two non-dimensional (Discharge Coefficient (C) and ratio R) indices (Talling & Lemoalle 1998). The two indices reflect the rain regime of the catchment and also give a relative measure of the annual range. The monthly Discharge Coefficient (C) is the ratio for a given month to the mean annual monthly discharge, while R is the ratio of the extreme monthly discharge coefficients (largest /smallest). Thus, the lower the minimum discharge, the higher the R value (Talling & Lemoalle 1998).

3.3.1.3 Lake water sampling

To determine the influence of the river input into the lake nutrient dynamics, water samples were taken at sub-surface (0.5–1.0 m) along a transect running from the river Malewa inlet into the open water (Figure 3.2) using an Institute of Oceanographic Sciences (IOS) messenger-activated tube sampler between September 1997 to March 1998. In addition water samples from the river Malewa inlet at the lake were collected monthly from October 1998 to September 1999. To monitor seasonal changes on limnological characteristics of the lake, weekly sampling (every Wednesday) was carried out at 0.5–1.0 m depth in the open water approximately 500 m off Hippo point in November 1998 to September 1999. To determine the influence of daily mixing of the water column to phosphorus changes, diurnal water samples were taken hourly at the surface (0-0.5 m), middle (2.0-2.5 m) and bottom (5-5.5 m) at the Hippo point station. This was repeated 4 times over the study period. The water samples were prepared the same way as in the rivers and conductivity, total dissolved solids (TDS), temperature, pH and alkalinity were determined every sampling session.

3.3.2 Sediment sampling

Three replicates sediment samples were collected at the same sites as the water samples in the rivers and streams (Figure 2.1 & 3.1), during the dry season and the low water levels. Approximately 100-200 grams of sediment was collected at each site. In dry riverbeds a small spade was used, whilst at low water levels a piston tube corer was used and an Ekman Grab in deep pools. The sediment samples were stored in Whirl-Pak sampling bags and transported to the laboratory in a cool box. Lake sediment cores with undisturbed sediment-water interface were collected with a rod-operated single piston corer (Wright 1980) from three major parts of the lake; Malewa inlet delta, central lake and further south at Elsamere bay (Figure 3.2, Table 3.2). The undisturbed water overlying the sediment was siphoned using an acid washed syringe and needle, and was treated like the other water samples. The core samples were extruded using a fixed interval lightweight extruder (Verschuren 1993) at 3 cm intervals in the boat. Each depth sediment sample was transferred to Whirl-Pak sampling bags and transported to the laboratory in a cool box.

3.4 Sample processing (laboratory techniques and data analyses)

3.4.1 Water samples

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. Magnesium hardness (MH) was calculated as the difference between total and calcium hardness. Concentration of Ca and Mg ions were calculated from the hardness relationships given by Hach procedures as follows:-

Magnesium ions (mg/l) = mg/l $MgCO_3$ x 0.29

Where, $MgCO_3$ = Magnesium hardness as $CaCO_3$ x 0.842

Calcium ions (mg/l) = Calcium hardness as $CaCO_3$ x 0.401

Where 0.29, 0.842 and 0.401 are manufactures conversion constants

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 ^{0}C for 24 hours before re-weighing them. The re-weighed filter papers were then ignited at 500 ^{0}C in a muffle furnace for 2 hours. Loss on ignition and organic content of the suspended solids was then calculated as follows:-

$$\text{TSS (mg/l)} = \frac{(\text{Wt B} - \text{Wt A})}{\text{Volume of sample filtered (litres)}}$$

$$\text{LOI (mg/l)} = \frac{(\text{Wt B} - \text{Wt C})}{\text{Volume of sample filtered (litres)}}$$

Organic content (mg/l) = TSS - LOI

Where
Wt A (g) = Dry weight oven-dried GF/C paper

Wt B (g)= Dry weight of GF/C paper after filtering a known volume of a sample

Wt C (g)= Weight of B after ignition

Phytoplankton biomass was estimated as chlorophyll *a* using 90% ethanol extraction method (HMSO 1980) and biomass calculated from absorbencies of the extract before and after acidification using HCl.

3.4.1.2 Nutrients analysis

3.4.1.2.1 Phosphorus analysis

Total phosphorus (TP) and total dissolved phosphorus (TDP) were analysed by converting all phosphorus into soluble inorganic phosphate, by digesting 20 ml of unfiltered and filtered water sample respectively, with 0.5 g of potassium persulphate and 1.2 ml of 10N H_2SO_4 in a pressure cooker for one hour. After cooling, the phosphorus concentration was determined as soluble reactive phosphorus (SRP). This used the Mackereth *et al.* (1989) molybdenum blue technique modified from Strickland & Parsons (1972). The phosphorus concentration was calculated through calibration with the method carried out on standard solutions of potassium dihydrogen phosphate (KH_2PO_4) with distilled deionised water as a control. The SRP is the main component of dissolved inorganic phosphorus (DIP), which is equivalent to the molybdate reactive phosphorus (MRP) of Heathwaite (1997). Dissolved organic phosphorus (DOP) was calculated as the difference between TDP and SRP as recommended by Lennox *et al.* (1997). There are several complicated methods for determining particulate phosphorus (PP) component in water more accurately, unfortunately due to limitation of equipment in the field station, PP was estimated from TP, TDP and SRP values. During phase 1 of the study PP was estimated as the difference between TP and SRP. In actual sense these values include the DOP component. Therefore to estimate more accurately the PP component in the water, PP was estimated as the difference between TP and TDP after further fractionation of phosphorus in the second phase of the study between September 1998 and September 1999. These values exclude the DOP content. The results obtained using the two formulas concurrently (appendix Table 1) portrays that when, PP was calculated as TP minus SRP the values were overestimated by 38.6% $\pm$ 4.96

SE and 42.6 ± 3.9 SE (n = 13) in the rivers Malewa and Gilgil respectively. Unfortunately I could not work out a correction factor for the river Karati, as it was dry when further fractionation of phosphorus was undertaken. The correction values obtained might have been different if the correction factors were estimated inclusive of the period between July 1997 and 1998 during the El Niño effect rains.

3.4.1.2.2 Nitrogen analysis

Ammonium nitrogen (NH_4-N) was analysed using the salicylate / dichloroisocyanurate technique modified from Havilan *et al.* (1977). 5 ml of sodium salicylate followed by 5 ml of sodium dichloroisocyanurate were added to 10 ml of filtered water sample. The bottles were swirled for a few seconds and absorbance read at wavelength 667 nm using Hach DR/2000 Direct Reading spectrophotometer after 30 minutes. The concentration of NH_4-N was calculated through calibration with standard solutions of ammonium sulphate, which had been analysed similarly. Nitrate nitrogen (NO_3-N) was determined by reducing it to nitrite using cadmium reduction Hach LR technique and calibrated by comparison with Hach nitrate nitrogen standard solutions. Dissolve inorganic nitrogen (DIN) was estimated by summing up the concentration of nitrite, nitrate and ammonium. Total nitrogen (TN) was analysed after the Mackereth *et al.* (1989) sodium hydroxide-persulphate digestion method, by digesting 20 ml of unfiltered water sample in a pressure cooker with 3.4 ml of 0.5M sodium hydroxide and 2.4 g of potassium persulphate for 45 minutes. After cooling the solution pH was adjusted to pH 8-9 using 0.5M NaOH and 0.1M H_2SO_4. Total nitrogen was then determined as NO_3-N using the cadmium reduction Hach HR nitrate technique calibrated by dilutions of Hach 1.0 mg/l nitrate nitrogen standard solution.

3.4.1.2.3 Calculation of nutrient yields and loading from the catchment into the lake

1. The daily phosphorus loss rates/ yields were calculated using the models in OECD (1982).

Phosphorus loss/ yield = discharge x phosphorus concentration x 0.0864
(kg/d) (l/s) (mg/l)

where 0.0864 is a conversion factor from seconds to days and mg to kg ($86400/10x10^6$)

2. Areal yield (kg/km²/yr) = $\frac{\text{Phosphorus loss (kg/d)}}{\text{catchment area (km}^2\text{)}} \times 365$

3. Phosphorus input into the lake from the catchment was calculated as a loading per unit surface area of the lake. The lake loadings values were used to classify the lake by plotting the values against lake mean depth and classified according to Vollenweider (1968) trophic categories.

The lake TP concentration and loadings were predicted using the Cooke *et al.* 1993 models, where

Predicted phosphorus loading (L) ($g\ m^{-2}\ yr^{-1}$) = $P_i z P_w$ and

$$\text{Lake P } (\mu g/l) = \frac{L\,(1-R_p)}{zP_w}$$

Where P_i = inflow TP concentration (μg/l)

z = mean lake depth (m)

P_w = lake flushing rate (yr^{-1})

R_p = phosphorus retention coefficient

Phosphorus mass balances for the river Malewa were estimated as the difference between the immediate upstream station and the station in question (for example M_4-M_3). This provided an indication of whether a section of the catchment was a source or sink of phosphorus.

Using the mean lake level recorded for 1997 to 1999, the lake area and volume were extrapolated from Åse *et al.* (1986) and mean water depth calculated from the volume-area relationship. The lake flushing rate (p_w) was estimated as Q/V where Q represents outflow discharge. But, because lake Naivasha is an endorrheic basin with no outflow the water loss estimate by Becht (in press) was used as the Q value. This gives the lake a steady state with significant amount of water loss through groundwater flows and abstractions (Becht in press), in conjunction with long time equilibrium of lake area and associated water levels (from Åse *et al.* (1986). The water residence time (T_w) per year was estimated using the Ahlgren *et al.* (1988) formula as:-

$$T_w = \frac{1}{P_w}$$

The Phosphorus retention coefficient (R_P) was estimated using Vollenweider (1976) :-

$R_P = z\sigma/(zP_w + z\sigma)$.

Where z = mean depth (m)
σ = phosphorus sedimentation rate (yr^{-1})
P_w = lake flushing rate (yr^{-1})

Sedimentation rate coefficient (σ) could not be determined in the lake directly because one cannot leave equipment out in the lake due to likelihood of theft, compounded by strong afternoon winds and extensive mats of floating macrophytes. However Vollenweider (1976) found that σ is inversely related to mean depth (z) and he proposed 10/z as a good approximate of σ. Therefore R_P was calculated by replacing σ with 10/z.

3.4.2 Sediment samples

On arrival in the laboratory 10 grams of each sediment sample was frozen for bound-phosphorus fractions analysis later. The sediment water content (H_2O % by weight) was determined by drying a weighed sediment sample for 24 hours at 100^0C before re-weighing. Water content was calculated as the percentage of the difference in weight before and after oven drying for 24 hours. The oven-dried samples were ignited at 500^0C in a muffle furnace for 2 hours to determine the loss on ignition (Dean 1974). Thereafter the ignited sediment samples were used to determine total phosphorus and total iron in the sediment, following the procedure discussed below.

At least 2 grams of air-dried sediment was sieved through a series Standard Retsch sieves and Test sieve shaker model EFL 1MK3 with a mesh size range of 6.3μm, 0.1, 0.5, 1.0, 6.3 mm for grain size analysis. After sieving, each grain size fraction was transferred in a weighing boat, re-weighed and expressed in percentage of the total sieved sediment. The rest of the air-dried sediment was used for phosphorus adsorption-desorption rates experiments.

3.4.2.1 Statistical analysis of grain size distribution

After sediment dry sieving and weighing, the cumulative percentages of different fractions were plotted in a frequency distribution plot against a Phi (ø) diameter on probability scale. Frequency distribution properties were determined, by reading selected percentiles (5, 16, 25, 50, 84 and 95) from the cumulative curves. The mean grain size (M_z) was calculated using Robert & William (1957) formula which takes into consideration both normal and strongly skewed curves. This is:-

$$M_z = \frac{(ø16 + ø50 + ø84)}{3}$$

Where ø = - $\log_2$ diameter (mm),

ø16 = the average of the courser third of sample,

ø84 = the average of the finest third

ø50 = the average of the middle third.

The sediment grain structure was described after Kohnke (1968) classification (appendix Table 2).

Inclusive Graphic Standard Deviation (SD) of Robert and William (1957) estimated sediment sorting as:-

$$SD = \frac{(ø84 - ø16)}{4} + \frac{(ø95 - ø5)}{6.6}$$

Distribution skewness which is geometrically independent of sorting was estimated by an overall skewness measure that caters for both central and extreme parts of the frequency curve using Inclusive Graphic Skewness (SK_1) of Robert & William (1957) :-

$$Sk_1 = \frac{(ø16 + ø84 - 2ø50)}{2(ø84 - ø16)} + \frac{(ø5 + ø95 - 2ø50)}{2(ø95 - ø5)}$$

To test for normality in distribution of the sediment sorting at the extremes of the distribution compared with the sorting in the central part of the curve, simple normalised kurtosis (KG') was used :-

$$KG = \frac{ø95 - ø5}{2.44(ø75 - ø25}$$

hence, KG was transformed to KG' = KG / KG + 1, which is used widely by sediment and soils scientists.

3.4.2.2 Phosphorus analysis in the sediment

Total phosphorus (TP) in the sediment was analysed by evaporating a known weight of ignited sediment sample (used for LOI above) in a volumetric flask with 10 ml of 1N HCl to dryness in a hot plate at 100^{0}C. After cooling of 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 hours to extract. After extraction phosphorus concentration was determined using the molybdenum blue method as in the water samples.

Following the complexity of phosphorus chemistry and mineralogy in the sediments discussed in Chapter 1, it is quite difficult to come out with clear phosphorus fractions in the sediment. As Petterson *et al.* (1988) recommended, the use of "operational definitions" of Hieltjes & Lijklema (1980) will be used during this study because it's technically simple to perform and provides information of the most important inorganic fractions in lake sediment. Thus, phosphorus fractions in the sediment were determined using the sequential chemical extraction scheme of Hieltjes & Lijklema (1980) modified by Nürnberg (1988) and the Environment Agency laboratory in Haddiscoe, UK (Pitt, pers. Comm.). Where iron-bound phosphorus was extracted using bicarbonate buffered solution of sodium dithionite (BD-reagents). The Iron-bound phosphorus was extracted by adding 25 ml of BD solution (containing 0.11m sodium bicarbonate and 0.11m sodium dithionite) to a known weight of sediment sample in a screw capped polypropylene bottle. The bottles were then incubated at 40^{0}C for 30 minutes in a water bath with a shaker. After centrifuging at 5000 rpm for 10 minutes, the phosphorus content of the supernatant was analysed using molybdenum blue method after 30 minutes aeration of each sample to oxidise the dithionite, which is known to interfere with the phosphorus analysis (Nürnberg 1988). To each sediment residue, 25 ml of 1M sodium hydroxide was added. The bottles were capped and shaken overnight using an automatic shaker. After centrifuging, aluminium bound phosphorus was analysed using molybdenum blue method in the supernatant after neutralising the extract solution to pH 7-8 using 0.5 HCl and a pH meter. To the sediment residue after aluminium bound phosphorus analysis, 25 ml of 1M HCl was added and the same procedure as above followed except that the supernatant was neutralised using 0.5 NaOH to pH 7-8 and calcium-bound or apatite phosphorus analysed using molybdenum blue method in the filtrate.

3.4.2.3 Determination of adsorption - desorption rates of the Naivasha ecosystem sediment

The phosphorus sorption-desorption rates were determined in sediment samples representing different courses of the catchment representing the headwaters (Nyambugi and tributery 3), middle course of the rivers (M_2 an M_3) and the lake (Malewa inlet and the open water). To separate chemical and biological sorption, 0.5 ml of 40% formaldehyde per litre was added to the phosphorus-enriched solution to eliminate the influence of micro-organisms. The adsorption-desorption rate for each sediment sample was determined using different phosphorus concentrations (0, 40,100, 200, 400, and 600μg/l) as KH_2PO_4 (SRP_1). Exposing known weight of air-dried sediment sub-samples in screw capped polypropylene bottles for each of the above phosphorus concentration solutions did this. A ratio of 100 ml solution to 1g of sediment was used as recommended by Sharpley & Smith (1990). The samples were equilibrated for 6 hours at an ambient temperature on an automatic water bath shaker. The aqueous and the sediment phases were separated by filtration using 0.45 μm membrane filters (Taylor & Kunishi 1971, Ryden *et al.* 1973), The filtrate was analysed for SRP using the molybdenum blue method and corrected for phosphorus adsorbed by the bottle (SRP_2). This was calculated by equilibrating phosphorus solutions for 6 hours without any sediment sample, however the amount adsorbed was negligible. The amount of phosphorus adsorbed or desorbed by the sediment was calculated as the difference between the initial SRP_1 and the final SRP_2 concentration in the water as shown below:-

$$\text{Phosphorus adsorbed/ desorbed } (\mu g\ P/g \text{ dry wt. sediment}) = \frac{\dfrac{(SRP_2 - SRP_1) \times \text{volume of solution (ml)}}{1000}}{\text{dry weight sediment (g)}}$$

where by SRP_1 = Initial SRP concentration added to the sediment (μg/l)

SRP_2 = SRP concentration after 6 hours incubation with sediment (μg/l)

To determine the influence of equilibration period to the adsorption-desorption rates, randomnly chosen sediment samples using 0, 200 and 400 μg/l phosphorus solutions were equilibrated for different length of time at 15 and 30 minutes, 1, 2, 3, 4, and 6 hours at an ambient temperature. The influence of temperature and pH on phosphorus adsorption-desorption rates were determined by equilibrating lake sediment samples using 0-600 μg/l phosphorus solution for 6 hours at ambient and 40^0C temperatures, with acidic (4-4.5), neutral (7-7.4) and alkaline (9-10) pH values. The water bath shaker had a temperature thermostat, which controlled the temperature required for the experiment. The pH was altered by addition of H_2SO_4 and NaOH to the solutions with a pH meter.

To characterise the sorption – desorption rates two factors were determined. One of them was the "zero equilibrium phosphate concentrations" (EPC_O) described by Klotz (1991), previously referred to as "equilibrium phosphate concentration" (EPC) by Meyer (1979) and Hill (1982). EPC_O represents phosphorus concentration at which there is neither adsorption or desorption of phosphorus by the sediment. EPC_O was extrapolated by plotting the amount of SRP adsorbed (μgP/g dry wt. sediment) for each sample against SRP concentration in the solution at the end of the experimental period as recommended by Taylor & Kunishi (1971) and Meyer (1979). The second factor determined was the phosphate sorption index (PSI) using the relationship described by Bache & Williams (1971) and modified by Meyer (1979) as:-

$$PSI = X/\log C$$

where X = Phosphorus (μgP/g dry wt. sediment) adsorbed from the initial concentration and

C = Final phosphorus (SRP) concentration (μg/l) in the solution after the experimental period.

CHAPTER 4

THE CHARACTERISTICS OF THE NAIVASHA CATCHMENT RIVERS AND STREAMS

4.1 Physical and chemical characteristics

The physical characteristics of the rivers in the Naivasha catchment are summarised in Table 4.1, 4.2 and 4.3. The basin consists mainly of alluvium deposits except in the upper Karati comprising of acidic tuffs. All the three river channels are highly disturbed by human activities within the river channel and the surrounding area (Table 4.4, 4.5 and 4.6).

Table 4.1 Physical characteristics and land use along the river Malewa

Station (Code)	**Distance** (Km) from lake edge -from M_1 in brackets	**Altitude** (metres a.s.l.) **-sediment deposits**	**River morphology** **-channel width** (metres)	**Riparian vegetation**	**Land use**
Upstream Ol kalou **M_1**	68 (0)	2360 Alluvial deposits	Smooth gentle gradient (8.1^0) 9.45-6.2m	Grassland and Pasture up to the river bank	Intensive livestock grazing
Gilgil pump house **M_2**	35.5 (32.5)	2222 River Alluvium	Fairly smooth gradient (4.2^0) with intermittent small rapids. 16.7-6.52	A few acacia adjacent to an exposed river bank	Arable small scale farming of vegetables, maize and tree nurseries
Turasha ridge settlement at the Happy valley **M_3**	30.5 (37.5)	2012 River Alluvium, silt and sand	Smooth slightly steep gradient (42^0) 26.7-15.0	Dense acacia woodland with only a small portion of the river being exposed	Very intensive livestock grazing and watering site
Naivasha – Nakuru road bridge **M_4**	10.5 (57.5)	1903 River Alluvium and lacustrine sediments	Gentle gradient. (5.5^0) 23.6 -19.2	Completely exposed river bank	Arable farming of vegetables and maize next to the river bank and a watering site
Marula farm **M_5**	2.5 (65.5)	1890 River Alluvium deposits	Gentle gradient (1.6^0) with steep banks. 15 - 2m.	Pasture, scrub/acacia woodland	Intensive livestock and game farming
Malewa inlet	0 (68.0)	1890 Unconsolidated organic mud	Floodplain (0^0) with a Smooth flow in both channels	Papyrus fringed with floating mats of water hyacinth	Wetland

Table 4.2: Physical characteristics and land use along the river Gilgil

Stations (Code)	Distance (Km) from lake edge - (From G_1)	Altitude (metres a.s.l.) -sediment deposits	River morphology	Riparian Vegetation	Land use
Morendat (G_1)	30.0 (0)	2012 Alluvial sediments	Smooth and gentle gradient (6.2^0)	Shrubs along the river bank bordered by pasture	Military barracks and small scale mixed farming
North lake road (G_2)	15.0 (15.0)	1950 Clay lacustrine sediments	Gentle gradient (6.2^0) with small rapids during low waters	Dense acacia woodland about 20-100wide with thick undergrowth	Intensive livestock and game farming
Marula (G_3)	2.0 (28.0)	1890 Alluvium lacustrine	Floodplain (4.6^0) with shallow water pools.	Thick papyrus fringed with Salvinia molesta mats	Intensive livestock and game farming.
Lake edge	0 (30.0)	1890 Organic mud and debris	Floodplain (0^0)	Thick papyrus wetland	Wetland

Table 4.3: Physical characteristics and land use along the river Karati

Stations (Code)	Distance (Km) from lake edge (From upstream)	Altitude (metres a.s.l.) and Geology	River morphology	Riparian vegetation
Karati Mission (K_1)	33.5 (0)	2745 Tuffs, sandy soils	Steep gradient (40^0) with gravelly riverbed. Channel width 2 m.	Pasture bordering a well covered channel by natural shrubs
Karati centre (K_2)	15 (18.5)	2134 Acidic tuffs, calcretized conglomerate alluvium	Relatively steep gradient (33^0) with gravels and boulders riverbed. River channel about 2-6 m	Well covered by natural shrubs
Nakuru road (K_3)	5.5 (28.0)	1903 Clay lacustrine sediments	Relatively steep gradient (24.3^0) with smooth riverbed. Channel width about 3 m.	Pasture and natural shrub vegetation
Delamere (K_4)	0.5 (33.0)	1890 Lacustrine mud	Gentle gradient (2.6^0) with a river channel of 2-4 m	Pasture and papyrus fringed
Karati inlet	0 (33.5)	1890 Lacustrine mud	Floodplain (0^0)	Papyrus fringed

Table 4.4: Human activities along the river Malewa

Stations	Human activities	Size of livestock groups visiting the river (an approximation)	Frequency of livestock visitation into the river	Disturbance scale	Disturbance rating (estimate ranging 0-5)
M_1	-Watering of livestock	Large groups (25-50 animals per group)	Frequent (5-10 visits a day)	Intensive	4
M_2	-Watering of livestock -Fetching of water for domestic use -Tree nurseries watering	Large	Frequent	Intensive	4
M_3	-Watering of livestock -Fetching of water by pedestrians, vans and carts -Washing of clothes	Very large (> 50 animals per group)	Very frequent (>10 visits per day)	Very intensive	5
M_4	-Watering of livestock -Washing of clothes -Cleaning vehicles -Fetching water	Large	Very frequent	Very intensive	5
M_5	-Watering of livestock	Large	Occasional (< 3 visits a week)	Regular	2
Inlet	Hippo-pools	N/A	N/A	Regular	2

KEY
Disturbance rating scale ranges from the least (0) to the most disturbed site, for example
Rating scale 0 indicates no human influence
5 indicates the most disturbed area

Table 4.5: Human activities along the river Gilgil

Stations	Human activities	Size of livestock groups visiting the river	Frequency of livestock visitation	Disturbance scale	Disturbance rating
G_1	-Watering of livestock -Cleaning of vehicles	Large (25 –50 animals)	Regular (at least 3 times a day)	Regular	3
G_2	-Watering of livestock	Very large (> 50 animals)	Very frequent (>10 visits per day)	Very Intensive	5
G_3	-Watering of livestock	Very large	Frequent (5-10 visits per day)	Regular	4

4.6: Human activities along the river Karati

Stations	**Human activities**	**Size of livestock** groups visiting the river	**Frequency** of livestock visitation	**Disturbance scale**	**Disturbance rating**
K_1	-Watering of vegetable gardens	N/A	N/A	Minimal	1
K_2	-Watering of livestock -Washing of clothes -Cleaning vehicles -Fetching of water	Large	Very frequent (> 10 times a day)	Very Intensive	5
K_3	- Livestock watering	Very large	Very frequent	Very intensive	5
K_4	-Watering of livestock	Large	Frequent (5-10 visits)	Intense	4
Inlet	Hippo-pools	N/A	N/A	Regular	2

4.2 Rainfall

The mean monthly rainfall averaged from 5 stations located on the lower catchment at approximately 1900 metres above sea level in 1997 to 1999 is illustrated in Figure 4.1A. In the first year of the study, the rainfall showed bimodal peaks in April and November 1997. But instead of short rains in November 1997, they continued for several months until June 1998, with the highest amount recorded in January 1998 and a short dry spell in March 1998. These unusual rains, called colloquially the "El Niño rains", caused flooding throughout the country and consequently caused an increase in lake level (Chapter 6). They were followed by unusual dry conditions with very brief rains in March and August 1999. Figure 4.1B gives a comparison of the rainfall received in the lower Naivasha catchment Water Develpoment Department (WDD) station with semi-arid climatic condition at 1935 metres above sea level, contrasted with a high altitude Kinangop forest (KF) station at 2630 metres above sea level. The Kinangop forest station was not significantly wetter ($p < 0.001$, $n = 12$) than the lower station in 1997, but considering rainfall data for 7 years since 1990 to 1997 there was a significant difference in the amount of rainfall received between the two stations ($P < 0.0001$) using ANOVA. The wet period of November 1997 to June 1998 will be referred to as "heavy rainy season", while the "normal" wet and dry year will be September 1998 to September 1999.

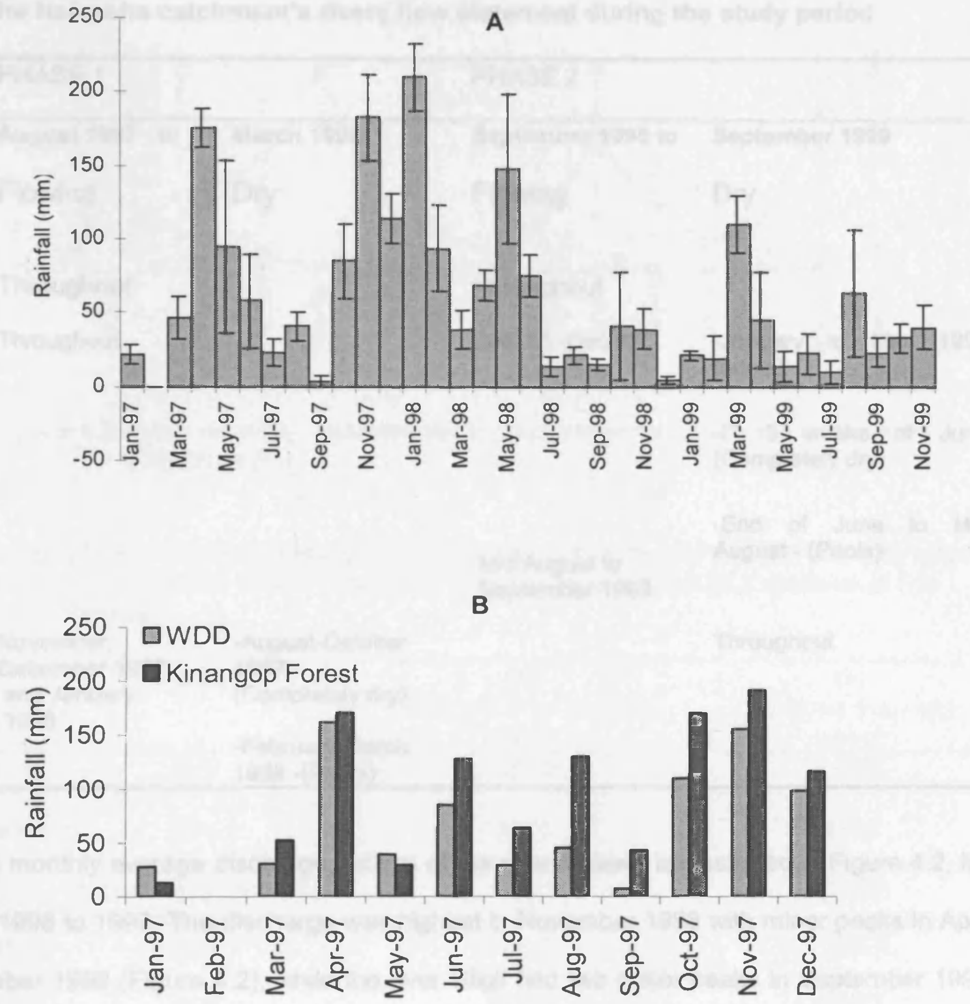


Figure 4.1 Rainfall pattern for the Naivasha catchment
A: Mean monthly rainfall of the lower catchment in 1997 to 1999.
(Data from Ministry of Water, Naivasha office)
B: Comparison of monthly rainfall of a lower (WDD) and an upper catchment (KF) meteorological stations .
(Data from Becht unpublished)

4.3 Discharge

The rivers Malewa and Gilgil were flowing throughout the study time except a few months during the dry season when the Gilgil was characterised either by stagnant pools, or was completely dry (Table 4.7). The river Karati was only flowing intermittently during the rainy season in 1997 and 1998 and dried up during the rest of the study period (Table 4.7).

Table 4.7 The Naivasha catchment's rivers flow statement during the study period

River	PHASE 1		PHASE 2	
Period	**August 1997 to**	**March 1998**	**September 1998 to**	**September 1999**
River state	Flowing	Dry	Flowing	Dry
Malewa	Throughout		Throughout	
Gilgil	Throughout		Sept 98 -Dec 98 Mid August to September 1999	-January to May 1999 (pools) -Ist 3 weeks of June (Completely dry) -End of June to Mid August - (Pools)
Karati	November, December 1997 and January 1998	-August-October 1997 (Completely dry) -February-March 1998 -(Pools)		Throughout

The monthly average discharge pattern of the river Malewa is illustrated in Figure 4.2, for September 1998 to 1999. The discharge was highest in November 1998 with minor peaks in April and September 1999 (Figure 4.2), while the river Gilgil had two major peaks in September 1998 and 1999 (Figure 4.2). However the November 1998 discharge peaks coincides with the short rains in October-November (Figure 4.1A) while the minor peaks April and September 1999 seems to show up a month after the heavy rains in March and August on the lower catchment (Figure 4.1A). Unfortunately the rainfall data for the wetter upper catchment during this period were not available, which probably may have explained the discharge peaks better than the lower catchment rain pattern.

The river Malewa discharge had an increase in water volume downstream except in the beginning and the end of the rainy season in October-November 1997 and February - March 1998 respectively (Table 4.8). This may be due to increase in water abstraction for irrigation and domestic use in the lower part of the river.

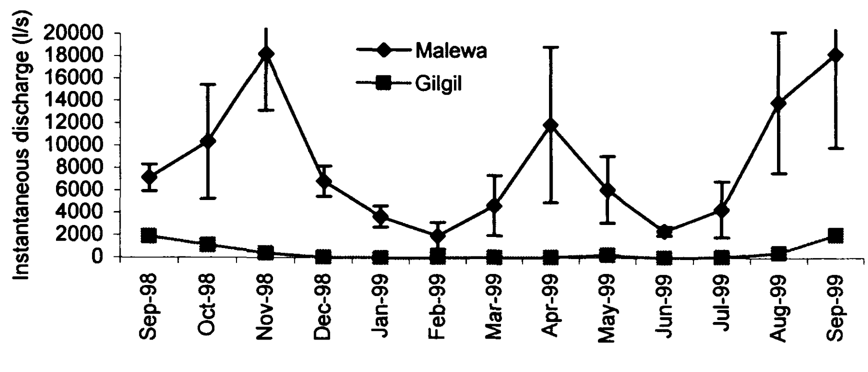


Figure 4.2 Mean monthly instantaneous discharges for the rivers Malewa (M_4) and Gilgil (G_2)

Table 4.8 Comparison of instantaneous discharge (l/s) of the middle course Turasha ridge settlement (M_3) and lower Naivasha - Nakuru road bridge (M_4) stations of the river Malewa

Month	Season	M_3 (30.5kms from the lake edge)	M_4 (10.5kms from lake edge)
August-97	Dry	12042	24893
September-97	Dry	8135	8740
October-97	Beginning of the rainy season	14091	12284
November-97	Wet	140697	155328
January-98	Wet	57697	96272
February-98	Slightly wet	42682	27236
March-98	Dry	5495	4945

Figure 4.3 illustrates variation of the monthly discharge coefficient (C) index in the rivers between September 1998 and 1999. Both rivers had high R indices, with 9.2 and 129.9 for Malewa and Gilgil respectively. However the river Gilgil had an extremely high R index mainly because it had a very low minimum discharge. Despite the bimodal peaks indicated in Figure 4.2, the minor flood peaks must have smoothed out either as a result of the monthly figures missing

flood peaks or the local rain distribution pattern or probably, due to increase in river water abstraction downstream in some months as indicated in Table 4.8.

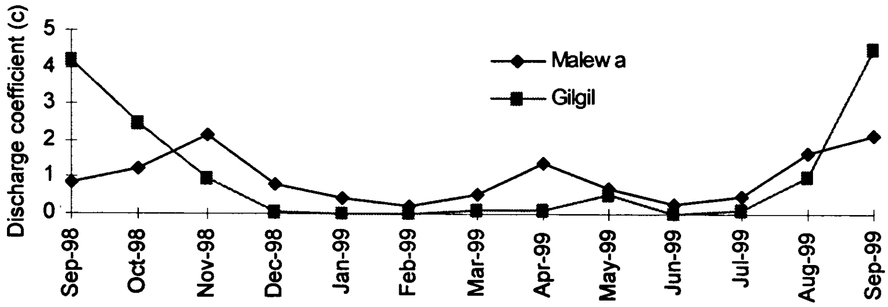


Figure 4.3 Annual variation of monthly Discharge Coefficient (C) (monthly discharge/mean annual monthly discharge) **for the rivers Malewa (M_4) and Gilgil (G_2)**

4.4 Total suspended solids (TSS) and their organic content (OC)

There is a clear variation of TSS along the course of the river Malewa unlike the other two rivers (Figures 4.4, 4.5 & 4.6). The highest values in the river Malewa coincided with high discharge, immediately at the beginning of the rain season in November 1997 followed by January 1998 (Figure 4.4). This relationship gave a significant ($p = 0.002$) positive correlation with low least of squares value (Figure 4.7). The discharge and TSS relationship, although significant, was not very strong probably due to the outlier points noted through out the study. However, the least of squares value (R^2) did not improve even when extremely high TSS outlier points were excluded (Figure 4.7). This indicates a localised increase in TSS concentration in some stations along the river channel, although it is not clear in Figure 4.7, they were more frequent during the medium and low discharges. Unfortunately December 1997 samples were not taken, which probably could have given a stronger relationship.

There seems to be no horizontal pattern in TSS concentration along the rivers (Figures 4.4, 4.5 & 4.6), except various localised sharp increases; for example at the Malewa inlet of the lake in September and October 1997, and at (M_4) in January and February 1998 (Figure 4.4). The increase in TSS at M_4 is probably due to the influence of human activities at this station (Table

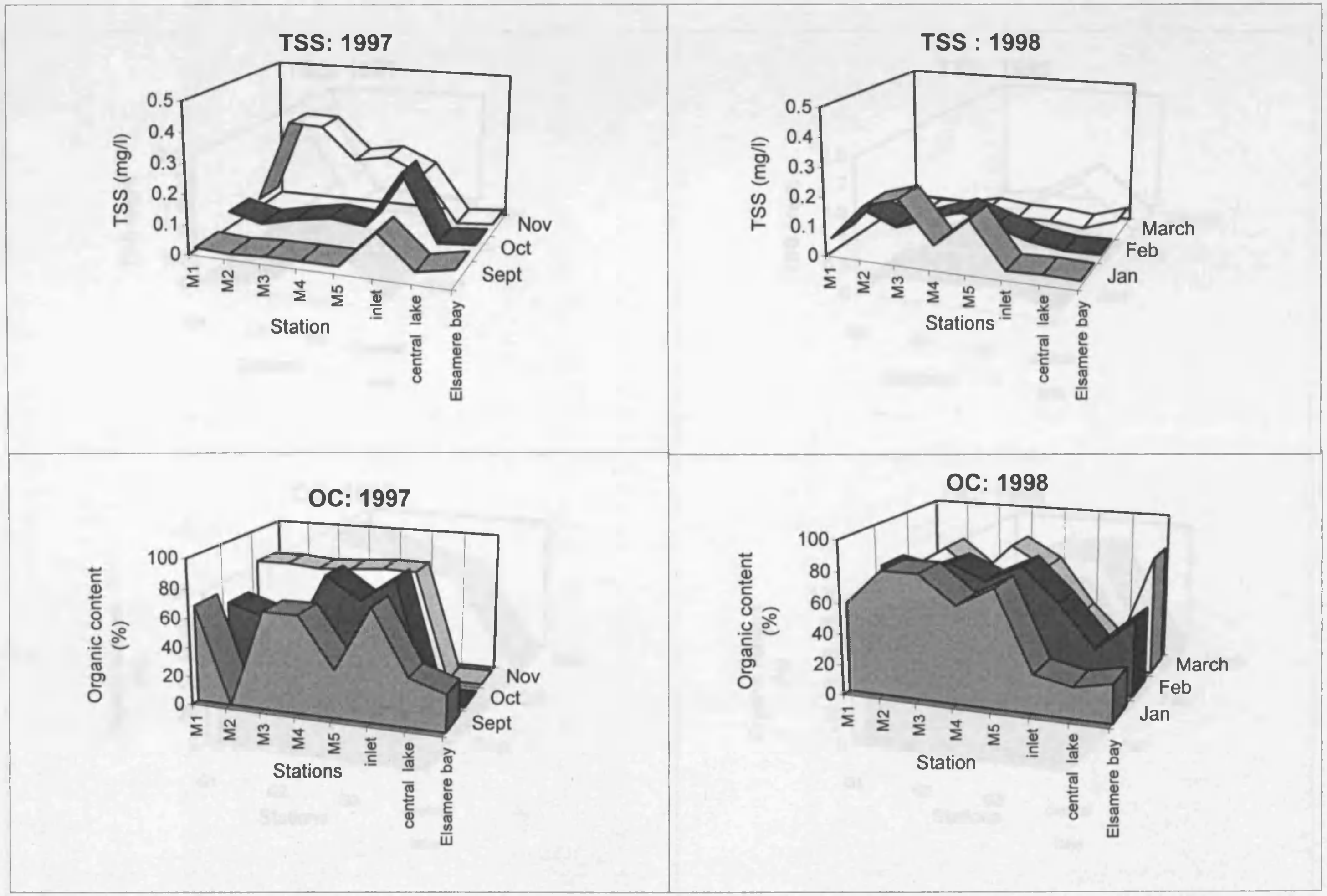


Figure 4.4 : Seasonal variation of TSS and its organic content (OC) along the river Malewa in 1997 and 1998

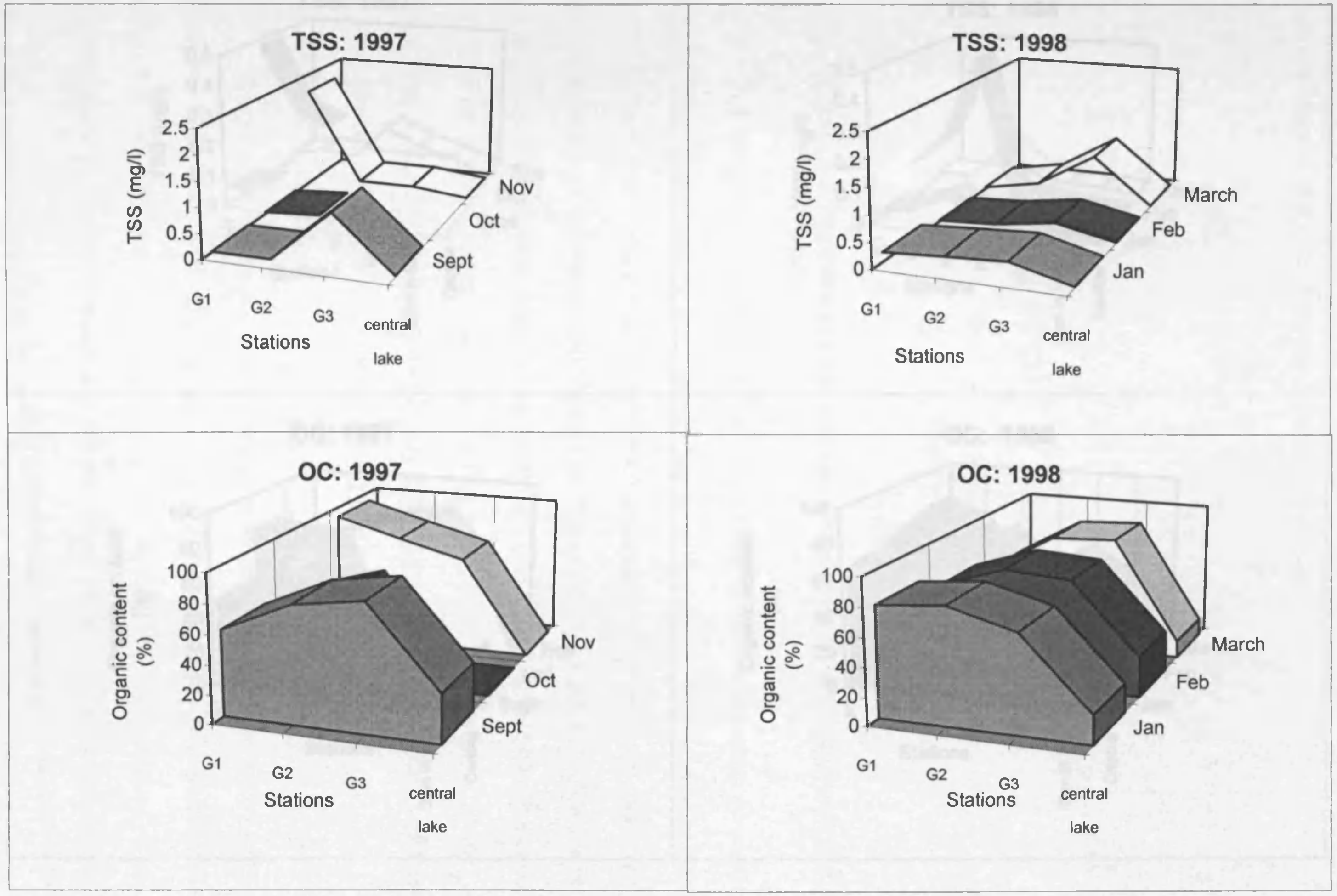


Figure 4.5: Seasonal variation of TSS and its organic content (OC) along the river Gilgil

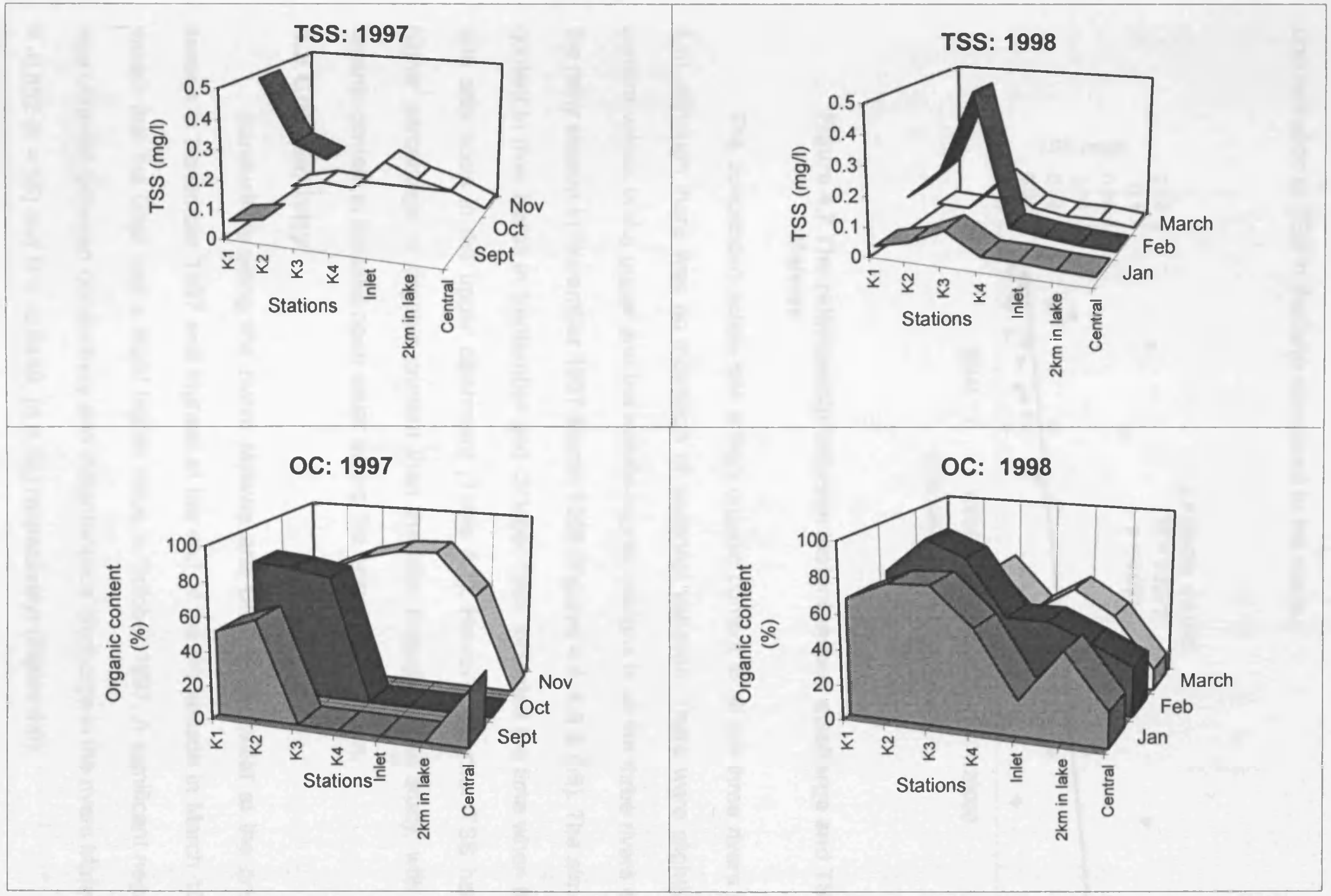


Figure 4.6: Total suspended solids and its organic content (OC) along the river Karati

4.4), while sediment disturbance by over 50 hippopotamus inhabiting a pool, 10 metres above the sampling point may be the reason for Malewa inlet. The other two rivers (Gilgil and Karati) did not show any consistent pattern (Figures 4.5 & 4.6). During the low discharges, turbid stagnant pool, characterized the rivers, especially in the Karati (Table 4.7). There was a consistent low concentration of TSS in the lake compared to the rivers.

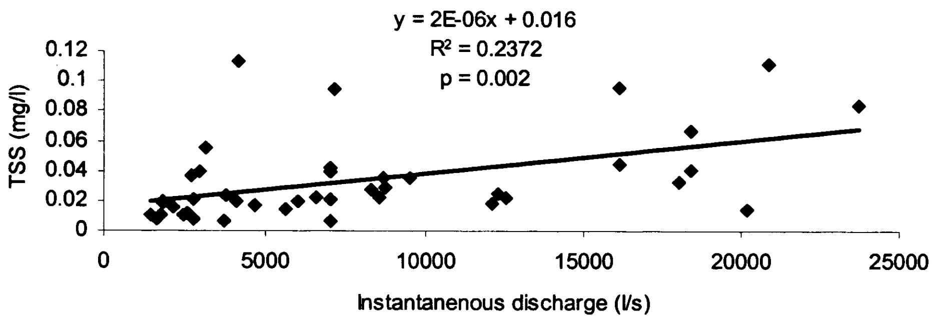


Figure 4.7 The relationship between instantaneous discharge and TSS in the river Malewa

The suspended solids had a high organic content in all the three rivers (Figure 4.4, 4.5, 4.6), although there was no indication of seasonal variation. There were slightly higher organic content values in the upper and the middle-course stations in all the three rivers especially during the rainy season in November 1997-March 1998 (Figures 4.4, 4.5 & 4.6). The almost zero organic content in river Karati in September and October 1997 indicated the time when the river was dry with only pools in the upper catchment (Table 4.7). However the river TSS had a consistently higher percentage of organic content than the lake throughout the study, with an increase of organic content in the lake open water during the heavy rainy season.

4.5 Conductivity

Conductivity along the rivers Malewa and Gilgil were lowest at the onset of the rainy season in November 1997 and highest at the end of the dry season in March 1998 (Figure 4.8) except that the Gilgil had a slight higher value in October 1997. A significant negative correlation was obtained between conductivity and instantaneous discharge in the rivers Malewa and Gilgil (R = -0.652 (n = 55) and R = -0.6449, (n = 52) respectively) (Figure 4.9).

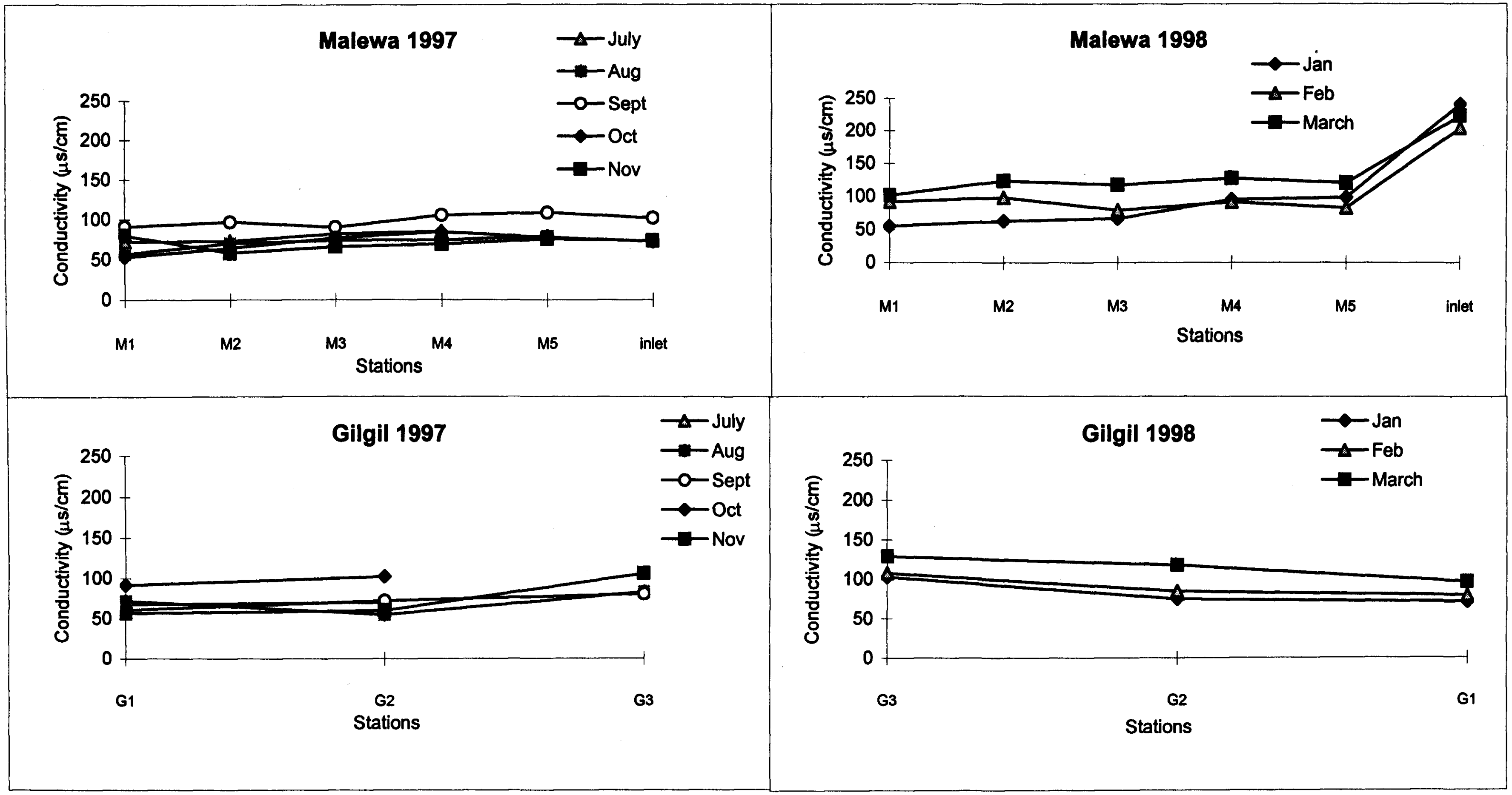
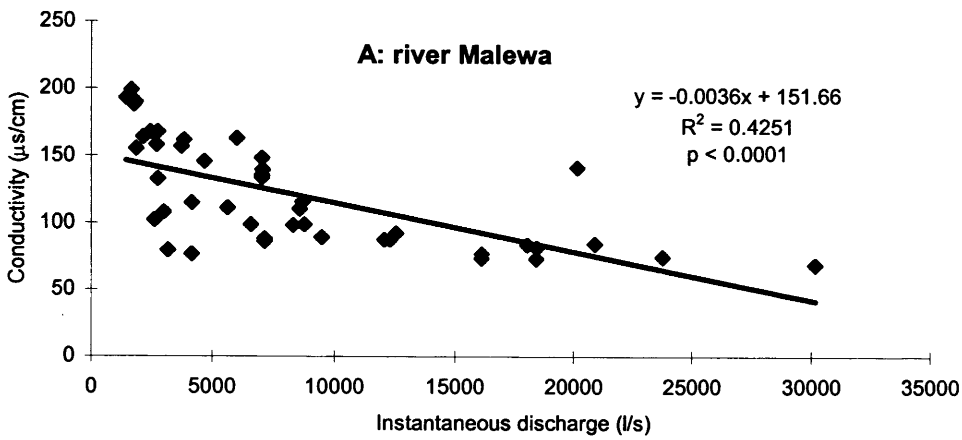


Figure 4.8 Seasonal variation of conductivity along the rivers Malewa and Gilgil in 1997 and 1998



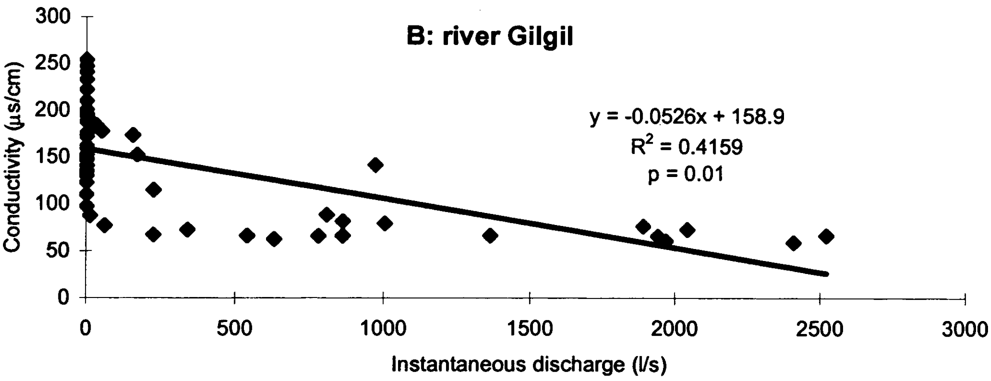


Figure 4.9 Instantaneous discharge relationship with conductivity in the rivers Malewa (A) and Gilgil (B)

This indicates ionic dilution with increase in water flow in the rivers. On the contrary conductivity increased by more than two fold at the Malewa delta in January, February and March 1998 (Figure 4.8). This was brought about by increase in lake volume in the middle of the heavy "El Niño" effect rains submerging the previous river mouth up to 2.5 Km upstream as illustrated in Figure 6.5B. The bimodal peaks with maximum values in February and July 1999 in both rivers (Figure 4.10) coincided with the time when the area was experiencing a dry period (Figure 4.1A). On the other hand September 1997 consistently had high values along the whole of the river Malewa channel compared to the other dry months of the year (Figure 4.8), although the reason for this is not clear from the results.

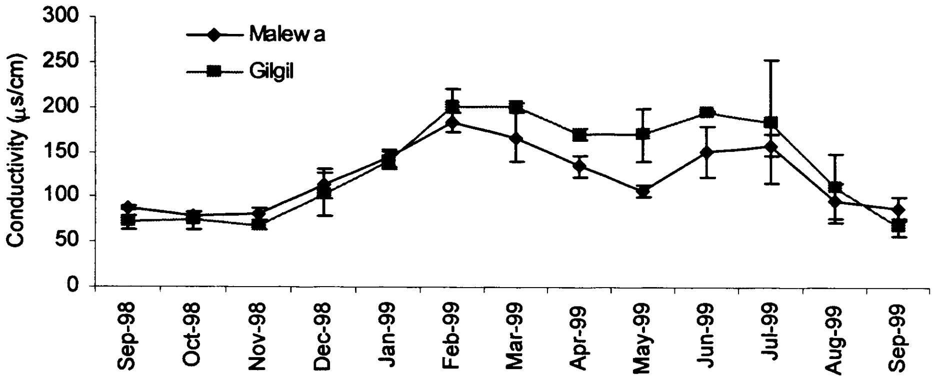


Figure 4.10 Mean monthly conductivity changes of the lower course of the rivers Malewa (M4) and Gilgil (G2)

The river Karati was either dry or dominated by stagnant pools during the dry season (Table 4.7) with high ionic concentration (Figure 4.11). During the rainy season in November 1997, January to March 1998, conductivity reduced as the river approached the lake. This contradicts the results obtained for the river Malewa delta, which has lower conductivity than the lake water. The river Karati has higher conductivity than the lake water and therefore, increase in lake level diluted the high ionic concentration of the incoming river water at the mixing region to create a salt sedge. This resulted in lower conductivity at the region compared to the upstream river stations. However, the river Karati still maintained higher conductivity than the other two rivers throughout the study, suggesting higher ionic content than the other two rivers. This may be a geological influence.

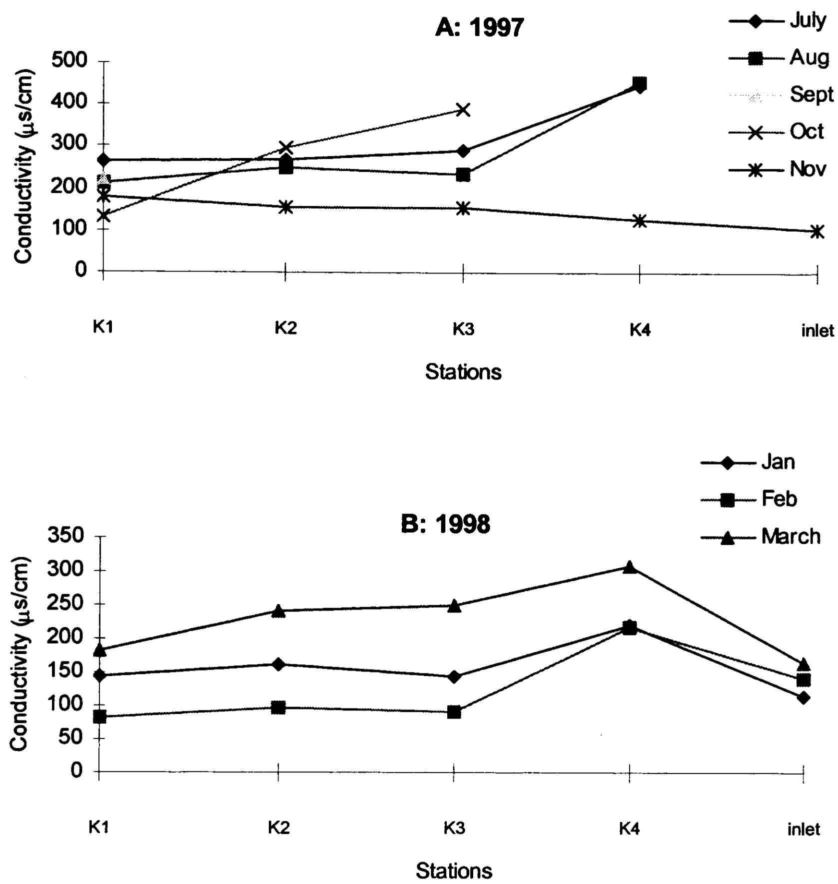


Figure 4.11 Conductivity changes along the river Karati in 1997 (A) and 1998 (B)

4.6 Other chemical characteristics

Alkalinity showed a general increase downstream in all the three Naivasha catchment rivers, although the river Karati had higher values than the other two rivers (Table 4.9). The high alkalinity values along the river Karati suggest that its sediments comprise high levels of organic components, with higher decomposition rates than the other two rivers. This is because increase in alkalinity can be due to the assimilation process of organic matter, followed by H^+ and OH^- uptake. High alkalinity may be a reflection of carbonate in rocks within the catchment, which likely give the high conductivity values obtained. The high alkalinity in the three rivers, portrays a high buffering water capacity. The river inlets had a more alkaline pH values indicative of the lake water while the upper Karati had neutral values (Table 4.9), with higher hardness values compared to the other two rivers. Total hardness increased downstream in all the rivers with calcium hardness dominating (Table 4.9). The concentration of calcium ions was highest in the river Karati (Table 4.9).

Table 4.9 Chemical characteristics of the Naivasha catchment rivers.

A: river Malewa

Station code	**pH**	**Alkalinity** (mg/l as $CaCO_3$)	**Total hardness** (mg/l as $CaCO_3$	**Calcium hardness** (mg/l as $CaCO_3$	**Magnesium hardness** (mg/l as $CaCO_3$	**Mg ions** (mg/l)	**Ca ions** (mg/l)
M_1	7.98±0.4	46±10	26.2±3.99	17.7±2.7	12.7±2.2	3.1	10.5
M_2	7.67±0.3	49.8±6.5	26.8±2.6	18.1±1.8	8.3±1.8	2.3	10.9
M_3	7.69±0.3	48.4±4.7	27.4±2.4	17.4±1.9	11.0±2.1	2.7	10.9
M_4	7.44±0.2	57.8±9.9	27.6±2.1	19.0±2.5	9.7±1.6	2.4	9.9
M_5	7.69±0.2	50.6±6.2	27.4±2.0	19.2±2.5	8.7±1.6	2.1	10.9
Inlet	7.61±0.2	113±19.4	48.8±7.8	28.0±5.0	14.2±4.2	5.1	19.5
200m from inlet into the lake	8.68±0.4	122.3±17	50.0±6.2	34.7±5.5	17.7±2.8	4.3	20.9
5km from inlet into the lake	8.67±0.1	176.3±11	69.4±4.5	48.9±2.4	20.5±2.7	5.01	27.8

* Values : mean ± standard error (n =16)

B: river Karati

Station code	pH	Alkalinity (mg/l $CaCO_3$)	Total hardness (mg/l as $CaCO_3$	Calcium hardness (mg/l $CaCO_3$)	Magnesium hardness (mg/l as $CaCO_3$	Mg ions (mg/l)	Ca ions (mg/l)
K_1	7.00±0.3	85.5±15.1	39.4±5.5	25.5±5.1	10.5±2.1	2.6	15.2
K_2	6.69±0.4	96.8±4.5	44.3±6.8	33.3±8.7	11.0±1.7	2.7	17.8
K_3	7.27±0.3	104.2±13.5	48.9±5.5	35.8±5.8	10.6±2.1	2.6	19.6
K_4	7.49±0.4	140.2±18.9	48.9±8.2	35.8±8.2	18.5±3.6	4.5	19.6
K_5	7.47±0.1	181.5±30.1	62.6±10.1	50.8±11.7	17.5±3.3	3.8	25.8
Inlet	7.93±0.5	124.3±10.9	59.3±2.5	38.6±4.2	22.5±3.0	5.5	23.9
200m into the lake	8.17±0.1	129.3±8.2	59.0±1.9	45.0±3.4	13.8±3.1	3.4	23.5
5 Km into the lake	8.67±0.1	176.3±11	69.4±4.5	48.9±2.4	20.5±2.7	5.0	27.8

C: river Gilgil

Station code	pH	Alkalinity (mg/l $CaCO_3$)	Total hardness (mg/l as $CaCO_3$	Calcium hardness (mg/l as $CaCO_3$	Magnesium hardness (mg/l as $CaCO_3$	Mg ions (mg/l)	Ca ions (mg/l)
G_1	7.96±0.2	38.7±7.2	17.68±2.0	11.05±1.4	6.44±1.3	1.6	7.1
G_2	7.54±0.2	47.3±5.4	21.85±3.3	15.35±3.4	7.56±1.5	1.9	9.0
G_3	7.48±0.2	55.1±3.3	24.44±2.6	14.97±1.4	13.7±3.6	3.4	10.6
5km into the lake	8.67±0.1	176.3±11	69.37±4.5	48.9±2.4	20.51±2.7	5.01	27.8

* Values: mean ± standard error

4.7 Characteristics of Naivasha catchment headwaters

Tables 4.10, 4.11 and 4.12 illustrate the physical and chemical characteristics of the Naivasha catchment headwaters, rivers and streams studied while human activities along the tributaries channels and within the rivers are summarised in Table 4.12 and 4.13.

Table 4.10 The physical characteristics of the river Malewa headwaters

Name of tributary	**Drainage region**	**Altitude range** (metres a.s.l)	**Catchment area** (km^2)	**Stream order**
Nyambugi	Bahati hills	2320 - 2620	17	1
Nyairoko	Bahati hills	2160 - 2760	35	2
Njangiri	Nyandarua ranges	2360 - 3620	10.5	2
Wanjohi	Nyandarua ranges	2340 - 3800	137.5	3
Engare mugutyu	Kipipiri	2469 - 2620	8	2
Turasha	Kipipiri	2000 - 3906	133.5	4
Kasuku	Kinangop plateau	2012 - 2316	< 1	1
Tributary 3	Kinangop plateau	2012 - 2316	<1	1
Tributary 5	Kinangop plateau	2012 – 2316	<1	1
Tributary 6	Kinangop plateau	2012 - 2316	<1	1

Table 4.11: Chemical characteristics of the river Malewa headwaters

Name	**Temperature** (^oC)	**Conductivity** (µs/cm)	**pH**	**Alkalinity** (mg/l $CaCO_3$)	**Total hardness** (mg/l $CaCO_3$)	**Calcium hardness** (mg/l $CaCO_3$)
Nyambugi	20.9	81	7.8	47	19	11
Nyairoko	22.2	92	7.7	40	20	12
Njangiri	16.6	72	7.4	33	28	22
Wanjohi	13.2	76	8.2	58	30	22
Engare Mugutyu	20.5	103	7.6	57	40	28
Turasha 1	20.4	80	7.5	56	33	23
Turasha 2	20	94	7.7	57	34	24
Turasha 3	19.8	84	7.7	49	26	17
Kasuku	18.2	372	7.6	189	58	43
Tributary 3	20.1	384	8.0	213	46	36
Tributary 5	19.9	500	8.2	288	44	40
Tributary 6	19.7	462	8.1	218	54	48

KEY

Turasha 1; upstream of Engare Mugutyu tributary

Turasha 2; 30m below the inlet of Engare Mugutyu to the main river Turasha

Turasha 3; the entry to the reservoir

Table 4.12: Characteristics of the river Gilgil headwaters

	Little Gilgil	Kariundu
Drainage region	Upper Gilgil agricultural land	Bahati hills
Altitude range (metres a.s.l)	1920 - 2400	2220 - 2740
Catchment area (km^2)	11.5	34
Stream order	2	2
Land use	Intensive mixed farming	Intensive mixed farming
Disturbance estimate (1-5)	4	4
Temperature range (^oC)	16.5 -20.3	16.5 - 16.9
Conductivity (μs/cm)	177 ± 22	125 ± 2
pH	7.7	7.7
Alkalinity (mg/l $CaCO_3$)	112	69
Total hardness (mg/l $CaCO_3$)	30.2	28
Calcium hardness (mg/l $CaCO_3$)	25	17

The headwaters comprise mainly of small, high altitude streams (2000 to 3906 metres above sea level) with a drainage area of less than 40 km^2 except the Wanjohi and Turasha which had more than 100 km^2. The streams draining the Bahati hills on the northeastern part of the catchment and the Nyandarua ranges were slightly alkaline with low alkalinities and ionic concentration. The high altitude Engare Mugutyu stream had a slightly higher conductivity than the main river Turasha. Its influence on the main river is indicated by slight increase in conductivity (from 80 to 94 μs/cm) after the tributary joins the main river (Table 4.12). The small streams draining the Kinangop plateau (Table 4.10) are rich in ionic concentration, more alkaline with high alkalinity values than all the other streams (Table 4.12). However the conductivity progressively increased at the streams located further south (Tributary 3 and 6) towards the Karati catchment. The total hardness was mainly due to calcium hardness in all the streams studied.

Table 4.13: Land use in the surrounding area and human activities in the river channel

Name	Land use	Human activities	Disturbance scale	Disturbance estimate (0-5)
Nyambugi	Pasture and small scale farming of maize	Watering of large number of livestock	Intensive	4
Nyairoko	Mixed farming, pasture	Watering of large number of livestock	Intensive	4
Njangiri	Mixed farming	Watering of large number of livestock	Intensive	4
Wanjohi	Forest and farming	Watering of regular number of livestock	Occasional	2
Engare Mugutyu	Forested			1
Turasha	Forested & mixed farming	Watering of livestock	Regular	3
Kasuku	Thick forest	Less than 10 houses	Minimal	1
Tributary 3	Thick forest	Nil	Minimal	1
Tributary 5	Thick forest	Nil	Minimal	1
Tributary 6	Thick forest	Nil	Minimal	1

The results of the seasonal variability of conductivity, alkalinity and TSS of three headwater tributaries studied are shown in Figure 4.12 below. The Little Gilgil was more alkaline during the rainy season with a consistent high conductivity. The lowest conductivities were recorded in November 1997 in all the three streams, were diluted by rainfall.

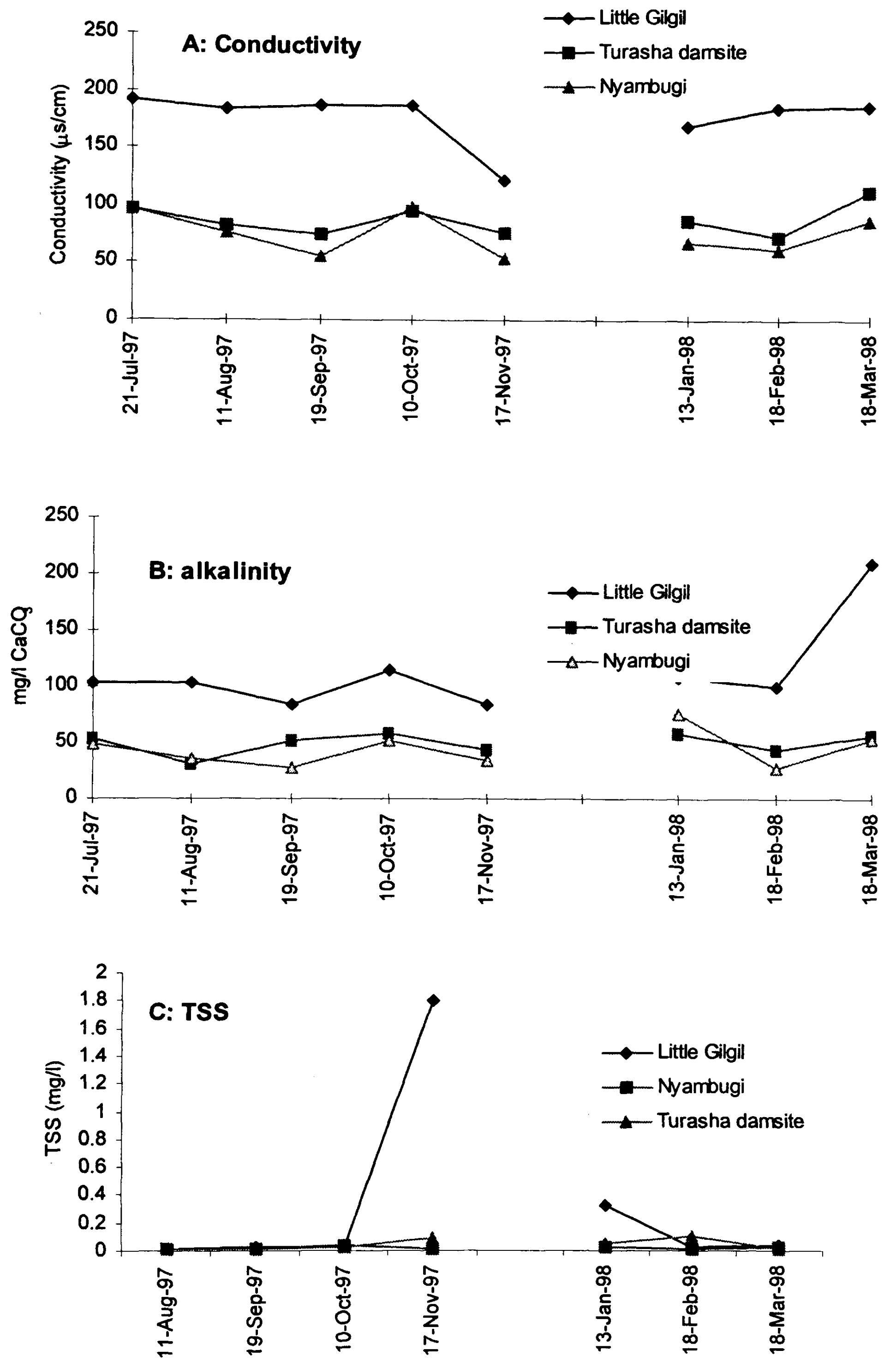
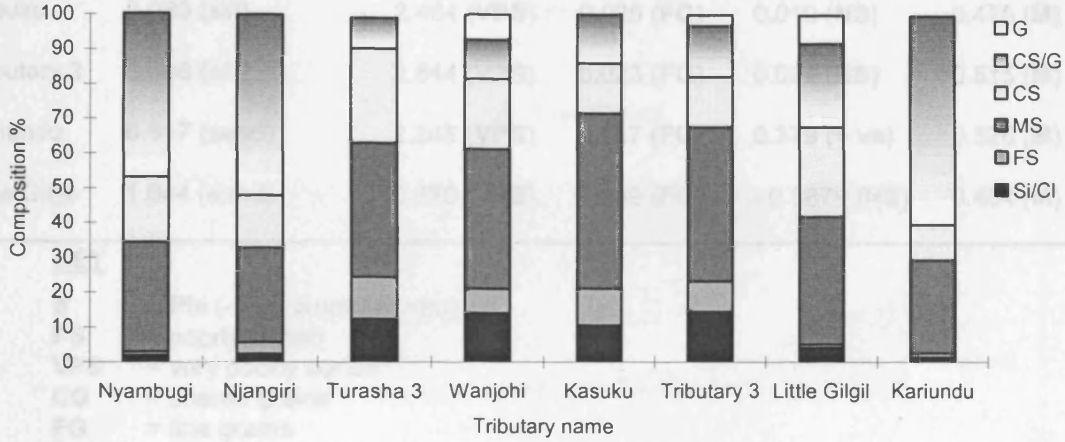


Figure 4.12 Seasonal variation of conductivity, alkalinity and TSS in three sites representing three headwater streams

4.8 Substrate structure of the streams and rivers of the Naivasha catchment

Different substrate components dominated the headwaters, with the Nyambugi, Njangiri, Little Gilgil and Kariundu consisting mainly of coarser sediment (Figure 4.13). The Phi (ø) mean grain size in Table 4.14 confirms these results.



KEY

G = Gravel (>2 mm diameter)
CS = Course sand (0.6 – 2 mm diameter)
MS = Medium sand (0.2 – 0.6 mm diameter)
FS = Fine sand (6.3 μm – 0.2 mm diameter)
Si/Cl = Silt/Clay (< 6.3 μm diameter)

Figure 4.13 Sediment structure of the headwaters rivers and streams

However, the skewness coefficient (SK) indicates that all the tributaries are dominated by fine grain sediment except the Nyambugi (Table 4.14). While using an overall skewness measure, which is geometrically independent of sorting SK_1 (Robert & William 1957), indicates that most of the streams have either medium grain size (neutral skewness) or fine class grain size (positive skewed) sediment, except the Nyambugi and Little Gilgil which have coarser grain (negative skewed) sediment (Table 4.14). In general all the headwater streams studied have very poorly sorted sediment as indicated by the sorting coefficient SD.

Table 4.14: The grain size distribution and associated statistical parameters of the headwaters streams

Tributary	Mean grain size (ø)	SD	SK	SK_1	KG'
Nyambugi	1.584 (sand)	2.249 (**VPS**)	1.06 (**CG**)	- 0.193 (**- ve**)	0.463 (**P**)
Njangiri	1.121 (sand)	2.379 (**VPS**)	0.209 (**FG**)	0.243 (**+ ve**)	0.454 (**P**)
Wanjohi	2.986 (silt)	2.929 (**VPS**)	0.036 (**FG**)	0.063 (**NS**)	0.517 (**M**)
Turasha 3	3.178 (silt)	3.055 (**VPS**)	0.033 (**FG**)	0.242 (**+ ve**)	0.479 (**M**)
Kasuku	3.089 (silt)	2.464 (**VPS**)	0.025 (**FG**)	0.019 (**NS**)	0.475 (**M**)
Tributary 3	3.308 (silt)	2.844 (**VPS**)	0.023 (**FG**)	0.094 (**NS**)	0.515 (**M**)
Kariundu	0.817 (sand)	2.248 (**VPS**)	0.047 (**FG**)	0.379 (**+ ve**)	0.526 (**M**)
Little Gilgil	1.644 (sand)	2.370 (**VPS**)	0.089 (**FG**)	- 0.0879 (**NS**)	0.484 (**M**)

KEY

ø = Phi (- $\log_2$ diameter mm)
PS = poorly sorted
VPS = very poorly sorted
CG = coarse grains
FG = fine grains
EFG = extremely fine grains
+ ve = positive skewed which indicates a tail of fine grain sediment
- ve = negative skewed which indicate a tail of coarser grains
NS = nearly symmetrical.
L = leptokurtic or excessively peaked curve
P = platykurtic or deficiently peaked curve
M = mesokurtic curve

Sand dominated the sediment of the rivers Malewa and Gilgil, with an increase in importance of gravel in the upstream stations and silt/clay close to the lake (Figure 4.14 A & B). However, the river Karati had a coarser sediment with a mean grain size > 2mm in K_1 and K_2 (Figure 4.15) and more than 40% in gravels and coarse sand in the entire channel (Figure 4.14B).

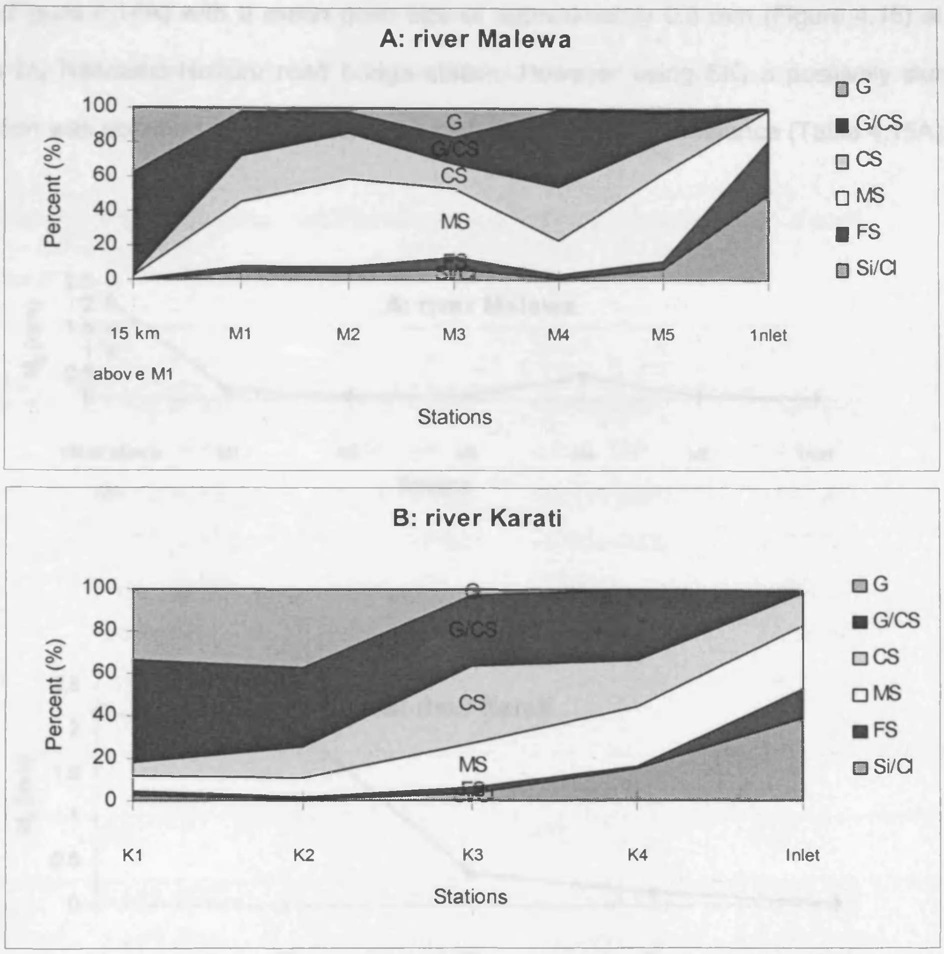
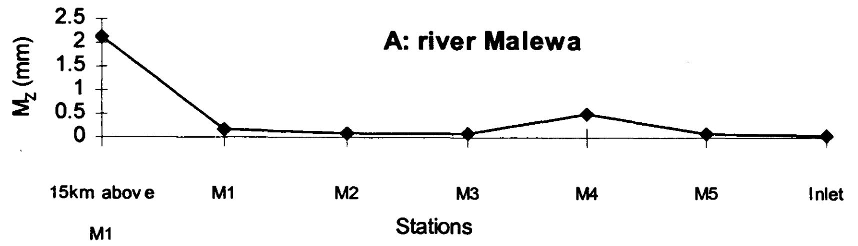


Figure 4.14 Sediment grain composition in the rivers Malewa (A) and Karati (B) (For key see Figure 4.13)

The SD and SK analysis given in Table 4.15 indicate that the river Malewa sediments are poorly sorted and dominated by smaller class grain size except at the additional upstream station (15 Km above M_1) at the slopes of the Nyandarua ranges. A negatively skewed distribution was obtained for this station, indicating a tail of coarser grains, unlike the nearly symmetrical in M_1 - M_3 and positively skewed on the lower course of the river at M_4 and M_5 (Table 4.15A). Despite this, there was a slight increase in gravel and course sand at M_3 and M_4 (Figure 4.14). At the same time a slight increase on silt and the fine sand was noted at M_3. The M_3 station is intensively disturbed by human activities, especially watering of livestock in the river (Table 4.4). As the animals drink water they trample and disturb the sediment causing an increase in re-suspension of the fine sediment particles, which consequently are washed downstream, resulting in sand dominance (Figure 4.14A) with a mean grain size of approximately 0.5 mm (Figure 4.15) at the downstream M_4 Naivasha-Nakuru road bridge station. However using SK_1 a positively skewed size distribution was obtained for M_4 station indicating fine grain size dominance (Table 4.15A).



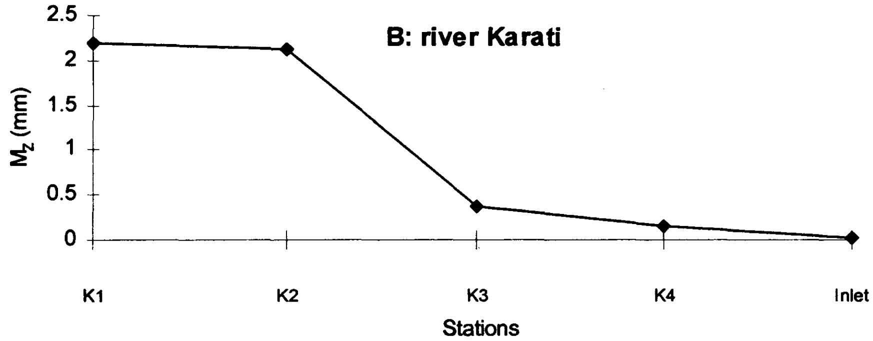


Figure 4.15 Mean grain size (M_Z mm) along the rivers Malewa (A) and Karati (B)

The station M_3 shows an overall reduction in the mean grain size (Figure 4.15), despite the dominance of medium to gravel portrayed in Figure 4.14A. This may be that the coarser grain size peak was smoothened out by the slight increase of the silt and fine sand (Figure 4.14) at this station. There is a very poor sorting coefficient (SD = >2) and nearly symmetrical curve with fine grains obtained for this station using different statistical analysis (Table 4.15A). To analyse the sensitivity of the normality of the grain size distribution, as a measure of sorting in the extreme ends compared with the sorting in the central part of the distribution curve, normal kurtosis analysis was used. The results obtained indicate that the grain size distribution data were not normally distributed (with values < and > 0 ± 1). A further analysis was done using transformed graphic kurtosis (KG') (Roberts & Williams 1957) and similar results were obtained except for the Malewa Nakuru road bridge (M_4) and Marula (M_5) stations which had a nearly symmetrical distribution.

Table 4.15 Sorting and skewness coefficients along the rivers Malewa and Karati

A: river Malewa

Station	SD	SK	SK_1	KG'
15 km above M_1	1.102 (**PS**)	1.313 (**CG**)	-0.108 (**NS**)	0.324 (**VP**)
M_1	2.341 (**VPS**)	0.094 (**VFG**)	0.033 (**NS**)	0.457 (**P**)
M_2	2.140 (**VPS**)	0.049 (**VFG**)	- 0.018 (**NS**)	0.443 (**P**)
M_3	2.220 (**VPS**)	0.036 (**VFG**)	- 0.019 (**NS**)	0.557 (**L**)
M_4	2.017 (**VPS**)	0.385 (**FG**)	0.259 **(+ ve)**	0.522 (**M**)
M_5	2.289 (**VPS**)	0.039 (**VFG**)	0.123 **(+ ve)**	0.481 (**M**)
Malewa inlet	1.549 (**PS**)	0.011 (**EFG**)	- 0.047 (**NS**)	0.466 (**P**)

B: river Karati

Station	**SD**	**SK**	**SK_1**	**KG'**
K_1	1.643 (**PS**)	1.221 (**CG**)	0.403 (**+ ve**)	0.489 (**M**)
K_2	1.970 (**PS**)	0.750 (**MG**)	- 0.087 (**NS**)	0.641 (**VL**)
K_3	2.159 (**VPS**)	0.240 (**FG**)	0.263 (**+ ve**)	0.550 (**L**)
K_4	2.905 (**VPS**)	0.136 (**FG**)	0.307 (**+ ve**)	0.520 (**M**)
Karati inlet	3.038 (**VPS**)	0.013 (**VFG**)	0.174 (**+ ve**)	0.421 (**P**)

In summary the overall view of the river Malewa grain size structure consists of, platykurtic or deficiently peaked curve on the upper three stations (Nyandarua slopes, M_1 and M_2), with the middle M_3 excessively peaked producing a leptokurtic curve and normal distribution on the lower course. These results imply that the sediment at M_3 was better sorted in the middle part of the curve than the fine and course grain tails.

The river Karati substrate structure consists of more extensive coarser grained sediment in the upstream and middle section of the river, with sandy sediment in the lower course and a subsequent increase in silt/clay fraction near the lake (Figure 4.14B & 4.15). Unfortunately the results obtained using the SK_1, indicate that the whole river channel is mainly positively skewed except at K_2, implying that, small size class grains dominated the channel. Considering Kurtosis (KG') analysis, the uppermost station (K_1) and Delamere farm (K_4) have a normal grain size distribution, with the middle stations (K_2 and K_3) having leptokurtic curves. Just like in the river Malewa, the river Karati sediment is poorly sorted in the whole channel (Table 4.15B).

The results of the only two stations studied in the middle and lower courses of the river Gilgil are given in Table 4.16. They show positively skewed to nearly symmetrical leptokurtic curves, with very poorly sorted sediment dominated by smaller size class in structure (Table 4.16), even though, results given by Figure 4.16 indicate an overall sand dominance.

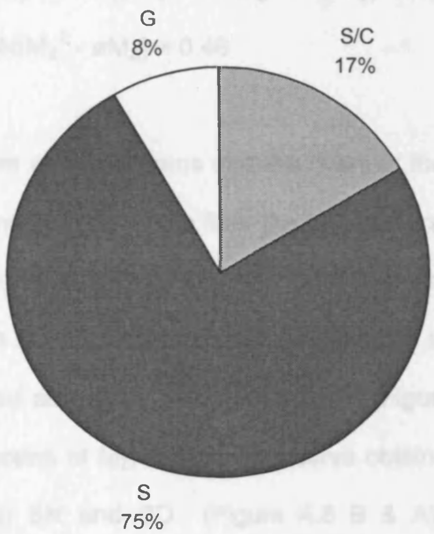


Figure 4.16 Sediment grain size structure of station G_2 of the river Gilgil (Key see Figure 4.13)

Table 4.16 Statistical results of grain size distribution of the two stations studied in the lower course of the river Gilgil (Key see Table 4.14)

Station	Mean grain size (ø)	SD	SK	SK_1	KG'
G_1 (30 km from lake edge)	2.687 (**FS**)	2.986 (**VPS**)	0.046 (**FG**)	0.114 (**+ ve**)	0.624 (**L**)
G_3 (15 km from lake edge)	2.090 (**FS**)	2.749 (**VPS**)	0.063 (**FG**)	0.020 (**NS**)	0.575 (**L**)

In theory, grain size distribution parameters are geometrically independent, but in reality most of these parameters are as a function of the mean grain size (M_Z), which means that, they can be linked by a mathematical relationship. The relationships between M_Z and other statistical parameters calculated from the averages of all the stations are summarised in Table 4.17.

Table 4.17: The overall relationship between mean grain size (M_Z) and other statistical parameters of the Naivasha catchment's rivers and streams

Sorting coefficient (SD) = $0.02(øM_Z^3 + øM_Z^2 + 17øM_Z) + 1.88$	$R^2 = 0.50$
Skewness coefficient (SK) = $0.08(øM_Z^2 - 6øM_Z) + 0.7$	$R^2 = 0.94$
Inclusive graphic coefficient (SK_1) = $0.02(øM_Z^3 – 5øM_Z^2 + 3øM_Z) + 0.25$	$R^2 = 0.19$
Kurtosis (KG') = $0.01(-øM_Z^3 + 4øM_Z^2 - øM_Z) + 0.46$	$R^2 = 0.12$

Sediment samples from all the streams and the rivers of the entire catchment are poorly to very poorly sorted, with a general trend of the finer the M_Z the worse the sorting coefficient (SD) with the poorest SD at ø2.13 to ø4.0 (Figure 4.17A). The skewness coefficient measures (SK & SK_1) follow a similar trend, with the M_Z of the coarser grains (ø0.5 to - ø 0.1) nearly symmetrical and becoming positively skewed as the M_Z becomes smaller (Figure 4.17 B & C). Considering that SD, SK and SK_1 are a function of M_Z, the elliptical curve obtained between SD and SK_1 and the linear relationship between SK and SD (Figure 4.8 B & A) is indicative that Naivasha catchment's sediments are predominantly composed of small class sizes, unimodal and poorly sorted (Figure 4.18 A & B). The relationship between kurtosis (KG') and other parameters (Figure 4.18 C, D & E) seems to be complicated and without a clear relationship except SD & KG' portrays a bimodal grouping of poorly and very poorly sorted sediment (Figure 4.18 C), with a KG' range of 0.33 to 0.65 for the entire Naivasha catchment's sediment.

The sediment of the Naivasha catchment rivers and streams have low values of weight loss on ignition (<15%) with low water content (< 50%), except in the lower course of the rivers with high silt/clay components

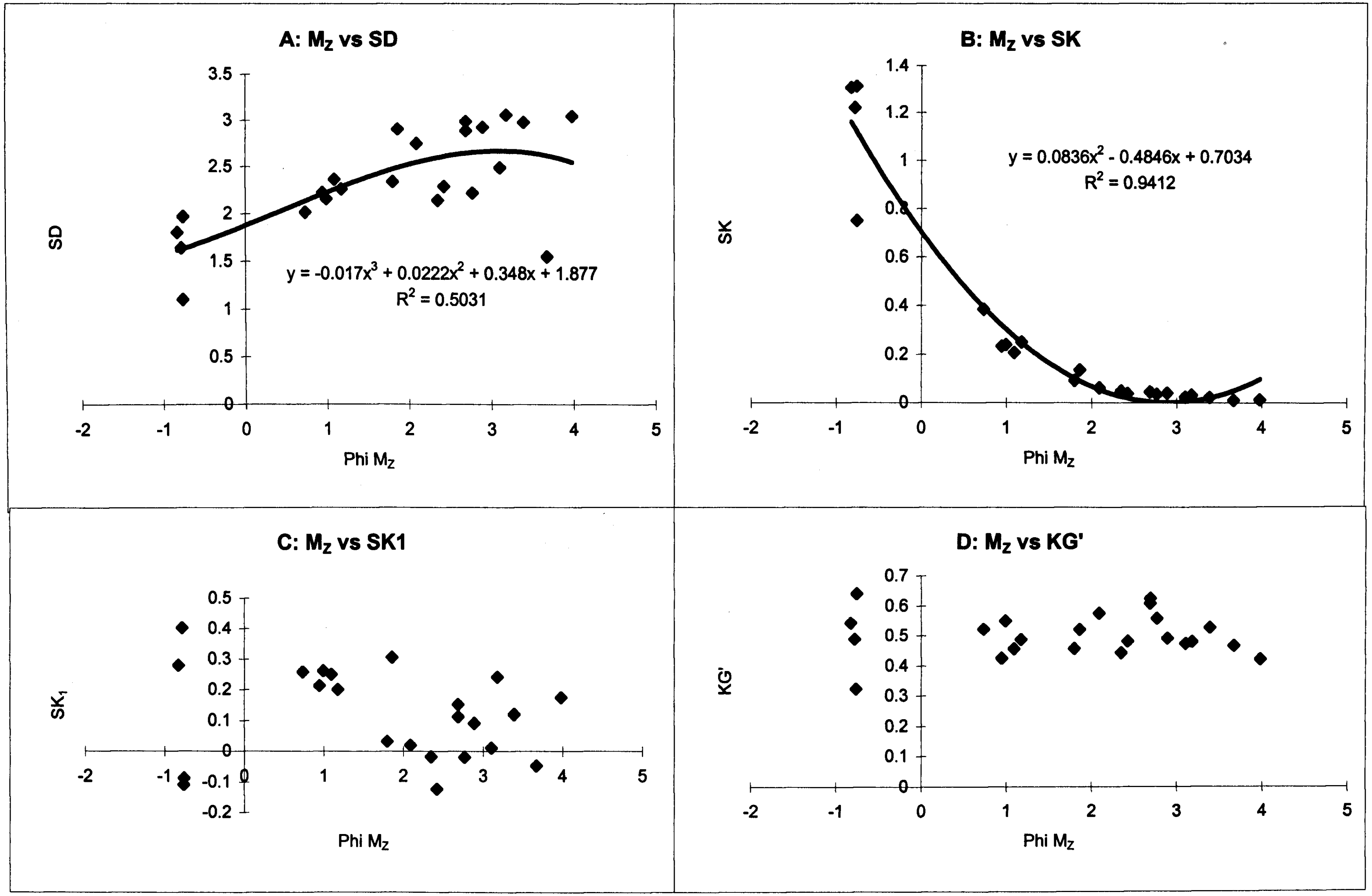


Figure 4.17 Interrelationship between Phi mean grain size (Mz) verses SD, SK, SK1 and KG' for the Naivasha catchment sediment

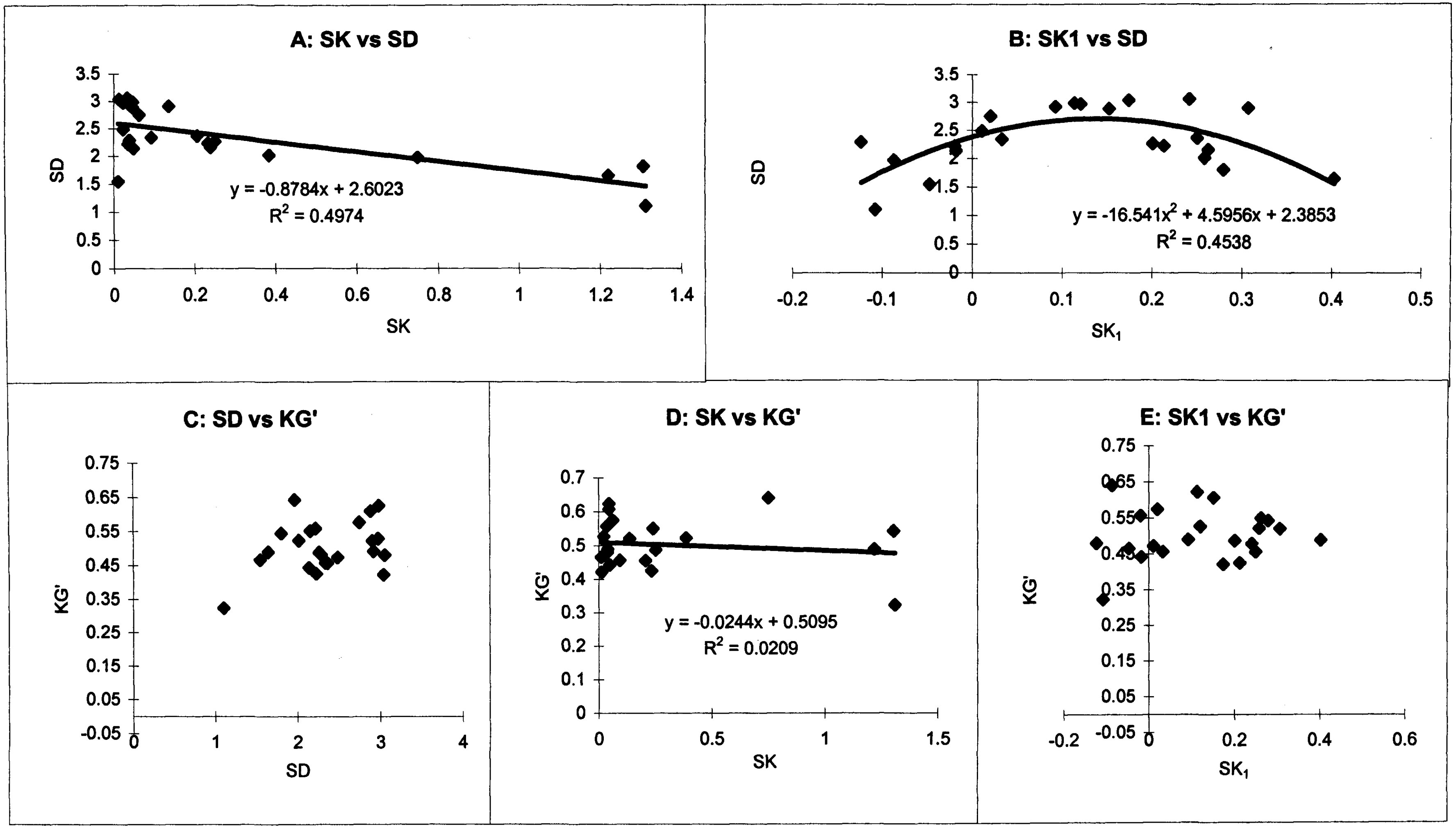


Figure 4.18 Scatter diagrams showing the relationship between SD, SK, Sk1 and KG' for Naivasha ecosystem sediment

4.9 Chemical composition of sediments in the three main rivers of the Naivasha catchment

The concentrations of major and minor elements in the sediment of the three rivers are shown in Table 4.18. The chemical constituents of different rivers substrate are remarkably similar although the river Karati had the highest total percentage. Among the major elements SiO_2 varies between 55 - 61% in the three rivers, while the minor elements such as Ni, Cu and Pb were low compared to other international quality standards.

Table 4.18: XRF-analysis results showing the percentage component of major and minor elements from two stations in each of the three main rivers of the Naivasha catchment (Analysed at Anglo American Research Labs, Johannesburg, South Africa)

	River Malewa		River Gilgil		River Karati	
	M_3	**M_5**	**G_1**	**G_2**	**K_1**	**K_4**
Total	89.6	91	89.7	89.3	91.7	93.1
SiO_2	55	55.2	58.1	57.8	57.3	61
Al_2O_3	14	14.5	13.5	15.5	12.4	14.2
Fe_2O_3	9.9	10.1	9.8	9.4	13.8	9.3
K_2O	3.6	3.6	3.1	2.0	3.2	2.6
Na_2O	2.3	2.4	1.7	0.9	2.3	1.4
CaO	1.8	2.1	1.0	1.0	0.9	1.6
MgO	0.9	0.9	0.7	0.9	0.5	1.1
MnO	0.2	0.2	0.4	0.1	0.2	0.2
Cr_2O_3	0	0	0	0	0	0
Cu	8	7	5	19	2	20
Zn	136	129	152	191	147	170
Pb	16	13	16	11	14	12
Ni	11	10	11	15	2	16

4.10 Overview

The Naivasha catchment rivers and streams are neutral with low alkalinities and low ionic concentration, probably due to the character of their bedrock which is either tertiary or recent volcanic origin. Volcanic rocks are considered to be relatively resistant to weathering processes and generate dilute runoff. But, with a long- term exposition to the prevailing warm humid climate, the action of natural agents on the bedrock can increase resulting in heavily leached soils. In fact the low concentrations of Total Dissolved Solids (TDS) indicated by low conductivities, reflect a prolonged leaching process. However bicarbonates are in sufficient quantity to buffer the systems.

The slightly high ionic concentration in the river Karati and the headwaters draining the Kinangop plateau clearly indicates the geological influence either at the origin or in their courses. The other rivers and streams draining the Bahati plains, Ol Bolossat plains and Nyandarua ranges have low conductivities. Geologically the Ol Bolossat and the Kinangop plateau are structurally of the same origin (Shackleton 1945), although, they might vary in nature and composition (Odingo 1971), creating the difference in ionic concentration observed.

During the rainy season, most of these rivers and streams are characterised by torrential flow with high turbidity waters. This was well portrayed by high TSS concentration, implying that the Naivasha catchment experiences loss of soils into the river systems during the rainy season. The land adjacent to the rivers is mainly composed of steep slopes and either intensively cropped without any tillage or overgrazed. This has left the soils bare, unprotected with little or almost no buffer zone, creating a conducive environment for erosion through surface runoff. Such soil mobilization poses a serious threat to the river systems and the recipient lake Naivasha and especially if the soils are rich in nutrients.

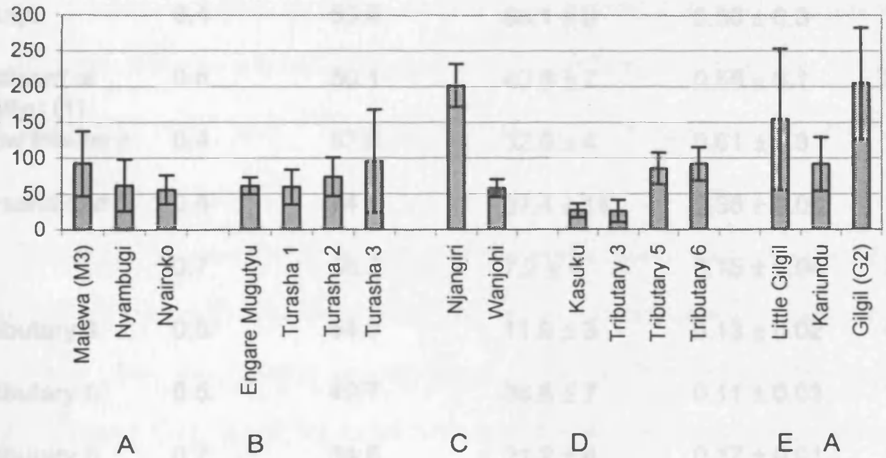
In general the chemical composition of the bedrock together with climate have a great influence in the Naivasha rivers and streams water chemistry. The anthropogenic impact also seems important.

CHAPTER 5

PHOSPHORUS IN THE STREAMS AND RIVERS

5.1. Phosphorus concentration and fluxes in headwaters streams and rivers

The phosphorus concentration in the three headwater streams sampled (Figure 3.1) could be grouped into three categories according to the total phosphorus concentration: - < 50 µg/l, 50 - 100µg/l and > 100µg/l (Figure 5.1). Streams draining the upper Kinangop plateau (Olmogogo hills) have the lowest concentration (category 1), despite their high ionic concentration (Table 4.11).



KEY
Turasha 1 is upstream of Engare Mugutyu
Turasha 2 is 30 m below the entry of Engare Mugutyu
Turasha 3 is at the mouth of the Turasha dam
Tributary 3, 5 and 6 are un-named tributaries
A - E are drainage areas representing each group from Tables 4.10 and 4.12
A = Bahati Hills
B = Kipipiri
C = Nyandarua ranges
D = Kinangop plateau
E = Upper Gilgil agricultural land

Figure 5.1 Mean (± SD) total phosphorus (TP) concentration of Naivasha headwater streams and the rivers Malewa at M_3 and Gilgil at G_2

But just like conductivity, TP concentration and SRP/TP ratio increased further south in the unnamed tributary 6, while the opposite is true for the PP % (Table 5.1). High SRP/TP ratio implies that most of the TP is in dissolved form. Since the streams further south are mainly spring fed flowing through undisturbed area with minimal human disturbance (Table 4.10 and 4.13), then the high phosphorus obtained is probably from leaching or mineralization of the bedrock.

Table 5.1: Nutrients in the headwater rivers and streams, and ratios

Tributary	**SRP/TP** ratio	**PP % of TP**	Mean **NH_4-N** ($\mu g/l$)	Mean **NO_3-N** (mg/l)	**TN/TP** ratio
Nyambugi	0.4	59.2	82.9 ± 35	0.1 ± 0.03	18
Nyairoko	0.2	75.7	8.6 ± 3	0.04 ± 0.01	228
Njangiri	0.1	89.6	604.3 ± 34	0.04 ± 0.01	63
Wanjohi	0.5	47.4	50 ± 2	0.11 ± 0.03	100
Engare Mugutyu	0.4	59.6	68.1 ± 9	0.56 ± 0.3	17
Turasha upstream of Engare Mugutyu (1)	0.6	50.1	40.8 ± 7	0.58 ± 0.1	20
Turasha below tributary (Turasha 2)	0.4	57.8	32.0 ± 4	0.61 ± 0.3	14
Mouth of Turasha dam (Turasha 3)	0.4	74	37.4 ± 14	0.36 ± 0.06	13
Kasuku	0.7	58.3	7.2 ± 4	0.15 ± 0.04	238
Un-named tributary 3	0.5	54.9	11.9 ± 3	0.13 ± 0.02	426
Un-named tributary 5	0.5	49.7	36.6 ± 7	0.11 ± 0.03	199
Un-named tributary 6	0.7	34.6	21.2 ± 4	0.17 ± 0.01	138
Kariundu	0.2	80.3	< detection	0.63 ± 0.2	165
Little Gilgil	0.6	63.7	26.5 ± 14	0.44 ± 0.07	15

Most of the other stations studied lie within the 2nd category and are comparable to the mean value of the main river Malewa at the middle course (M_3) (Figure 5.1). These streams pass through intensive human activities especially small scale farming of food crops and dairy (Table 4.13). Further support is given by the high ammonium (NH_4-N) concentration (Table 5.1) in most of the tributaries water, indicating organic input.

There is a progressive increase of TP concentration (Figure 5.1) and PP % component (Table 5.1) downstream of the main Turasha confluence. Increase in PP content might indicate anthropogenic influence. However, geological phosphorus input is more likely because the Turasha tributary, Engare Mugutyu, which is a high altitude stream passing through a non-cultivated, pristine area, lies in the same category (2^{nd} category) as the other tributaries flowing through an intensive farmed catchment from the N.E. The influence of the Engare Mugutyu tributary on the main Turasha's phosphorus content is indicated by an increase in TP concentration and PP component at Turasha 2, which is below the entry point of Engare Mugutyu stream (Figure 5.1 & Table 5.1). Njangiri had the highest TP concentration and the lowest SRP/TP ratio of the Malewa headwaters studied, with most of the phosphorus is in PP form. The difference in the PP component (Table 5.1) between Njangiri and its main river Wanjohi could imply difference in human activities upstream of these two systems indicated in Table 4.13. The river Gilgil's headwater streams are rich in phosphorus (Figure 5.1), with Kariundu and little Gilgil placed at the upper limit of 2^{nd} and 3^{rd} categories respectively, although to the main river Gilgil (G_2) has the highest concentration.

There is a seasonal variation of TP and PP portrayed by the three above tributaries when sampled repeatedly (Figure 5.2). The Little Gilgil and Turasha demonstrated a clear phosphorus flush in with runoff, with the highest concentration mostly in PP form at the beginning of November 1997 (Figure 5.2), which coincides with the start of the heavy rainy season (Figure 4.1A). There was a highly significant strong correlation between TSS and TP, PP in the Little Gilgil ($P < 0.001$) (Figure 5.3) indicating that most TP is bound in the suspended solids in the river to form PP, even though such a strong correlation was not obtained for Turasha at the dam mouth (Turasha 3) ($P > 0.05$) (Figure 5.3). On the other hand Nyambugi tributary had the lowest TP concentration during the rainy season in November 1997 to February 1998 (Figure 5.2A), indicating ionic dilution by rainfall. However PP dominated in October and November 1997 in the Nyambugi (Figure 5.2) indicating a short time span of phosphorus input in PP, which might explain the weak correlation obtained between TSS and TP, PP (Figure 5.3).

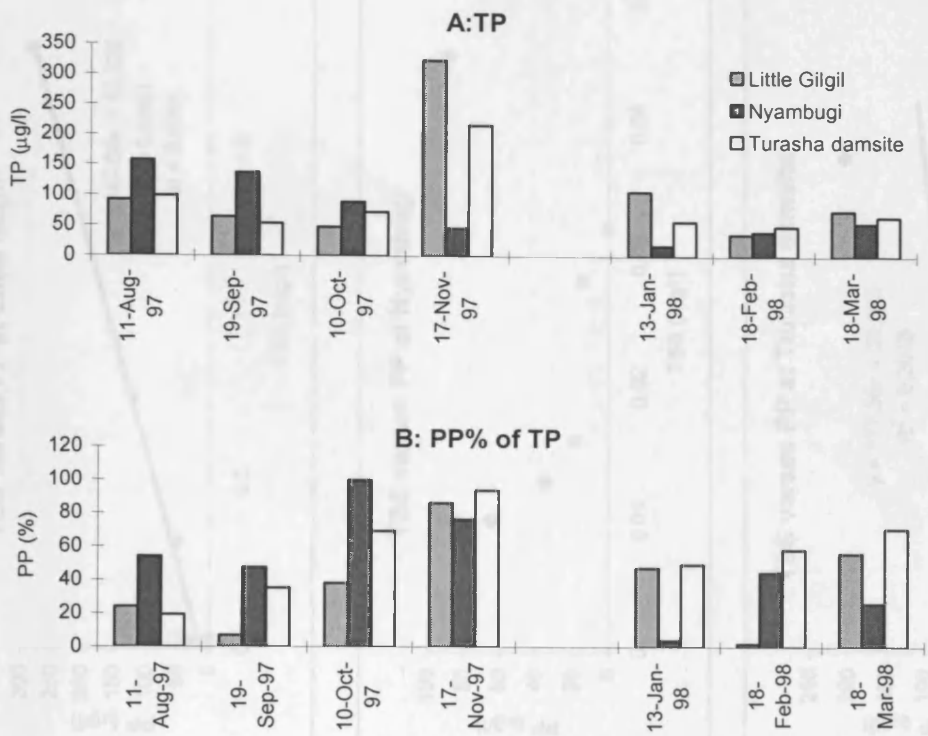


Figure 5.2 Seasonal variations of TP (µg/l) and PP (%) in three headwater streams in 1997 to 1998

5.2 Seasonal dynamics and longitudinal distribution of different forms of phosphorus in the Gilgil and Malewa rivers

The highest concentration of total phosphorus (TP) was observed at the beginning of the rainy season in November 1997, at the middle and the lower courses of the rivers Malewa and Gilgil (Figure 5.4A and 5.5). In addition extremely low SRP/TP ratios were obtained at the same time (Figure 5.6A) along the two river channels except 15km above M_1 on the slopes of Nyandarua ranges and at the entry point of the river Gilgil in the north-swamp (G_3). PP dominated most of the rivers during the beginning of the heavy rainy season (El Niño rains). Thereafter the TP concentration and SRP/TP ratio reduced as the rainfall progressed in January 1998 (Figure 5.4 and 5.6), which indicates a phosphorus flush as PP into the rivers at the onset of the rains through surface runoff. The positive correlation between discharge and TP, PP (Figure 5.7), which, together with the discharge and TSS previously obtained in Chapter 4, indicates PP dependency on episodic events of high transport of particulate material in the flowing river water.

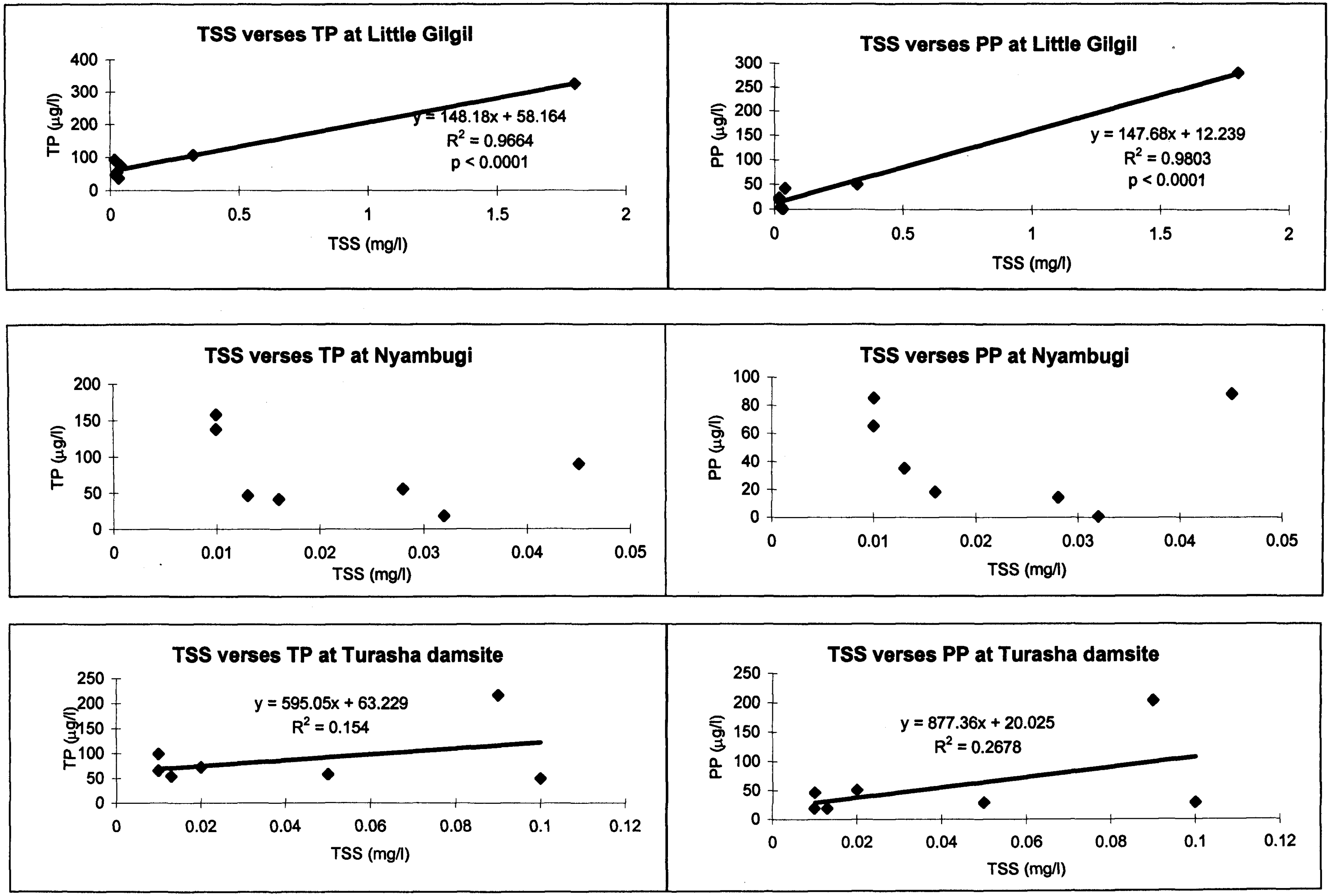


Figure 5.3 Scatter diagrams of TSS verses TP and PP in Turasha, Nyambugi and Little Gilgil

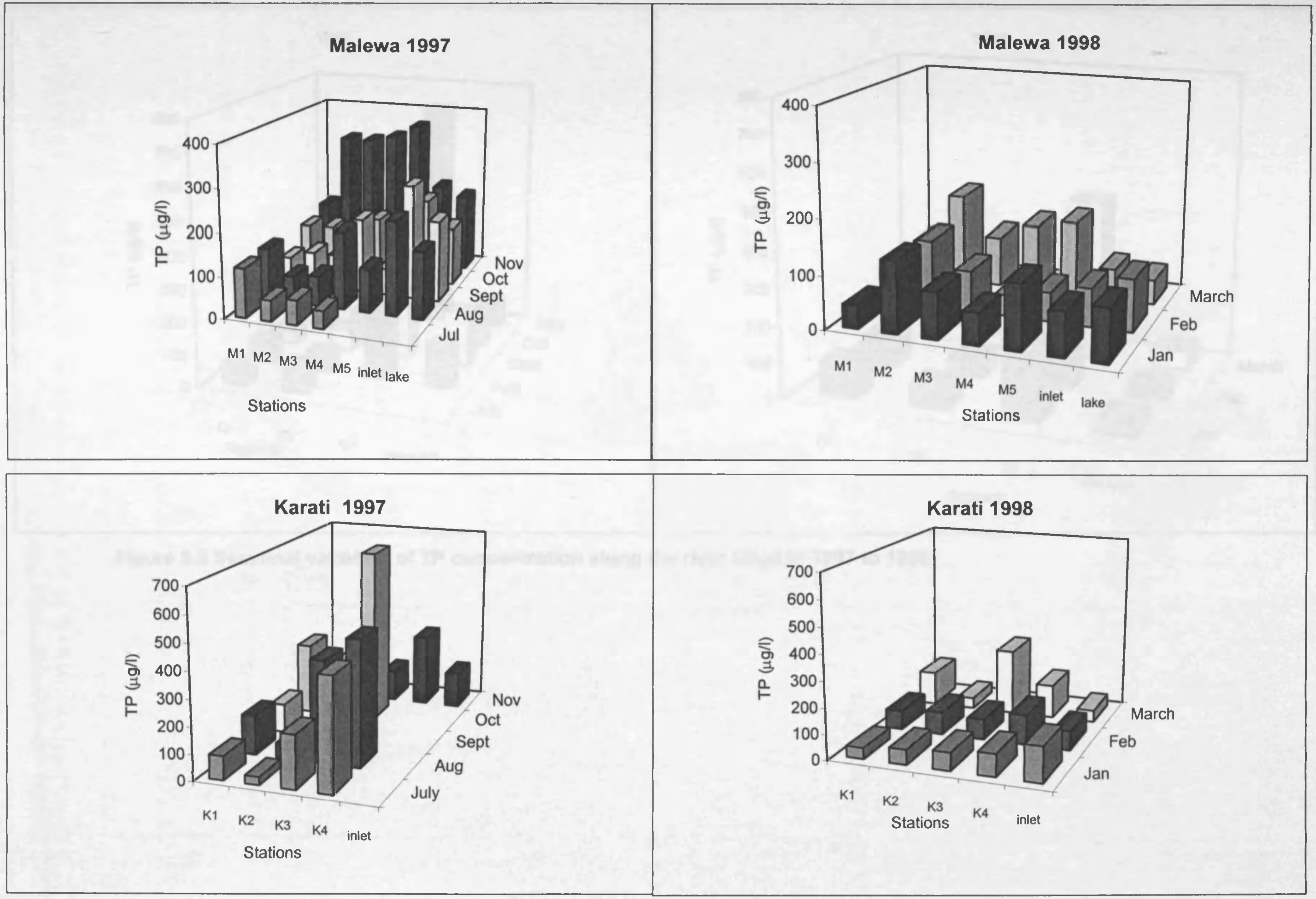


Figure 5.4 Seasonal variation of TP concentration along the rivers Malewa and Karati in 1997 to 1998

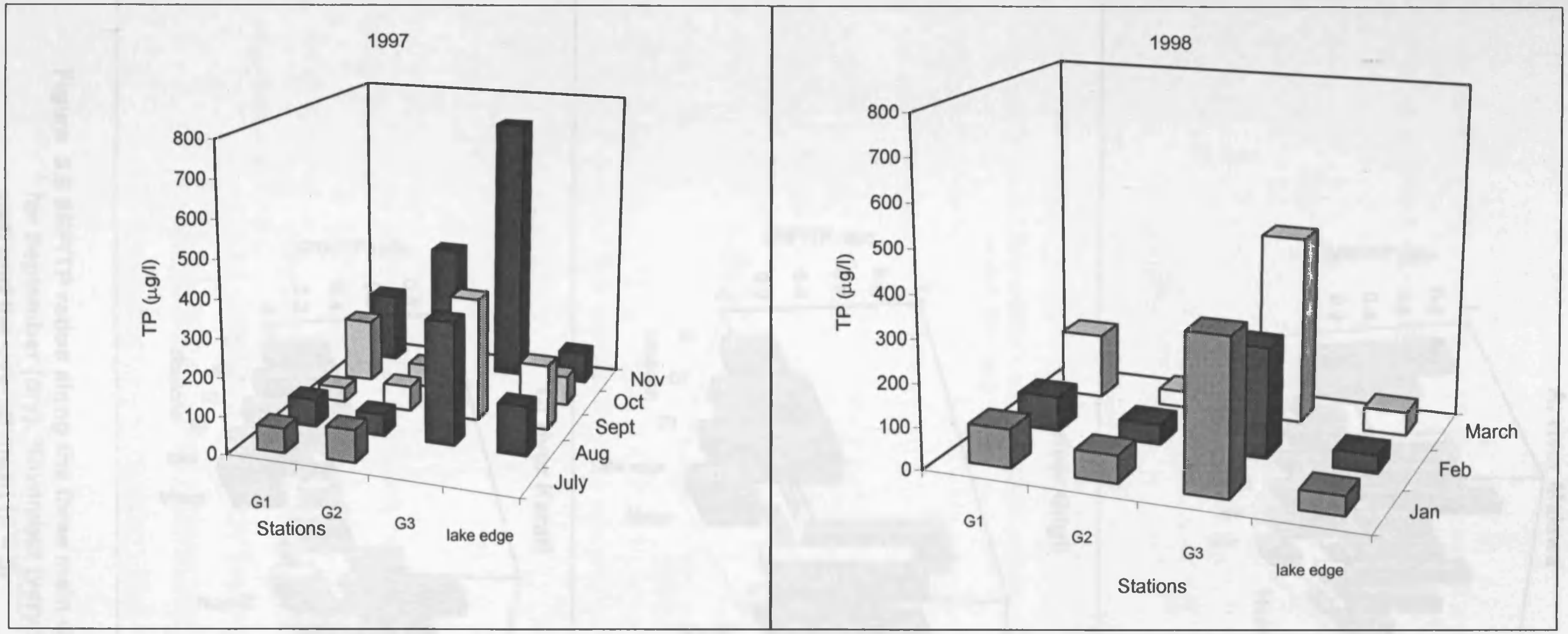


Figure 5.5 Seasonal variation of TP concentration along the river Gilgil in 1997 to 1998

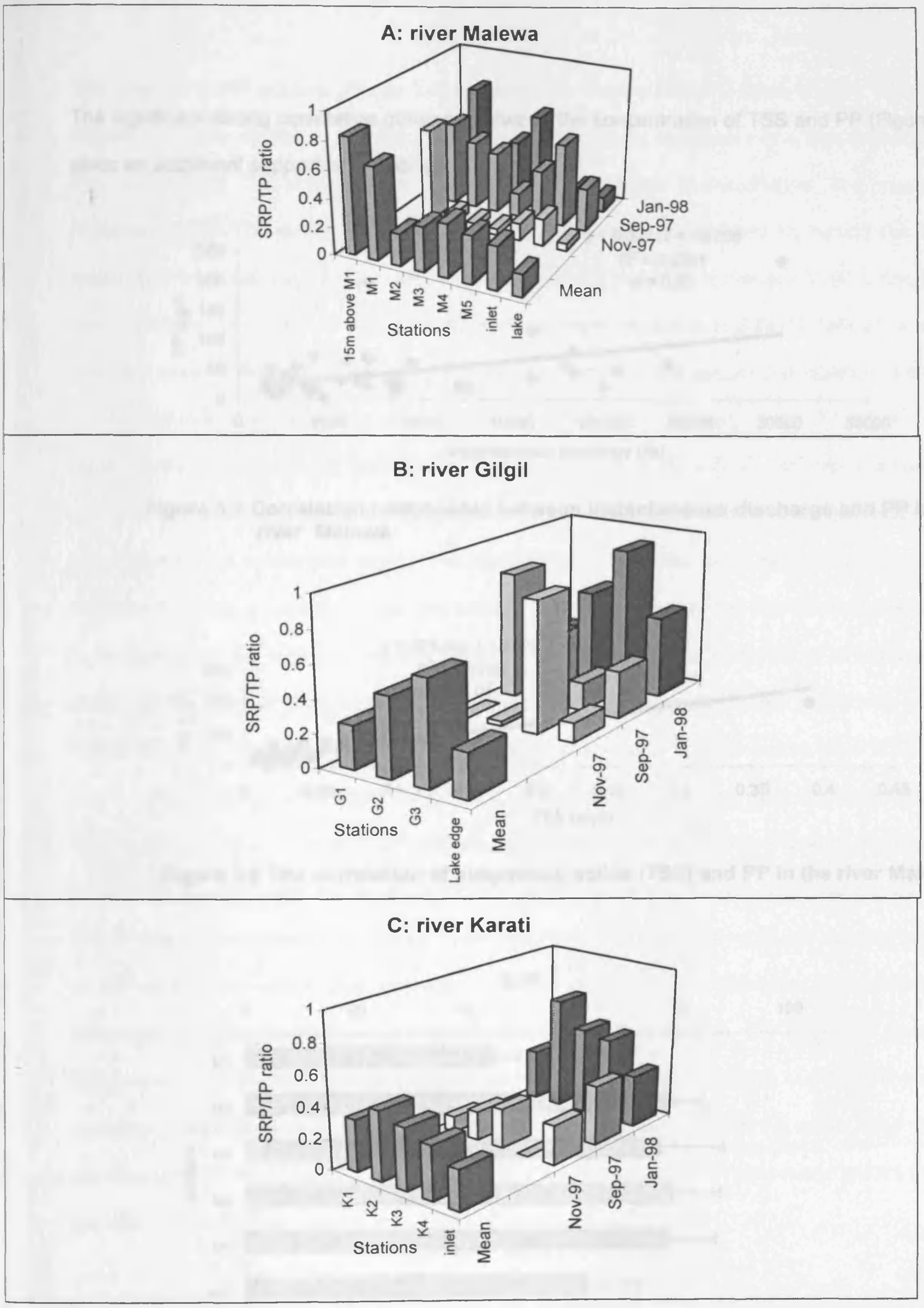


Figure 5.6 SRP/TP ratios along the three main rivers of the Naivasha catchment for September (dry), November (very wet) 1997, January 1998 (normal wet) and the overall mean (n = 9)

The significant strong correlation obtained between the concentration of TSS and PP (Figure 5.8) gives an additional support of the above.

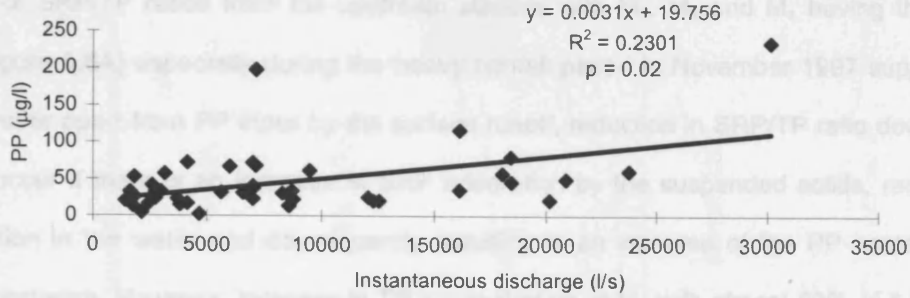


Figure 5.7 Correlation relationship between instantaneous discharge and PP in the river Malewa

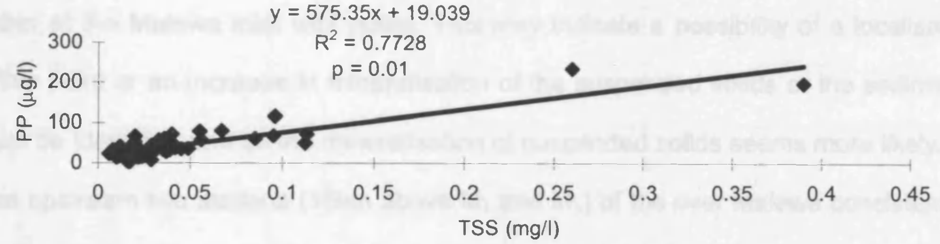


Figure 5.8 The correlation of suspended solids (TSS) and PP in the river Malewa

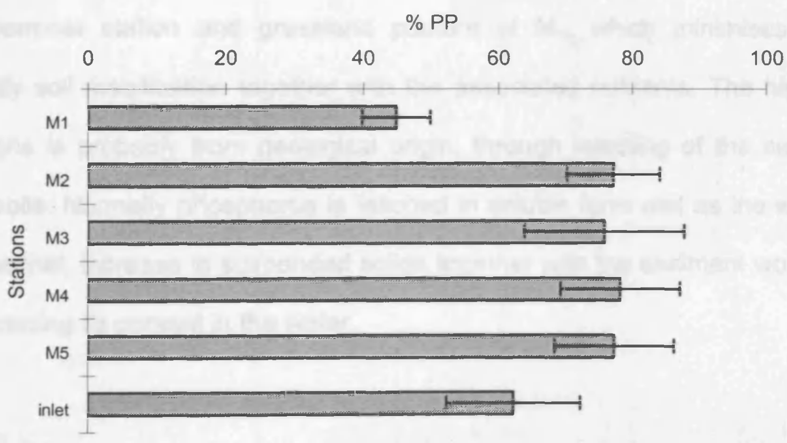


Figure 5.9 The mean (n =9) particulate phosphorus (PP) content (%) along the river Malewa between 1997-1998 (phase 1)

The increase in PP content (Figure 5.9) together with the low SRP/TP ratios (Figure 5.6A) in the middle and lower course at M_3 and M_4 of the river Malewa is suggestive of a higher phosphorus input in PP form. The probable sources will be discussed later in this chapter. The progressive reduction of SRP/TP ratios from the upstream stations with M_2, M_3 and M_4 having the lowest values (Figure 5.6A) especially during the heavy rainfall period in November 1997 supports this idea. However apart from PP input by the surface runoff, reduction in SRP/TP ratio downstream can also occur if there is an increase in SRP adsorption by the suspended solids, reducing its concentration in the water and consequently resulting in an increase of the PP content in the water downstream. However, increase in TP concentration at M_4 with almost 80% of it being PP suggests an increase in phosphorus input in PP form at this station and not just increase of SRP adsorption by the suspended solids. The reduction in TP concentration as the river approached the lake, indicates a possibility of sedimentation. A slight increase in the SRP/TP ratios especially in September at the Malewa inlet was noted. This may indicate a possibility of a localised SRP source at this point or an increase in mineralisation of the suspended solids or the sediment. No source could be identified and so the mineralisation of suspended solids seems more likely.

The upstream two stations (15km above M_1 and M_1) of the river Malewa consistently had low TP concentration (Figure 5.4A) and the highest mean SRP/TP ratio (Figure 5.6A) along the whole river channel, with >50% of phosphorus in SRP form (Figure 5.9, and Figure 5.10A). The low TP concentration observed here is mainly because the adjacent land is well covered by forest in the uppermost station and grassland pasture at M_1, which minimises soil erosion and consequently soil mobilization together with the associated nutrients. The high SRP content in these stations is probably from geological origin, through leaching of the surrounding volcanic rocks and soils. Normally phosphorus is leached in soluble form and as the water flows through the river channel, increase in suspended solids together with the sediment would adsorb most of the SRP reducing its content in the water.

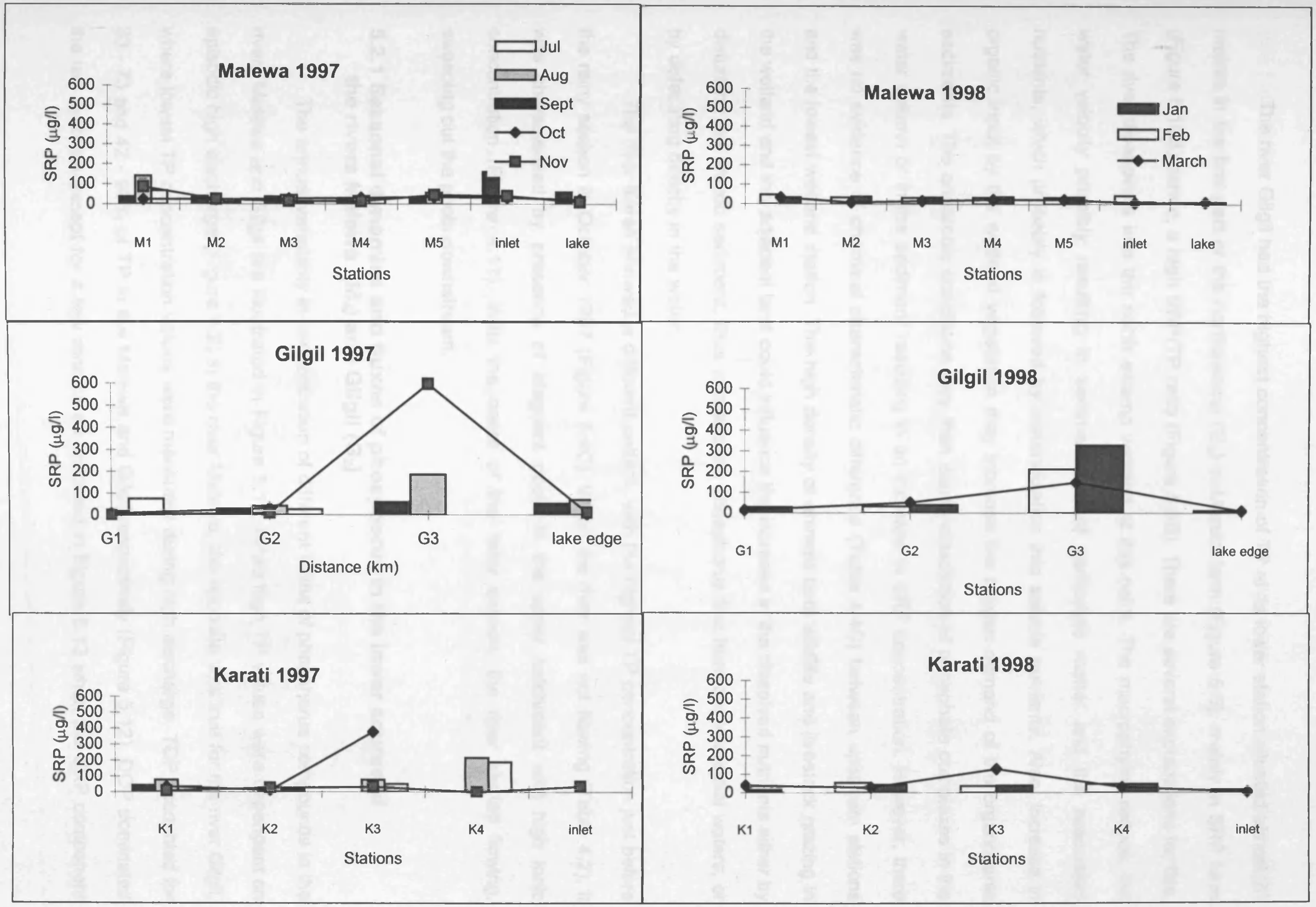


Figure 5.10: Seasonal variation of SRP concentration along the rivers, Malewa, Gilgil and Karati in 1997 to 1998

The river Gilgil had the highest concentration of TP at its lower station situated almost 20 metres in the first part of the northswamp (G_3) in Marula farm (Figure 5.5), mainly in SRP form (Figure 5.10B) hence, a high SRP/TP ratio (Figure 5.6B). There are several explanations for this. The river disappears into the north swamp wetland at this point. The macrophytes reduce, the water velocity possibly resulting in sedimentation of particulate matter and the associated nutrients, which probably is followed by mineralization into soluble nutrients. Also, increase in organic input by the wetland vegetation may increase the oxygen demand of the organogenic sediments. The anaerobic conditions may then cause dissolution of phosphate complexes in the water column or in the sediment resulting in an increase in SRP concentration. However, there was no evidence of chemical characteristic difference (Table 4.4C) between upstream stations and the lowest wetland station. The high density of animals both wildlife and livestock grazing in the wetland and the adjacent land could influence the increase in the dissolved nutrients either by disturbing the anoxic sediment, thus accelerating phosphorus flux from the interstitial waters, or by defecating directly in the water.

The river Karati showed a different pattern, with the highest TP concentration just before the rainy season in October 1997 (Figure 5.4C). When the river was not flowing (Table 4.2), it was characterized by presence of stagnant pools in the upper catchment with high ionic concentration (Figure 4.11). With the onset of the rainy season, the river started flowing, sweeping out the pools downstream.

5.2.1 Seasonal dynamics and fluxes of phosphorus in the lower course of the rivers Malewa (M_4) and Gilgil (G_2)

The annual variability in concentration of different forms of phosphorus compounds in the rivers Malewa and Gilgil are illustrated in Figure 5.11. While high TP values were dependent on episodic high discharge (Figure 4.2) in the river Malewa, the opposite was true for the river Gilgil, where lowest TP concentration values were measured during high discharge. TDP accounted for 33 - 73 and 42 - 90% of TP in the Malewa and Gilgil respectively (Figure 5.12). DOP dominated the two systems except for a few months as indicated in Figure 5.13 when the SRP component was high. But there was no clear pattern in relation to discharge. The mean annual SRP/TP ratio of 0.25, means that at least 25% of TP reaching the lake is in inorganic soluble form

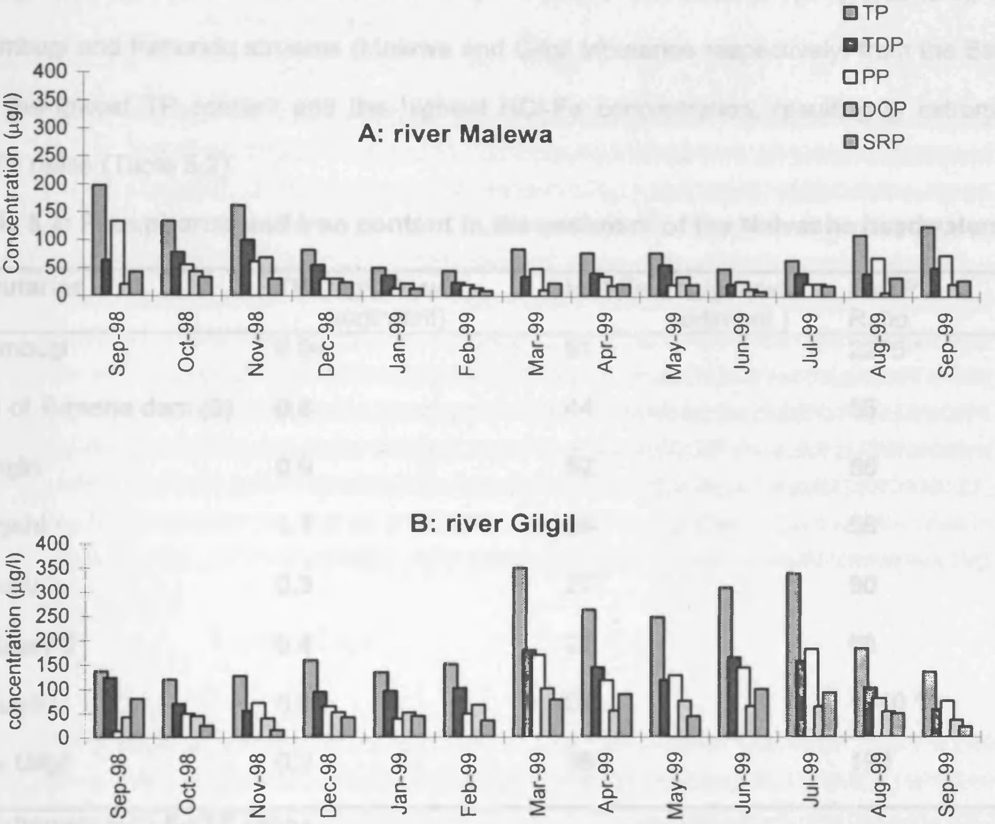


Figure 5.11 Annual concentration of different forms of phosphorus on the lower course of the rivers Malewa (M_3) and Gilgil (G_2)

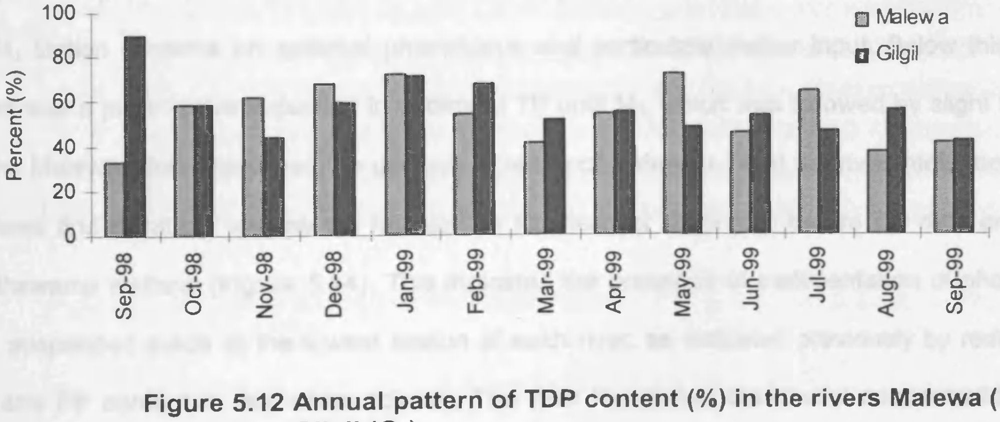


Figure 5.12 Annual pattern of TDP content (%) in the rivers Malewa (M_4) and Gilgil (G_2)

5.3 Phosphorus in the sediment.

Among the headwaters streams and rivers, the river Wanjohi and its tributary Njangiri had the highest sediment TP content, followed by the inlet of the Turasha dam (Turasha 3), while the Nyambugi and Kariundu streams (Malewa and Gilgil tributaries respectively) from the Bahati hills had the lowest TP content and the highest HCl-Fe concentration, resulting in extremely high Fe/TP ratios (Table 5.2).

Table 5.2: Phosphorus and iron content in the sediment of the Naivasha headwaters

Tributaries	**TP** (mg/gdrywt. sediment)	**HCl-Fe** (mg/gdrywt. sediment)	**Fe/TP** Ratio
Nyambugi	0.04	91	2275 *
Inlet of Turasha dam (3)	0.8	44	55
Njangiri	0.9	52	58
Wanjohi	1.1	64	58
Kasuku	0.3	27	90
Tributary 3	0.4	27	68
Kariundu	0.05	67	1340 *
Little Gilgil	0.2	38	190

* Extremely high Fe/TP ratios

The river Malewa had the highest sediment TP among the three main rivers of the Naivasha catchment, with the highest concentrations in the middle course of the river at M_3 (Figure 5.14). Increase in sediment TP, silt and clay component and PP form in the water column at M_3 station confirms an external phosphorus and particulate matter input. Below this station there was a progressive reduction in sediment TP until M_5, which was followed by slight increase at the Malewa inlet. There was the general increase of sediment TP at the river inlets, both at the Malewa and Karati as well as the last station for the river Gilgil (G_3) before the river enters the northswamp wetland (Figure 5.14). This indicates the presence of sedimentation of phosphorus rich suspended solids at the lowest station of each river, as indicated previously by reduction in TP and PP content in the water column. The river Karati had the lowest concentration in the middle course at K_2 and K_3 with an increase upstream at K_1 and downstream by the lake -side at the inlet (Figure 5.14C), unlike the river Malewa, which had the highest sediment TP at the middle course of the river in M_3.

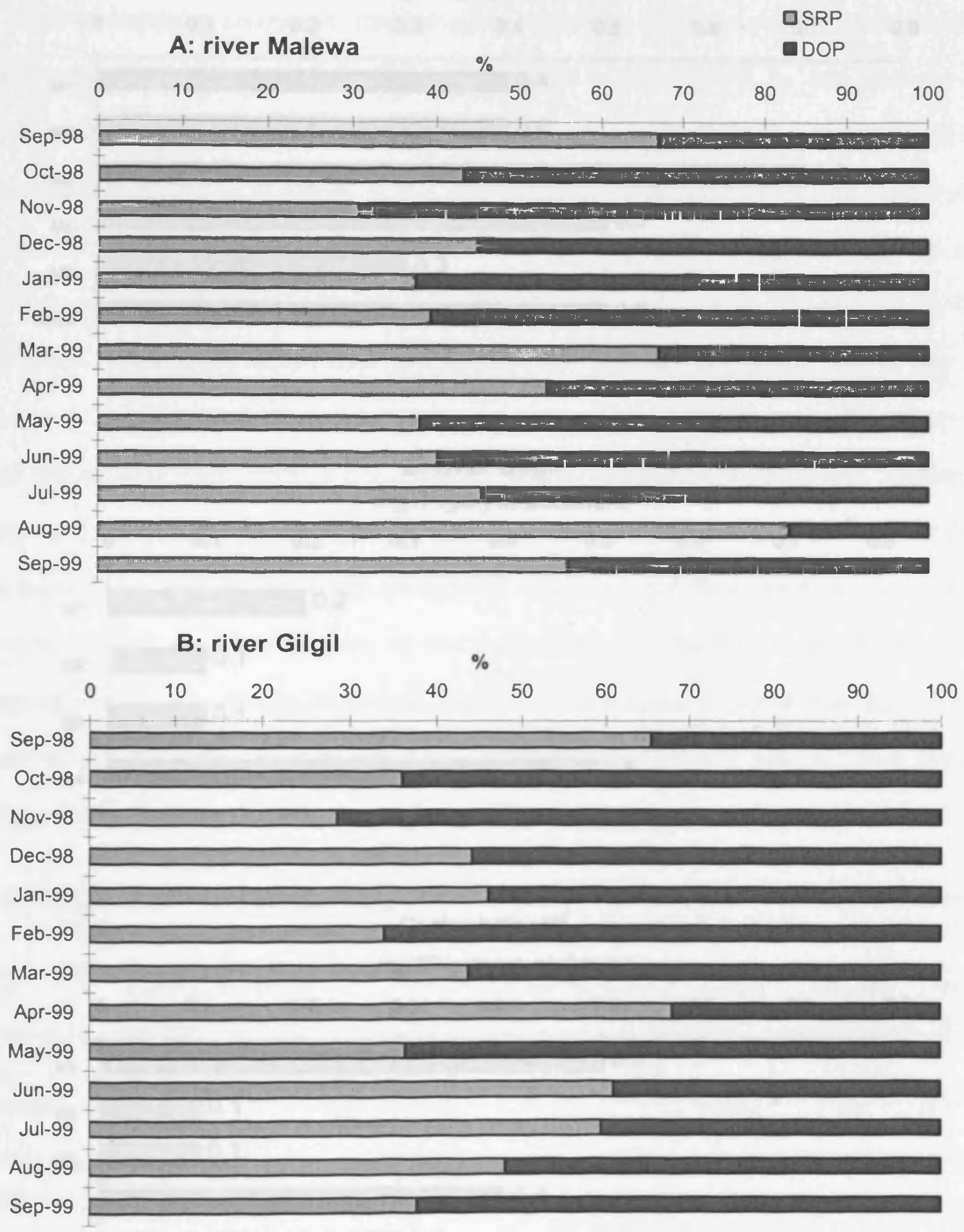


Figure 5.13 Annual pattern of TDP components (%) in the rivers Malewa (M_4) and Gilgil (G_2)

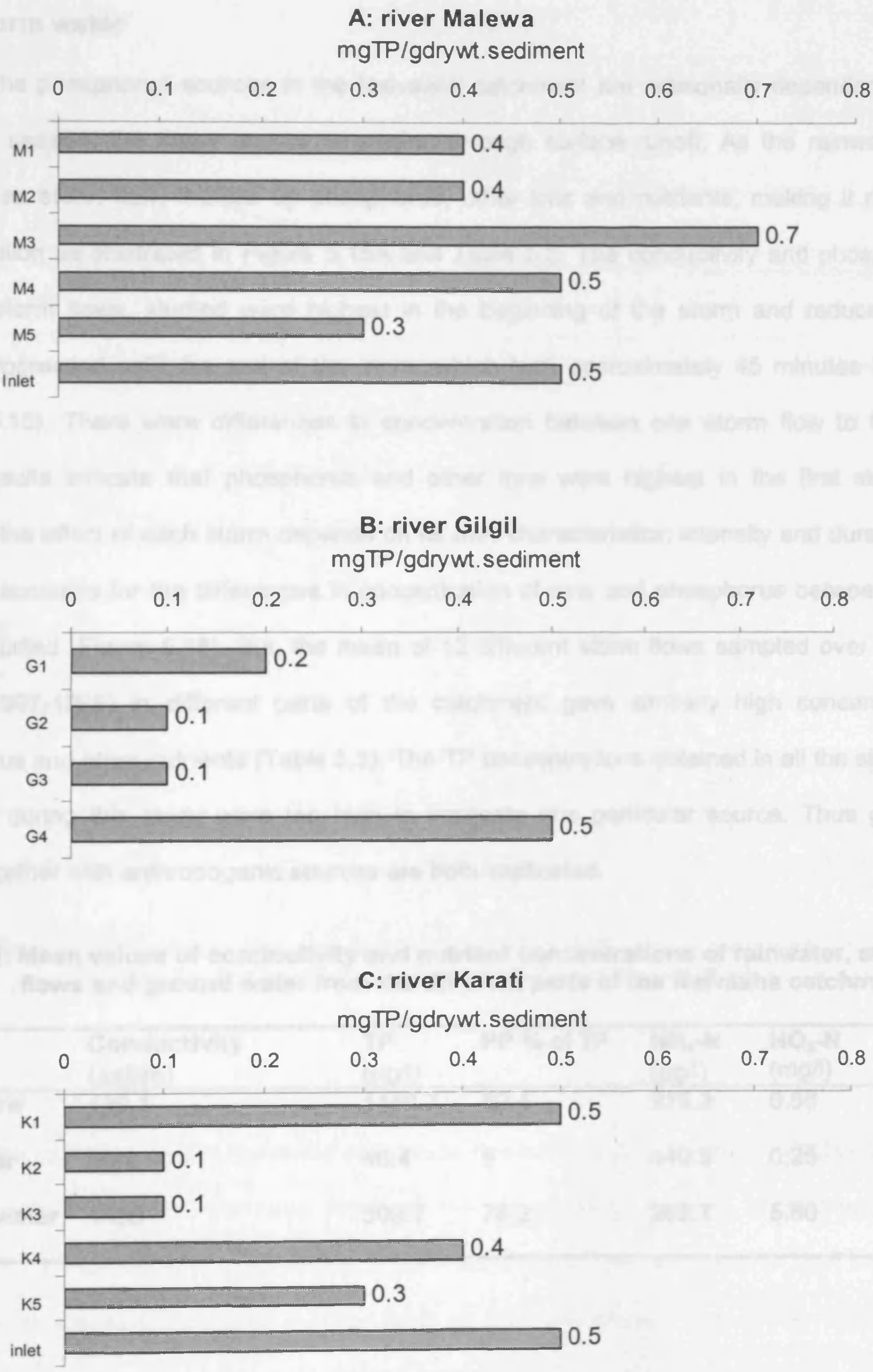


Figure 5.14 Total phosphorus in the sediment along the three main rivers of the Naivasha catchment

5.4 Sources of phosphorus in the catchment

5.4.1 Storm water

The phosphorus sources in the Naivasha catchment are seasonally dependent. During the rainy season, the major source is erosion through surface runoff. As the rainwater flows overland as storm flow, it picks up phosphorus, other ions and nutrients, making it rich in ion concentration as illustrated in Figure 5.15A and Table 5.3. The conductivity and phosphorus of the two storm flows, studied were highest in the beginning of the storm and reduced as the rainfall progressed until the end of the storm which took approximately 45 minutes to 1 hour (Figure 5.15). There were differences in concentration between one storm flow to the other. These results indicate that phosphorus and other ions were highest in the first storm flow, although the effect of each storm depends on its own characteristics; intensity and duration. This probably accounts for the differences in concentration of ions and phosphorus between the two storms studied (Figure 5.15). But, the mean of 12 different storm flows sampled over the study period (1997-1999) in different parts of the catchment gave similarly high concentration of phosphorus and other nutrients (Table 5.3). The TP concentrations obtained in all the storm flows analysed during this study were too high to implicate one particular source. Thus geological inputs together with anthropogenic sources are both implicated.

Table 5.3: Mean values of conductivity and nutrient concentrations of rainwater, storm flows and ground water from the different parts of the Naivasha catchment

Source	**Conductivity** (μs/cm)	**TP** (μg/l)	**PP %** of TP	**NH_4-N** (μg/l)	**NO_3-N** (mg/l)	**TN/TP** ratio
Storm flow (n = 12)	139.1	1168.7	50.4	219.3	0.58	6:1
Rainwater (n = 8)	10.6	46.4	5	440.5	0.25	21:1
Ground water (n = 4)	1460	509.7	78.2	262.7	5.80	118:1

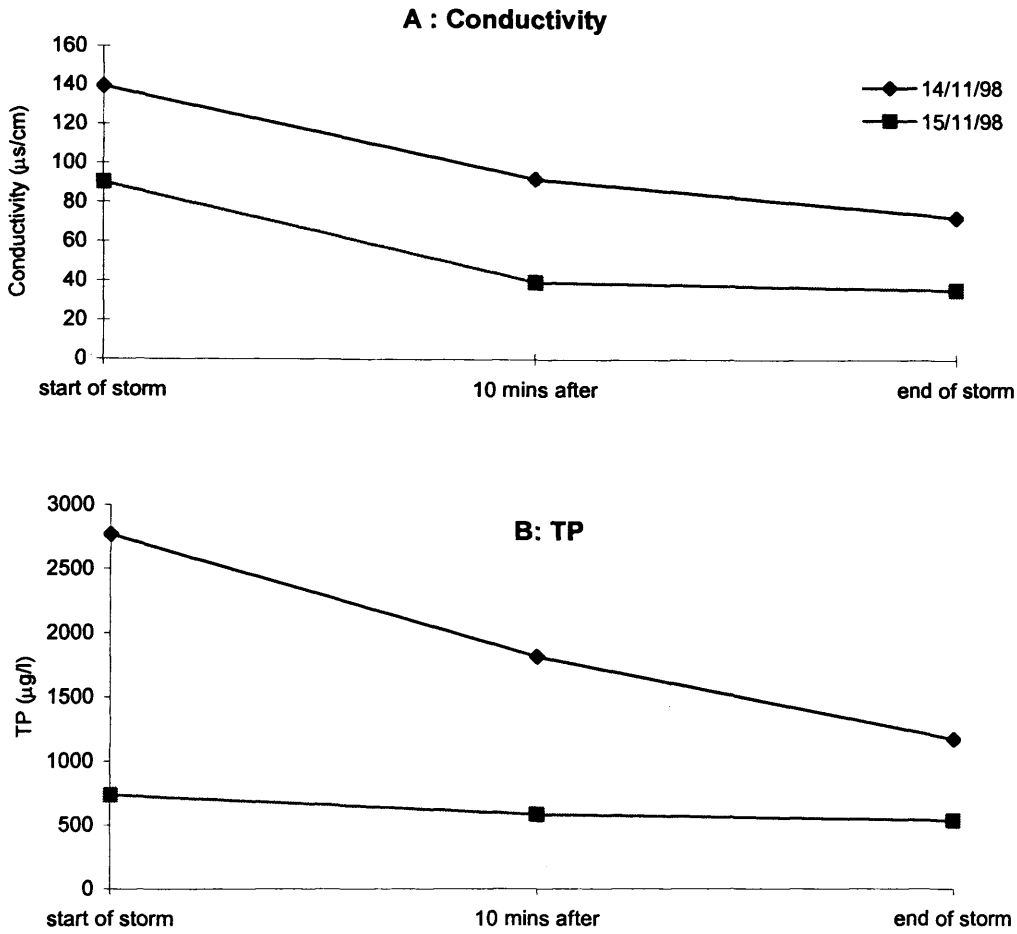


Figure 5.15 Conductivity and total phosphorus (TP) concentration of two storms in the beginning of the rainy season in November 1998

5.4.2 Rainwater

The rainwater of the Naivasha catchment is extremely rich in NH_4-N (Tables 5.3 & 5.4), probably originating from microbial debris in the atmosphere. Analysis of different forms of phosphorus at the start of the rainy season from mid October 1997 to February 1998 showed that TP concentration was highest at the beginning of the rainy season with PP dominating (Table 5.4). The three rainwater samples collected between October 1997 and February 1998 shows that TP concentration and PP content decreased as the rainy season progressed (Table 5.3), with SRP component becoming more important with an overall content of 95% of TP (Table 5.3).

Table 5.4: Chemical composition of three rainwater samples from the lower Naivasha catchment during the extremely rainy season in October 1997 to February 1998

Date		Conductivity (μs/cm)	TP (μg/l)	PP % of TP	NH_4 - N (μg/l)	NO_3 - N (mg/l)	TN/TP ratio
20/10/97	Start of the rainy season	13.4	123.7	73.4	1130.4	0.58	23:1
30/10/97	10 days later	10.2	57.1	1.2	230.0	0.42	13:1
14/11/97	Middle of the rainy season	6.9	17.7	15.8	310.2	0.13	31:1

Presence of atmospheric dust is indicated by high percentage of PP in the beginning of the rainy season. This suggests that atmospheric dust around the Naivasha town is rich in phosphorus. In normal circumstances the amount of atmospheric dust is expected to be at its maximum just before the rains and most of it is washed down in the beginning of the rainy season together with associated nutrients. Lake Naivasha lies in an intensive agricultural area with volcanic soils, meaning that the atmospheric dust might be rich in nutrients since they originate from the fertilized agricultural soils or from nutrient rich volcanic ash. This explains why conductivity, TP and PP concentration reduced in the rainwater as the rainy season progressed (Table 5.4). However, the slight increase in PP % content in the middle of the rainy season would imply a slight re-introduction of atmospheric dust probably from the short spells of hot non-rainy days.

During the heavy rainy season, the soils in the upper catchment got waterlogged and ground springs started oozing from the riverbanks into the rivers especially the Malewa and Karati. The chemical composition of the water from these springs was extremely rich in ions and nutrients especially phosphorus (Table 5.3). However it was not possible to estimate the actual TP yields into the rivers from these springs.

5.4.3 Livestock watering

One of the most frequent disturbances experienced by the Naivasha catchment streams and rivers during the dry season is watering of livestock in the river. This is indicated by the frequent occurrence of watering sites in the river Malewa illustrated in Table 4.4 & Table 5.5. An elevated concentration of TP was obtained at the most disturbed site (impact site, B) and 500 m below (C) between 11.00 AM and 4.00 PM (Figure 5.16), with an increase range between 6.5 - 15 μg/l (Figure 5.16). This coincides with the high disturbance period (when most of the livestock were visiting the river) between 12.00 and 3.00 PM (Tables 5.6 & 5.7). However, TP concentration was not significantly different between the three sites (A, B, C) ($p > 0.05$), but was significantly different over the hours of the day ($p < 0.0001$) using two way ANOVA.

Table 5.5: Livestock watering sites from M_3 at the middle course of the river Malewa up to the lake

Station	**Distance** from the lake edge (Km)	**Human activities** (disturbance scale from Table 4.4)
Malewa pump House (M_2)	35.5	Intense watering of livestock, and tree nurseries and vegetable gardens (**4**)
Turasha ridge (M_3)	30.5	Very intense watering site (**5**)
Kigio campsite	29.0	Occasional watering site (**2**)
Kasuku (River lodge)	27.1	Occasional watering site and river canoeing (**2**)
Below River lodge	26.5	Intense watering site and river canoeing (**4**)
Kigio pump house	25.5	Intense watering site and river canoeing (**4**)
Malu farm	15.5	Intense watering site (**4**)
Naivasha-Nakuru Road (M_4)	10.5	Very intense watering site, and heavy washing of cars and clothes (5)
Marula dam site	3.5	Intense watering site (**4**)
Marula lower (M_5)	2.5	Occasional watering site (**2**)

As the animals drink water they trample and disturb the streambed resulting to re-suspension of sediment together with its bound phosphorus (Table 5.6). Increase in TSS concentration at the impact site (Figure 5.17) at the time when most of the livestock are frequently visiting the river, although not significant ($p > 0.05$) is evidence of sediment disturbance (Table 5.6). The re-suspension of the sediment might result in release of phosphorus from the interstitial waters, mainly in dissolved form. This may account for the slight increase of TDP at the impact site and below between 10.00 AM to 4.00 PM (Figure 5.18).

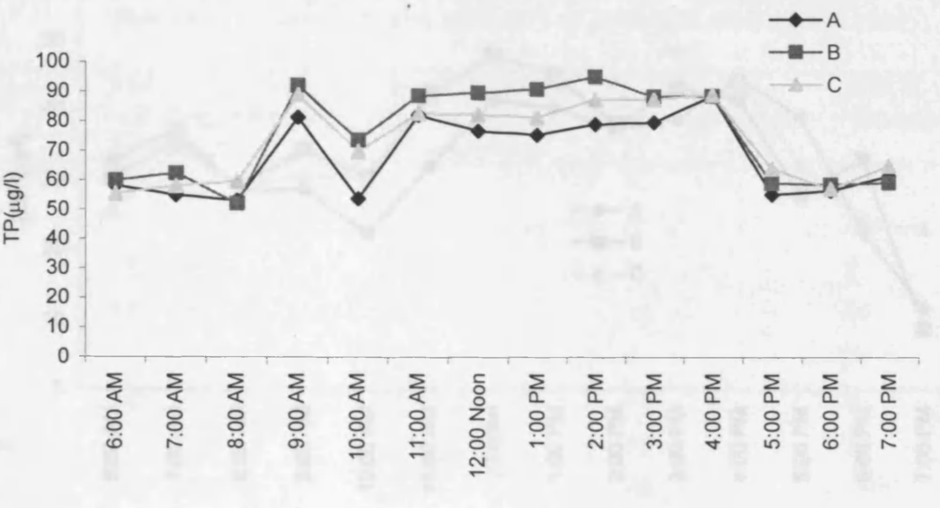


Figure 5.16 Hourly changes of total phosphorus (TP) concentration at M_3 station in the middle course of the river Malewa (A = above impact site, B = impact site and C = below impact site)

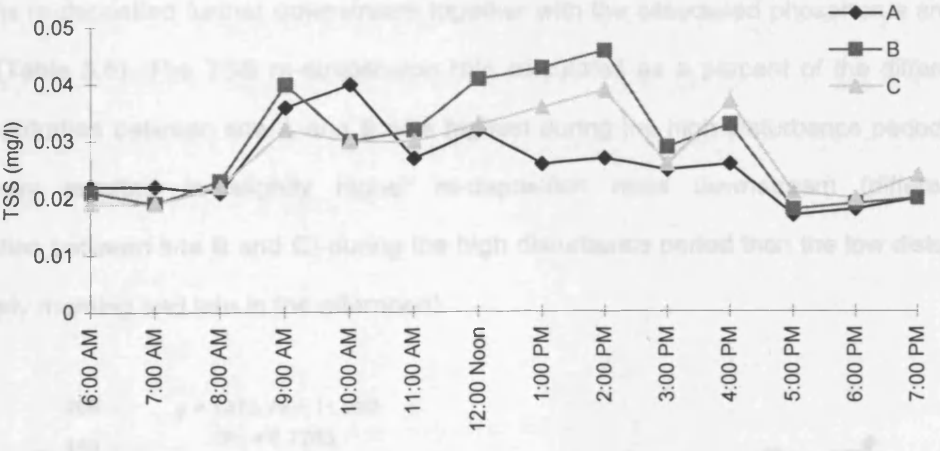


Figure 5.17 Mean hourly changes of TSS at M_3 above the impact site (A), impact site (B) and below the impact site (C)

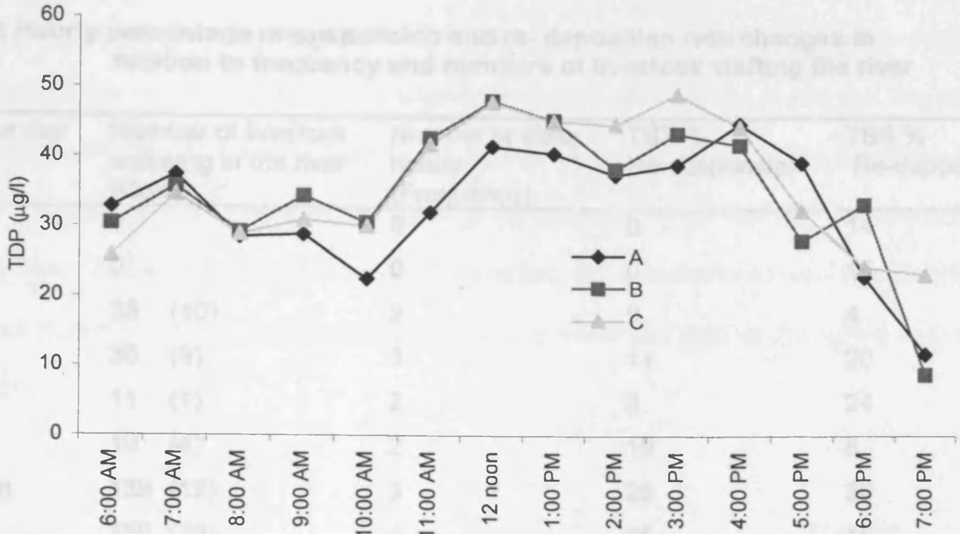


Figure 5.18 Comparison of hourly changes of total dissolved phosphorus (TDP) at M_3 above the impact site (A), impact site (B) and below the impact site (C)

Reduction of TSS concentration occurred below the impact site at C (Figure 5.17), although this was not significant (P > 0.05), but it indicates that some of the re-suspended and re-mobilized sediment is re-deposited further downstream together with the associated phosphorus and other minerals (Table 5.6). The TSS re-suspension rate calculated as a percent of the difference in TSS concentration between site A and B was highest during the high disturbance period, which consequently resulted in slightly higher re-deposition rates downstream (difference in concentration between site B and C) during the high disturbance period than the low disturbance period (early morning and late in the afternoon).

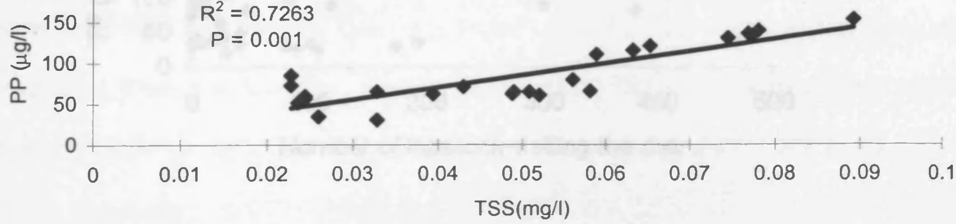


Figure 5.19 The correlation between TSS and PP below the impact site at C

Table 5.6: Hourly percentage re-suspension and re- deposition rate changes in relation to frequency and numbers of livestock visiting the river

Time of the day	Number of livestock watering in the river (Cows)	Number of visits hourly (Frequency)	TSS % Re-suspension	TSS % Re-deposition
6.00 am	0	0	0	14
7.00 am	0	0	0	14
8.00 am	38 (10)	3	9	4
9.00 am	36 (9)	3	11	20
10.00 am	11 (1)	2	3	24
11.00 am	10 (4)	2	19	8
12.00 noon	139 (12)	3	28	20
1.00 pm	159 (28)	4	65	16
2.00 pm	194 (32)	4	70	15
3.00 pm	26 (4)	3	16	10
4.00 pm	8 (3)	1	27	3
5.00 pm	8 (8)	1	6	0
6.00 pm	0	0	6	0
7.00 pm	0	0	3	0

The highly significant correlation between TSS and PP obtained for site C below the impact site (Figure 5.19) give further evidence of sediment disturbance upstream. However this is not clearly portrayed the correlation (R2 = 0.0016) between the number of livestock visiting the river and the total phosphorus concentration (Figure 5.20).

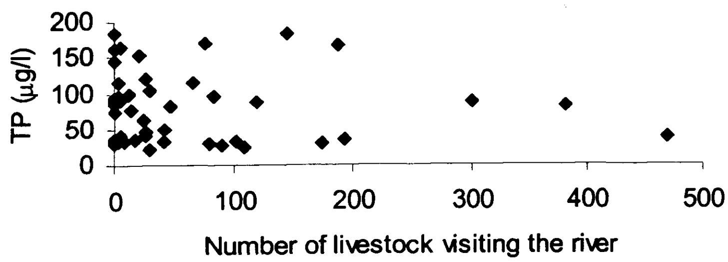


Figure 5.20 The relationship between total phosphorus (TP) and the number of livestock visiting the river at the impact site(B) in station M_3.

Figure 5.21 illustrates the difference in TP concentration between upstream of the impact site (A) and the disturbed impact site (B) for the time when most of the livestock were visiting the river. There was loss of phosphorus in the water column between the site A and B in the morning hours before 10.00 AM, followed by progressive gain of TP concentration at site B with maximum at 1.00 to 2.00 PM in the afternoon during high disturbance, when most of the livestock are visiting the river (Table 5.7). The amount of TP input into the water column was significantly ($p = 0.01$) higher during base-flow than medium flow with a maximum gain of 20 µgTP/l at 2.00 PM (Figure 5.21).

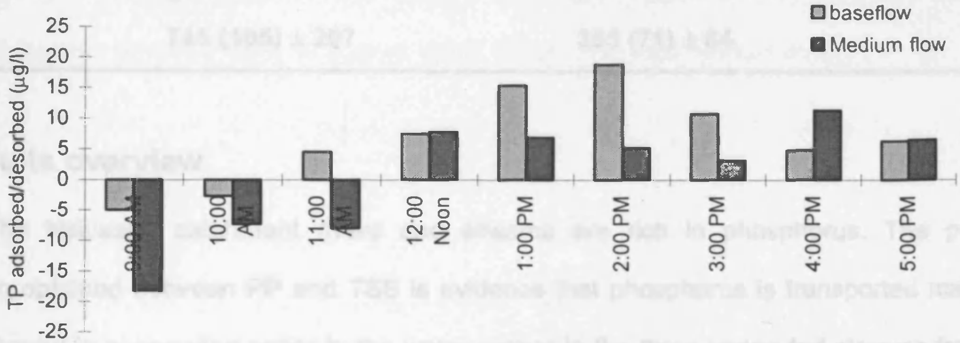


Figure 5.21 Hourly changes in TP adsorbed (minus) or desorbed (plus) from the water column at site B of M_3 during low and medium discharges

There were almost twice as many livestock visiting the river during the period of low flow compared with medium-high flow (Table 5.7). This implies that there was either more frequent, or larger groups of livestock visiting the river during the day resulting in a higher intensity disturbance during the low-flow hence, the higher nutrient input. On the other hand the TP concentration could be exaggerated as a result of low dilution by the low water flow in the river. However, there was more TP removal from the water column in the morning hours during the medium flow period than the low flow (Figure 5.21) either through sedimentation, sediment sorption or biological uptake, although none of these was investigated during this study.

Table 5.7: Comparison of mean (± SD) number of livestock (Cows in brackets) visiting the river Malewa at M_3 station during low and medium discharges

Time	**Low flow** (3914 l/s ± 114, n = 3)	**Medium-high flow** (16545 l/s ± 299, n = 3)
9:00 AM	54 (9) ± 10	0
10:00 AM	4 (1) ± 3	23 (2) ± 5
11:00 AM	14 (3) ± 5	5 (5) ± 2
12:00Noon	161 (3) ± 20	105 (26) ± 10
1:00 PM	193 (41) ± 55	109 (10) ± 38
2:00 PM	271 (39) ± 102	79 (24) ± 25
3:00 PM	35 (5) ± 8	13 (2) ± 3
4:00PM	13 (4) ± 4	2 (2) ± 1
5:00 PM	0	0
Total	**745 (105) ± 207**	**355 (71) ± 84**

5.5 Results overview

The Naivasha catchment rivers and streams are rich in phosphorus. The positive correlation obtained between PP and TSS is evidence that phosphorus is transported mainly in PP form bound in suspended solids in the water except in the three spring fed streams from the Olmogogo hills and the upper stations of the river Malewa with a good vegetation cover where dissolved phosphorus transport dominated. Transport and mobilization of PP and TSS is controlled by the hydrological regimes of the rivers and streams as indicated by the positive correlation obtained between discharge and PP together with TSS. Total phosphorus (TP) in the sediment did not follow the same trend as the water column, although only a few stations were analysed for sediment TP and occasionally its components.

There is phosphorus flush into the rivers and streams during the rainy season. The high concentration of different forms of phosphorus in the storm flow as opposed to the low concentrations in the rainwater within Naivasha and its environs suggests phosphorus input through surface runoff. As Heathwaite (1997) noted, the balance between rainfall input and runoff generation is an extremely important factor in phosphorus loss (P loss), despite being a highly site-specific process (Morgan 1997). These results also evidently suggest that watering of livestock in the river causes elevated concentrations of phosphorus, dominated mainly by PP form. Increase in TSS at the impact site and below, implicate that most PP is bound in suspended solids, which mainly consist of re-suspended fine sediment caused by sediment disturbance by the livestock as they drink water during the dry season. The influence and extent of sediment disturbance by livestock to phosphorus content and other nutrients downstream depends on discharge, intensity and frequency of the disturbance.

In addition atmospheric deposition of phosphorus in the lake seems important at the beginning of the rainy season, however its importance reduces as the rainy season progresses. This implies that most of the atmospheric dust with the associated nutrients are washed down at the beginning of the rainy season either directly into surface water or may reach the streams, rivers and the lake as storm flows or ground water, influencing their nutrient status.

CHAPTER 6

PHOSPHORUS DYNAMICS IN LAKE NAIVASHA

6.1 Chemical characteristics of lake Naivasha

The riverine influence on water chemistry of lake Naivasha is shown by a spatial variation in conductivity (Figure 6.1), transparency measured as Secchi depth (Figure 6.2), and chlorophyll *a*, (Figure 6.3), from the Malewa inlet to the open water. Lowering of lake water conductivity through dilution by the river water and a decrease in transparency due to increase in TSS extended almost to 0.5 km into the lake in November 1997. There was a significant negative correlation between Secchi depth and TSS (Figure 6.4 1A & 1B). A stronger negative correlation between chlorophyll *a* and Secchi depth was obtained in the open water compared to the Malewa inlet (Figure 6.4 2A & 2B). The inference here is transparency in the open water is induced by variations in algal biomass as well as suspended solids, although the latter has the greatest influence in the riverine ecotonal region. However using multivariate analysis, TSS significantly ($R^2 = 0.67$, $p < 0.0001$) influence water transparency in the open water than algal biomass ($R^2 = 0.003$, $p > 0.05$). But a strong significant positive correlation between TSS and Chlorophyll *a* ($R = 0.871$, $R^2 = 0.758$, $n = 20$ $p < 0.0001$) was obtained at the open water station, suggesting that the

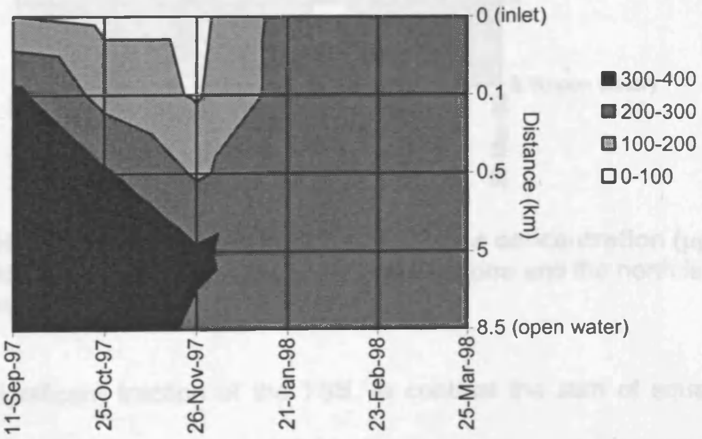


Figure 6.1 Longitudinal variation of conductivity (μs/cm) along a transect from the Malewa inlet into the open water. Note that the scale is not uniform and north is approximately upwards

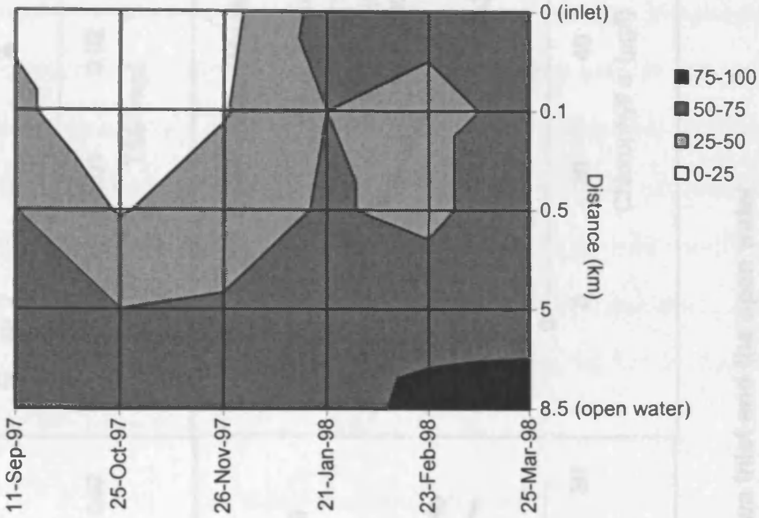


Figure 6.2 The river Malewa influence in water transparency measured as Secchi depth (cm) in lake Naivasha. Note that the scale is not uniform and north is approximately upwards

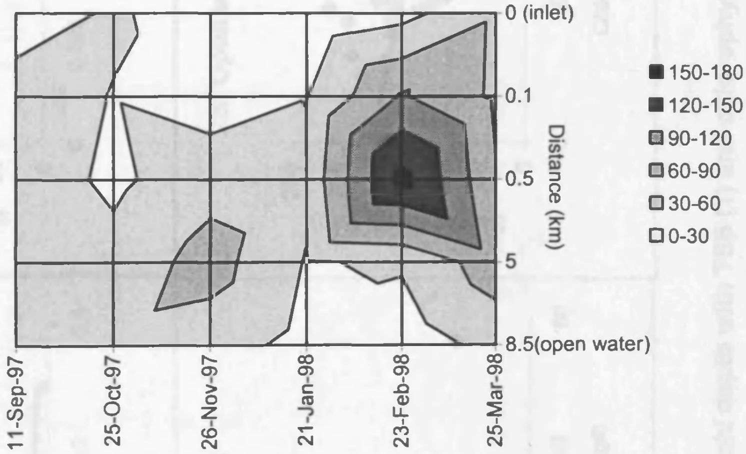


Figure 6.3 Horizontal distribution of chlorophyll *a* concentration (µg/l) in lake Naivasha. Note that the scale is not uniform and the north is approximately upwards

algae make up a significant fraction of the TSS. In contrast the sum of squares (R^2) obtained between Chlorophyll *a* - Secchi depth and TSS in the open water was almost twice as large when using monthly mean values than weekly values (Figure 6.4 2B & 2C). This suggests that wind-induced circulation of the lake does bring sediment up into the water column and consequently

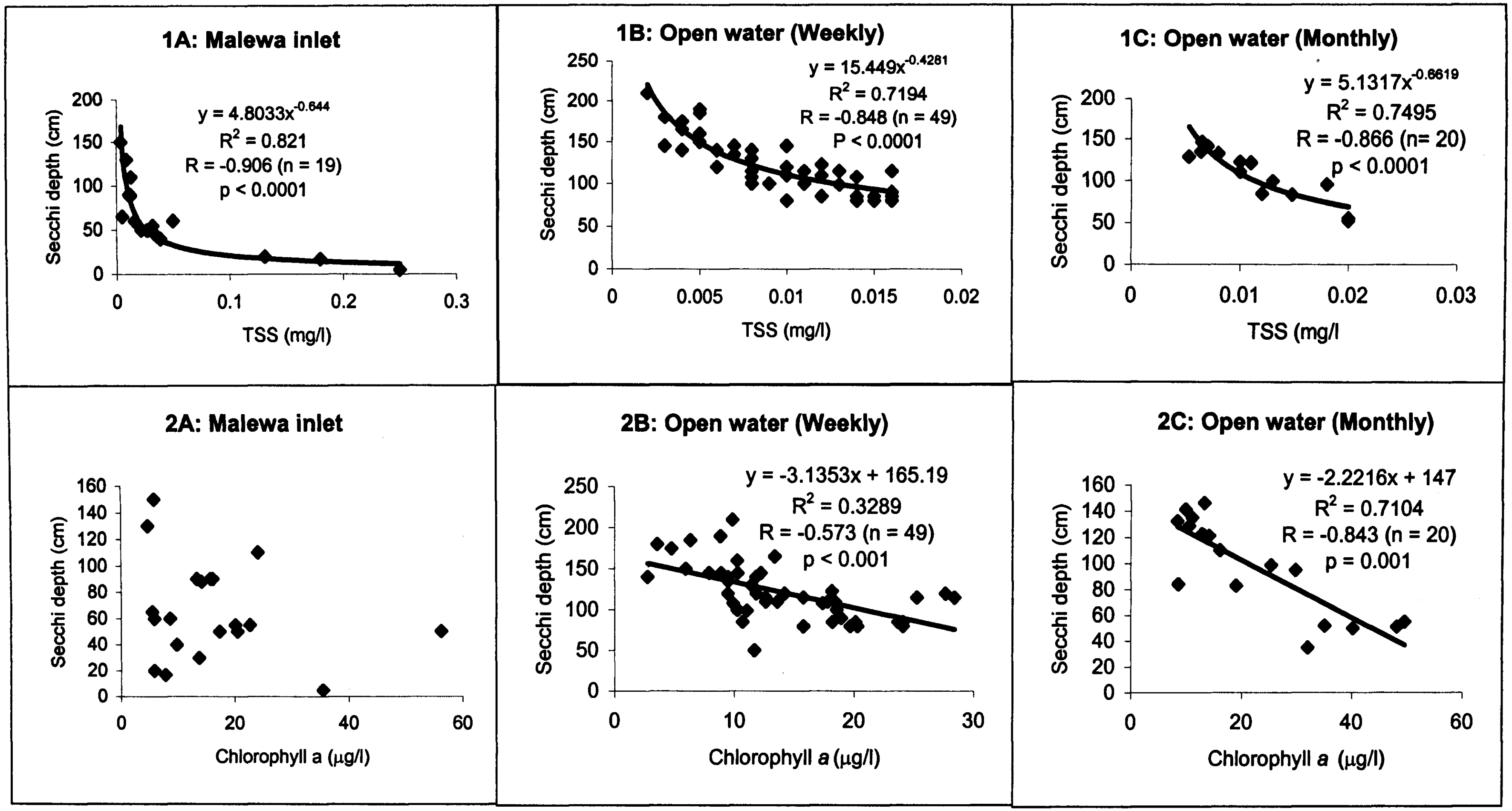


Figure 6.4 Relationship of Secchi depth with TSS (1) and chlorophyll *a* (2) at the Malewa inlet and the open water

reduce the water transparency (Secchi depth) even during low algal biomass.

The chemical characteristic changes along the transect from the Malewa inlet to the open water were more pronounced at the beginning of the heavy rainy season between October and November 1997 for as much as 0.5 km from the river mouth into the lake (Figure 6.1- 6.3). The heavy rainfall started at the end of October 1997 but the lake level did not change immediately, until almost two months later in January 1998, (Figure 6.5) when the river mouth was almost 2.5 km upstream of its normal position as demonstrated by changes in conductivity (chapter 4). This dramatically changed the riverine characteristics portrayed in September to November 1997 into lake conditions in January to March 1998 (Figure 6.1 – 6.3).

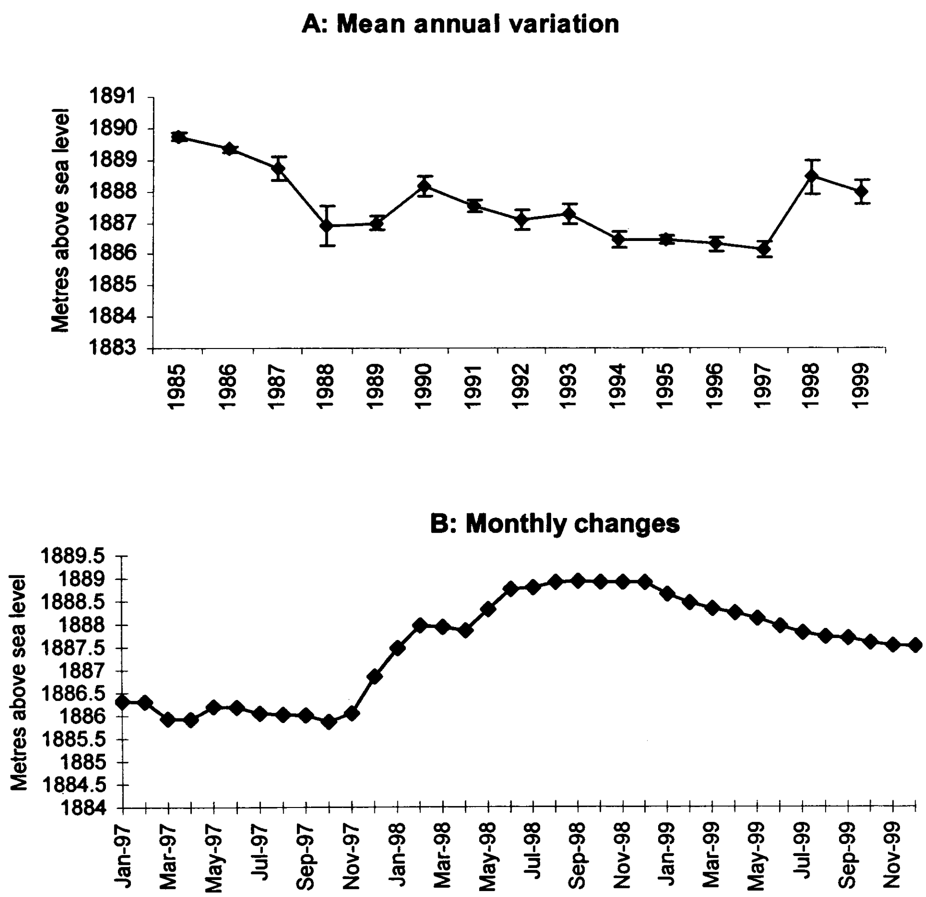


Figure 6.5 Lake Naivasha mean annual lake level for 1985-1999 (mean ± SD) and monthly changes in 1997-1999 (data by courtesy of Sulmac Horticultural farm, Naivasha)

Mean horizontal variations of other chemical characteristics are illustrated in Table 6.1. They all show a general increase from inlet towards the open water over about 5 km, although most changes occurred in the first 0-0.5 km.

Table 6.1: Mean (± SD) values showing longitudinal distribution of some chemical water characteristics of lake Naivasha (n = 7)

Distance (km)	**Temperature** ($0^{C)}$	**pH**	**Alkalinity** (mg/l $CaCO_{3)}$	**Total hardness** (mg/l $CaCO_{3)}$	**Calcium hardness** (mg/l $CaCO_3$)
Malewa inlet	22.0 ± 2.7	7.6 ± 0.4	113 ± 47	43 ± 16	21 ± 8
0.1	23.2 ± 1.6	7.4 ± 1.3	134 ± 50	52 ± 17	35 ± 10
0.5	24.8 ± 0.4	8.3 ± 0.4	156 ± 32	61 ± 11	50 ± 11
5 (central)	24.8 ± 1.9	8.7 ± 0.1	161 ± 46	69 ± 11	50 ± 8
8.5 (south)	25.4 ± 1.4	8.7 ± 0.8	162 ± 61	71 ± 14	49 ± 5

6.2 Phosphorus dynamics in the water column

6.2.1 Horizontal distribution

The horizontal distribution of TP showed a general decrease in concentration from the river mouth (Malewa inlet) into the open water, as illustrated in Figure 6.6.

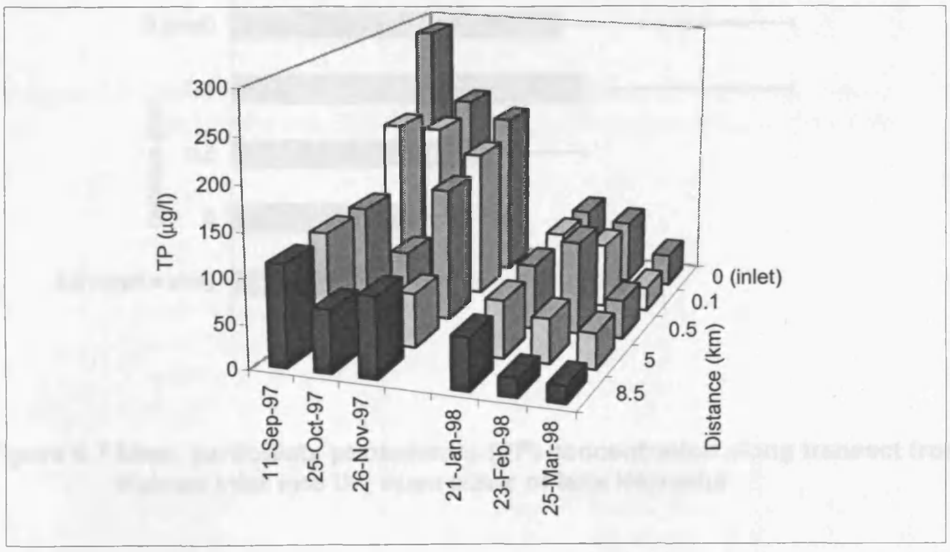


Figure 6.6 Horizontal TP concentration of lake Naivasha from the Malewa inlet into the open water

The riverine influence on TP in the lake is well demonstrated by increase in TP concentration at 0.5 and 0.1 km from the Malewa inlet in November 1997 in comparison to the open water (Figure 6.6). This was brought about by incursion of river water in the lake indicated by reduction in ionic concentration (Figure 6.1). The highest concentration at the Malewa inlet was observed in September 1997, which was much higher than the upstream station at M_5 (Figure 5.4A), indicating a possibility of a localised phosphorus source at this point. One major possibility could be through sediment disturbance by the large population of hippopotamus at 50 metres above the station.

Particulate phosphorus (PP) consisted of >90% of TP at the inlet and reduced to more than half (45.2%) in the open water (Figure 6.7). A significant positive correlation between TSS and PP obtained at the inlet ($R = 0.917$, $R^2 = 0.841$, $n = 20$, $p < 0.0001$) compared to the main open water ($R = 0.615$, $R^2 = 0.378$, $n = 20$) is indicative that most of the phosphorus coming into the lake from the catchment is bound in suspended soil particles (as shown in chapter 5). Once the PP reaches the lake, sedimentation together with dilution takes place, thus reducing its concentration in the water column.

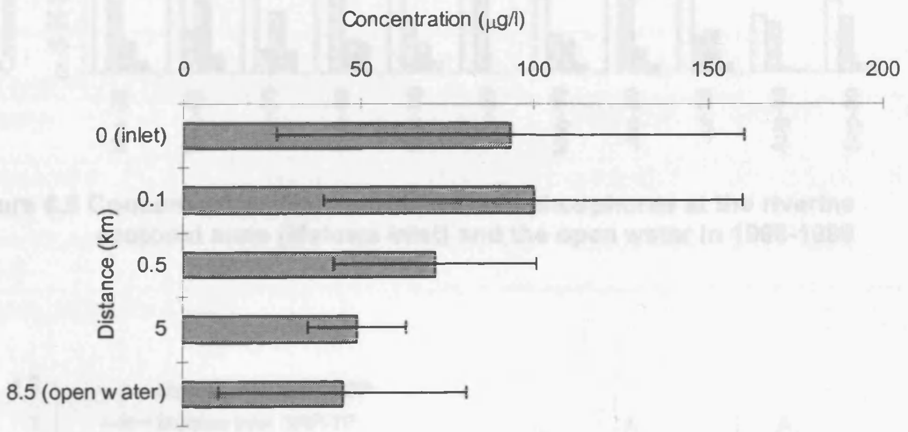


Figure 6.7 Mean particulate phosphorus (PP) concentration along transect from Malewa inlet into the open water of lake Naivasha

Seasonal variation of different forms of phosphorus for the different zones, Malewa inlet and the open water is illustrated in Figure 6.8. More than 50 % of TP is in PP form at both stations (Table 6.2), although lower in the open water. Figure 6.9 illustrates the seasonal variation of

SRP/TDP and SRP/TP ratios between November 1998 and September 1999. The mean SRP/TDP ratio was almost 1.5 times higher at the inlet than the open water (Table 6.2) despite being high in the open water in November 1998 to March 1999.

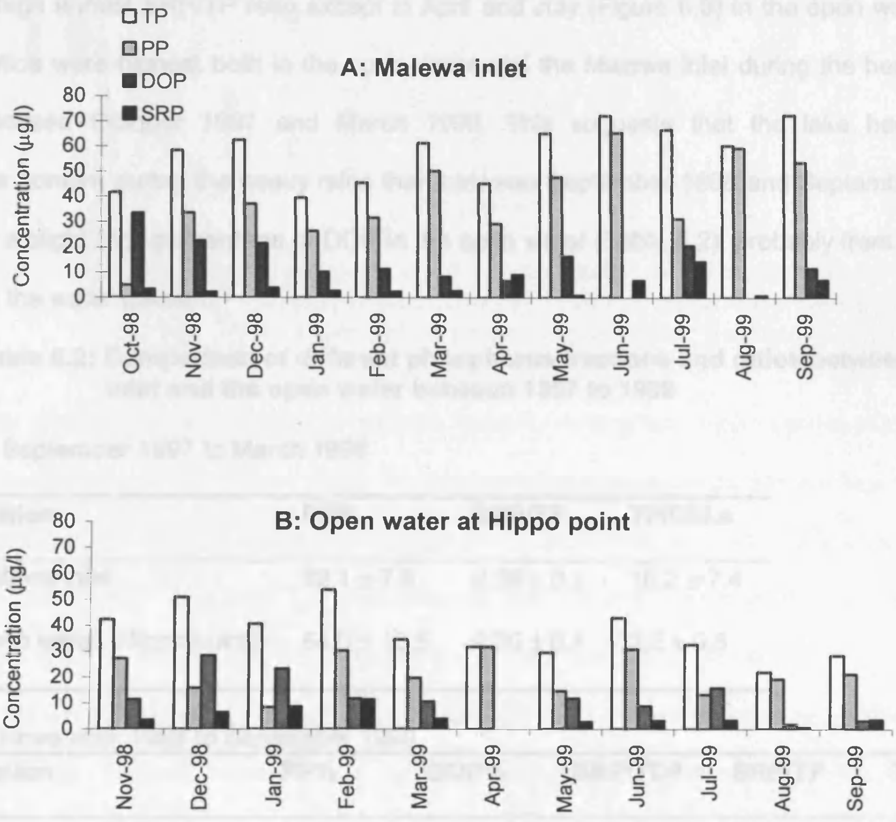


Figure 6.8 Concentration of different forms of phosphorus at the riverine ecotonal zone (Malewa inlet) and the open water in 1998-1999

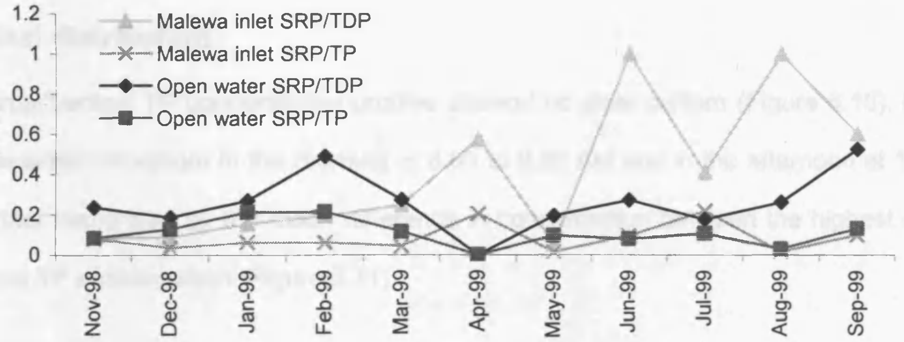


Figure 6.9 Seasonal variations of phosphorus ratios (SRP/TDP and SRP/TP) in the two zones of lake Naivasha

Table 6.2B shows that 40% of the TDP coming through the river into the lake is in SRP form as opposed to only 26% in the open water. The difference in content could be due to high biological demand for SRP by the algal population in the open water reducing its concentration. However, there is a high annual SRP/TP ratio except in April and July (Figure 6.9) in the open water. The SRP/TP ratios were highest both in the open water and the Malewa inlet during the heavy rainy season between October 1997 and March 1998. This suggests that the lake had higher phosphorus content during the heavy rains than between September 1998 and September 1999. There was a slight high percentage of DOP in the open water (Table 6.2), probably from biomass residues in the water column.

Table 6.2: Comparison of different phosphorus fractions and ratios between the inlet and the open water between 1997 to 1999

A: September 1997 to March 1998

Station	PP%	SRP/TP	TP/Chl.a
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

B: November 1998 to September 1999

Station	PP%	DOP%	SRP/TDP	SRP/TP	TP/Chl.a
Malewa inlet	66.1 ± 7.0	25.4 ± 6.7	0.40 ± 0.1	0.11 ± 0.02	5.3 ± 0.8
Open Water (Hippo point)	59.7 ± 7.1	29.5 ± 5.9	0.26 ± 0.04	0.12 ± 0.02	2.7 ± 0.4

* Value ± standard error

6.2.2 Vertical distribution

Diurnal vertical TP concentration profiles showed no clear pattern (Figure 6.10). Notable is the middle water maximum in the morning at 8.00 to 9.00 AM and in the afternoon at 1.00 PM which is further elaborated by the mean difference in concentration between the highest and the lowest vertical TP concentration (Figure 6.11).

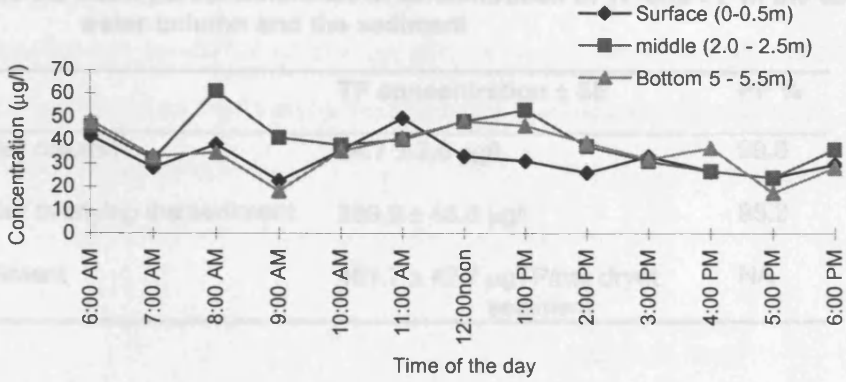


Figure 6.10 Mean diurnal variation of TP concentration at the surface (0-0.5 m), middle (2.0-2.5 m) and bottom (5-5.5 m) depths at the Hippo point station (open water) of lake Naivasha between May and July 1999 (n=3)

This can be attributed to daily mixing of the lake water by wind action moving water masses with different phosphorus concentration. Also TP concentration reduction at the surface water at around mid-day could indicate a biological uptake at the time when the lake is expected to be at its photosynthetic peak. The high TP concentration with PP dominance at sediment overlying water (Table 6.3) is most likely a consequence of sediment disturbance by wind - induced circulation indicated in Figure 6.4 resulting in re–suspension of phosphorus rich fine sediment into the water column (Table 6.3) rather than sediment P-release by mineralization. There was no indication of phosphorus-release by mineralization in the lake during this study, but its possibility cannot completely be ruled out.

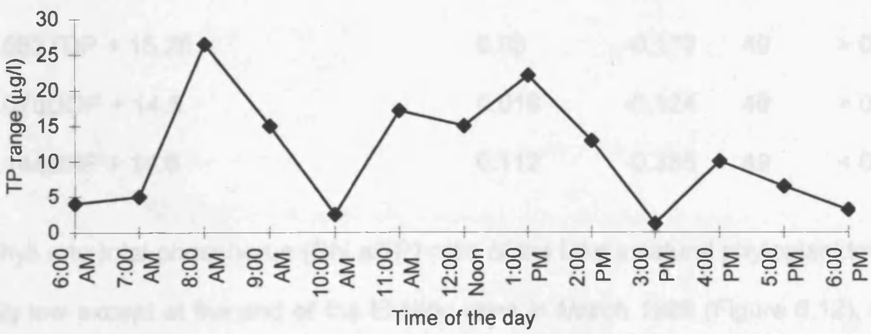


Figure 6.11 Diurnal TP range between the vertical highest and lowest TP concentration in the water column

Table 6.3 Mean partial difference in concentration of TP and PP in the lake water column and the sediment

	TP concentration ± SE	PP %
Water column	34.7 ± 2.6 μg/l	99.8
Water overlying the sediment	289.9 ± 43.3 μg/l	95.2
Sediment	461.7 ± 42.7 μgTP/mg drywt. sediment	NA

6.3 Phosphorus verses chlorophyll correlations

The graphical relationship between different fractions of phosphorus and chlorophyll *a* are summarised in Table 6.4. Total phosphorus and particulate phosphorus are positively correlated with chlorophyll *a* in the open water while TDP and SRP give negative correlations.

Table 6.4: Summary of chlorophyll *a* relationships with different forms of phosphorus in lake Naivasha (with probability (P) indicated for significant relationships)

Regression equation (s)	R^2	R	n	p * significant
A: Malewa inlet				
Chl. *a* = -0.024TP + 18.2	0.018	-0.134	19	> 0.05
Chl. *a* = -8.49LnPP + 49.796	0.264	-0.11	19	> 0.05
Chl. *a* = -0.045SRP + 17.002	0.018	-0.133	19	> 0.05
B: Open water (off Hippo point)				
Chl.*a* = 0.226TP + 10.296	0.443	0.666	18	0.005 *
Chl.*a* = 0.281PP + 10.71	0.36	0.60	18	0.02 *
Chl.*a* = - 0.082TDP + 15.28	0.03	-0.173	49	> 0.05
Chl.*a* = - 0.075DOP + 14.8	0.016	-0.124	49	> 0.05
Chl.*a* = - 0.144SRP + 14.6	0.112	-0.335	49	< 0.0001*

The chlorophyll *a* to total phosphorus (Chl.*a*/TP) ratio of the lake's natural phytoplankton biomass was generally low except at the end of the El Niňo rains in March 1998 (Figure 6.12), implying a high TP with low algal biomass in the water column. The overall annual variability ranged between 0.25 - 0.86 and 0.09 - 0.44 in the open water and inlet respectively. The much lower values obtained for the inlet indicates that the fraction of TP bound to phytoplankton is quite small. This is because phosphorus is mostly bound to other particulate and dissolved matter brought in by the river from the catchment as indicated by the significant positive correlation between TSS and PP above and in the previous chapter.

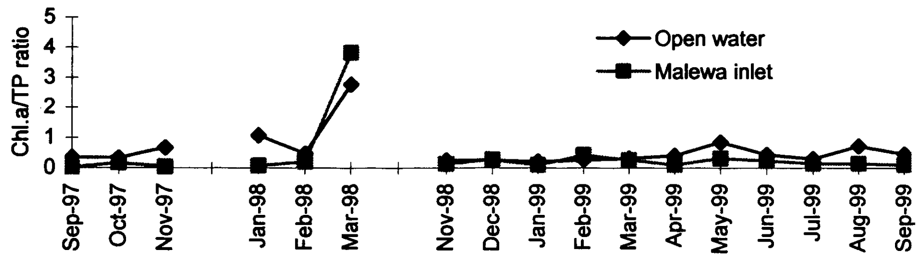


Figure 6.12 Chlorophyll a/ TP ratio of the inlet and the open water in lake Naivasha

To relate the overall Chl.*a*/TP as a function of TP concentration in the lake, I obtained a curvilinear relationship (Figure 6.13); were Chl.*a*/TP ratio decreased with increase in TP concentration up to approximately 50 μg/l, acquiring a low and consistent ratio thereafter. This suggests that only a small fraction of TP is bound in phytoplankton biomass in the lake and an increase in TP concentration does not produce a higher standing crop of algae. This is probably because of the biological unavailability of TP or a variation in abiotic and biotic factors inhibiting its uptake.

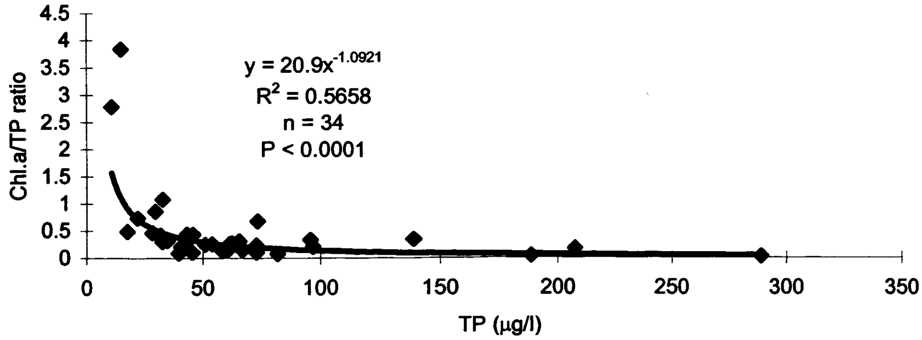


Figure 6.13 Variation of Chl.*a*/TP ratio in relation to TP concentration in lake Naivasha

6.4 Phosphorus status of the sediment

6.4.1 Characteristics of the Lake Naivasha sediment

The vertical distribution of water content (%) and the grain size composition of lake Naivasha sediment, in both the open water and the river inlet are summarised in Table 6.5. The Malewa inlet sediment consists mainly of silt/clay, with little change in water content down the profile, while the open water had a sandy substrate with the highest water content at the surface layer (0 –3 cm). Organic matter content estimated as loss of ignition shows little change down the profile but twice the amount in the lake, with a range of 11.3 -17.3 and 27.8 - 45.7 % in the Malewa inlet and open water respectively.

The mean grain size (M_Z) expressed in Phi (ø) units (where ø = $-\log_2$ of mean particle size in mm) shows predominantly a poorly sorted silt sediment (Table 6.5.), with flattened platykurtic curves and kurtosis (KG') scale range of 0.401 - 0.474. The skewness coefficient analysis gave positive skewed values, ranging between +0.1 to +0.3 especially in the open water. The data points are concentrated to the left side of the curve, indicating dominance of smaller size classes.

The relationships of mean grain size (M_Z) with other statistical parameters are illustrated in Figure 6.14. As the lake Naivasha sediment consisted mainly of small range fine grain size, the relationship between M_Z verses SD shows a direct upward single line, representing one limb of the expected M, V or inverted V shaped curves when dealing with wide to medium ranges of grain sizes. Presumably if more samples covering broader lake micro-habitat had been analysed, the interrelationship plots would have portrayed a shape closer to that expected. M_Z relationship with other parameters portray that sorting worsens as the grain size becomes finer.

Table 6.5. Characteristics of lake Naivasha sediment at the Malewa inlet and the open Water

A: Malewa inlet

Depth (cm)	**Water content** (%)	**Sand** (%)	**Silt/clay** (%)	**Mean grain size (M_Z)** (ø)	SD	**SK_1**	**KG'**
0-3	77.1	28.5	71.5	3.763	1.938 (*)	0.011	0.416
3- 6	65.3	29.6	70.4	4.124	2.363 (**)	0.067	0.410
6- 9	61.4	23.6	76.4	5.098	2.93 (**)	0.025	0.420
9-12	65.3	34.5	65.5	4.195	2.619 (**)	0.098	0.410
12-15	62.7	32.9	67.1	4.411	2.738 (**)	0.149	0.405

B: Open water

Depth (cm)	Water content (%)	Sand (%)	Silt/clay (%)	Mean grain size (M_Z) (ø)	SD	SK_1	KG'
0-3	93.9	65.2	31.8	4.042	3.09 (**)	0.203	0.431
3-6	91.04	60.9	33.1	4.141	3.036 (**)	0.209	0.425
6-9	88.7	63.7	32.0	4.101	3.239 (**)	0.206	0.437
6-12	90.7	64.7	35.3	4.029	2.966 (**)	0.156	0.399
12-15	91	66	31.0	4.149	3.378 (**)	0.237	0.439
15-18	91.5	64.8	33.5	4.571	3.688(**)	0.236	0.436
18-21	91.9	62.3	34.6	6.022	5.413(***)	0.323	0.457
21-23	91.8	67.6	32.4	4.414	4.406(***)	0.117	0.442

KEY

SD = Inclusion graphic standard deviation described by Robert & William (1957),

* = Poorly sorted,

** = Very poorly sorted and

*** = Extremely poorly sorted using Robert & William (1957) catagories (Appendix Table 3)

SK_1 = Skewness coefficient

KG' = Normalised kurtosis as described by Robert & William (1957)

6.4.2 Total phosphorus distribution

There was a general increase of sediment TP concentration from the northern riverine inlet to the southern part at Elsamere bay (8.5 km from the inlet) (Figure 6.15). The TP depth profiles exhibited different patterns at different parts of the lake. For example, there was no TP concentration gradient at the Malewa inlet, while at 100 m from the inlet in the lake an increase in TP concentration on a dry weight basis with sediment depth was noted, either due to mineralization or compaction of sediment leading to reduced water content (Table 6.5). In the central part of the lake and the extreme south (5 and 8.5 km from the inlet) the highest TP concentrations were obtained at sub-surface sediment depth (3 - 12 cm). This probably indicates delayed mineralization of settled material either due to increase in sedimentation rate or reduction in biological activity.

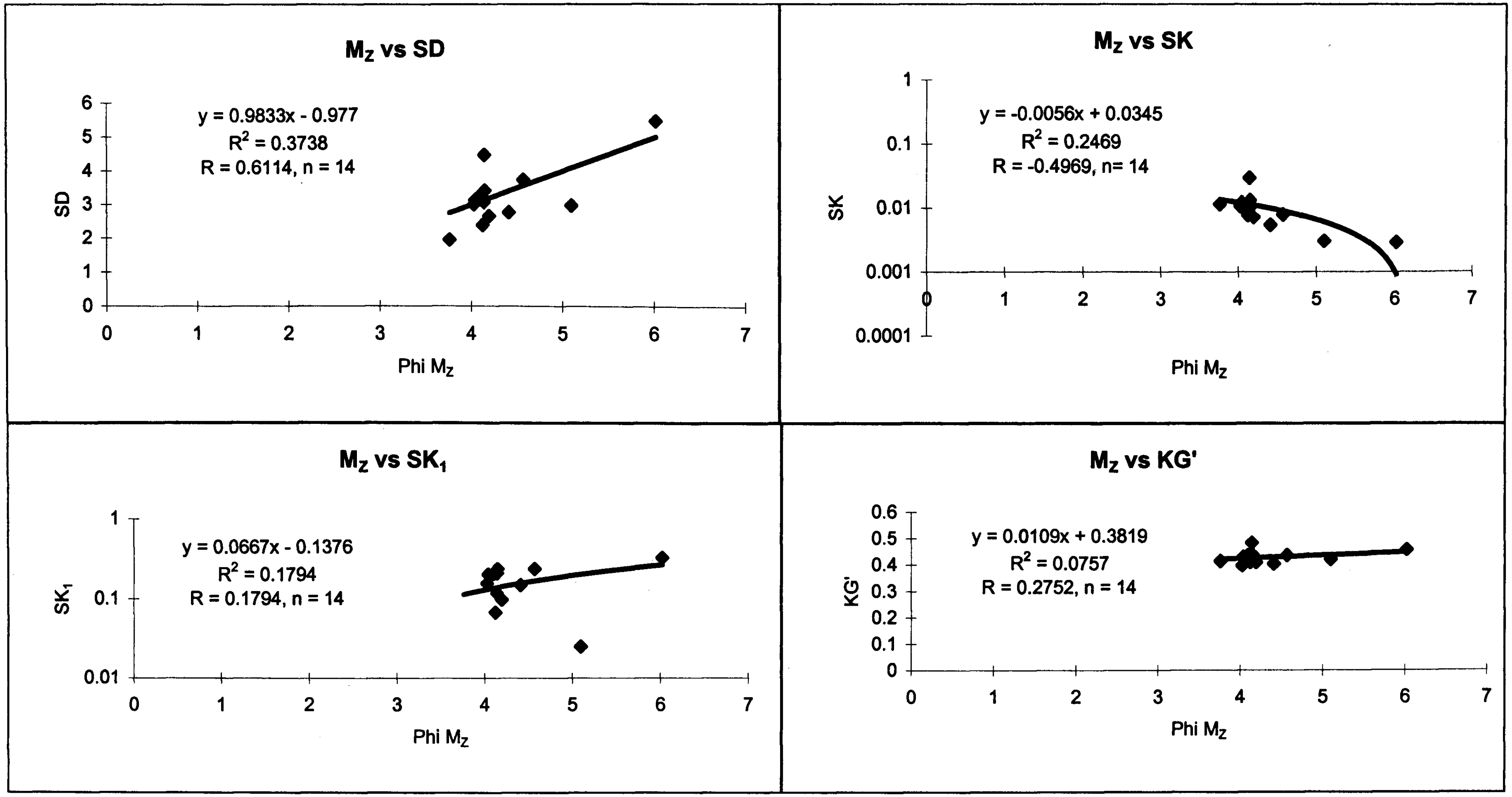


Figure 6.14 Lake Naivasha sediment mean grain size (Mz) and its relationship with SD, SK, SK1 and KG'

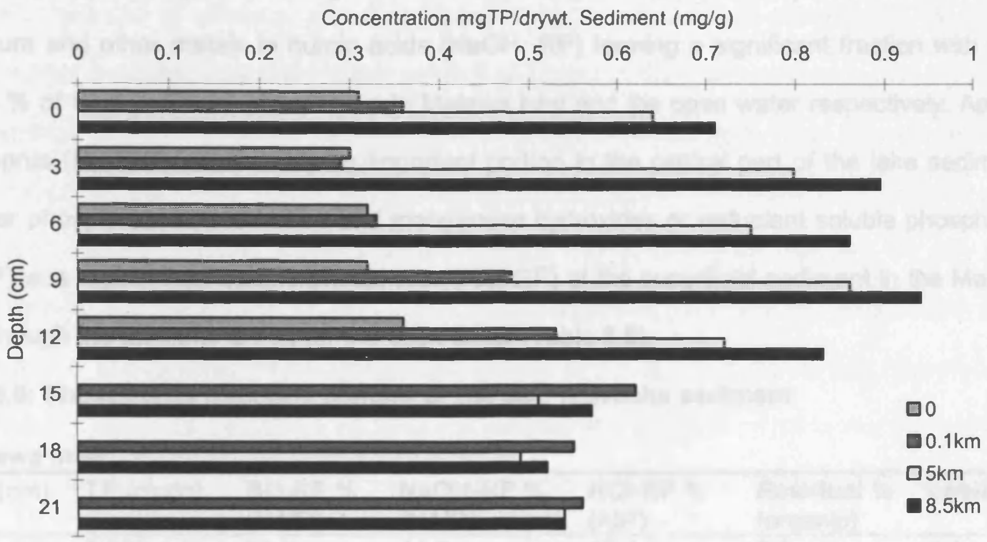


Figure 6.15 Vertical distribution of sediment TP along the Malewa inlet – open water lake transect

6.4.3 Phosphorus fractions composition

Inorganic phosphorus (TIP) dominated the sediment phosphorus component of both the Malewa inlet and the open water stations (Figure 6.16) with >90% at the superficial sediment, reducing with depth (Figure 6.16).

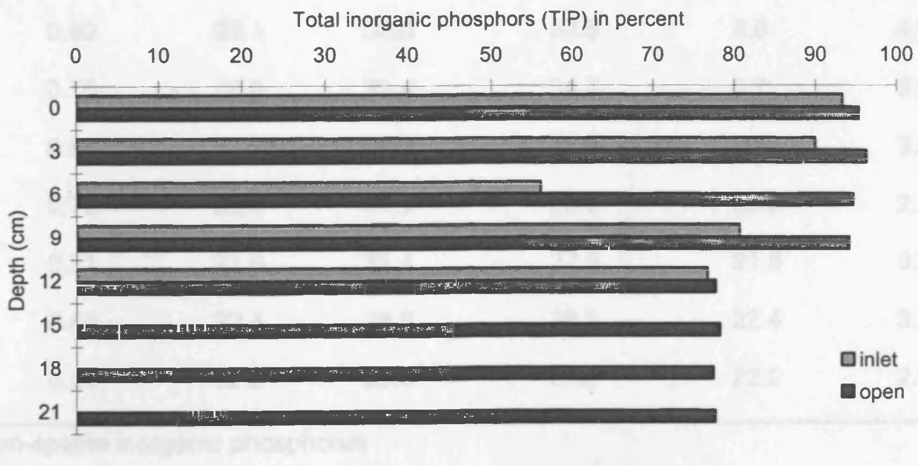


Figure 6.16 Vertical distribution of total inorganic phosphorus (TIP) content of the Malewa inlet and the open water sediment

Table 6.6 represents the different forms of extractable phosphorus. In general non-apatite inorganic phosphorus (NAIP) formed the dominant inorganic fraction with phosphorus bound in aluminium and other metals in humic acids (NaOH -RP) forming a significant fraction with 41.9 and 36 % of total sediment phosphorus in Malewa inlet and the open water respectively. Apatite phosphorus (HCl-RP) was equally an important portion in the central part of the lake sediment. However phosphorus bound in iron and manganese hydroxides or reductant soluble phosphorus (BD-RP) was higher than apatite phosphorus (HCl-RP) at the superficial sediment in the Malewa inlet although the opposite is true for the open water (Table 6.6).

Table 6.6: Phosphorus fractions content of the lake Naivasha sediment

A: Malewa inlet

Depth (cm)	**TP** (mg/g)	**BD-RP** % (NAIP)	**NaOH-RP** % (NAIP)	**HCl-RP** % (AIP)	**Residual** % (organic)	**Labile** %
0	0.30	29.0	41.9	19.4	6.5	2.1
3	0.30	25.7	41	23.3	10.0	3.3
6	0.31	15.6	13.1	27.5	43.8	1.5
9	0.26	15.6	25.3	24.7	21.9	1.8
12	0.30	17.2	27.2	19.4	16.7	1.5

B: Open water

Depth	**TP** (mg/g)	**BD-RP** % (NAIP)	**NaOH-RP** % (NAIP)	**HCl-RP** % (AIP)	**Residual** % (organic)	**Labile** %
0	0.64	28.4	35.9	31.3	4.7	5.5
3	0.80	28.1	35.6	32.5	3.8	4.0
6	0.75	28.0	32.4	34.7	6.7	3.9
9	0.86	27.9	34.9	31.4	5.8	3.0
12	0.72	22.2	31.9	23.6	22.2	2.8
15	0.51	21.6	31.4	27.5	21.6	3.7
18	0.49	22.4	28.6	26.5	22.4	3.7
21	0.54	22.2	29.6	25.9	22.2	2.96

NAIP = Non-apatite inorganic phosphorus

AIP = Apatite inorganic phosphorus

However, the values obtained for the BD-RP fraction might be overestimated as it may include a substantial amount of calcium- and organic-bound phosphorus. Labile phosphorus, (extracted using distilled deionised water as recommended by Logan (1982)) was extremely low (< 10%) in both stations (Table 6.6). Similarly, residual phosphorus content was low although its concentration increased with depth, with the lowest concentration at the superficial sediment (0 –3 cm) in both stations. Residual phosphorus estimated as the difference between TP and IP as recommended by Pettersson *et al.* (1988) is equivalent to the organic phosphorus form. Exchangeable phosphorus, which constitutes 19-43% of TP (Li *et al* 1972) was highest in the riverine region with a range of 0.09 - 0.37 at the Malewa inlet and 0.06 - 0.16 in the central part of the lake. However, this fraction might include a significant proportion of "relatively stable inorganic phosphorus" (Logan 1982).

Relating the concentration of different phosphorus fraction to sediment grain size, the apatite phosphorus was higher at the central part of the lake with coarser grain size. The non-apatite phosphorus was highest at the Malewa inlet with finer grain sediment than the open water (Table 6.5 and 6.6). However the relationship between silt/clay content and TP, TIP (Figure 6.17A, B) in lake Naivasha seems complicated, but it suggests that the finer the sediment the lower the TP, particularly TIP sediment retention capacity.

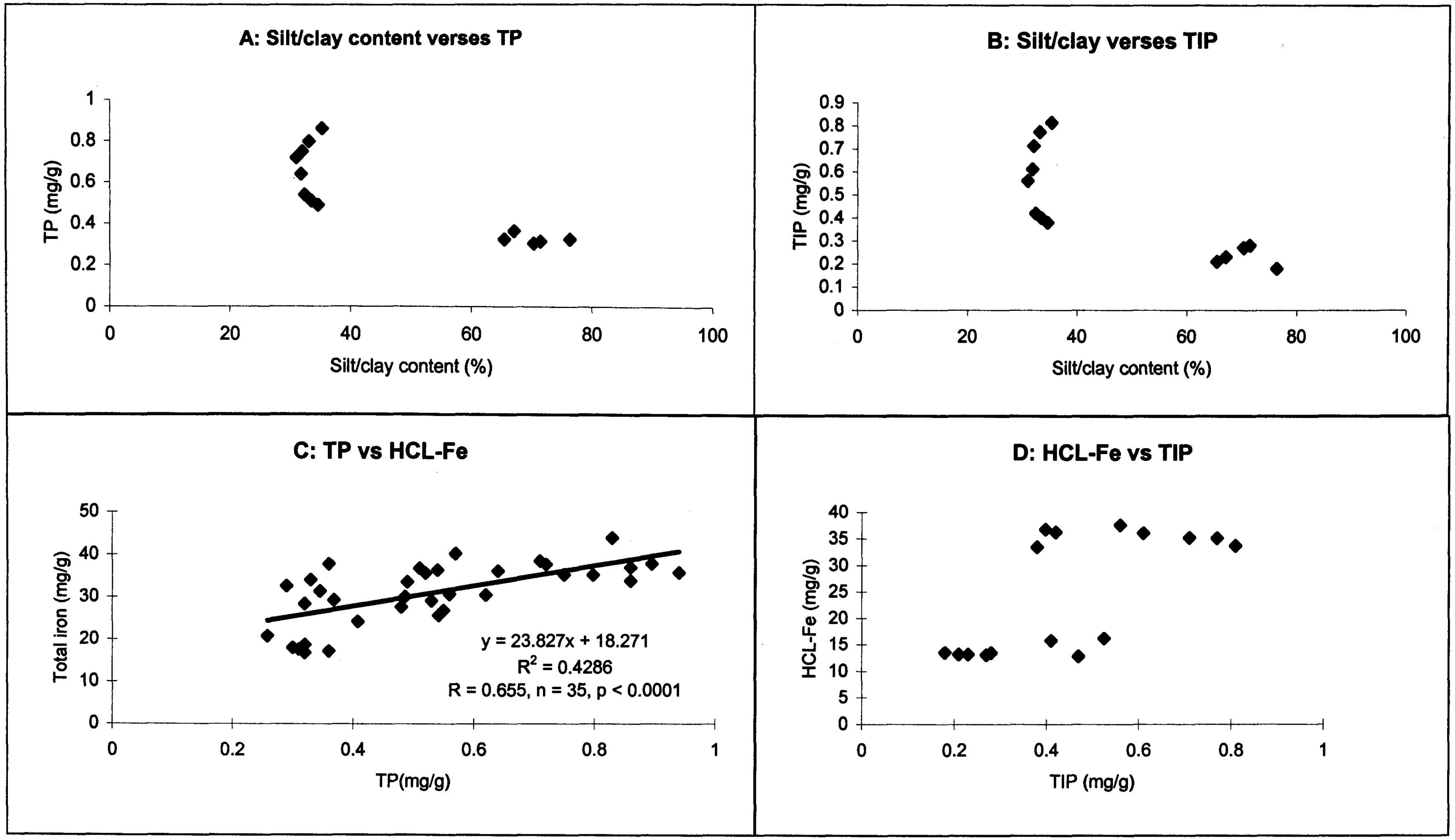


Figure 6.17 The relationship between TP, IP and silt/clay content, HCL-Fe in lake sediment

CHAPTER 7

SYNTHESIS; THE PHOSPHORUS STATUS OF LAKE NAIVASHA

7.1 Phosphorus transport from the catchment

The mean daily TP transport was highest in November 1997, with most of it in PP form in both the rivers Malewa and Gilgil (Table 7.1).

Table 7.1: Phosphorus and TSS transport for the two major rivers ; Malewa (A) and Gilgil (B)

	TP (kg/d)		**PP %** content		**TSS** (kg/d)	
	A	B	A	B	A	B
September 1997	120.4	5.9	82.1	23.9	7.6	7.6
October 1997	131.7	30.8	75.1	78.8	74.3	22.1
November 1997	4256.9	63.1	95.5	94.0	2818.3	158.7
January 1998	414.6	25.6	43.1	67.9	606.7	55.1
February 1998	188.3	26.5	58.9	60.5	254.2	29.1
March 1998	85.2	41.8	82.6	68.6	28.2	64.8

A strong significant ($p < 0.01$) positive correlation between TP transport and discharge obtained for the river Malewa (Figure 7.1) indicates that most of the TP was transported during the high discharge period. The amount of phosphorus transported in the river Gilgil was low by comparison. The river Malewa being the largest, transported almost 30 times more TP than the other rivers during the heavy rainy season and 13 times more during the dry months. With additional fractionation of TP between September 1998 to 1999 (Figure. 7.2), the contribution of TDP and its components, especially DOP reduced the dominance of PP transported, when only three fractions of phosphorus (TP, PP, and SRP) were considered between September 1997 and March 1998 (Table 7.1). This is because PP constitutes a significant amount of DOP (as shown earlier in Chapter 3).

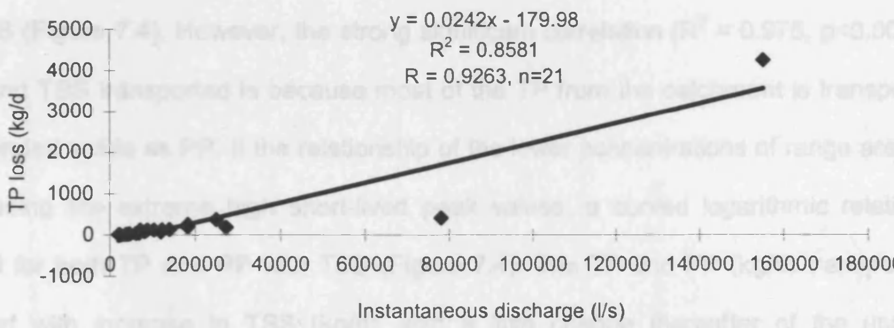


Figure 7.1 The relationship between TP export (kg/d) and the instantaneous discharge (l/s)

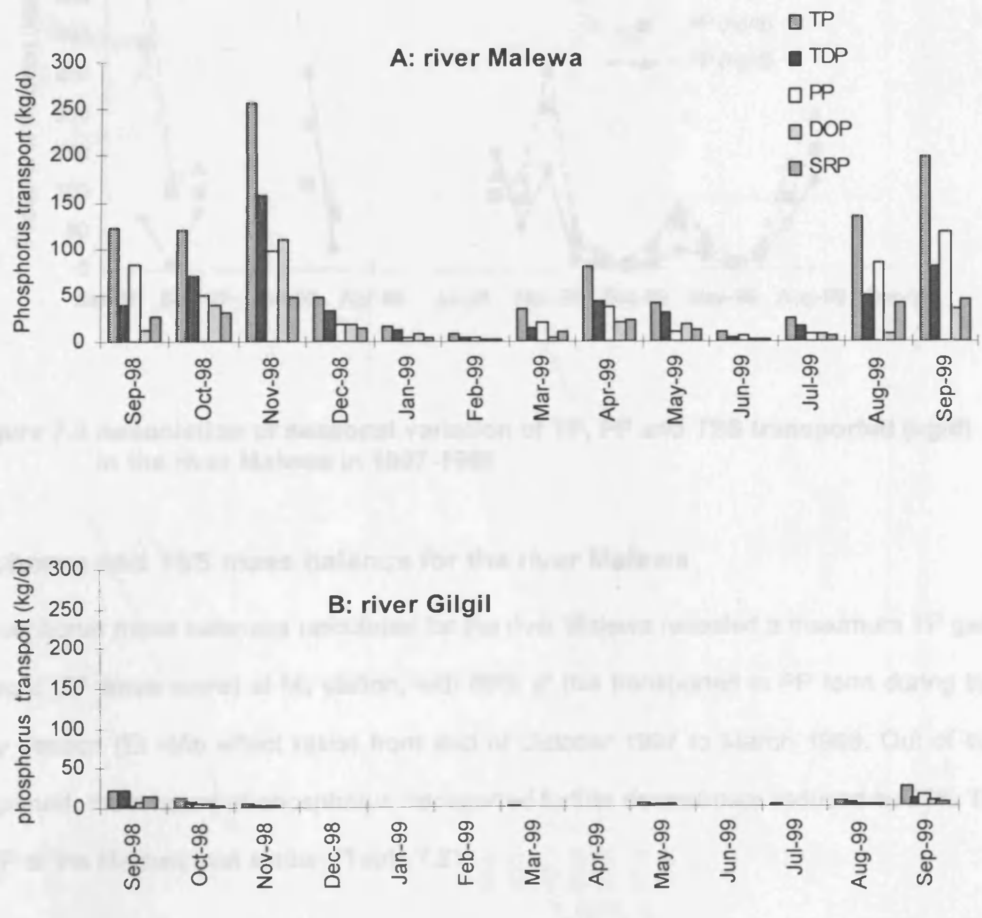


Figure 7.2 Variation of different forms of phosphorus transported (kg/d) in the rivers Malewa and Gilgil in 1998-1999

The close association between TP, PP and TSS loss is demonstrated in Figure 7.3, and the importance of PP content is supported by the significant positive correlation between PP and both TSS (Figure 7.4). However, the strong significant correlation (R^2 = 0.976, p<0.001) obtained for TP and TSS transported is because most of the TP from the catchment is transported bound in suspended solids as PP. If the relationship of the lower concentrations of range are considered by excluding the extreme high short-lived peak values, a curved logarithmic relationship was obtained for both TP and PP with TSS (Figure 7.4). The TP and PP (kg/d) transported initially, increased with increase in TSS (kg/d), with a little change thereafter of the upper level of approximately 200 and 100 kg/d of TP and PP respectively (Figure 7.4).

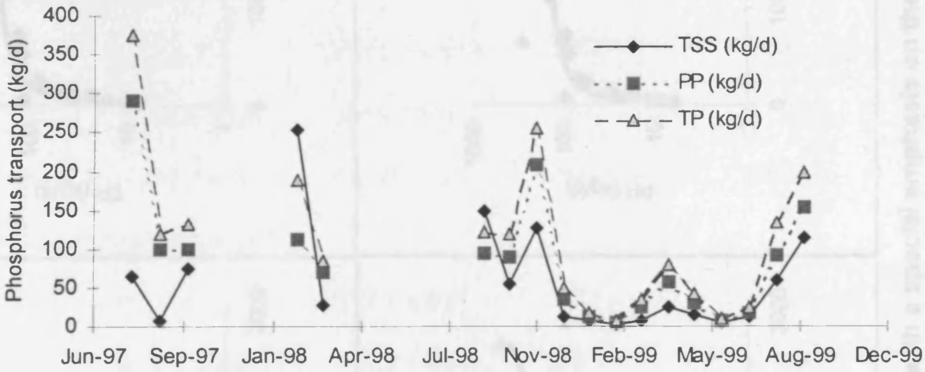


Figure 7.3 Association of seasonal variation of TP, PP and TSS transported (kg/d) in the river Malewa in 1997-1999

7.2 Phosphorus and TSS mass balance for the river Malewa

Phosphorus mass balances calculated for the river Malewa revealed a maximum TP gain of 1084.3 kg/d (37 times more) at M_3 station, with 89% of this transported in PP form during the heavy rainy season (El niño effect rains) from end of October 1997 to March 1998. Out of the above TP gained, the amount of phosphorus transported further downstream reduced by 28% TP and 37% PP at the Malewa inlet station (Table 7.2).

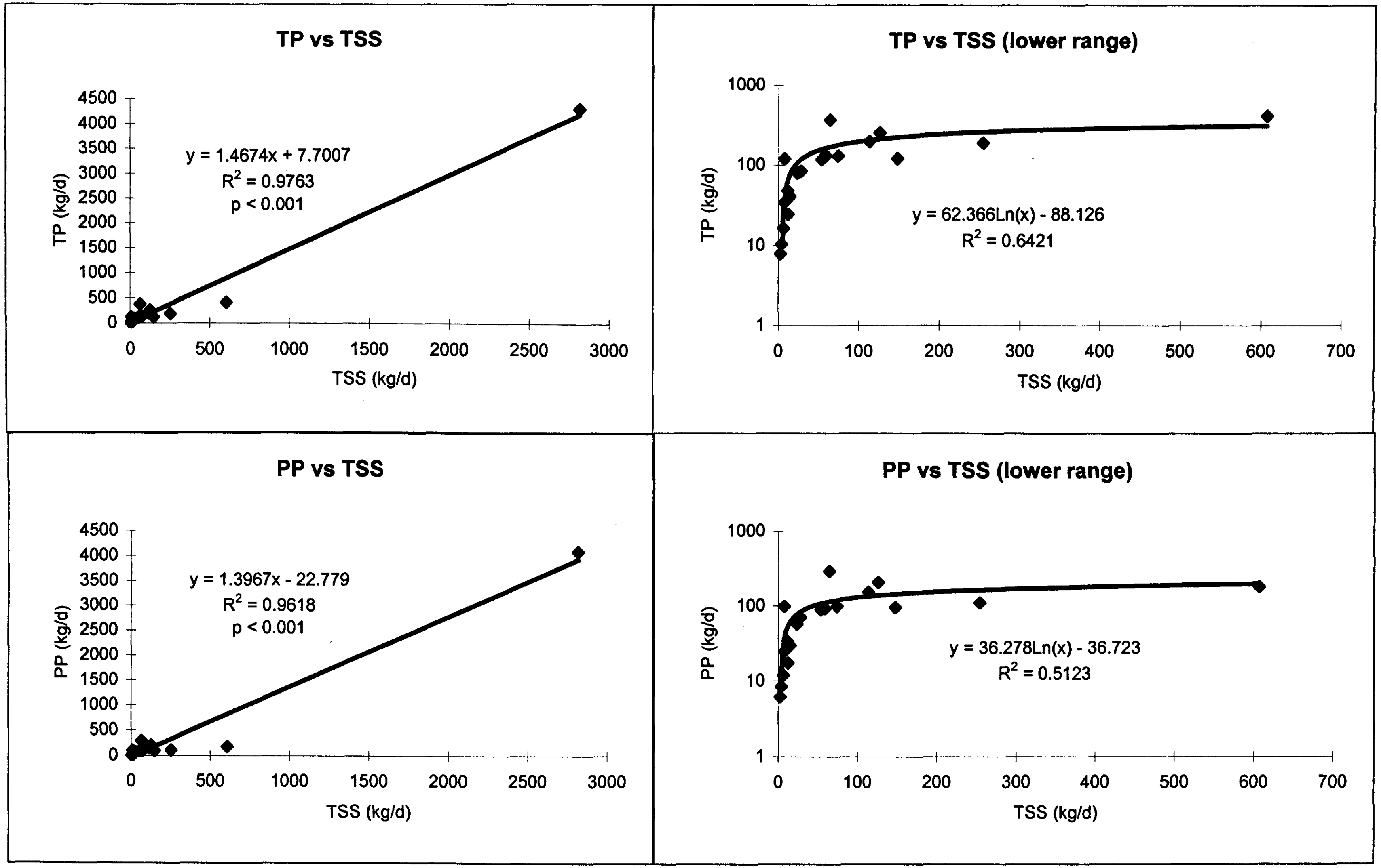


Figure 7.4 The relationship between TSS and TP, PP with a special emphasis on the lower range in the river Malewa

The slightly higher percentage of the PP fraction removed from the water column at the Malewa inlet station together with loss of 58% of TSS, could imply phosphorus loss through sedimentation. A loss of 99.6% of the SRP at the inlet had occurred from the 109.5 kg/d of SRP recorded at station M_3. The lower part of the river Malewa flows through a papyrus-dominated wetland and SRP, being biologically available, may have been actively taken up by emergent plants or adsorbed either in the suspended solids or directly in the sediment.

Table 7.2: Mean (± S.E) daily input and output of different forms of phosphorus and TSS (kg/d) in the middle and the lower course of the river Malewa during a heavy rainy season (El niño effect rains) in October 1997 to March 1998

	Input (kg/d) to the site	**Output** (kg/d) from the site	**Net gain /loss** (kg/d) (output-input)	**Gain/ loss %** of the Maximum input (*)
A: Total phosphorus (TP)				
M_3	29.3± 7	1113.6 ± 578	1084 *	>100 gain
M_4	1113.6 ± 578	1015 ± 579	-99	9 loss
Inlet	1015 ± 579	707.7 ± 325	-307	28 loss
B: Particulate phosphorus (PP)				
M_3	11.7 ± 3	979.1 ± 564	967*	>100 gain
M_4	979.1 ± 564	904.8 ± 564	-74	8 loss
Inlet	904.8 ± 564	542.6 ± 561	-362	37 loss
C: Soluble reactive phosphorus (SRP)				
M_3	0.2 ± 0.1	1.9 ± 0.8	+2	2 gain
M_4	1.9 ± 0.8	111.4 ± 37	+110*	>100 gain
Inlet	111.4 ± 37	2.3 ± 1	-109	99.6 loss
D: Total suspended Solids (TSS)				
M_3	14.8± 2.6	1326 ± 664	1311*	> 100 gain
M_4	1326 ± 664	756.3 ± 368.2	-570	43 loss
Inlet	756.3 ± 368.2	0.01 ± 0.0001	-756	58 loss

Comparing the amount of phosphorus lost or gained in the lower course of the river during two contrasting seasons, there was an overall gain of all forms of phosphorus and TSS at M_4 during the dry season as opposed to a general loss during the heavy rainy season except for SRP (Table 7.3). The highest phosphorus removal from the water column occurred between M_4 and the inlet during the heavy rainy season (Figure 7.5).

Table 7.3: Mean daily gain and loss of different forms of phosphorus and TSS (kg/d) of the lower course at M_4 and the inlet stations in the river Malewa for the normal wet and dry year (September 1998-1999)

		Normal rainy season			**Dry season**		
Station		**Input** (kg/d)	**Output** (kg/d)	**Gain/ Loss**	**Input** (kg/d)	**Output** (kg/d)	**Gain/ Loss**
M_4	TP	189.7 ± 31	123.9 ± 22	-66	13.5 ± 3	42.2 ± 15	+ 29
	PP	149.5 ± 32	95.3 ±18	-54	8.5 ± 2	29.9 ± 21	+21
	SRP	0.5 ± 6	28.6 ± 4	+28	0.017 ± 0.01	12.3 ± 5	+ 12
	TSS	74.2 ± 21	70.3 ± 19	-4	7.7 ± 2	17.1 ± 7	+ 10
Inlet	TP	123.9 ± 22	68 ±19	-56	42.2 ± 15	26.5 ± 6	-16
	PP	95.3 ± 18	62.8 ± 18	-33	29.9 ± 10	24.6 ± 6	- 5
	SRP	28.6 ± 4	0.03	-29	12.3 ± 5	0.01	-12
	TSS	70.3 ± 2.5	0.0001	-70	17 ± 2	0.0001	-17

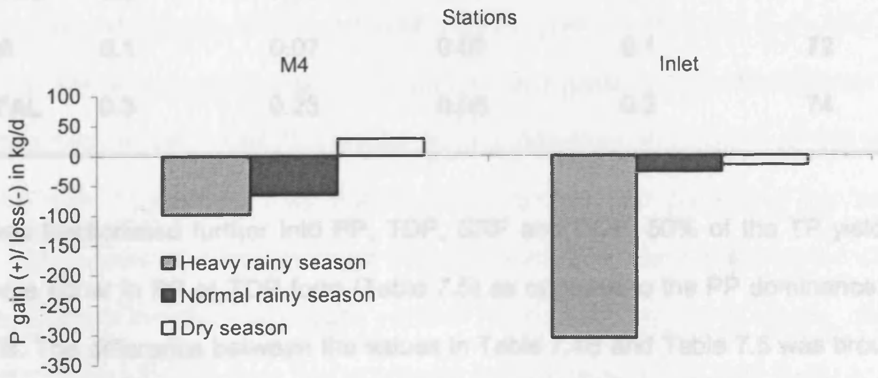


Figure 7.5 Total Phosphorus gain and loss in the lower two stations of the river Malewa during an heavy rainy (November 1997-February 1998) and a normal rainy (September 1998-February 1999) and dry seasons (June-September 1999)

7.3 Catchment yields of phosphorus

The calculated values of areal yields from the three rivers summarised in Table 7.4 shows that the river Malewa had higher phosphorus yield than the other two rivers. The TP yield values were approximately 9 and 4 times higher in the rivers Malewa and Gilgil respectively, during the extremely wet year (1997-1998), than the normal dry and wet year (September 1998 and 1999), with PP dominance in both phases (Table 7.4). In addition the high yield of TSS (Table 7.4) give further support that most of the phosphorus is transported bound in suspended solids in water.

Table 7.4: TP, PP, SRP and TSS areal yields (kg $ha^{-1}yr^{-1}$) of the Naivasha catchment rivers

A: Extremely wet year (1997-1998)

River	TP	PP	SRP	TSS	PP%
Malewa	1.78	1.58	0.2	1.2	89
Gilgil	0.2	0.15	0.06	0.4	71
Karati	0.01	0.01	0.003	0.02	~100
TOTAL	1.98	1.78	0.3	1.6	86

B): Normal wet and dry year (1998-1999

	TP	PP	SRP	TSS	PP%
Malewa	0.2	0.15	0.04	0.1	76
Gilgil	0.1	0.07	0.02	0.1	72
TOTAL	0.3	0.23	0.06	0.2	74

When TP was fractionated further into PP, TDP, SRP and DOP, 50% of the TP yield from the catchment was either in PP or TDP form (Table 7.5) as opposed to the PP dominance portrayed in Table 7.4B. The difference between the values in Table 7.4B and Table 7.5 was brought about by the difference in PP estimation during the two terms. When PP was estimated by subtracting SRP from TP (Table 7.4B), its export coefficient includes that of DOP fraction. Considering the values given in the two tables, PP yield given in Table 7.4B is overestimated by 25% and 30% for the rivers Malewa and Gilgil respectively and 27% for the overall total.

Table 7.5 The areal yields (export coefficient) of different forms of phosphorus ($kg\ ha^{-1}yr^{-1}$) in 1998-1999

	TP	PP	TDP	DOP	SRP
River Malewa	0.2	0.1 (50%)	0.1 (50 %)	0.05 (25 %)	0.04 (20 %)
Gilgil River	0.1	0.05 (50%)	0.05 (50 %)	0.03 (30 %)	0.02 (20 %)
TOTAL	0.3	0.15 (50%)	0.15 (50 %)	0.08 (27 %)	0.07 (23 %)

7.4 Phosphorus and TSS lake loading

7.4.1 From the catchment

Estimates of loading per unit area of the lake surface from the catchment are summarised in Table 7.6. The TP loading was 10 times more during the heavy rainy season in 1997 -1998 with PP dominating (85%) even after DOP correction.

Table 7.6: Phosphorus loading into the lake from the catchment ($g\ m^{-2}\ yr^{-1}$)

	TP	PP	TDP	DOP	SRP	TSS
Extremely Wet year (1997-1998)	1.41	1.27	ND	ND	0.21	1.14
Normal (wet & dry) year (1998-1999)	0.21	0.11	0.11	0.06	0.05	0.14

Unfortunately, the constituents of TDP, especially DOP, were not analysed during the extremely wet year, which would have given a good comparison, and probably explain why there was more PP loaded than TSS in 1997-1998.The results show a difference of 0.2 $g\ m^{-2}\ yr^{-1}$ PP transported more than the TSS. This portion may probably represent the DOP fraction of the fine colloidal organic matter. However the amount of phosphorus loaded unquestionably varied significantly between the different hydrological phases studied (Table 7.6). An overall loading summary of different forms of phosphorus from the catchment per unit area of the lake surface is given in Table 7.7, with an overall mean TP loading value of 0.60 $gTPm^{-2}$ of the lake surface per year.

Table 7.7: Overall mean of phosphorus loading ($g\ m^{-2}\ yr^{-1}$) from the catchment in 1997 to 1999 (n = 41)

TP	PP	TDP	DOP	SRP
0.60	0.45	0.17	0.11	0.06

7.4.2 Atmospheric input

With a mean lake area of 152 km^2 estimated from lake levels (Table 7.9) and a mean total rainfall of 726.87 mm at the WDD station for 1997 to 1999 (Figure 2.4), the total amount of rainfall received in volume over the lake surface was 110.5 $x10^6\ m^{-3}\ yr^{-1}$. With a mean total phosphorus (TP) concentration of 46.4 μg/l in rainfall (Table 5.3), the total TP input into the lake from the atmosphere is 5.08 kgTP per year. If the total loading value is expressed per unit area of the lake surface, a TP loading of 0.033 $g\ m^{-2}\ yr^{-1}$ (equivalent to 5.5% catchment overall TP loading) with 0.0313 $g\ m^{-2}\ yr^{-1}$ in TDP and 0.0017 $g\ m^{-2}\ yr^{-1}$ in particulate form assuming PP consists of 5% TP as shown in Table 5.3.

7.4.3 Littoral zone input

Phosphorus input from the Naivasha municipality sewage, horticultural farms (Homegrown, Sher agencies and Safari Holticulture) and the surrounding villages (Kwa-Muhia, KenGen lake side estate and Sulmac village) were insignificant. The Naivasha municipality sewage treatment works has tertiary oxidising ponds and produces effluents which does not reach the lake (Harper *et al.* 1993) unless through seepage inflow. However the thick papyrus swamps and floating mats of water hyacinth in the enclosed lagoon especially around the sewage could be taking up most of the nutrients before they get into the lake. Some of the farms, effluents are channeled through established man made wetlands, which are quite efficient in nutrient uptake, for example Homegrown Farm, while the others have to adhere by the rules of the Ramsar Convention and the Growers association, both of which control effluent input into Ramsar sites.

7.5 The quotient relationship of the river and the lake total phosphorus

The quotient between mean in-lake (P) and mean inflow phosphorus concentrations (P_i) portray an equilibrium state, with overall mean concentration of P in the lake (52.2 ± 18 μg/l) being less than that of the river inlet, P_i (83.9 ± 33.2μg/l). An overall ratio P/P_i of 0.62 for the years 1997-1999 was estimated with a phosphorus retention coefficient (R_P) of 0.38 ($1-P/P_i$). According to Ahlgren *et al.* (1988) the ratio between P and P_1 should be directly proportional to annual retention of phosphorus in the sediment. However R_P calculated on a monthly basis increased with increased inflow phosphorus concentration from the catchment with the highest R_P during the heavy rainy season (Table 7.8). R_P was significantly different during the three seasons ($p < 0.05$) implying that phosphorus retention was significantly higher during the heavy rainy season.

Table 7.8: Quotient relationship between inflow phosphorus and lake concentration over three different seasons in 1997 to 1999

Season	P_i (μg/l)	P (μg/l)	P/P_i	R_P ($1-P/P_i$)
Heavy rainy (n = 9)	117.8 ± 80	45.9 ± 37	0.39	0.61
Normal rainy (n = 6)	62.5 ± 10	36.6 ± 9	0.59	0.41
Dry (n = 7)	57.8 ± 13	41.0 ± 8	0.71	0.29
Overall mean (n = 41)	83.9 ± 33.2	52.2 ± 18	0.62	0.38

Using Nürnberg's (1984) model as recommended by Cooke *et al* (1993), the sedimentation rate coefficient (σ) is equal to R_P multiplied by the mean annual TP loading (mg m^{-2} yr^{-1}), given in Table 7.7. A sedimentation rate coefficient of 0.23 TPgm^{-2} yr^{-1} was calculated for lake Naivasha. When this concept was applied to TSS, a sedimentation rate coefficient of 0.64TSSg m^{-2} yr^{-1} was estimated.

Yield coefficients can be used to estimate phosphorus budget, only when the annual water budget is well known, since models for nutrient budgets and loading always assume steady state conditions. With lake Naivasha being an endorrheic basin, there is uncertainty over the steady state concept. However Becht (in press) has estimated a first water budget for Naivasha, showing a significant amount of water loss by evaporation, groundwater flows and abstractions. With a long-term equilibrium between lake area and associated water levels documented by Åse *et al.* (1986), the lake volume, area and depth were estimated from lake levels for the period 1997-1999 (Table 7.9), followed by estimation of lake flushing rate and water residence period (Table 7.9) using Becht's (in press) values (Table 2.2, appendix Table 12). Consequently lake TP concentration and loadings from the catchment were predicted using Cooke *et al.* 1993 models for the two different study phases (Table 7.9)

Table 7.9: Predicted TP loading with the associated parameters estimated for lake Naivasha

	Extremely wet year (1997-1998)	**Normal wet and dry** year (1998-1999)	**Overall mean** for the years 1997-1999
Mean lake level (metres a.s.l)	1888.47 ± 0.53	1887.53 ± 0.38	1888 .05 ± 1.1
Lake volume (km^3)	780	600	700
Lake area (km^2)	160	148	152
Mean depth (m) (Volume/Area)	4.9	4.1	4.6
Flushing rate (year)	0.68	0.55	0.59
Water residence time (years)	1.5	1.8	1.7
Predicted lake TP (μg/l) (**Observed** TP) (Cooke *et al.* 1993)	45.04 (45.94)	37.72 (37.2)	51.18 (52.2)
Predicted lake TP **loading** ($g\ m^{-2}\ yr^{-1}$) (Cooke *et al.* 1993)	0.39	0.14	0.23
Observed lake TP **Loading** ($g\ m^{-2}\ yr^{-1}$)	1.41	0.21	0.60

The TP loading predicted values were lower than the amount obtained for both phases. This suggests that either the amount of phosphorus input from the catchment was too high for Cooke *et al.* (1993) models rendering them inaccurate or the Becht's water budget might be missing or underestimate/overestimate some pathways.

7.6 Trophic status of Lake Naivasha

The trophic status of lake Naivasha is estimated for the three different seasons encountered during the study period; heavy rainy, normal rain and the dry seasons. Using Vollenweider's five-class tentative classification based upon TP concentration (Vollenweider 1968), lake Naivasha lies in the category of eu-polytrophic (30-100 μg/l) during the extremely wet and the dry seasons and meso-eutrophic (10-30 μg/l) during a normal wet season. If the quotient between in-lake phosphorus and mean inflow phosphorus concentration P/P_1 ratio is plotted against P_1 on a logarithmic scale and extrapolated using Ahlgren *et al.* (1988), lake Naivasha falls in the eutrophic category (Figure 7.6).

As discussed by Jones & Lee (1982), TP concentrations in a water body should not be considered as the only indicator of water quality without considering its consequences to algae. Several authors have extended the trophic state classification to include chlorophyll *a* concentration and transparency measured as Secchi depth in addition to TP concentration (as discussed in Harper 1992a). Considering these parameters, lake Naivasha is generally classified as eutrophic with chlorophyll *a* concentration > 10 μg/l, Secchi depth < 1.7 metres and TP concentration of > 40 μg/l using 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 7.10. An alternative classification of Carlson (1977) based upon calculation of a "Trophic State Index" (TSI) was also considered (Table 7.10) and using Kratzer & Brezonik's (1981) index scale, Naivasha was approaching hyper-eutrophic status during the heavy rainy season between October 1997 and March 1998 with TSI scale values range of 58 – 66.

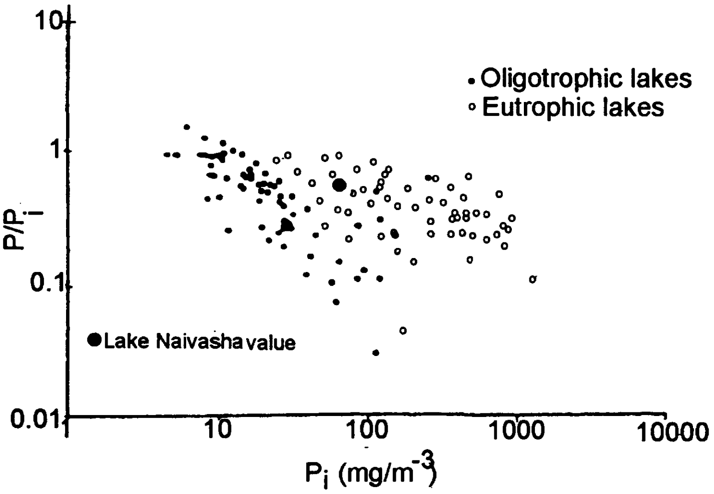


Figure 7.6 Quotient between mean inlake phosphorus and inflow concentration (P/Pi) as a function of mean inflow phosphorus concentration (Pi) for lake Naivasha extrapolated on Alhgren *et al.* 1988 curve

During the normal rainy season in March - May 1999 and the dry season in September 1998 to February 1999 the lake lay in the eutrophic category with TSI scale values ranging from 56 - 59 for both seasons (Table 7.10). Considering phosphorus loading ($gTPm^{-2}\ yr^{-1}$) against the mean lake depth (Figure 7.7), lake Naivasha lies in the "naturally or artificially" eutrophic category of Vollenweider (1968).

Table 7.10: OECD and Carlson's Trophic State Index (TSI) with the associated parameters for lake Naivasha.

Season	**TP** (μg/l)	**Chlorophyll a** (μg/l)	**Secchi depth** (m)
Heavy rainy (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 rainy (March -May 99)			
Measured value in the lake	**29.5**	**13.5**	**1.3**

OECD	meso-trophic	eutrophic	eutrophic
TSI index	58.7	56.5	57.4
Dry (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)

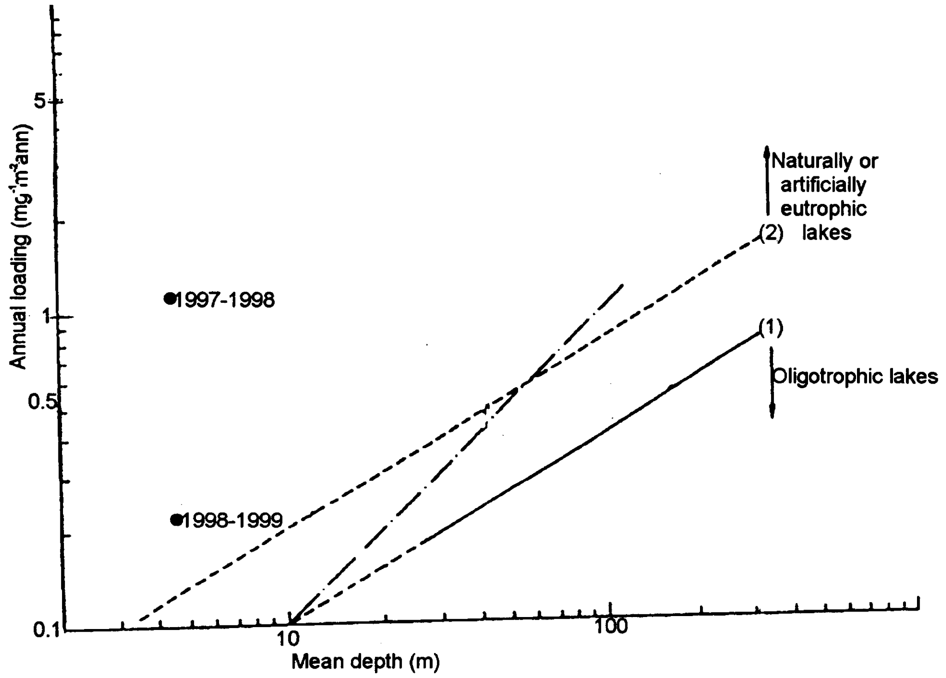


Figure 7.7 The lake Naivasha loading rate verses depth for the two different phases studied (1997-1998 and 1998-1999), extrapolated on Volleinweder (1968) curve modified by Harper (1992a)

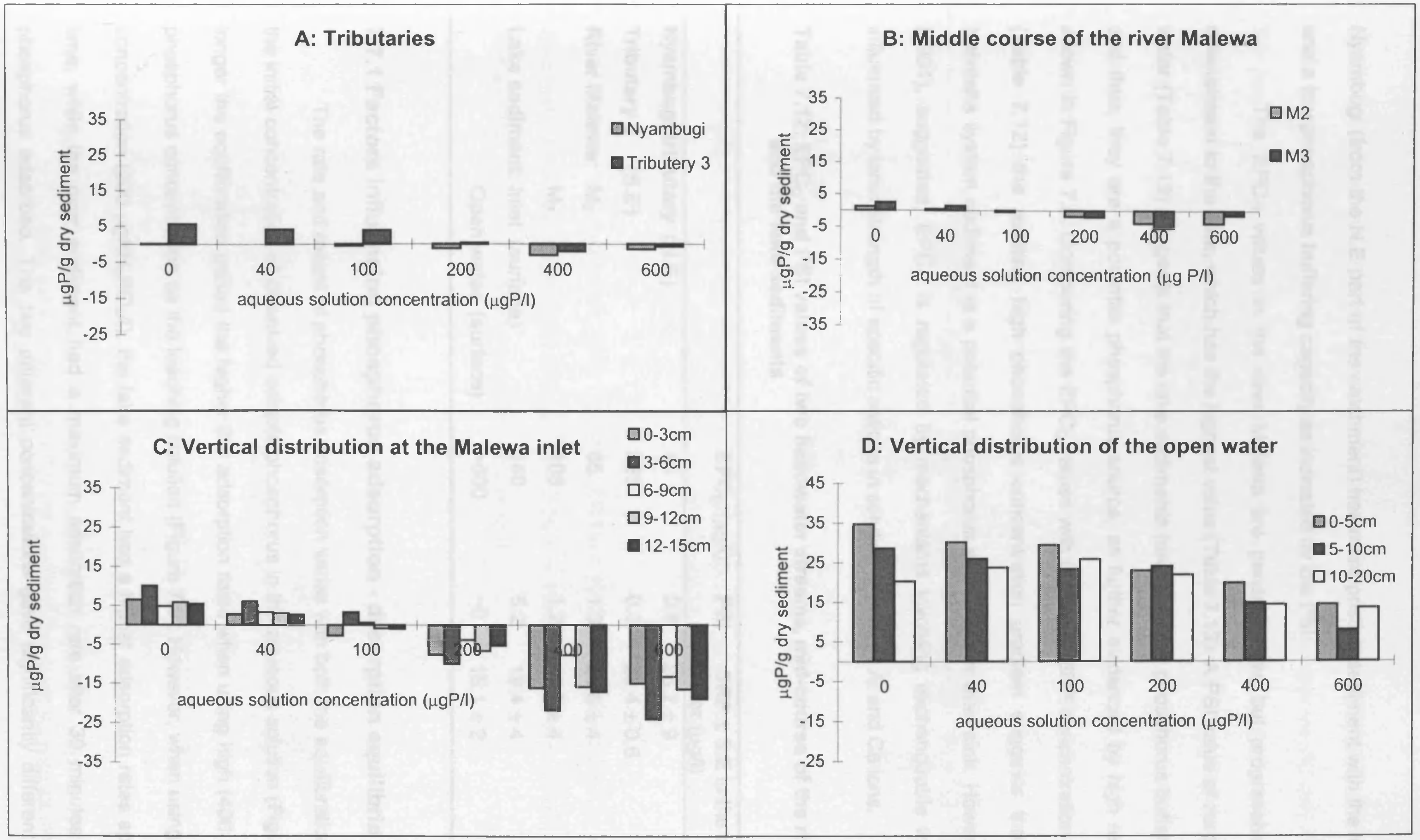
Comparing the TP loading values obtained during this study with Vollenweider's permissible and dangerous loadings illustrated in Table 7.11, lake Naivasha lies above the lower limit of dangerous loadings (> 0.13 $gTPm^{-2}\ yr^{-1}$) for a mean depth < 5 metres (Table 7.9) for all the seasons. Comparing the lower limit of Vollenweider (1968) and 1.41 loading obtained for the heavy rainy season, unquestionably lake Naivasha received high TP loadings during the "El Niño effects rains". These high loading values may have exceeded the upper limit of the Cooke *et al.* (1993) model rendering it unreliable, hence the underestimated predicted TP loading values in Table 7.9. Even the underestimated loading values are still within the dangerous loading category. But, despite the high TP loadings, most trophic classification models classify lake Naivasha as eutrophic but not hyper-eutrophic as would be expected from the loadings values. OECD (1982) classifies the lake as hyper-eutrophic during the heavy rainy season when considering chlorophyll *a* concentration and lake transparency (Table 7.10).

Table 7.11: Vollenweider's (1968) permissible and dangerous TP loadings (g m^{-2} yr^{-1}) in comparison to lake Naivasha values in relation to its mean depth (inserted are the values obtained for different season in lake Naivasha)

Mean depth up to	Permissible TP loading up to	Dangerous TP loading up to
5 m	0.07	0.13
Lake Naivasha (<5 m)		**0.61 (overall mean)** **0.21 (normal)** **1.41 (extremely wet year)**
10 m	0.1	0.2
50 m	0.25	0.5
100 m	0.4	0.8
150 m	0.5	1.0
200 m	0.6	1.2

7.7 Phosphorus adsorption - desorption rates in the sediment

Phosphorus adsorption-desorption rates for sediments from different parts of the Naivasha system from the headwaters to the lake are illustrated in Figure. 7.8, while the "zero equilibrium phosphorus concentration" (EPC_O) and "phosphorus sorption index" (PSI) values are given in Table 7.12. The PSI values are shown to be significantly different in different parts Naivasha using a one-way ANOVA ($p < 0.001$). Of the two-headwater streams studied, the



KEY: The symbols plus (+) represent desorption while negative (-) is adsorption rate

Figure 7.8 Adsorption - desorption rates of different parts of the Naivasha system from the headwaters up to the lake

Nyambugi (from the N.E part of the catchment) has more pristine sediment with the lowest EPC_O and a low phosphorus buffering capacity as indicated by low PSI.

The EPC_O values in the river Malewa are generally low, but progressively increase downstream to the lake, which has the highest value (Table 7.12). A PSI value of zero in the open water (Table 7.12) suggests that the lake sediments have very low phosphorus buffering capacity and thus, they are a potential phosphorus source, as further evidenced by high release rates, shown in Figure 7.8. Comparing the EPC_O values with the mean SRP concentration in the water (Table 7.12) the existing high phosphorus concentration gradient suggests that the entire Naivasha system sediment is a potential phosphorus source rather than sink. However, as Klotz (1991), suggested, EPC_O is regulated by mechanisms involving exchangeable ions that are influenced by ionic strength of specific cations in solution especially Al and Ca ions.

Table 7.12: EPC_O and PSI values of two headwater streams, mid-course of the river Malewa and the lake sediments

	EPC_O (µg/l)	PSI	SRP ± S.E in the overlying water (µg/l)
Nyambugi tributary (N.E)	45	0.8	25.7 ± 9
Tributary 3 (S.E)	225	0.3	23.4 ± 0.6
River Malewa: M_2	65	1.3	24.5 ± 4
M_3	105	1.2	27.2 ± 4
Lake sediment: Inlet (surface)	140	5.2	19.4 ± 4
Open water (surface)	>600	~0	16.1 ± 2

7.7.1 Factors influencing phosphorus adsorption - desorption equilibria

The rate and extent of phosphorus adsorption varies with both the equilibration period and the initial concentration of dissolved soluble phosphorus in the aqueous solution (Figure 7.9). The longer the equilibration period the higher the adsorption rates when using high (400 $\mu gKH_2PO_4/l$) phosphorus concentration as the leaching solution (Figure 7.9). However, when using much lower concentration (200 $\mu gKH_2PO_4/l$), the lake sediment had a higher adsorption rates spread across time, while the river sediment had a maximum adsorption rate after 30 minutes with 10.8% phosphorus adsorbed. The two different concentrations gave significantly different adsorption-desorption values and PSI indices ($p = 0.01$) at the Malewa inlet station but not at the M_4 ($p > 0.05$). However, the phosphorus adsorption-desorption rates were not significantly different over the time in both stations using two way ANOVA ($p > 0.05$). To standardise the variation of adsorption-desorption rates, which could result due to differences in equilibration period, the adsorption-desorption rates experiments used to calculate the EPC_O and PSI were equilibrated for 6 hours.

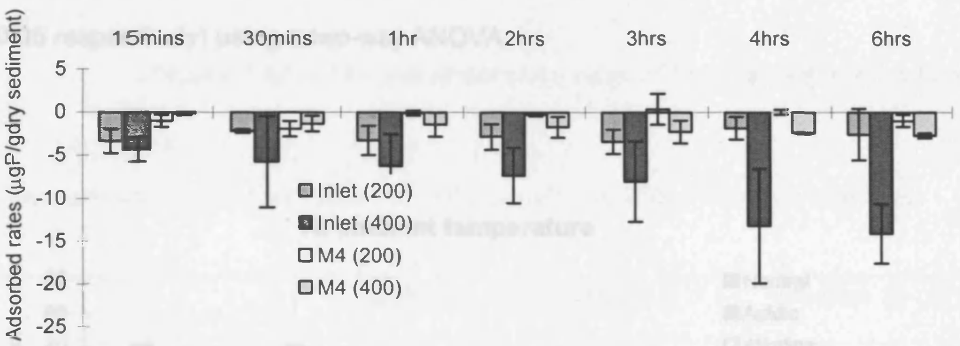


Figure 7.9 Influence of equilibration period and concentration of aqueous leaching solution (200 and 400 µg/l) to adsorption rates at the M_4 station and the Malewa inlet

The difference in desorption rates of three different stations are illustrated in Figure 7.10. Desorption rates were significant different ($p < 0.001$) in the three different stations (open water, inlet and M_4), but not with different equilibration periods.

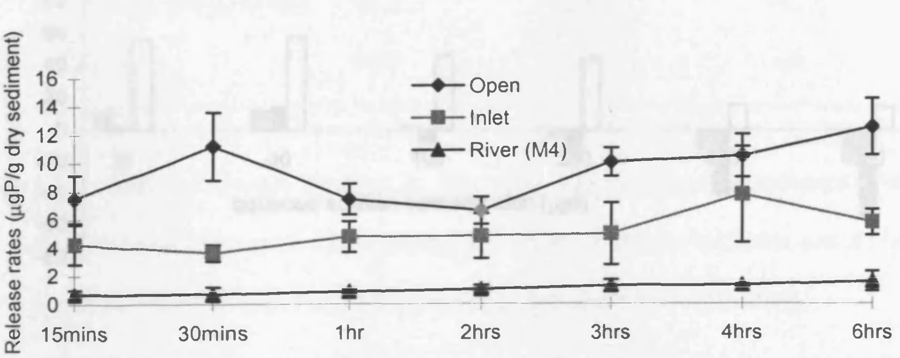


Figure 7.10 Mean release (desorption) rates (± SD) of different parts of the Naivasha system at different equilibration period ranging from 15 minutes to 6 hours

The influence of temperature and pH in adsorption-desorption rates is summarised in Figure 7.11. Increase in temperature resulted in higher EPC_O mainly in alkaline conditions but, lower in acidic conditions (Table 7.13). To the contrary buffering index (PSI) increased at higher temperature in acidic and neutral conditions in the Malewa inlet. This is probably due to increase in rate of sorption reaction rather than change in the capacity of the sediment to absorb phosphorus. Increase in phosphorus desorption in high pH is well demonstrated by the positive correlation in Figure 7.12. pH changes significantly influenced the EPC_O and PSI values ($p = < 0.0001$ and 0.05 respectively) using a two-way ANOVA.

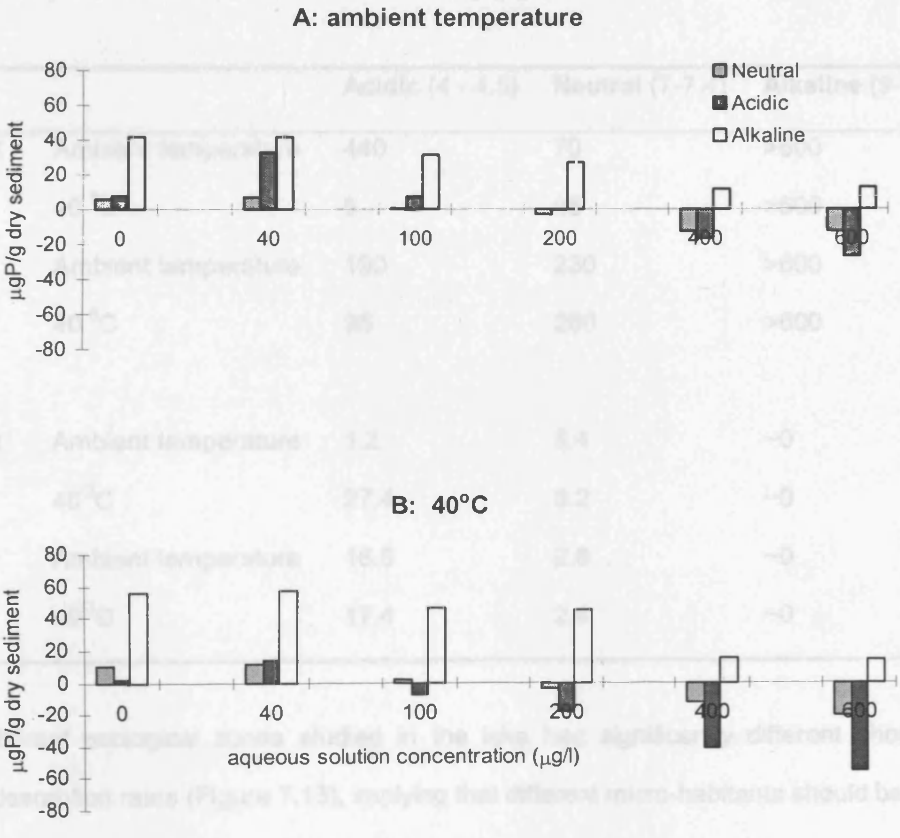


Figure 7.11 Influence of temperature and pH on adsorption-desorption rates of the Malewa inlet sediment

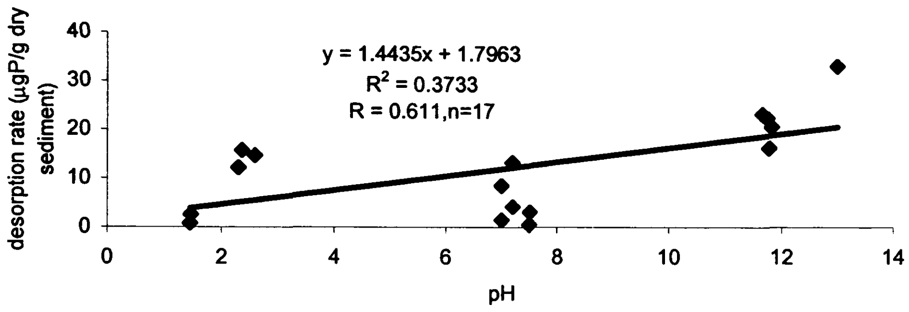


Figure 7.12 pH verses desorption rates of the Malewa inlet sediment

Table 7.13 Temperature and pH influence on EPC_O (µg/l) and PSI of the lake sediment

A: EPC_O

Station		**Acidic** (4 - 4.5)	**Neutral** (7-7.4)	**Alkaline** (9-10)
Malewa inlet	Ambient temperature	440	70	>600
	40 °C	5	85	>600
Open water	Ambient temperature	190	230	>600
	40 °C	95	260	>600
B: PSI				
Malewa inlet	Ambient temperature	1.3	5.4	~0
	40°C	27.4	8.2	~0
Open water	Ambient temperature	16.6	2.6	~0
	40°C	17.4	2.4	~0

The two different ecological zones studied in the lake had significantly different phosphorus adsorption-desorption rates (Figure 7.13), implying that different micro-habitants should be treated as entities and generalization of adsorption-desorption rates could be misleading.

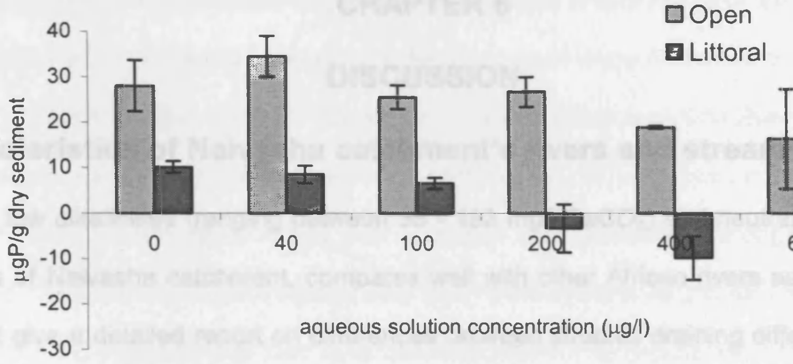


Figure 7.13 Comparison of adsorption-desorption rates in two lake ecological zones

CHAPTER 8

DISCUSSION

8.1 Characteristics of Naivasha catchment's rivers and streams

The low alkalinities (ranging between 38 - 192 mg/l $CaCO_3$) and neutral pH of the rivers and streams of Naivasha catchment, compares well with other African rivers as shown in Table 8.1. I cannot give a detailed report on differences between streams draining different parts of the upper catchment area. The difficult in stream accessibility especially during the rainy season resulted in inconsistent and limited sampling sessions (with a minimum of n = 3 in each stream).

Table 8.1: Comparison of Naivasha catchment rivers with other African rivers.

River	**Region** (in Africa)	**Conductivity** (µs/cm)	**pH**	**Total alkalinity** (mg/l as $CaCO_3$)	**Total Hardness** (mg/l as $CaCO_3$)	**Reference**
Malewa	East (Kenya)	53 - 224	7.24 - 8.38	16 - 142	22.2 - 56.7	This study
Gilgil	East (Kenya)	57 - 129.	7.28 - 8.16	16 - 88	19.7 - 27.1	This study
Karati	East (Kenya)	82 - 458	6.29 - 8.43	76.2 - 202	33.9 - 72.7	This study
Tana	East (Kenya)	80	6.9	45	_	Pacini 1994
Kaihungu	East (Kenya)	139 - 150	7.1	92	_	Pacini & Harper (1996)
Nile	North Eastern	140 - 350	7.9 - 9.1	37	_	Dumont 1986
Zaire (Kinshasa)	Central	_	6.3 - 8.2	_	_	Bailey 1986
Zambezi (Kariba)	Central-Southern	51.4 - 97.8	7.1 - 7.6	21 - 45.1	21.6 - 41.5	Davies 1986
Kafue	Central - Southern	168 - 293	7.04 - 8.02	89 - 158.7	_	Davies 1986
Luanga	Central-Southern	61 - 233	7.69 - 8.17	32 - 82	25 - 87	Davies 1986
Orange – Vaal	South	71 - 214	6.4 - 8.0	22.1 - 210	_	Davies *et al.* 1995
Black Volta	West	41 - 124	6.5 - 7.3	79 - 90	_	Petr. 1986
Niger	West	31 - 99	6.0 - 8.0	_	_	Welcomme 1986
Gambia	West	32 -77	6.9 – 7.4	_	_	Lesack *et al.* 1984

The bicarbonate dominance obtained in the rivers portrays a well-buffered system. The high Ca^{++} ion concentration in all the rivers, streams and the lake, could imply that most of the bicarbonates are present as $CaHCO_3$ derived from limestone. This compares well with rivers from Zaire and western rift studied by Kilham (1972). He observed that high Ca^{++} ion concentration was found in regions containing metamorphic rocks, rich in calcite and dolomite, although potassium and magnesium dominated in volcanic regions. The lake Naivasha and its catchment lie in a volcanic area (Odingo 1971) consisting of trachytes, alkaline basalt and phonolites with acid to alkaline black-red soils, typical for areas with its type of basement rock. But, according to Shackleton (1945) the soils colour may not depend on the nature of the bedrock, but rather on the slope, which controls the drainage and consequently the oxygen content of the soils. Although the major ionic components in the water were not determined, the cationic dominance ($K \geq Na \geq Ca$) reflected by the sediment classifies the streams and rivers into "Common" category of Kilham (1972) together with other great rivers of Africa and other "rain dominated" catchments.

The reduction of ionic concentration observed in the rivers and the tributaries during the rainy season is a well-known phenomenon and has been documented in many rivers of the world (Davies & Walkers 1986). The negative correlation ($R = -0.652$, $R^2 = 0.425$) obtained for the river Malewa in this study is comparable to Pacini's (1994) value ($R = -0.677$, $R^2 = 0.458$) for Kaihungu of the Upper Tana river catchment, Kenya. Dunne & Leopold (1978) also obtained a good relationship between discharge and TDS in Athi river in Kenya.

The suspended solids (TSS) and discharge relationship obtained during this study was not very strong. This may be due to anthropogenic influence. The intensive human activities in the rivers and streams, especially watering of the livestock in the rivers disturb the sediment causing re-suspension and consequently high TSS loads during low discharges, which is not expected normally. Pacini (1994) obtained strong correlations for the rivers situated on the western slope of the Nyandarua ranges in cultivated areas with fewer cattle.

The high discharge coefficient indices (R) obtained for both the rivers Malewa and the Gilgil, compared to other tropical rivers reported by Talling & Lemoalle (1998), reflect a "unimodal tropical rain regime". The extremely high R index for the river Gilgil classifies it further into a "dry tropical river" Talling & Lemoalle (1998). The inference here is that the association between rainfall regimes and discharge are no longer apparent within the Naivasha catchment. This is probably due to presence of different microclimates between the upper and the lower catchment, with higher rainfall in the upper catchment. Hubble (2000) also found a significant difference in the amount of rainfall received between lakeside and upland climatic conditions throughout a 66-year period 1932 to 1997. The human activities involving water abstraction from the rivers and streams for irrigation farming might be contributing to the imbalance between the rainfall and discharge.

8.2 Phosphorus forms and concentration in the rivers and streams

The Naivasha rivers and streams have more phosphorus concentration than the 10 μg/l (SRP) or 25 μg/l (TDP) estimated by Meybeck (1982) to represent world-wide unpolluted rivers. Furthermore the total TP export of 1.98 kg $ha^{-1}yr^{-1}$ for the three rivers during the heavy rainy season (1997-1998) lies within the range of 0.01-3.0 kg $ha^{-1}yr^{-1}$ documented by Reckhow & Chapra (1983) and 1-3 kg $ha^{-1}yr^{-1}$ by Reckhow & Simpson (1980) for agricultural land. In addition the 1997-1998 total yield was almost 4 times the maximum value (0.5 kg $ha^{-1}yr^{-1}$) given by Rast & Lee (1978), while the normal wet and dry year (1998-1999) gave low values (0.3 kg $ha^{-1}yr^{-1}$). However, when the overall mean of the phosphorus transported (kg/d) in each river for the years 1997 to 1999 was estimated (333.3 ± 930, 14.1 ± 16.7 and 0.33 ± 5 for rivers Malewa, Gilgil and Karati respectively), the total yield of 0.84 kgTP $ha^{-1}yr^{-1}$ still exceeds the maximum value of Rast & Lee (1978). This value is almost five fold that of Kaihingu stream on the western side of the Nyandarua ranges with extremely high TSS yield (Pacini & Harper 1996). This implies that the Naivasha catchment soils might have high phosphorus content probably from anthropogenic influence, as Hinga (1973) and Nyandat (1981) pointed out that phosphorus content was low in Kenyan soils. However Gaudet (1979) estimated a loading value of 0.16 kg $ha^{-1}yr^{-1}$ for the river Malewa from the north swamp, which is much lower than the 0.3 kg $ha^{-1}yr^{-1}$ value for the 1998-1999 (normal wet and dry year), and almost 10 times less the yield obtained during the heavy rainy season in 1997-1998. However during the time of Gaudet's work the river was flowing through a vast swamp, while during this study the river was flowing through an open channel most of the time except a few cases when the river mouth was blocked by floating island consisting mainly of papyrus and water hyacinth.

The high R^2 correlation value and linear relationship obtained between PP and TSS in Naivasha catchment rivers and tributaries is evidence that most phosphorus is transported in PP form bound in soil particles. PP dominance in runoffs from cropped watersheds have been reported by Burwell *et al.* (1977), Nelson *et al.* (1979) and Sharpley & Smith (1990) elsewhere. Pacini (1994) working in the rivers of the Upper Tana river catchment obtained similar strong correlation ranging between R^2= 0.80 to 0.842. Kronvang *et al.* (1996) working in the arable Galbaær catchment in Denmark also obtained a significant strong correlation (R^2 = 0.87, $p <$ 0.001). Further significant positive correlation obtained during this study between discharge and PP, TSS in the rivers especially the river Malewa signifies the importance of hydrological regime of the rivers in controlling particulate matter and PP mobilization and transport. Such soil mobilization could pose a serious threat to rivers if the surface soils are rich in phosphorus. They can also be potential risk to contamination with other substances (Kronvang *et al.* 1996). There is a possibility of microbial contamination especially in the upper catchment where the degree of hygiene is low, while pesticides and heavy metal contamination can occur on the lower horticultural area.

The increase of TP from < 50 µg/l to ≥ 150 µg/l at the start of the rainy season is evidence of phosphorus flush into the rivers and streams during the rainy season mainly as surface runoff. This is probably the result of erosion caused by poor farming methods practiced almost in the entire catchment area. Most of the land is cultivated intensively up to the riverbank without any tillage on the steep slopes, or is overgrazed, leaving the soils bare. This provides suitable conditions for source of surface runoff. Dethier (1986) found out that high surface runoff resulted in approximately 10 times greater rate of weathering than during low runoff. Thus catchments with high surface runoff resulting from soil erosion consequently have high phosphorus input into the rivers during the rainy season. As Heathwaite (1997) pointed out, the balance between rainfall input and runoff generation is extremely important when it comes to phosphorus loss, although Morgan (1997) shows that it is a highly site-specific process. The high concentration of different forms of phosphorus in the surface runoff as opposed to the low concentrations in the rainwater within Naivasha and its environs, confirms the importance of surface runoff in phosphorus concentration and fluxes in rivers and streams rather than aerial sources. Although the amount of phosphorus lost in this way might seem insignificant, most of the people living in the upper catchment are small-scale farmers who cannot afford to use inorganic fertilisers intensively. Instead, they use organic manure cheaply harvested within their farms. (Information to quantify the amount of organic fertiliser used was not available.) But, Harrison (1987) showed that addition of organic manure or excreta from grazing animals to soils, increases the mobility of soil's organic phosphorus, although according to (Brooks *et al.* 1997) the process is highly dependent on soil microbial cycling. Heathwaite (1997) on the other hand suggested that DOP is mainly generated from organic matter and organic biomass residues. Probably this can explain the presence of DOP form in the Naivasha rivers and streams.

The importance of vegetation cover in reducing soil mobilization and associated nutrients in Naivasha catchment is suggested by the low concentration of TP in the high altitude M_1 station in the river Malewa, with the highest SRP/TP ratio (>50% in SRP form) in the river, rather than the PP which dominated the middle and lower course stations. The 50% of TP transported as SRP obtained for this station compares well with 62% from the grass watersheds on the southern plains area of Oklahoma and Texas studied by Sharply & Smith (1990). This is because runoff from grassland carries little soils and is dominated by phosphorus of geological origin released in soluble form (mainly in SRP) through mineralization (Heathwaite 1997, Sharpley & Rekolainen 1997). As SRP spirals through the river channel it may be adsorbed by the suspended solids resulting in increase in PP form downstream, or may be adsorbed in the sediment reducing the concentration in the water all together. Also SRP uptake by the riverine vegetation along the river channels could have taken place as Walton & Lee (1972) and Nürnberg & Peters (1984) stated that SRP is immediately available for biological uptake. The exhibit of slight elevated SRP levels accompanied by decrease in conductivity at M_1 station and elsewhere during the heavy rainy season, probably indicates decrease in ionic strength and cation concentrations, meaning that part of the SRP increase may have occurred as a result of phosphate buffer mechanism and not increase by input. However considering phosphorus loss from other grassland-based agricultural catchments the calculated mean TP loss of 0.56 kg TP ha^{-1} yr^{-1} for this station (M_1) lies at the upper limit (0.5 kg P $ha^{-1}yr^{-1}$) of TP loss from pasture-land documented by Sonzongni *et al.* (1980) and (0.4 kg P $ha^{-1}yr^{-1}$) of Crisp (1966). In areas with good vegetation cover most phosphorus loss occurs via sub-surface runoff. The M_1 adjacent steep slopes can accelerate the creation of sub-surface runoff into the river from the pastureland, thus enhancing TP transport during the rainy season. High phosphorus export from fertilized grassland has been documented previously by Heathwaite & Johnes (1996), Heathwaite 1997. On the Severn Trent catchment in UK (Midlands region), phosphorus concentration increased at least 16 times in heavily grazed grassland (with > 16 cows per hectare) areas (Heathwaite *et al.* 1990), while Ryding & Forsberg (1979) obtained similar results in six different catchments. However the Naivasha catchment lies in the Heathwaite's (1997) lightly grazed category with 1 cow per 2.5-3 hectares, but this would be considered as heavily grazed for a semi arid climate considering that approximately only a quarter of the land is arable and used for both cultivation and pasture.

Heathwaite (1997) classified feeding and watering site as high risk areas for phosphorus loss into rivers and streams. During the dry season, due to scarcity of water, most of the livestock within the Naivasha catchment are watered directly in the rivers. As the livestock dash into the river in groups, they erode the riverbank at their entry point by degrading the riverbank vegetation either by trampling on it or grazing. This provides the best conditions for accelerated surface runoff into the river even with the slightest downpour. The slight increase of silt content at M_3 could indicate bank erosion. The livestock also trample the riverbed and consequently disturb the sediment as they drink water. The increase in TSS concentration and dominance of PP form at the M_3 site could be mainly due to re-suspension of sediment and its associated nutrients. In addition higher SRP concentration at this site may diffuse from the interstitial waters due to sediment disturbance. The sediment grain size structure obtained for the M_3 station, which is dominated by coarser grain size despite the slight increase of silt/clay noted, is probably due to the frequent sediment disturbance in the main channel resulting in downstream wash of the fine grains. As Heathwaite (1997) pointed out, transport of eroded material or suspended solids is particle size selective, with the highest mobility in fine silt and clay sized soil fractions. This study shows that watering of livestock in the rivers causes elevated concentration of phosphorus at the impact site and downstream of M_3 station. The extent to which this source influences phosphorus content downstream depends on discharge, number of livestock visiting the river and frequency of disturbance. The Naivasha catchment is disturbed continuously almost throughout the year, so the riparian land can be classified into "high risk land category" of Heathwaite (1997).

The lower sections of the rivers are surrounded by thick papyrus-dominated swamp, which is inhabited by hippopotamus and buffaloes immediately before the entrance of the lake. Increase in concentration of nutrients, especially phosphorus, at G_3, K_4, M_5 and the inlets, might indicate the animal's impact on nutrient concentration and fluxes on the lower part of the rivers. However, this concept could not be tested during this study. On the other hand there could be other explanations for these results. These being the lowest stations before the rivers enter the north swamp, reduction in water flow due to change in gradient, may result in sedimentation of most bound chemical elements including phosphorus, which together with mineralization can cause an increase in concentration.

Other human practices such as intensive washing of clothes and vehicles in the rivers, in conjunction with the above could cause increase in phosphorus concentration in the flowing waters especially along the river Karati and the lower stations in the river Malewa, due to their proximity to human settlements and urban centres.

8.3 Lake phosphorus status

The TP concentration in the lake increased 9 fold in 1997 during the heavy rainy season, and by 5.5 times in 1999 by average compared with the situation in 1990. The difference in TP concentration in the open water for 1990, 97, and 99 are summarised in Figure 8.1 below.

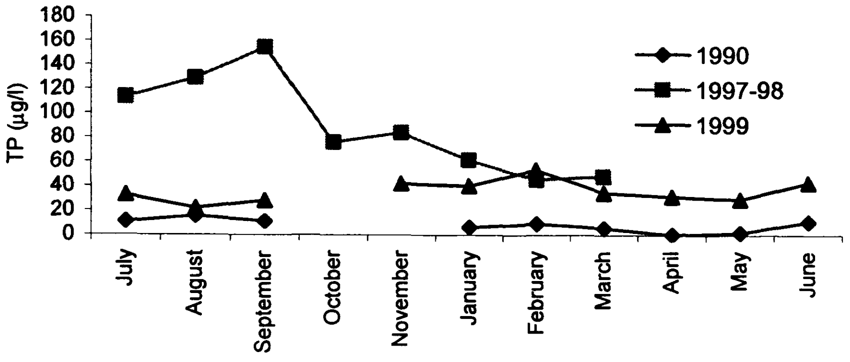


Figure 8.1 Lake Naivasha mean total phosphorus (TP) concentration over different years (1990 data from Kitaka 1991)

This shows that the lake received more phosphorus during the El Niño rains than the previous years. The TP concentration reduced 3 times by the year 1999 compared to 1997, probably because of less flooding with low surface runoff and consequently low phosphorus flush into the rivers. The TP loading per unit area of the lake surface was 1.41g m^{-2} yr^{-1} in 1997-1998 compared to 0.21g m^{-2} yr^{-1} for 1999. However such a great increase in concentrations and loading cannot be explained by changes in lake level alone (Kitaka *et al.* in press). Increase in input under heavy rainfall due to changes in land practices and management of the catchment are more likely to be the cause. In addition, the possibility of sediment loading is indicated by high phosphorus release rates in the adsorption-desorption experiments using the lake sediment.

Yield coefficients can provide a reasonable estimate of TP loading to a lake (Rast & Lee 1978), but the TP loading values predicted for lake Naivasha were more than 2 fold lower than the observed values. There could be several explanations for this. The high TP loading obtained during this study were not normal because of the abnormal extremely wet year which means that the loading values could be too high to have a reliable relationship with any lake parameter, or the lake water budget proposed by Becht (in press) may not be comprehensive enough to account for the steady state concept of the lake. This would occur if all the input or output water pathways had not been accounted for. Therefore, since nutrient budget models and lake mass balances in the literature are based on the steady state concept, the budget for lake Naivasha was not estimated. This may be possible in the near future when the lake's water budget is more clearly understood.

8.4 The relationship between different forms of phosphorus and algal biomass

Open water verses littoral algal biomass difference in lake Naivasha, has been previously documented by Melack (1976,1979), Harper (1987) and Kitaka (1991), although the difference between the inlet and the open water could be more complicated than a normal littoral zone. This is because in addition to normal nutrient competition between phytoplankton and macrophytes there is an additional riverine influence, which may alter the biological uptake of nutrients, and hence affect the algal biomass either positively or negatively. The inverse correlation between chlorophyll and TDP and its constituents may portray their biological uptake, reducing the concentration in the water column, and consequently result in low algal biomass. This is similar to Rigler (1966), Peters & MacIntyre (1976) and Biney (1990) results. However, the interpretation of the correlation between TDP and chlorophyll *a* is more complicated, because both organic and inorganic molecules are involved. The dissolved fraction is operationally defined by filtration (Meyer 1979, Lesack *et al.* 1984), which does not eliminate the colloidal particles. It is most likely that the negative correlation obtained for TDP and chlorophyll *a* is mainly due to the SRP fraction, which is biologically available.

The chlorophyll versus total phosphorus ratio (Chl.a/TP) with a range 0.5-4.5 for the lake, compares with the values of Ahlgren *et al.* (1988) for lakes Norrviken and Vallentungsjön in Sweden. The curvilinear relationship between chlorophyll-phosphorus ratio with total phosphorus concentration compares partially to the results obtained using Megard's (1978) model and OECD (1982) as opposed to other models used by Ahlgren *et al.* (1988). The latter suggested that variation in Chl.a/TP ratios in lakes are due to changes in chlorophyll and phosphorus content of the phytoplankton. Shapiro (1978) argued that chlorophyll-TP regression models can be misleading when applied to individual lakes and especially when plotted on a linear scale as the variance in the Chl.a/TP ratio becomes more obvious. Allan (1980), Smith (1982) and Canfield (1983) suggested that the Chl.a/TP ratio variance can be refined by taking into consideration the water nitrogen content and nitrogen/phosphorus (TN/TP) ratios. However Praire *et al.* (1989)

suggested that TP ratios are consistently a better predictor of chlorophyll than TN except in lakes with very low TN/TP ratios. He further suggested that the Chl.*a* = f(TP) relationship should be restricted to lakes with similar TN/TP ratios, as lakes with ratios between 23 - 28 showed the steepest Chl.*a* = f(TP) and Chl.*a* = f(TN) slope indicating the largest chlorophyll changes relative to nutrient concentration changes.

Phosphorus–chlorophyll relationships in lakes have been extensively reviewed by Nicholls & Dillon (1978), Ahlgren *et al.* (1988) and Harper (1992a). The outcome of these reviews may be difficult to compare because authors have used different time periods for their calculations, with most of the models developed in the temperate zone using summer means, except OECD (1982) where annual mean values were used. However there is good linear correlation between chlorophyll a and TP concentration in most cases. The slopes obtained during this study where much lower than the general range of 0.4-1.0 obtained in most models considered by Ahlgren *et al.* (1988). However, there is certainly a dependence of chlorophyll concentrations on phosphorus concentrations, which can be used to estimate the maximum chlorophyll of the lake. The mean TP concentration 52.2 ± 18 and 83.9 ± 33.2 µg/l respectively in the open water and the Malewa inlet obtained during this study (1997-1999), predicted lake Naivasha chlorophyll *a* using several models considered by Ahlgren *et al.* (1988) is illustrated in Table 8.2 below.

Table 8.2 The observed mean chlorophyll a (µg/l) for the years 1997-1999 and the predicted concentration using different models in the open water and the Malewa inlet of lake Naivasha

	Open water	Malewa inlet	Reference
Observed (mean value ± SD)	22.07 ± 13.8	19.12 ± 12.5	This study
1.**Predicted using linear models**	22.09	16.19	Table 6.4 for open water
	23.91	41.35	Edmonson & Lehman (1981)
	20.99	34.41	Berge *et al.* (1980)
	34.5	52.9	Megard (1978)
	54.8	92.5	Schindler *et al.* (1978)
2. **Using logarithmic models**	38.5	81.6	Sakamoto (1966)
	22.4	44.6	Dillon & Rigler (1974)
	1.4	2.2	OECD (1982)

Despite the fact that these models were designed for temperate waters, the chlorophyll *a* concentration for the open water in lake Naivasha can be accurately predicted using most linear and logarithmic models except that of Schindler *et al.* (1978), whose prediction gave a significantly higher value, while the OECD (1982) model underestimated the concentration. This is not surprising as the OECD (1982) model used annual means, including the low winter values, which would underestimate chlorophyll *a* concentration of tropical waters with continuous phosphorus input and annual algal growth. The concept of Kilham & Kilham (1990), of "endless summer", which states that biological control of essential elements cycles in the tropics takes place all the year round rather than a few months in summer emphasizes the differences between the two types of lake. However, they agree that analogues are necessary because algal and nutrient dynamics of most tropical lakes are unknown. Kalff & Watson (1986) had earlier proposed that tropical lakes can be limnologically similar to temperate lakes during their summer, which means that summer values of temperate lakes can serve as analogues for tropical lakes on a year round basis.

All the models overestimated the chlorophyll *a* concentration at the inlet (except the OECD (1982)). This could be due to the fact that TP at the inlet is also bound into other particulate matter brought in by the river, making the TP-chlorophyll relationship unreliable. However, Ahlgren *et al.* (1988) cautioned that changes in plankton community structure, which may occur as a result of changes in nutrient loading, could change the relationship and make the predictions less accurate. Harper (1992a) also cautions over the use of regression equation models, because of the unpredictability of other abiotic factors.

8.5 Water - sediment interaction

Comparison of phosphorus content in the sediment with literature data has to be cautiously treated because, as Pettersson *et al.* (1988) showed, results are normally heavily biased by the method of analysis used. However, the superficial sediment TP content in the central and southern part of the lake lie within the 0.66-4.70 mgTP/gSed.drywt obtained in sediments of different types of lakes ranging from oligotrophic to polytrophic by Boström *et al*

(1982) and the 0.55-6.49 mgTP/gSed.drywt of Pettersson *et al.* (1988). While the littoral sediment at the Malewa inlet and off Crescent Island (0.3 and 0.37 mgTP/gSed.drywt respectively), had much lower concentration. Comparing the general mean of 0.64 ± 0.4 mgTP/gSed.drywt for 1997-1998 with a mean of 0.46 ± 0.1 mgTP/gSed.drywt obtained for lake sediment samples taken in 1992 and analysed in 1997 portrays an increase of 28% in sediment TP.

In a similarity with results obtained by Pettersson *et al.* (1988), the inorganic phosphorus was considerably higher than the organic phosphorus content in all the sediment samples analysed for the lake, with most of it in non-apatite form. Inorganic non-apatite phosphorus dominance has been observed in calcium-rich sediments by Williams *et al.* (1971a).

Several studies have successfully supported the hypothesis that finer-grained size sediments have more phosphorus content, especially in inorganic form, similar to the results obtained in this study. Williams *et al.* (1976) explains, that the silt/clay particles are associated with greater amounts of organic matter, iron compounds by virtue of the great surface area to volume ratio, thus they can bind more phosphorus especially the non-apatite inorganic form than the coarse grain sediment. The differences in phosphorus sorption capacity between the two headwater tributaries studied may probably be due to contrast in particle size distribution of the sediments, which consequently influences their mineral composition. Tributary 3 consisted mainly of fine sand, silt and clay with M_Z Phi (ø) 3.308 (0.037mm) grain sizes as opposed to the sandy sediment M_Z ø1.584 (0.21mm) found in Nyambugi. These results are similar to Meyer's (1979) observation that course sandy sediments had a lower phosphorus sorption capacity than silt sediments. Stumn & Leckie (1971), Golterman (1973) and Syers *et al.* (1973) have all shown that sediment adsorptive capacity largely depends on the silt/clay fraction by virtue of their large adsorptive area. However, the high release rates obtained for the Naivasha lake sediment contrasts with the dependency of sediment grain size to adsorptive capacity as portrayed by the streams and the main river Malewa.

In natural conditions sediment does not provide a limitless sink or source of phosphorus. This is because sediment P-sorption is reversible (Meyer 1979), depending on the balance between ambient and equilibrium concentrations or environmental change. The mechanisms involved in sediment-water phosphorus exchange are known to be complex and variable (Boström *et al* 1988), although Twinch & Breen (1982) caution that they are poorly understood. However, caution should be used when comparing the adsorption-desorption results of different studies. This is because results obtained are dependent upon the experimental technique used (Meyer 1979). Difference in equilibration time and the concentration partial difference between the sediment and the overlying aqueous solution turned out to be important factors in Naivasha. The fact that the ionic strength of aqueous solution influences P-sorption in soils is well known by soil scientists, but it was only documented recently as being important in water systems (Klotz 1988).

Several studies have shown enhanced adsorption capacity in sediments by high pH (Lijklema 1980, Boström *et al.* 1982 and Magnus & Löfgren 1988), although Boström *et al.* (1982) cautions that exchange rates obtained at high pH (8-10) may not be reliable, since sediments are naturally well-buffered systems with approximately neutral pH. Holten *et al.* (1988) further suggested that pH strongly influences the chemical reactivity of the soil/sediment constituents. This is because at high pH conditions, oxides have a negative surface charge decreasing the binding capacity, as opposed to positive surface charges at low pH. But, according to Golterman (1988) there is no experimental evidence for this. Acidity and temperature increase simultaneously resulted in accelerated adsorption rates during this study. In natural conditions increase in temperature is known to stimulate the overall mineralization and thereby releasing the organic phosphorus (Jensen & Andersen 1992). In addition, an increase in microbial activity does occur, lowering the redox potential of the surface sediment, which may then induce release of iron-bound phosphorus (Kamp-Nielson 1975). Hynes (1964) showed that the role of microbes especially bacteria in expediting phosphorus exchange across the sediment interface is of minor effect compared to chemical equilibria processes. This agrees with Meyer (1979) that chemical reactions would be expected to surpass uptake by small microbial standing stock except during low phosphorus concentrations. During the adsorption-desorption rate experiments for Naivasha, the microbial organism's influence had been eliminated by drying the sediment at 100^0 C, followed by addition of formaldehyde in the aqueous solution. This was necessary as biological processes are known to modify the chemical environment, thereby altering the physical and chemical mobilization processes as well as transport mechanisms.

The parameters investigated during this study, were experimentally well defined. But extrapolation that these results are representative of the natural conditions in lake Naivasha and its catchment rivers may be taken with caution. This is because according to Anja *et al.* (1990), different environmental variables may be synergistic while *in situ* making the whole processes very complicated. The adsorption-desorption rates obtained for the lake sediment portray a possibility of phosphorus source from sediment to the overlying water unlike the phosphorus sink proposed by Phillips & Harper in 1992. The high phosphorus concentration gradient between the overlying water and the sediment in the natural situation supports this interpretation. In addition the pH exceeds 8.0 in the lake water most of the time, which possibly may trigger release of phosphorus from the aerobic superficial sediments or re-suspended sediments. Rippey (1977) and Boström *et al.* (1982) showed that high pH in the overlying water could decrease the P-binding capacity of iron and aluminium compounds, primarily by OH^- ion exchange with PO_4^{3-} on surfaces of metal oxides. Despite the high total iron and calcium content of the lake Naivasha sediment, "aerobic phosphorus release" could occur. This has been shown to occur by a number of investigations particularly in well-mixed, shallow lakes with a high sediment/surface area ratio (Boström *et al.* 1982 & 1988, Marsden 1989) similar to lake Naivasha. Boers (1991) demonstrated high pH enhancement of phosphate release in the water column of lake Veluwe in Netherlands. Rippey (1977) found a simultaneous increase in water pH and orthophosphate concentration in Loch Neagh, suggesting that the first triggers the latter. Ryding (1985) showed that internal phosphorus load increased in a few shallow eutrophic lakes during periods of high pH in the water. However, Boström (1984) observed that the greatest pH effect is found in sediments with high NaOH-extractable phosphorus giving them a high buffering capacity similar to the lake Naivasha condition. The lake Naivasha sediment had high Fe/P ratio (above 8.5), meaning that the lake sediment would be expected to retain phosphorus in the oxidised surface layer as phosphate, but considering the laboratory-controlled adsorption-desorption rates experiment, this does not seem to be the case. However, the release rates observed may portray just the sediment potential to release phosphorus and bear little relation to the release rates *in situ.* Also generalization of the adsorption-desorption rates of different ecosystems could be misleading, as different ecological zones in both the lake and the rivers showed different rates.

8.6 Hypotheses review and conclusions

Revisiting aims, hypothesis and predictions set up in the beginning of the study at sub-section 1.8, the study was to address the following questions

a) Do the human activities within the catchment's area of the lake have any influence on the lake's phosphorus dynamics and budget and if to so what extent?

b) Do the sediments have any impact on the phosphorus budget of lake Naivasha ? If so, how, and to what extent?

c) Are recently observed increases in phosphorus concentration in the lake associated with changes in phosphorus loading or changes in the lake volume?

d) What are the main sources of phosphorus in the catchment area ?

The following is a brief summery.

Question a: The contrast in phosphorus concentration between the upstream stations (M_1 and Malewa Aberdares) and the middle-lower course stations indicates that human activities, especially cultivation on the steep slopes without any management practices, are contributing to surface storm flows which would erode the soil and move it plus the bound phosphorus (PP) into the river systems and subsequently the lake. In addition most of the land adjacent to the rivers is overgrazed with bare soils. In the Kinangop only ¼ of the land carries livestock and with a livestock density estimation of 1 cow per 4 acres (0.62 cows per hectare) this would represents overstocking (Simpson pers. comm.). The lower catchment has an overall livestock density of 0.42 livestock per hectare or 1 cow per 3.23 hectares, calculated from the total number of livestock over the surface area (Appendix Table 11), although it varies depending on the land management. For example Manera, estate which is a well-managed, irrigated livestock farm has a higher density of 2.5 cows per hectare while Marula estate next to the lake has a density of 0.41 cows per hectare in addition to a large number of game (Simpson pers. comm.)

Question b: Laboratory experiment shows that the Naivasha catchment sediments have high phosphorus equilibrium constant (EPC_O), meaning they have a potential to release phosphorus.

The implication from these experiments is that, the lake sediments have almost no phosphorus buffering capacity and wind-induced sediment disturbance can be a potential source of phosphorus cycling. However in the natural environment, the daily water overturn keeps the sediment well aerated, together with high total iron and calcium sediment content for the Naivasha ecosystem maintains a high phosphorus binding capacity, but any changes which could result to anoxic conditions in the sediment would results to phosphorus release into the water from the sediment. On the other hand phosphorus is released through trampling of the river sediment by the livestock as they drink water especially during the dry season.

Question c: The increase in lake phosphorus is associated with increase in phosphorus loading from the catchment especially during the heavy rains in 1997-1998, rather than changes in lake levels. However the increase in lake level in 1998 as a result of the El Niño rains submerged previous land, which had been bare mud, subsequently introducing nutrients into the lake.

Question d: Agricultural activities rather than geology are the major contributor of phosphorus input in the Naivasha ecosystem except in small spring fed streams and the upstream stations in Nyandarua ranges where geological influence was indicated. Point source from the littoral zone was insignificant.

8.6.1 Conclusions

The following conclusions can be drawn from this study

1. There is more phosphorus transported in the Naivasha catchment rivers and streams during the rainy seasons than the dry seasons.
2. The main source of phosphorus in the catchment during the rain season is diffuse from the surrounding agricultural areas.
3. Watering of livestock in the rivers causes elevated concentration of phosphorus and suspended solids at the disturbed (impact site) area and downstream.
4. Most of the phosphorus in the Naivasha rivers and streams is transported in particulate (PP) form.

5. The river Malewa is the major source of the phosphorus input into the lake from the catchment, with most of it acquired in the middle course of the river, in particulate form.

6. The heavy rainy season (El Niño effect rains) resulted in dangerous phosphorus (Vollenweider 1968) lake loading from the catchment.

7. Lake Naivasha is already eutrophic.

8. The Naivasha ecosystem has poorly-sorted sediment, dominated by gravel and coarse sand (> 0.6mm diameter) in the upper catchment, coarse and medium sand (0.2-2mm diameter) in the middle and the lower courses of the rivers and fine sand and silt/clay (< 0.2 mm diameter) at the inlet and in the lake.

9. The lake Naivasha sediment is a potential phosphorus source rather than a sink.

8.7 Management issues and recommendations

Management of river ecosystems is made difficult by lack of basic knowledge, because very few rivers remain pristine in the sense of being unaffected by man. It is clear from this study that human activities in the catchment area have a great influence on nutrient input into the lake. Small-scale farming forms the major part of it. This might create a problem to manage because in 1981/82 the government encouraged landowners with river frontage to reclaim the wetlands and swamp area to maximise food production (Olindo 1992). At the same time people were encouraged to use large quantities of chemical fertilizers and organic manure. This was geared towards making Kenya a self-sufficient country in food production. But, since more than 75% of Kenya's land surface lies within the Arid and Semi-Arid Lands (ASAL) inherent lack of water is a major problem. For conservation programmes to succeed, faced with an additional human population increases, there is a need for a clear water resource policy, which will give priority to both uses and users. An opportunity does now exist with the new Environmental Bill and Ministry. However its effectiveness has yet to be seen, as problems of poor planning and lack of co-ordination, common in most developing countries, exist. For example agricultural rule No. 26 of 1965 "agriculture (basic land) usage rules" stated that no one could cultivate or pasture livestock on slopes exceeding 35^0 in Kenya (Okoth-Ogendo 1991). Not much attention has been paid to this in the Naivasha catchment.

If the LRNA are to succeed in implementing the new "Lake Naivasha Management Plan", immediate measures to include the upper catchment area should be considered, with an intention of creating long-term "Catchment Management Practices". These practices should be cheap to implement and community-oriented. As in most cases the rural people do understand the issues and problems they face and are anxious to see improvements in their condition. Most of them are prepared for radical transformation in attitudes, but this can only be done if they are equal participants in the process. Therefore for any programme to be successful it should be geared towards community participation in planning and decision-making processes, which will convince them of the wider economic and environmental benefits they would enjoy. The following are some recommendations, which can be implemented in the Naivasha catchment.

1. To control nutrient flush into the water systems during the rainy season, agricultural practices, which are geared towards controlling the topsoil's erosion should be encouraged by:-

    a. Planting trees and hedgerows around their properties to act as windbreaks, which would cut down wind erosion of susceptible soils especially during the dry season.

    b. Use of terracing and till on steep slopes.

    c. Practice contour farming.

    d. Practice on small plots, crop rotation of maize and other ground covering crops, for example, beans, peas and potatoes. This would help to protect and enrich the soils.

    e. Farmers should be educated to avoid use of excessive manure. This can be achieved through educational awareness programmes by encouraging them to sell the excess organic manure harvested from their farms as an extra source of income. This can be conducted through schools, churches, women groups and public meetings with help of extension officers.

    f. Use of manure for biogass to avoid "kuni" or charcoal. This would help to re-establish and sustain tree cover within the catchment.

2. To control livestock related diffuse phosphorus sources.

a. The community should be encouraged to construct watering holes and drinking troughs away from the rivers, although severe water shortages especially during the dry season might cause a problem.

b. To overcome severe water shortages, the people should be encouraged to use cheap methods of rainwater harvesting either at family or communal level. This would help to reduce the pressure in the rivers.

c. The people should be encouraged to minimise grazing near the rivers, which would result in re-establishment of natural land filters and buffer zones.

d. The community should be encouraged in physical replanting of buffer zones as community "lots".

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APPENDICES

Table

Table 1: PP concentration and DOP content for Rivers Malewa and Gilgil using two different ways of calculating PP content

	River Malewa			River Gilgil		
Date	**PP_1 (TP-SRP)**	**PP_2 (TP-TDP)**	**DOP %**	**PP_1 (TP-SRP)**	**PP_2 (TP-TDP)**	**DOP%**
Sep- 98	154.7	133.5	13.8	56.9	13.9	75.8
Oct -98	100.1	55.7	44.4	95.3	50.2	47.3
Nov-98	131.5	62.1	52.8	112.5	72.2	35.9
Dec-98	57.2	31.1	53.9	118.1	65.0	44.9
Jan-99	37.2	14.1	61.8	91.2	38.9	57.4
Feb-99	36.1	20.9	42.1	117.12	49.3	57.97
Mar-99	61.3	49.6	19.1	272.18	170.8	37.3
Apr-99	55.4	35.8	35.4	173.9	118.2	32.0
May-99	56.5	21.4	62.3	205	129.3	36.98
Jun-99	40.7	26.9	33.7	209.2	144.6	30.9
Jul-99	46.3	23.2	49.9	246.5	182.6	25.97
Aug-99	76.9	69.9	9.1	134.7	81.3	39.7
Sep-99	97.1	74.2	23.5	114.8	76.0	31.1
Mean	**73.1**	**44.1**	**38.6**	**149.8**	**104.7**	**42.6**
SD	37.4	40.1	17.9	65.5	104.3	13.998
SE	10.4	5.5	4.96	18.2	14.6	3.88

Table 2: Grain size classification after Kohnke (1968)

Grain diameter (mm)	**Sediment component**
> 2mm (2000 μm)	Gravel
0.61 to 2 mm	Course sand
0.2 to 0.6 mm	Medium size sand
0.063 to 0.2	Fine sand
0.002 to 0.063	Silt
< 0.002	Clay

Table 3: Robert & William (1957) SD Scale

SD scale range	
< 0.35	Very well sorted
0.35 to 0.5	Well sorted
0.5 to 1.0	Moderately sorted
1.0 to 2.0	Poorly sorted
2.0 to 4.0	Very poorly sorted
> 4.0	Extremely poorly sorted

Table 4: Robert & William (1957) SK_1 Scale

SK_1 scale range	
-1.00 to - 0.3	Very negative skewed
-0.3 to -0.1	Negative skewed
-0.1 to 0.1	Nearly symmetrical
0.1 to 0.3	Positive skewed
0.3 to 1.00	Very positive skewed

Table 5: Robert & William (1957) KG' Scale

KG' Scale	
≤ 0.401	Very platykurtic
0.401 to 0.474	Platykurtic
0.474 to 0.526	Mesokurtic
0.526 to 0.6	Leptokurtic
>0.6	Very leptokurtic

NB: Range of KG' = 0.33 to 0.90 in natural sediment (Robert & William 1957)

Table 6: Trophic State Index (TSI) and its associated parameters (adopted from Carlson, R.E.1977)

TSI	**Secchi depth** (m)	**Surface phosphorus** (mg m^{-3})	**Surface Chlorophyll a** (mg m^{-3})
0	64	0.75	0.04
10	32	1.5	0.12
20	16	3	0.12
30	8	6	0.94
40	4	12	2.6
50	2	24	6.4
60	1	48	20
70	0.5	96	56
80	0.25	192	154
90	0.12	384	427
100	0.062	768	1183

Where TSI is calculated as

$$TSI = 10(6-\log_2 SD)$$

$$= 10(6-\log_2 7.7/Chl.a^{0.68})$$

$$= 10(6-\log_2 48/TP)$$

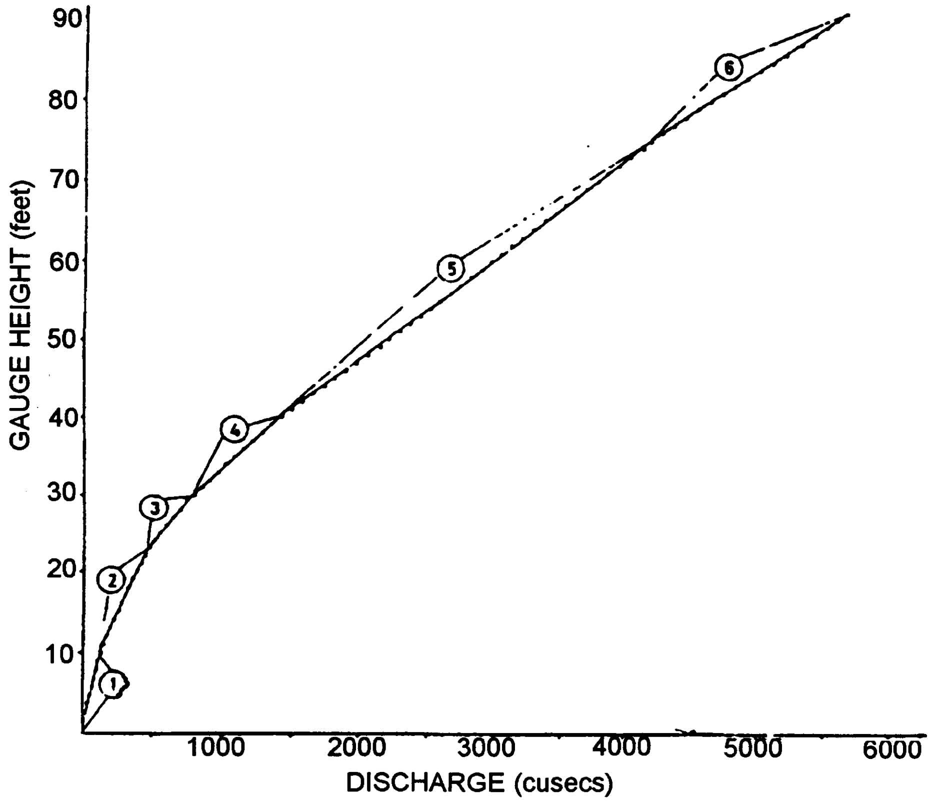

Figure 1: Åse *et al.* (1986) discharge rating curve for the gauge at the river Malewa at M_4 station calculated using the equations below in Table 7

Table 7: Åse *et al.* (1986) regression equations used to calculate appendix Figure 1

Equation No.	**Gauge height interval**	**Equations** (y = a + bX)	**Correlation (R^2)**
1	0.00 – 0.99	$Y = 0.08 + 7.59 * 10^{-3}X$	0.988
2	1.00 – 2.29	$Y = 0.53 + 3.79 * 10^{-3}X$	0.998
3	2.30 – 2.99	$Y = 1.23 + 2.26 * 10^{-3}X$	0.997
4	3.00 – 4.00	$Y= 1.76 + 1.58 * 10^{-3}X$	0.999
5	4.01 – 7.49	$Y = 2.21 + 1.26 * 10^{-3}X$	0.999
6	7.50 – 9.10	$Y = 3.06 + 1.06 * 10^{-3}X$	0.999

Table 8: Phosphorus-chlorophyll models discussed in the thesis

Models	Reference
Chlorophyll *a* = 1.19TP-7.3	Schindler *et al.* 1978
Chlorophyll *a* = 0.58TP + 4.2	Megard 1978
Chlorophyll *a* = 0.55TP – 4.8	Edmondson & Lehman 1981
Chlorophyll *a* = 0.42TP – 0.93	Berge *et al.* 1980
Chlorophyll *a* = $0.0735TP^{1.583}$	Sakamoto 1966
Chlorophyll a = $0.0724TP^{1.45}$	Dillon & Rigler 1974
Chlorophyll *a* = $0.028\ TP^{0.98}$	OECD 1982

Table 9: Mean sediment total phosphorus and total iron in in lake Naivasha sediment (off Elsamere bay)

A: Sediment sample taken in 1992

Depth (cm)	Water content (%)	**Loss on ignition** (%)	**TP**. Sed/drywt (mg/g)	**Fe**. Sed/drywt (mg/g)	**Fe/P ratio**
1	98.5	24.6	0.45 ± 0.18	15.6 ± 9.3	32.2
2	98	24.7	0.43 ± 0.13	22.4 ± 16.7	33.5
3	96.8	27.3	0.52 ± 0.2	20.8 ± 11	37.3
4	96.7	27.1	0.58 ± 0.23	23.1 ± 11	38.1
5	94.6	26.1	0.47± 0.24	18.5 ± 10.2	38.5
6	93.3	25.5	0.45 ± 0.25	19.4 ± 12.1	39.2
7	91.8	25	0.43 ± 0.23	18.1 ± 11.4	40
8	95	24.7	0.56 ± 0.25	22.3 ± 11.8	38
9	93.8	26.5	0.48 ± 0.14	19.3 ± 8.1	39.1
10	92.4	24.9	0.46 ± 0.24	21.6 ± 10.9	50.4
11	96.1	27.9	0.54 ± 0.2	26.5 ± 9.6	48.5
12	96.4	28.4	0.48 ± 0.13	25.8 ± 12	50

B: Sediment sample taken in 1997

Depth (cm)	Water content (%)	Loss on ignition (%)	TP.Sed/drywt (mg/g)	Fe. Sed/drywt (mg/g)	Fe/P ratio
0	93.2	29.5	0.71 ± 0.38	38.4 ± 1.4	58
3	92	29.6	0.90 ± 0.27	37.8 ± 2.6	49
6	89.3	28.1	0.86 ± 0.35	36.9 ± 3.1	62.5
9	92.1	28.8	0.94 ± 0.37	35.7 ± 1.7	48.7
12	92.4	36.1	0.83 ± 0.49	43.8 ± 6.9	95
15	92	30.6	0.57± 0.32	40.2 ± 6.3	103.3
18	91.7	30.8	0.52 ± 0.3	35.6 ±2.9	89.5
21	91.8	28.7	0.54 ± 0.2	36.3 ±1.6	77.5

Table 10: Overall open water sediment total phosphorus and iron for the lake Naivasha in 1997-1999

Depth (cm)	Water content (%)	Loss on ignition (%)	TP.sed/drywt (mg/g)	Fe. Sed/drywt (mg/g)	Fe/P ratio
0	93.9	28.3	0.64 ± 0.38	36.1± 4.14	69.1
3	91	28.6	0.80 ±0.31	35.1 ± 5.9	51
6	88.7	27.8	0.75 ± 0.38	35.2 ± 4.4	67.7
9	90.7	28.2	0.86 ± 0.36	33.7 ± 4.3	48.4
12	91	45.7	0.72 ± 0.2	37.6 ± 10.8	100.1
15	91.5	30.9	0.51 ±0.31	36.8 ± 7	93
18	91.9	31.8	0.49 ± 0.28	33.5 ± 4.1	89.8
21	91.8	28.7	0.54 ± 0.2	36.3 ± 1.6	77.5

Table 11: Livestock Density estimation for Naivasha Division

(Data courtesy of Naivasha DO's office, Serah Higgins and Angus Simpson)

Division Area =1648 km^2

Lake's total surface area = 241 km^2

Density calculated with 1407 km^2(1648 –241)

Grazing effect is 1cow is equivalent to 4 goats/sheeps (Simpson pers. Comm.)

	Total number	Density
Total livestock (cows, goats and sheep)	68148	1 animal per 2.44 hectare
Cows	51460	1 cow per 3.25 hectare
Goat/sheep	16685	1goat/sheep per 8.43 hectare
Grazing Density	55631	1 cow per 2.53 hectare

Table 12: Water Budget (m^3/yr) for Lake Naivasha (Data from Becht in Press)

1 Surface inflow = 2.174×10^8

2 Rainfall = 9.393×10^7

3 Evaporation = 2.563×10^8

4 Ground water outflow and evapotranspiration = (4.7×10^6 per month) thus, 5.640×10^7 per year

5 Abstraction = 6.00×10^7

6 Sum error = 1.358×10^6

Therefore calculated total water loss (Q) as No.3+ 4+ 5+6 = 3.74×10^8

Table 13: Total phosphorus concentration for Naivasha rainwater

Date	TP µg/l	PPµg/l	SRPµg/l	TN mg/l	NH4 -Nµg/l
16/7/97	98	0.3	97.7	1.1	1134.9
20/10/97	123.7	90.8	32.9	2.9	573.2
21/10/97	50.5	2.1	48.4	0.25	163.4
30/10/97	57.1	0.7	56.4	0.75	230.9
14/11/98	17.7	2.8	14.9	0.4	311.5
15/11/97	8.1	7.8	0.3	0.54	383.1
10/1/98	13.3	0.3	13.0	0.51	300.7