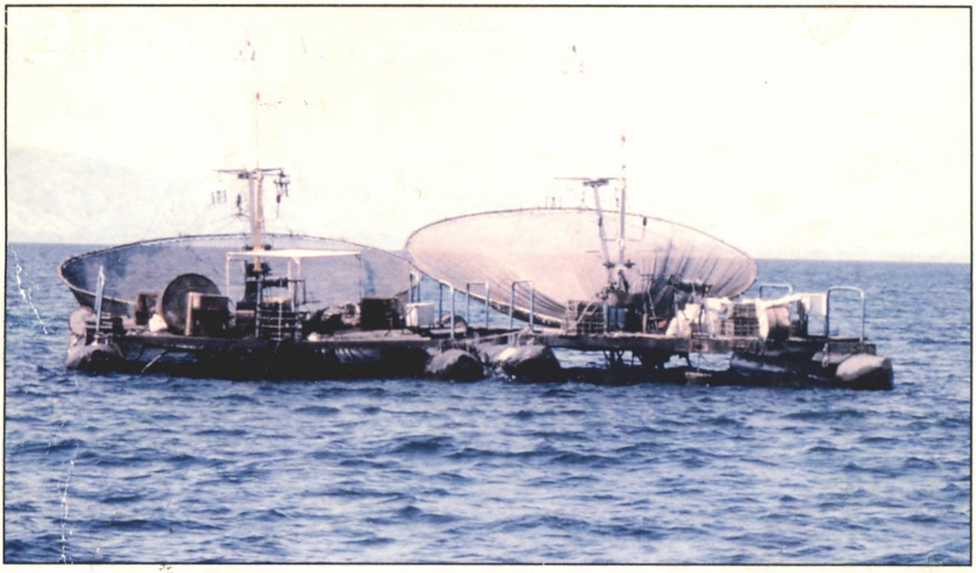

ADVANCES IN THE ECOLOGY OF LAKE KARIBA

Edited by Jacques MOREAU

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Cover Top: Typical ringnets as utilized in Kapenta fisheries on Lake Kariba
Bottom: Lake Kariba: The littoral area and draw-down zone
Back cover: Lake Kariba: The ecology of the littoral area is strongly influenced by wildlife.

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1

SEDIMENTS CHARACTERISTICS IN RELATION TO NUTRIENT DISTRIBUTION IN LITTORAL AND PELAGIC WATERS OF LAKE KARIBA

Gunilla Lindmark

INTRODUCTION

Littoral areas are of great importance in the dynamics of most lakes. In artificial lakes, like in Lake Kariba, water flows which follow the annual floodings of vast and inundated lowland areas combined with extensive water level fluctuations are bound to exert a strong impact on the lake ecosystem development in time and space. Besides, long-term natural droughts superimpose the impact from annual and man-controlled water level changes.

Transport of silt and organic material to the lake during the flooding periods and heavy rains after the exposure of draw-down zones during low water periods impose strong pressures on mechanisms and processes to regulate and stabilize the lake system. Interactions between soil/silt and the water phase will thus have a profound impact on the control of water quality, and changes in its mineral content and physical-chemical properties.

As a natural consequence, the imposed stress will influence the nutrient pool in the lake, i.e. the concentration, composition and turn-over of nitrogen and phosphorus, which are the most essential regulators for primary production and any production in general, in littoral as well as in pelagic waters.

The Zambezi catchment area, its geology and soil in the Kariba basin, is presented in detail in Balon and Coche (1974). In addition, physical and physical-chemical conditions and lake hydrology are well described (see also introduction, this volume). Although the chemical composition of major ions is well defined, the information is limited on nutrient levels and utilization (opt. cit.).

Therefore, it was most essential to focus on an analysis of the nutrients and their regulating factors. In order to evaluate the influence and importance of various factors controlling nutrient concentrations and regeneration, it was a must to further characterize the shoreline and bottom substrate and analyse sediment properties and functions. So far, only geographically limited areas had been investigated in terms of sediment properties and interactions with water (Mc Lachlan and Mc Lachlan 1971, Bowmaker 1976).

In summary, the objectives of this paper project were:

- to characterize bottom substrate/sediment, its structure and composition
- to analyse nutrient levels in shallow and near-bottom water,
- to study sediment properties related to nutrient exchange ability, and
- to analyse nutrient levels, utilization and growth-limiting factors in riverine, littoral and pelagic waters.

MATERIALS AND METHODS

Sample collection and processing

During a survey in October November 1984, 19 transects were selected to represent the littoral area along the Zimbabwean side of Lake Kariba (Figure 1.1 and Table 1.1). From the 19 transects, some 60 "undisturbed" sediment/water cores were collected. In shallow waters (< 2 m), a core sampler with a plexiglass tube was used (diameter: 7 cm; length: 50 cm). When the sediment was hard a sharp iron ring was attached to the tube. In deeper waters, SCUBA divers pushed the plexiglass into the sediment. Sediment was collected from a water depth range of 0.2–8 m.

Table 1.1 Littoral transects; location and general characteristics

Basin	*Transect ID*	*No*	*General characteristics*
1. Mlibizi	Mlibizi	II	river bank; shallow and no trees
1. Mlibizi	Sebungwe	III	near river outlet; shallow tree area
2. Binga	Binga	IV	wind exposed shore; steep and rocky
2. Binga	Chete	V	exposed shore; shallow tree area
3. Sengwa	Croc Creek	VI	sheltered river bank; tree area
3. Sengwa	Mwenda Creek	VII	sheltered river bank; tree area
3. Sengwa	Sinamwenda South	VIII	wind exposed shore; steep with rocks/sand
3. Sengwa	Sengwa	IX	shore; very shallow near tree area
3. Sengwa	Paradise Island	X	sheltered shore; steep tree area
4. Ume	Namenbere Island	XI	exposed shore; vulcanic rocks and no trees
4. Ume	Bumi	XII	exposed shore; very shallow and no trees
4. Ume	Bumi East	XIII	shore; rather steep tree area
4. Ume	Sanyati West bay	XIV	exposed shore, shallow sand bank and no trees
5. Sanyati	Long Island	XV	wind exposed shore; shallow and some trees
5. Sanyati	Sanyati East bay	XVI	wind exposed bay; very shallow and no trees
5. Sanyati	Prawn Farm	XVI	exposed shore; shallow with no trees
5. Sanyati	Gache-Gache-exp	XVI	exposed shore; shallow sand bank with no trees
5. Sanyati	Gache-Gache-tress	XIX	sheltered shore; very shallow bay with trees
5. Sanyati	Nyaodza Bay	XX	river bank; shallow tree area

Water above the sediment surface was withdrawn from 22 of the cores for analysis of total phosphorus and nitrogen. The cores were then sliced into 2.5 cm sections down to 10 cm. All samples were frozen in the field. All sediments were analysed for dry weight and organic matter content. Concentration of phosphorus, nitrogen, calcium, sodium, potassium, magnesium, iron, aluminum and some other heavy metals was analysed on 50 selected sediment samples.

Water was collected along the lake at 40 stations (Figure 1.1). Some 20 stations were pelagic and the others were littoral stations, rivers and sediment transects. Sampling in pelagic waters was performed with a Ruttner sampler. Surface water samples (0–5 m) were mixed from 3 depths (0.5, 2.5 and 5 m). Samples were also collected from 30 m and 50 m, if the water column was deep enough. From each basin a depth profile was analysed for selected physical-chemical parameters.

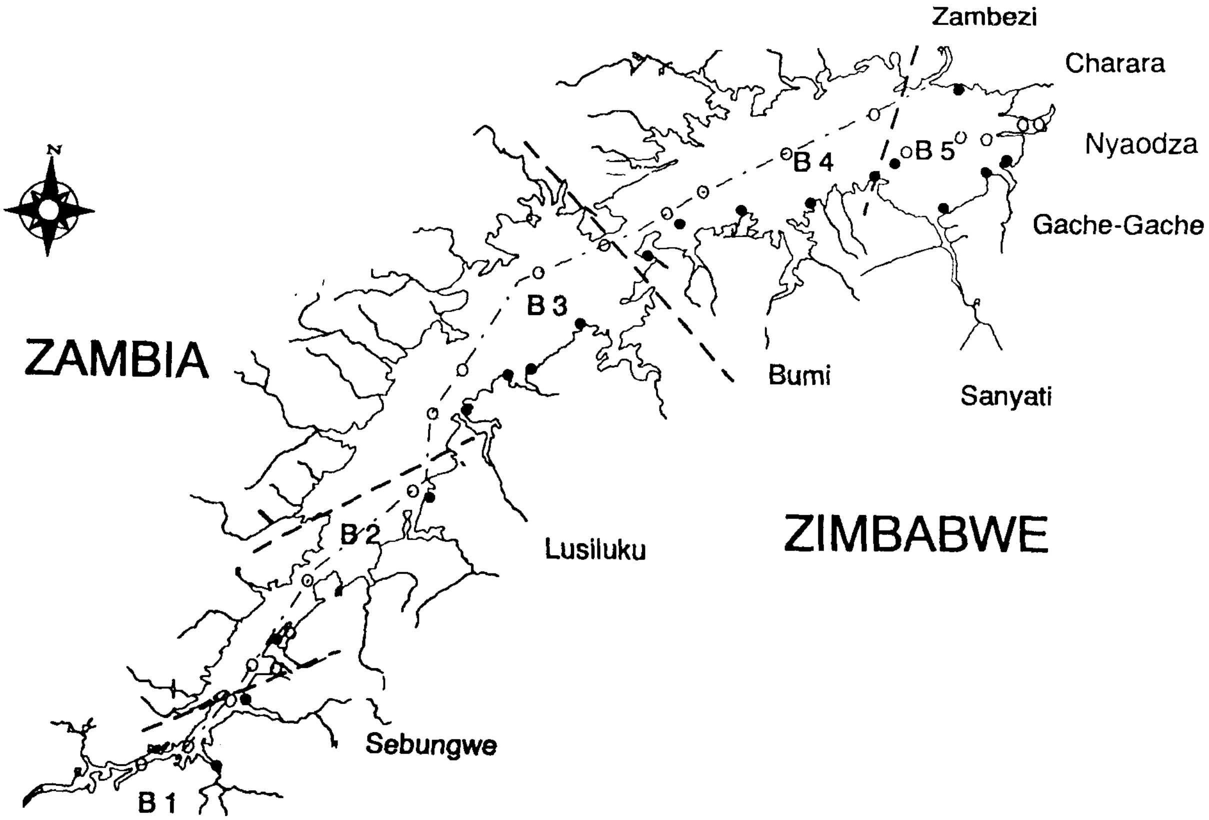


Figure 1.1 Lake Kariba: Pelagic stations (o) and littoral transects (•) for sampling of water and sediment

Temperature and oxygen were recorded using YSI oxygen meter. In littoral areas and rivers, surface water was collected as 0–1 m with a plexiglass tube.

In 1986, water sampling occurred on three occasions; in March, June and November. In March 1988, another sampling was performed along the lake in combination with algal bioassays. Sediment experiments were performed during periods in 1985–87. In March 1989, a survey was performed for analysis of horizontal and depth distribution of silt and nutrients in the Sanyati basin and in two of its rivers; Nyaodza and Sanyati Gorge.

All collected samples were immediately processed as far as possible onboard the boat. Nutrient samples were placed in individual bottles and frozen after appropriate pre-treatment. Samples for total phosphorus (TP) and nitrogen (TN) concentration were frozen unfiltered. For total dissolved and inorganic fractions of P and N, the samples were filtered through membrane filters (HA 0.45 μm) and glass fiber filters (GF/C) respectively, before frozen in individual plastic bottles. Ammonia was analysed on unfiltered samples. For chlorophyll *a* analysis, the algae were collected on GF/C filters and freeze-dried. pH, conductivity and turbidity were measured in the field on the day of sampling.

Analytical methods

Ammonium was analysed according to Chaney and Marbach (1962). Nitrate was analysed as nitrite according to Bendschneider and Robinson (1952) after reduction in a copperized Cd-column. Total nitrogen (TN) and total dissolved nitrogen (TDN) were measured as nitrate after oxidation with potassium peroxodisulphate in an autoclave. Phosphorus fractions in water were analysed using a single solution, molvbdate blue method (Murphy and Riley 1962). Soluble reactive phosphorus, DIP, (PO_4-P) was measured in GF/C filtered water; TP and total dissolved P (TDP) were measured in unfiltered and filtered water respectively, after digestion in an autoclave with potassium peroxodisulphate. Particulate P (PP) was calculated as difference between TP and TDP. Chlorophyll *a* was extracted in 100% methanol.

Sediment dry weight, loss on ignition (L.O.I.) and Kj-nitrogen were determined according to Enell and Bengtsson (1985). Total P in sediment was analysed by using the ignition method (Andersson 1976). Sediment nitrogen was analysed as Kjeldahl-N after digestion in a Tecator digestion rack. Sediment alkali and heavy metals were analysed by ICP spectrometry.

Experiments

Sediment studies and experiments

Nutrient sorption/desorption was studied in "undisturbed" sediment/water cores in plexiglass tubes. The water phase was enriched with phosphate to be a final addition of 100 μg P l^{-1}.

Phosphate and ammonia concentrations were analysed before and after P enrichment. Two consecutive enrichments were done. In another set of sediment cores, nutrient exchange was followed under aerobic and anaerobic conditions. Anoxic conditions were controlled by N_2-flushing and oxic conditions by air bubbling. Concentrations of ammonia and phosphate in the sediment interstitial water were analysed in samples obtained by a dialysis membrane technique.

Algal bioassays

The bioassays were performed as bottle tests. One station in each basin was sampled. Surface water (0–5 m) was filtered through glassfiber filter (GF/C) and divided into 8 bottles. Two bottles were kept as controls without nutrient addition, while the others were enriched with N (as NH_4NO_3), P (as K_2HPO_4) or N+P. One set of 4 bottles was inoculated with a starved culture of *Selenastrum capricornutum*. The other set of 4 bottles was inoculated with an indigenous "natural phytoplankton community" from each basin. These so called natural phytoplankton communities were obtained by filtrations to represent the 20–70 μm community in size. All processing and inoculation with "algae" were performed in the field. In total 40 bottles were processed. *In situ* chlorophyll *a* and inorganic nutrients were also analysed. 15 days after inoculation the water was analysed for chlorophyll *a*.

RESULTS

Sediment characteristics and chemical composition

Littoral areas along the Lake Kariba shoreline show large geographical variations. The transects selected for the study covered well this range in variation (see Figure 1.1 and Table 1.1). When the bottom substrate (hereafter referred to as sediment) was sampled along water depth profiles from the shore, the sediment structure and composition strongly confirmed and/or demonstrated the individual transect characteristics (see below). Transect features, like exposure to wind and waves, shoreline development and slope, shore vegetation, bottom vegetation and inundated trees etc., have pronounced impact on sediment texture and the chemical composition.

Generally speaking, transects exposed to wind and waves, all revealed sediments with a high dry matter content; for example at Binga and Chete in the Binga basin, at Sinamwenda in the Sengwa basin, at Namenbere and Sanyati West in the Ume basin, and at Long Island, Sanyati East and Gache-Gache (exposed) in the Sanyati basin (Figure 1.2A to D), more than 60% of wet weight was dry matter, mostly consisting of minerogenic matter as sand and gravelly sand. The organic matter content was, as a consequence, very low, i.e. often less than 2–3% of dry weight (Figure 1.2A). A significant change in sediment character at these stations was found in the sediments collected from more than 3 m water depth. They displayed a fine texture and showed an organic matter content more than twice as high, with values in the 5–7% range, and consequently the dry matter values were lower (Figure 1.2A). A sedimentation of fine silt and clay material in the deeper areas must be the explanation, as confirmed by the very fine texture and "dusty" appearence observed for the dried sediment.

In the river estuaries, Mlibizi and Sebungwe rivers, in the Mlibizi basin, the sediment showed a rather high content of organic matter, i.e. 10–15%, when water depth surpassed 0.5 m (Figure 1.2A). These high values were also a consequence of river transport of fine silt and organic debris which settles out and accumulates in deeper areas. Sediments just below water surface (0.2 m) showed a coarse sandy material, typical for erosion bottoms.

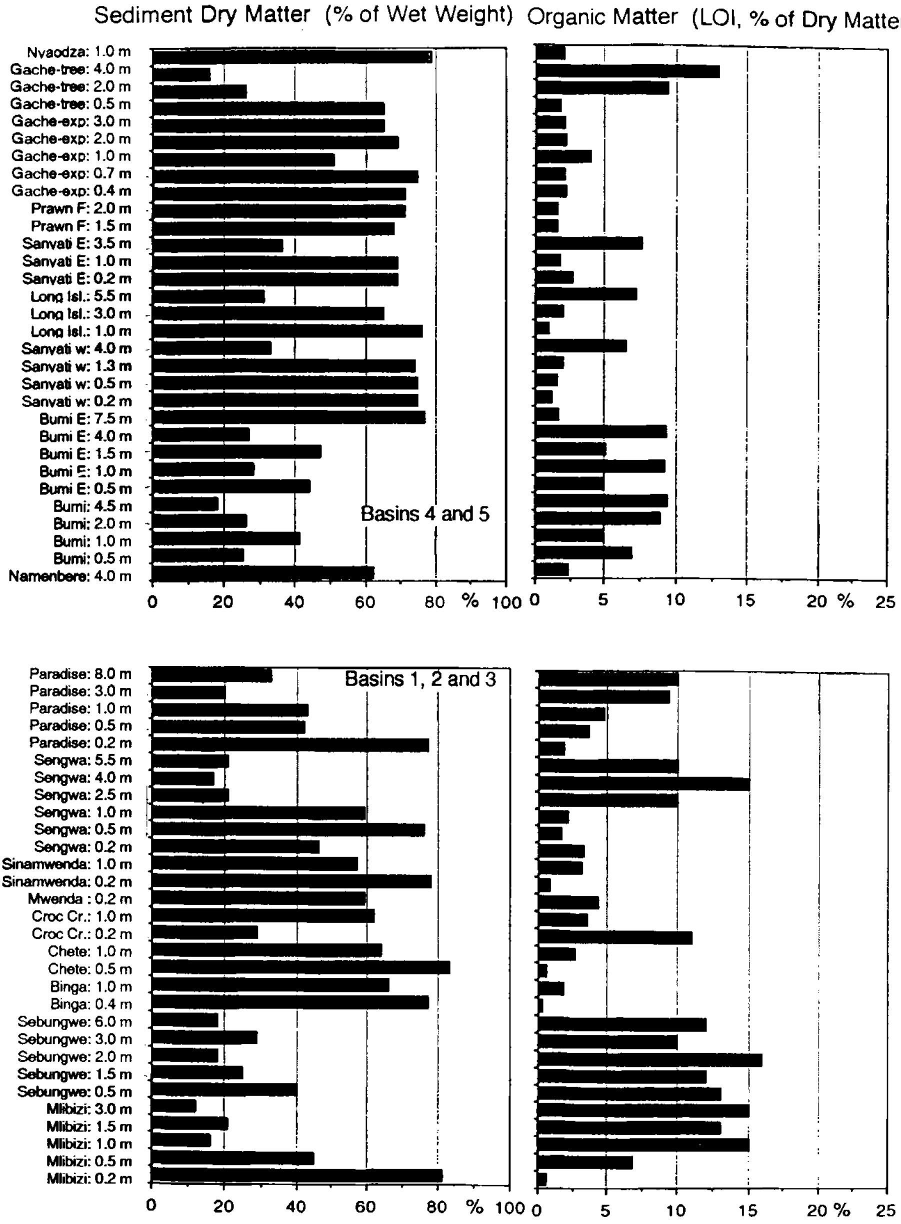


Figure 1.2A Dry matter and loss on ignition (organic matter) in sediment cores from 19 transects and different water depths, presented as % of wet weight and % loss on ignition (L.O.I.) for the sediment layer 0–2.5 cm

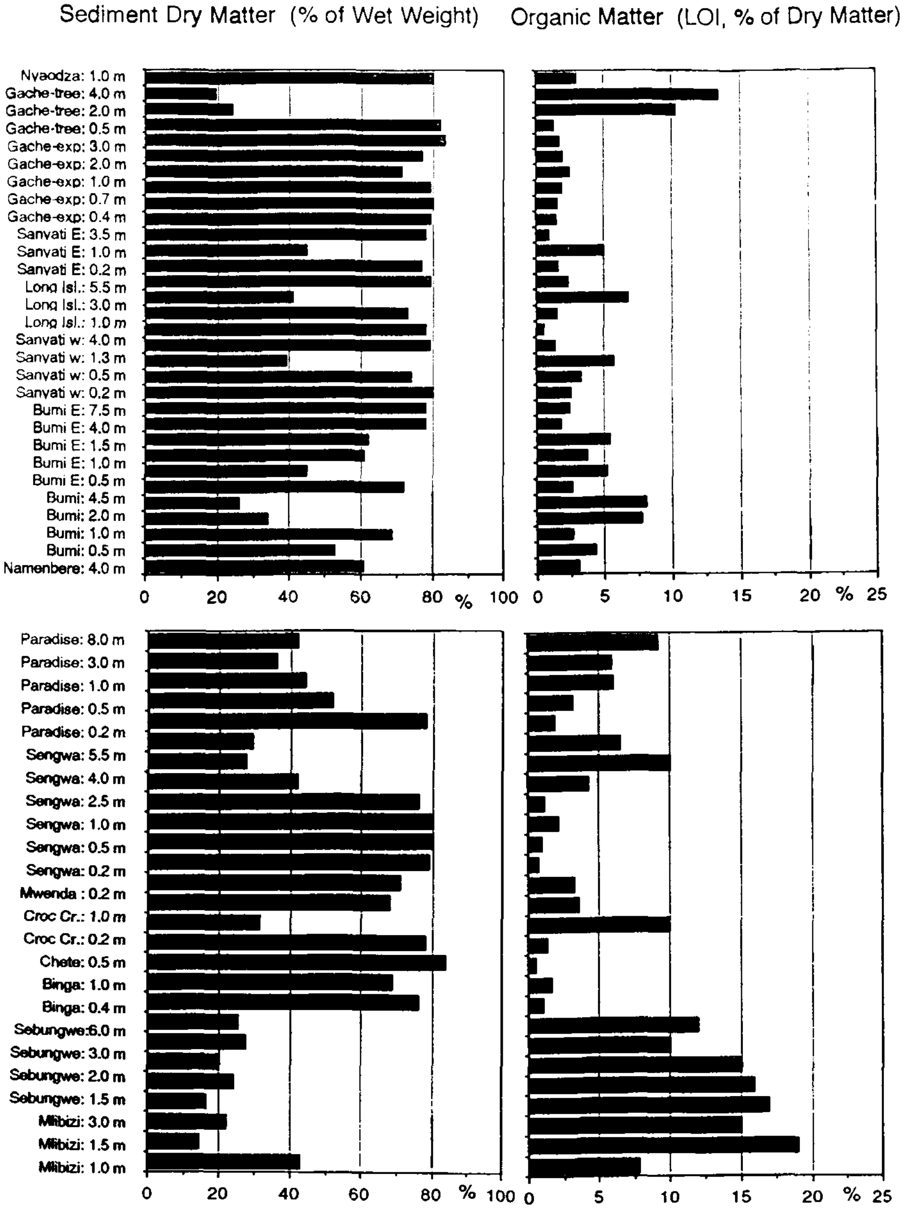


Figure 1.2B Dry matter and loss on ignition (organic matter) in sediment cores from 19 transects and different water depths, presented as % of wet weight and % loss on ignition (L.O.I.) for the sediment layer 2.5–5.0 cm

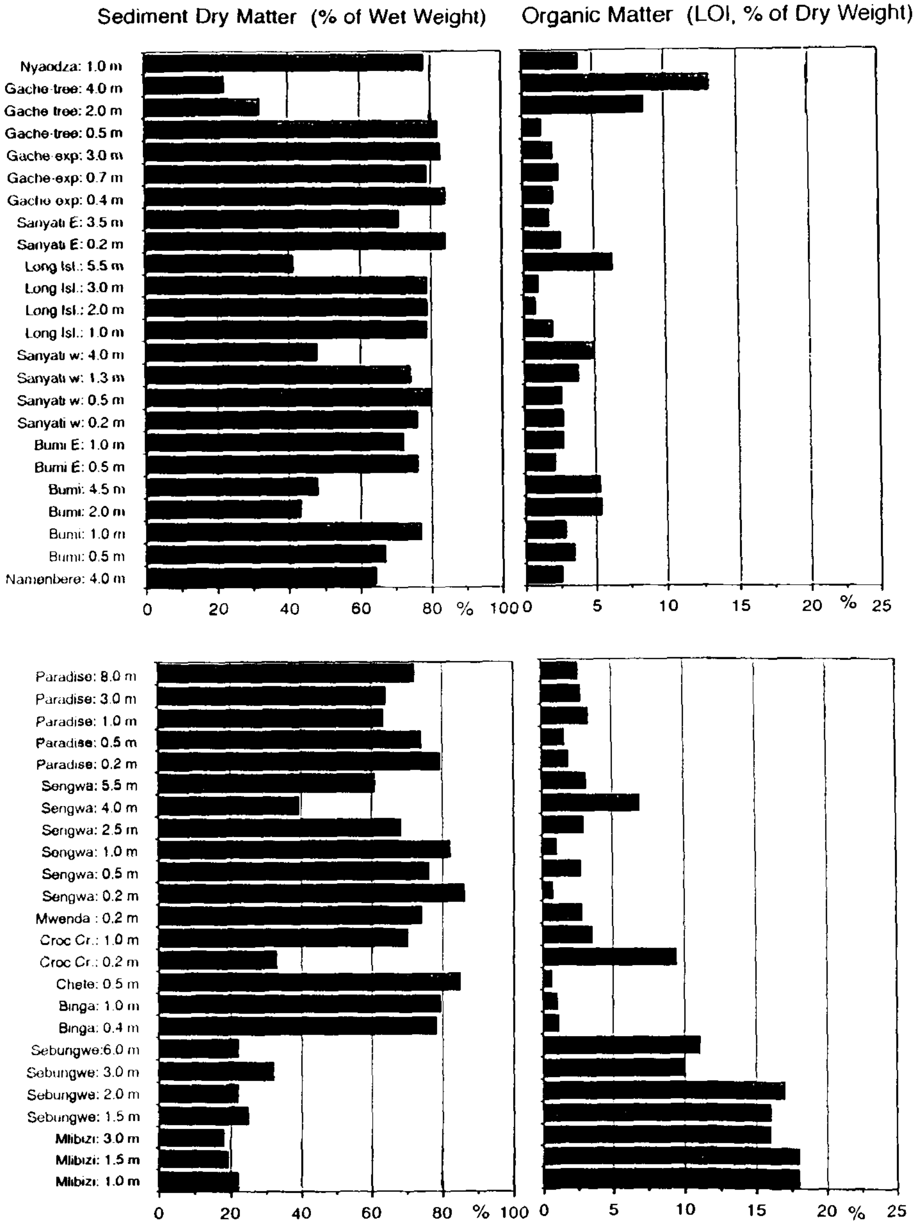


Figure 1.2C Dry matter and loss on ignition (organic matter) in sediment cores from 19 transects and different water depths, presented as % of wet weight and % loss on ignition (L.O.I.) for the sediment layer 5.0–7.5 cm

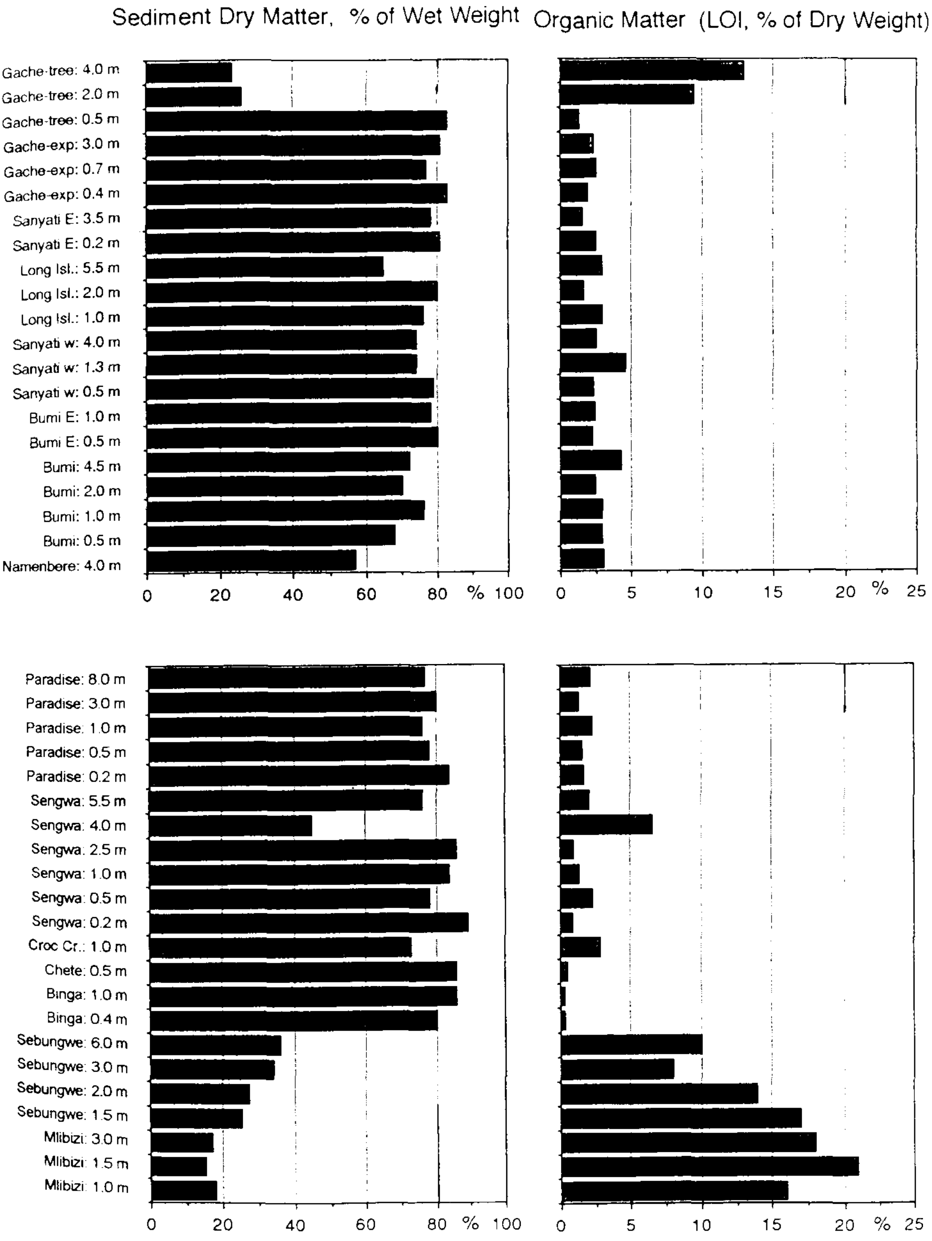


Figure 1.2D Dry matter and loss on ignition (organic matter) in sediment cores from 19 transects and different water depths, presented as % of wet weight and % loss on ignition (L.O.I.) for the sediment layer 7.5–10 cm
]

In the protected Mwenda. Crocodile and Nyaodza river estuaries, the intensive activity from game kept shallow water turbid by re-suspension of silt and organic matter above the fine and sandy sediment.

Along the very shallow lowlands in the Sengwa and Ume basins, vast areas are regularly inundated. Silt and organic material is transported to the shallow water and the existing macrophyte beds. The elevated organic content and the low dry weight in the sediments at the Sengwa and Bumi transects could thus be a result of the presence of dense macrophyte beds, which are intervening in the silt transport by reducing water velocity, trapping sediment particles and inducing sedimentation. Inundated trees have a similar effect on the material transport and sedimentation. Also those areas showed sediment with higher content of organic matter than found in exposed no-tree areas; cf Gache-Gache transect with and without trees (Figure 1.2A). Macrophytes and periphyton had colonized the tree areas as well.

Deeper down in the sediment stratum (2.5–10 cm), the dry matter values increased to around and above 80% at the wind exposed transects and the sediments consisted of coarse consolidated minerogenic material (Figures 1.2B and 1.2D). In the sediments from the sheltered bays and river estuaries, the dry matter content remained low at 20–30% of wet weight, while the organic content increased to above 15% and even higher, i.e. 20% in Mlibizi sediment (Figure 1.2D).

Sediment nutrients and mineral components were analysed in 50 samples. from 14 transects and the 0–10 cm sediment depth. The highest sediment nitrogen values were recorded at Mlibizi, Sebungwe and Gache-Gache "tree area", where the concentration was in the range of 2–4 mg N g^{-1} dry weight (Figures 1.3A and B). At the other stations, nitrogen was considerably lower and varied largely from station to station. The nitrogen range was 0.2–1.5 mg N g^{-1} dw, with the higher values found in the deep water sediments whereas the lower values were recorded in shallow areas with gravelly sand (Figures 1.3A and B). The sediment phosphorus showed a less pronounced variation. The highest levels were found in sediments from deep water, with about 0.4 mg P g^{-1} dw, in sheltered tree areas (Sebungwe and Gache-Gache trees) and in the Nyaodza river estuary (Figure 1.3A and B). The phosphorus concentration seemed related to a presence of silt particles in the sediment, and increased in areas of silt deposition. The very fine particle size sediment, contained the most phosphorus. In exposed areas and erosion bottoms with coarse sediment, phosphorus content was low; in the range of 0.1–0.2 mg P g^{-1} dw.

Due to the low nitrogen and comparably high phosphorus levels in the sediment, the TKN/TP ratios were found very low, i.e. 3–10 (by weight), in the two sediment stratum, 0–5 cm and 5–10 cm (Figures 1.3A and B). This indicates an excess of phosphorus in relation to nitrogen in terms of plant requirements for those elements.

This fact demonstrates a special situation for biological activity, i.e. plant colonization and growth. In connection with the presentation of nutrient data from the water in the littoral habitats, these circumstances will be elucidated.

The concentrations of the alkali metals, calcium and magnesium, were around 5 mg g^{-1} dry matter (DM) (Figure 1.4).

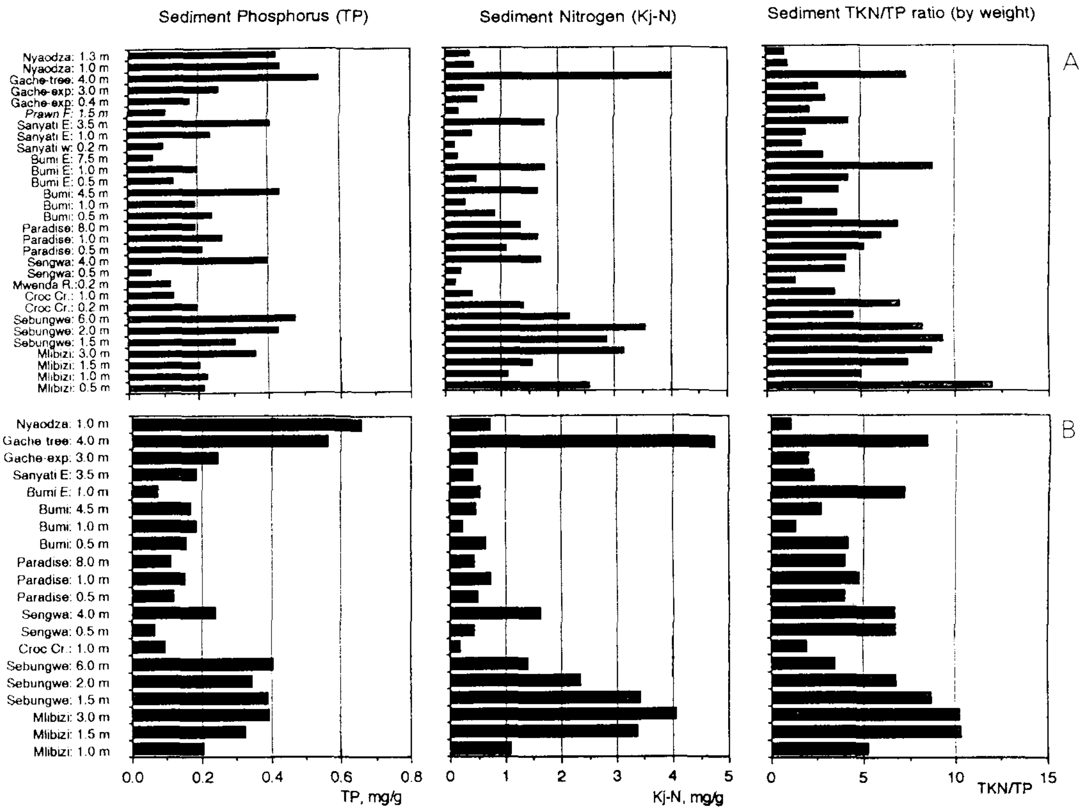
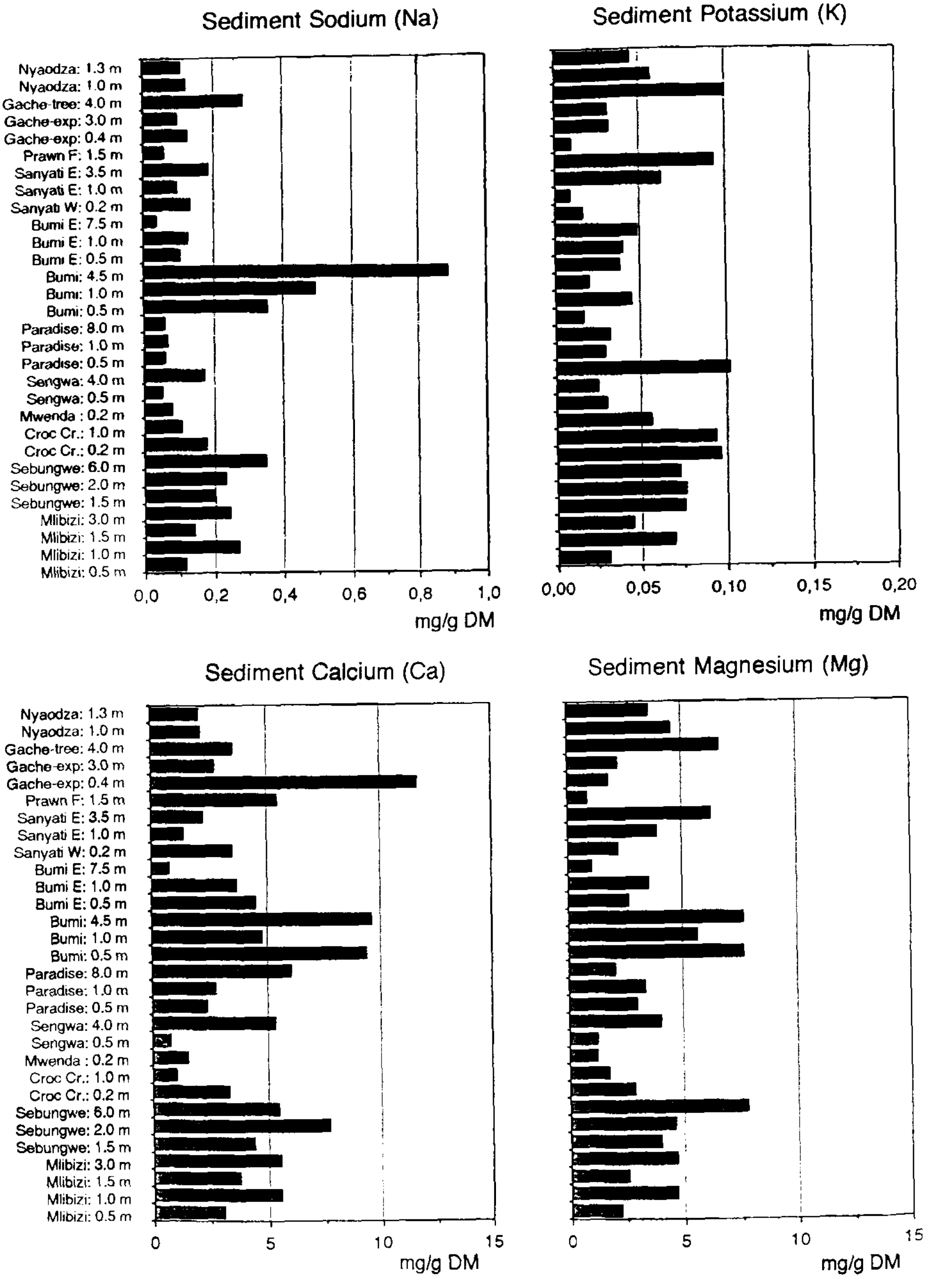


Figure 1.3 Total phosphorus (TP) and Ljeldahl-nitrogen (TKN) concentrations, and TKN/TP ratio (by weight) in sediments from 14 transects. Top (A): sediment layer 0–5 cm Bottom (B): 5–10 cm


Sediment Sodium (Na)

Sediment Potassium (K)

Sediment Calcium (Ca)

Sediment Magnesium (Mg)

Figure 1.4 Concentration of sodium, potassium, calcium and magnesium in surface sediment layer (0–5 cm) per gram sediment dry matter (DM)

Iron and aluminium, however, dominated the macroconstituents in the mineral composition of the sediments (silica excluded), and the most common values were in the range of 20–40 mg g^{-1} DM (Figure 1.5). The highest calcium levels were recorded in the Bumi area and in shallow Gache-Gache exposed area whereas the highest iron and aluminum concentrations were found in the deposition bottoms (deep water) and in sheltered bays. The dominating elements relate to the surrounding soils and minerals, like various sandstones and mudstone (Balon and Coche 1974). The elevated sodium concentrations in the sediments from Bumi area is difficult to explain. The heavy metals on the other hand, nickel, lead, chromium and zinc were found most dominant (although in moderate concentrations) in the deposition bottoms at deep waters, at Sebungwe and Bumi area (Figure 1.6); this can be related to the silt transported from the watershed.

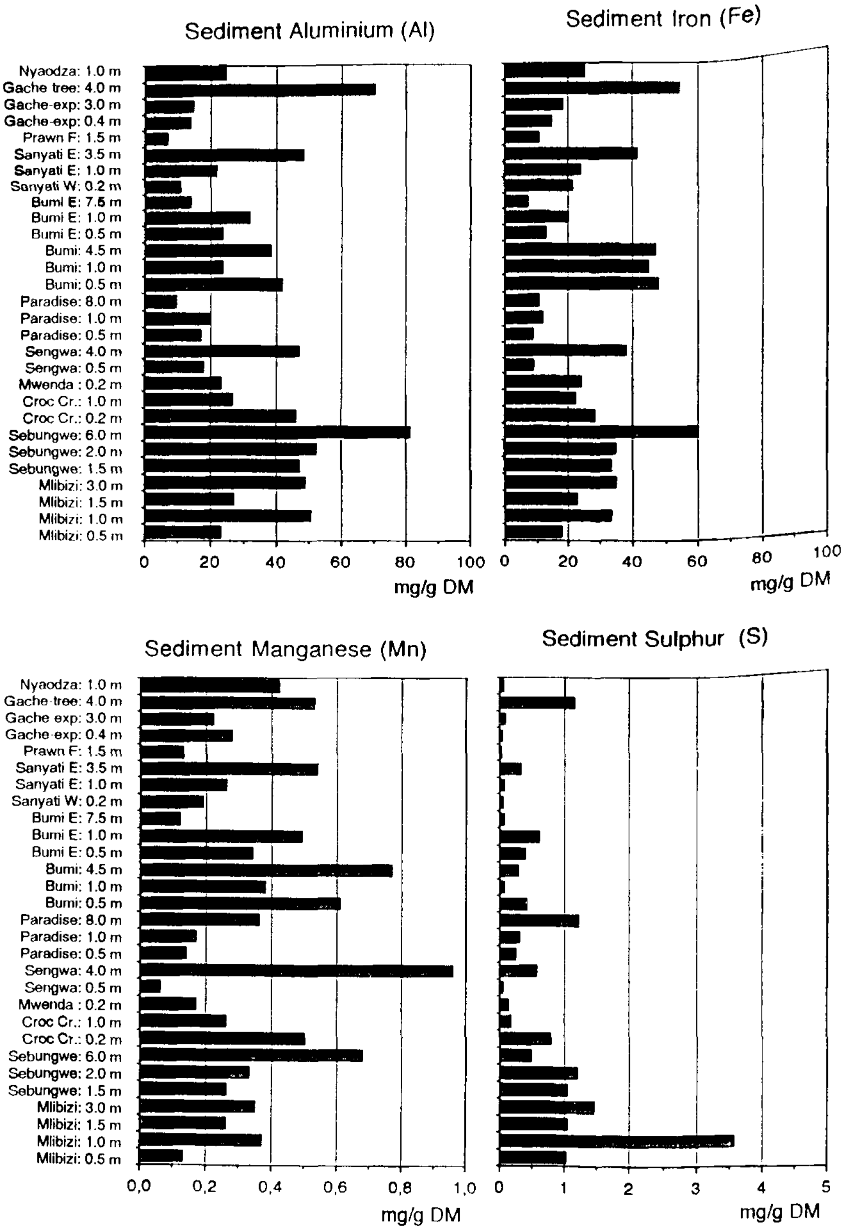
When sediment dry matter was plotted against sediment organic matter ($n = 50$), a high inverse correlation was found between the two parameters (Figure 1.7). A substitution of organic matter for total nitrogen showed a similar inverse correlation ($R = 0.81$) (Figure 1.8). Sediment organic matter content was a good indicator for a presence of sediment nitrogen, and nitrogen increased with elevated organic matter, although two samples strongly deviated (Figure 1.8). The outliers, with low N but high organic matter were located in the Mlibizi basin, and no explanation can be found.

Sediment phosphorus plotted against sediment dry matter and against organic matter (LOI) showed no significant relationship (Figure 1.9). The TKN/TP ratios, however, were inversely correlated to dry matter with a coefficient of $R = 0.69$ (Figure 1.9). When plotted against aluminum and iron, sediment phosphorus showed a positive significant correlation to both aluminum and iron concentration (Figure 1.10), confirming their associations to silt/clay particles.

Nutrient levels and exchange in littoral areas

During the survey in October 1984, water above sediment surface was collected and analysed for TN and TP, and for pH. Total N concentration was above the average value of 0.5 mg N l^{-1} in the near shore water at two shallow and exposed stations, Sengwa and Sanyati East, (Figure 1.11). A "wash-out" zone without sedimentation and without bottom vegetation could temporarily give high nutrient levels in the water. The high nitrogen levels in Mwenda river and Crocodile creek must be an effect of game activity. Also total phosphorus concentration was in the range of 20–40 µg P l^{-1} with a few exceptions (Figure 1.11). At the two shallow and exposed stations, total P was about 100 µg P l^{-1} in the near shore water phase. At the same time, sediment P was only about 100 µg P g^{-1} DM at those stations, and dry matter was around 80% (see Figures 1.2 and 1.3).

As a contrast to the low TN/TP ratios in the sediment (an average of 5), the TN/TP ratios in the water were almost all above 10, and more often in the 10–20 range (Figure 1.11), indicating a slight P deficiency in relation to N in the water. Occasionally, the TN/TP ratio was as high as 35 in the Mwenda estuary, as a consequence of high nitrogen levels, most probably due to intensive game activity. pH in the water was stable around 8.



Sediment Aluminium (Al)

Sediment Iron (Fe)

Sediment Manganese (Mn)

Sediment Sulphur (S)

Figure 1.5 Concentration of aluminium, iron, manganese and sulphur in surface sediment layer (0–5 cm) per gram sediment dry matter (DM)

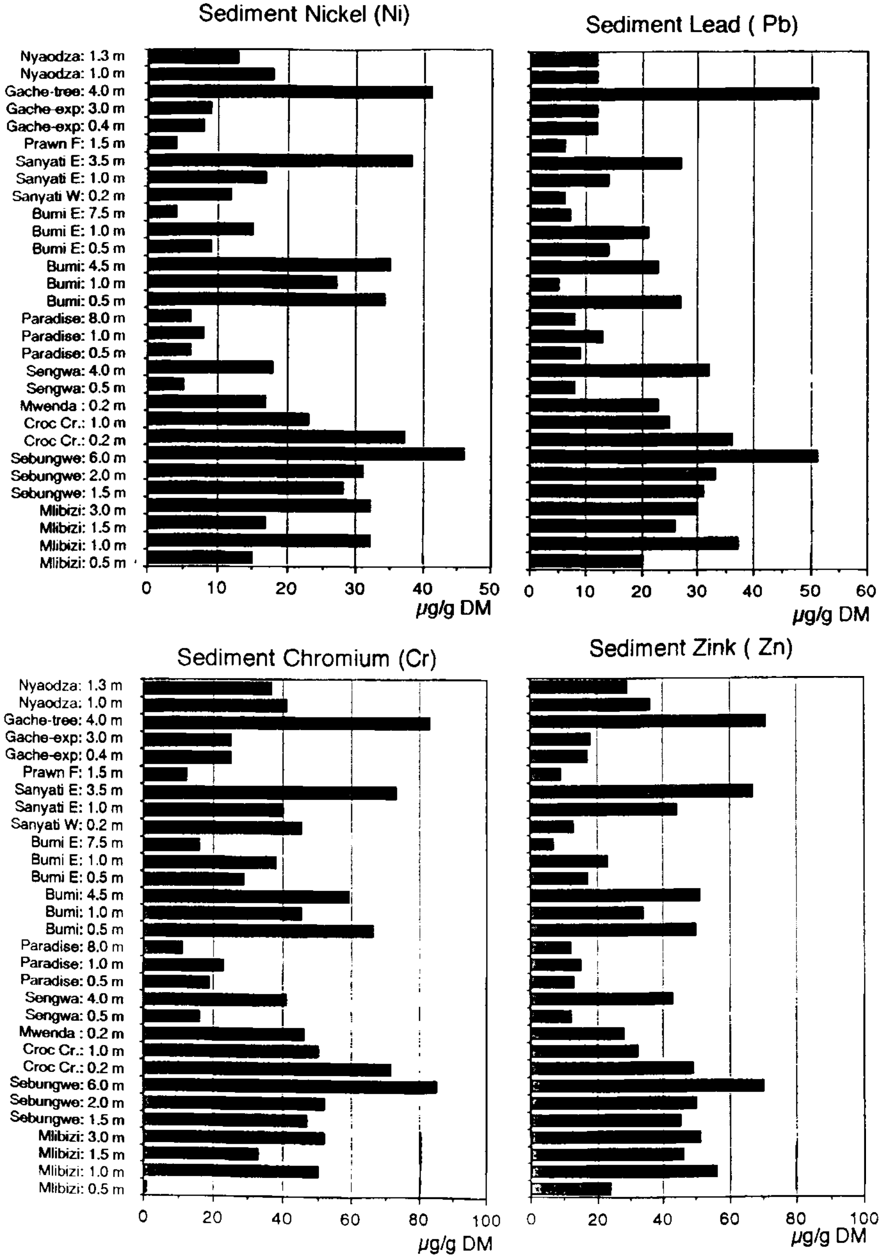


Figure 1.6 Concentration of nickel, lead, chromium and zink in surface sediment layer (0–5 cm) per gram sediment dry matter (DM)

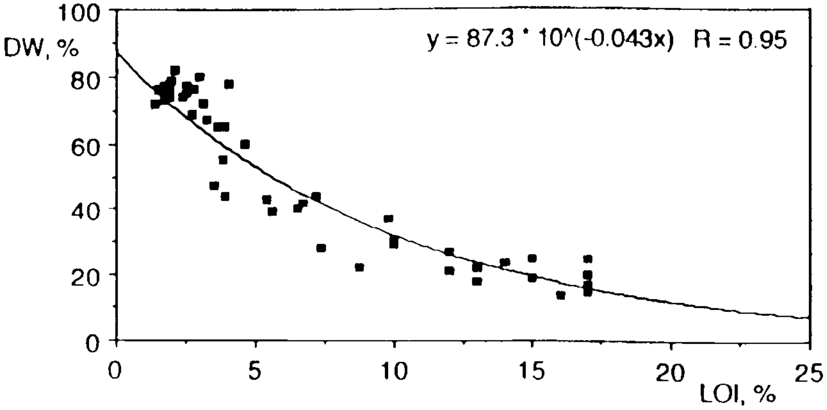


Figure 1.7 Correlation between sediment dry matter (ordinate: % dw) and organic matter, loss on ignition (L.O.I.) for n = 50

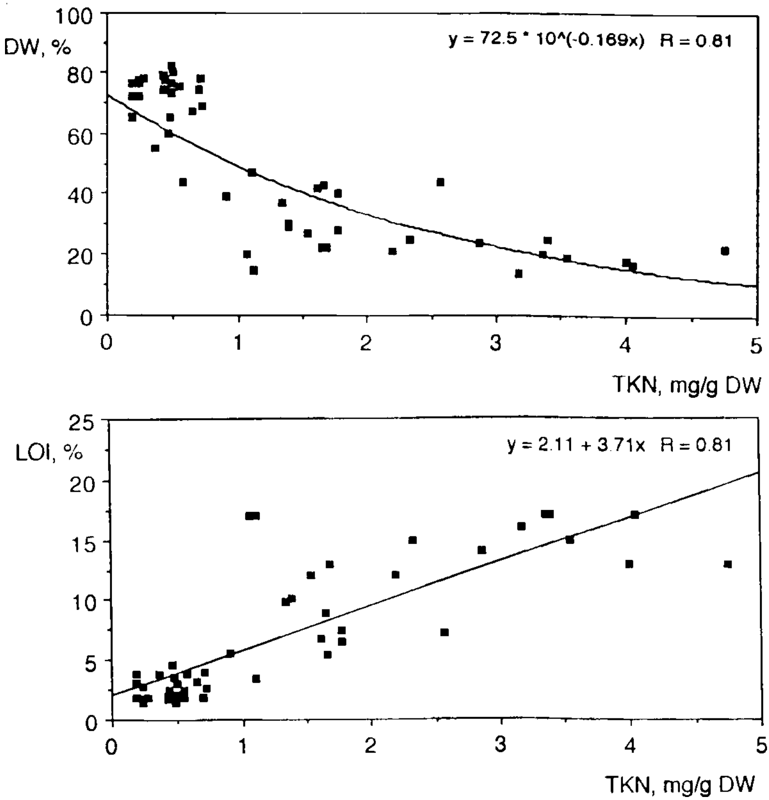


Figure 1.8 Correlation between sediment dry matter and nitrogen concentration (top), and between organic matter and nitrogen concentration (bottom)

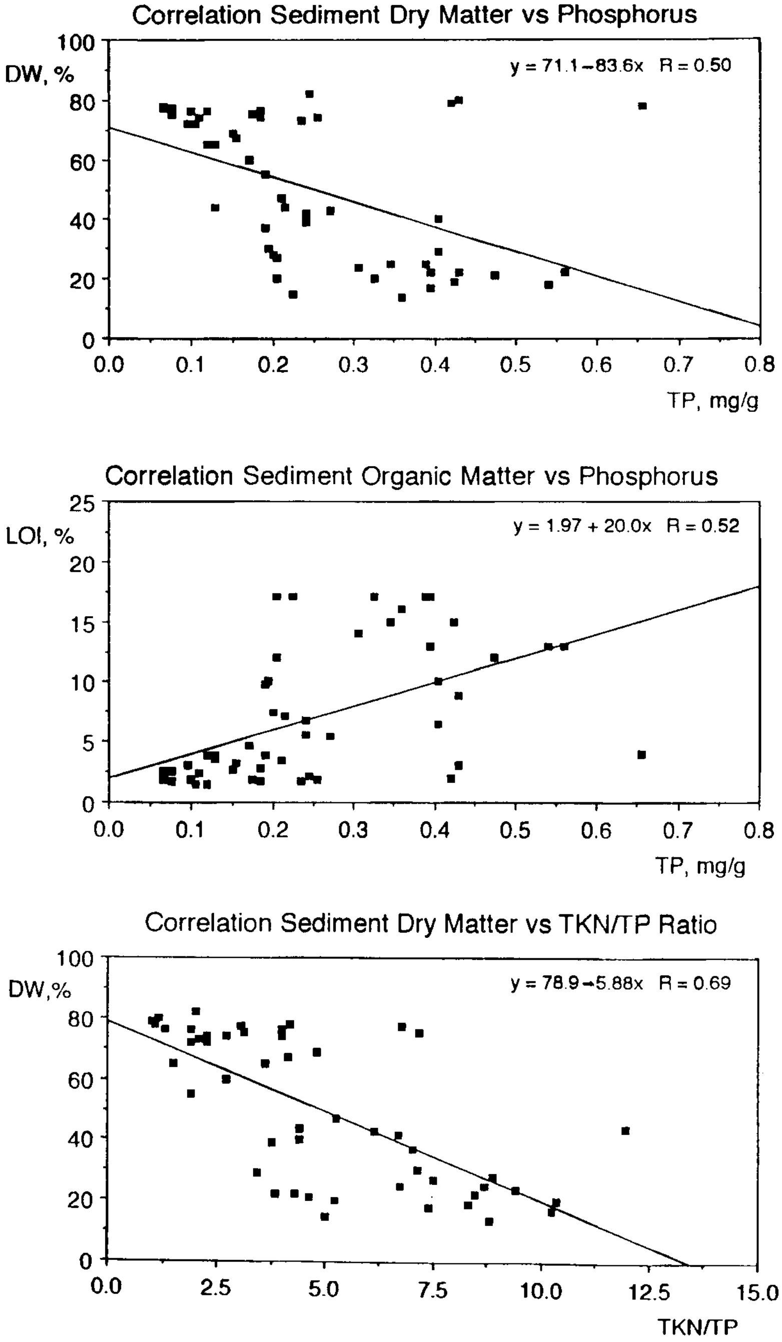


Figure 1.9 Correlation between sediment dry matter and total phosphorus (TP) concentration (top), between organic matter and TP (middle), and between dry matter and TKN/TP ratio (bottom)

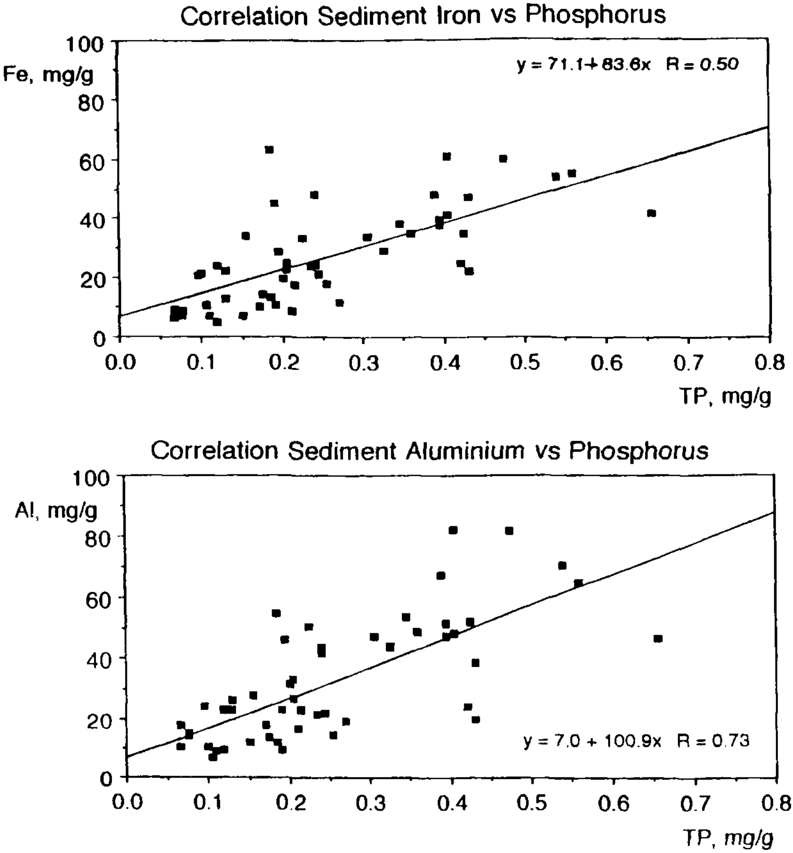


Figure 1.10 Correlation between iron (Fe) and TP (top), and between aluminium (Al) and TP (bottom)

In order to highlight seasonal variations in nutrient supplies in bays and rivers, and to understand a potential impact from sediments and water above sediments, sediment/water experiments were considered necessary together with the analysis of *in situ* nutrient concentrations.

In the first set of experiments, "undisturbed" water/sediment cores were selected from seven stations. The water phase was analysed before (Figure 1.12) and after addition of phosphate under aerobic conditions. The P added was equivalent to a concentration increase of 100 μg P l^{-1} in the water. The added phosphorus was rapidly sorbed by the sediment with a rate of 0.25–0.5 mg PO_4-P m^{-2} h^{-1} (Figure 1.13), the Mlibizi core giving another value. Only traces of phosphate were left in the water column. The P addition was performed on two occasions using same sediment cores. Mlibizi and Sengwa were only tested once. The second time, the cores were poisoned with $HgCl_2$ to avoid any potential biological uptake (Kamp-Nielsen 1979).

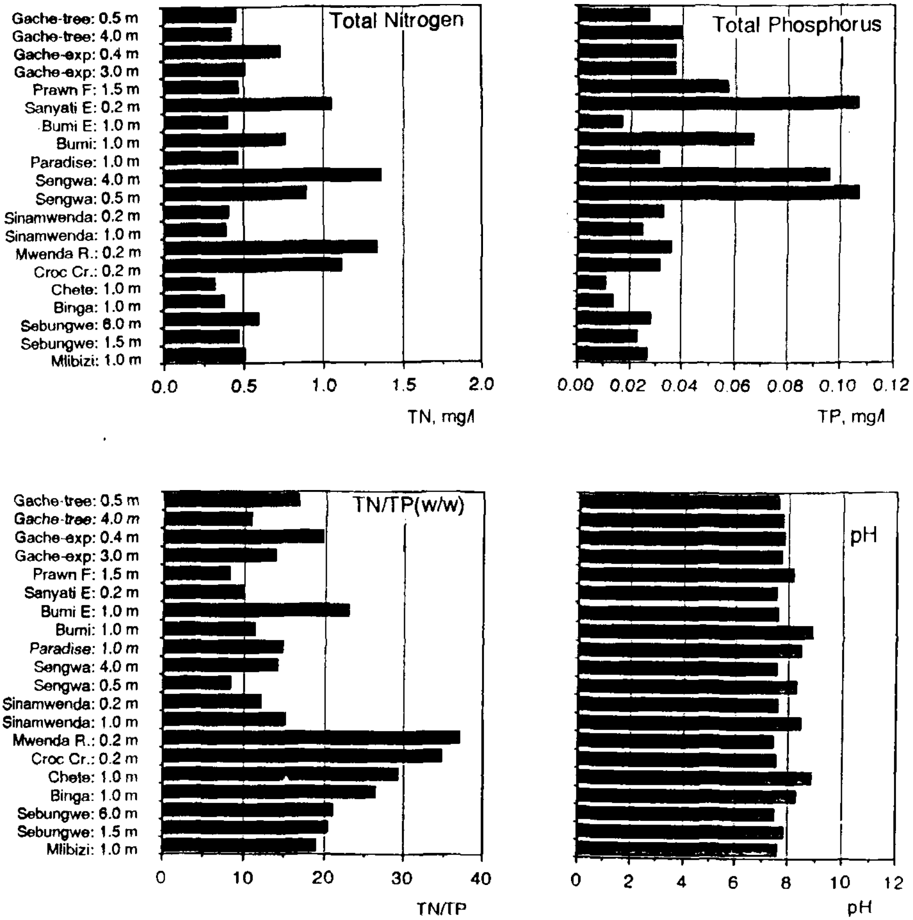


Figure 1.11 Total phosphorus (TP) and total nitrogen (TN) concentration, TN/TP ratio (by weight) and pH in water above sediment surface (10–0 cm), November 1984

The Mlibizi sediment showed another sorption rate than the other sediments, which is explained by the initially higher phosphate concentration in the water phase (Figure 1.12). Considering the P concentration of 275 µg P l^{-1}, i.e. almost three times the enrichment dose in the other cores, and the sorption of 1.5 mg P m^{-2} h^{-1}, the Mlibizi sediment would also take up about 0.5 mg P m^{-2} h^{-1}, if only 100 µg P l^{-1} was available. It should be noticed that, in the present experiments, the rate of P sorption related to the initial phosphate was in the same range as observed in far more advanced experimentation by Twinch and Peters (1984). They obtained an uptake rate of 0.46 mg P m^{-2} h^{-1} after enrichment to an initial P concentration of 100 µg P l^{-1} in the water phase. In addition, a direct correlation was found between initial phosphate concentration in water phase and phosphate uptake rate (Twinch and Peters 1984), which confirmed the result in the Mlibizi core. Nutrient exchange behaviour in sediments from African lakes has been analysed in experiments by Kamp-Nielsen (1979) and Viner (1975) giving similar results as well.

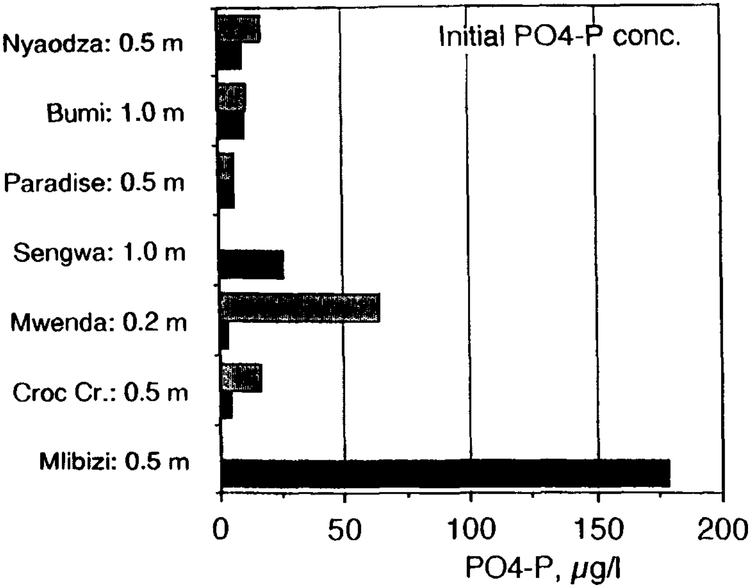


Figure 1.12 Phosphate concentration in water above sediment (10–0 cm) in water/sediment cores. Initial concentrations before P additions

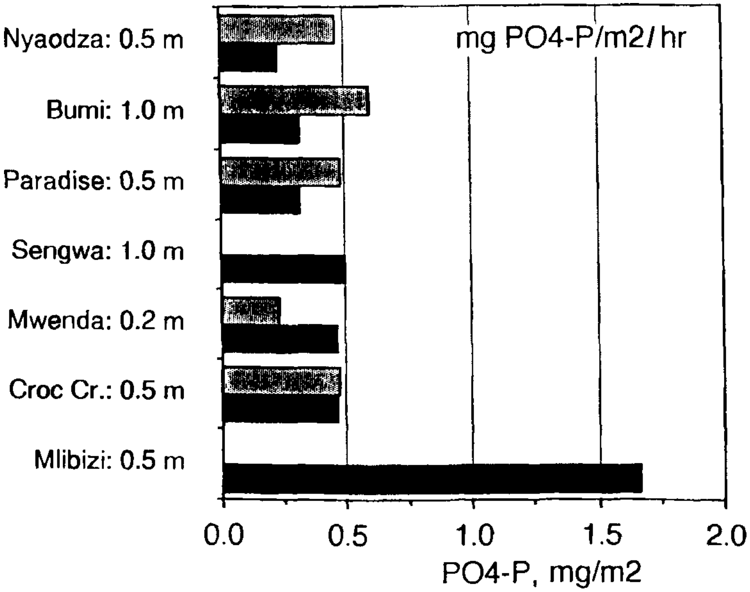


Figure 1.13 Phosphate sorption rate by different sediment types. P added on two occasions. Undisturbed water/sediment cores collected in October 1985

Interstitial water concentration of ammonia and phosphate in sediment from Mlibizi, Sengwa and Paradise Island increased just below an oxidised microzone on sediment surface, in particular the ammonia concentration was elevated. As soon as anoxic conditions appeared in the water phase of the cores, ammonia and phosphate concentrations increased. Additional sediment desorption/sorption experiments related to oxygen were therefore performed in water/sediment cores from Mlibizi, Sebungwe, Paradise and Bumi stations. By alternating anoxic and oxic conditions, release and sorption of ammonia and phosphate was followed. Sediment nutrient release was ruled not only by oxygen conditions, but also by the organic content in the sediment and sediment re-suspension.

- In summary, the lake sediment showed a strong and rapid uptake of P and N under good aerobic conditions and a significant nutrient release under anoxic conditions quantified by the organic matter content. In addition, the sediment serves as a sink for silt and associated nutrients, which can, however, be easily changed to a source when fine clay associates are resuspended by strong flows and/or game activities.
- Littoral surface water samples from March, June and November 1986 were analysed for conductivity, turbidity, phosphorus, nitrogen and chlorophyll *a*.
- In March, the water in Mlibizi and Nyaodza river was very turbid as a result of the high load of suspended silt/clay particles (Figure 1.14). The suspended particles were associated with high concentrations of particulate phosphorus (c. 90 μg P l^{-1}). In the Mlibizi river, water conductivity was three times the normal value, associated not only with high P but also with high ammonia and particulate nitrogen (2 mg N l^{-1}). Despite the turbid water and a transparency less than 0.5 m, chlorophyll *a* was 160 μg l^{-1} in the river water.

Once the water reached the bay, conductivity had decreased and so had chlorophyll *a* to a value of 25 μg l^{-1} (Figure 1.14). The TN/TP ratio in the Mlibizi area was around 20 but only 10 in inner bay, in the Nyaodza area whereas it increased to 15 downstream the estuary. The low ratio indicate a potential nitrogen limitation for algal growth in the inner bay and give space for nitrogen-fixing algae or attached macrophytes (see Moyo, this volume). In general, the TN/TP ratios were in the range 15–25.

Apart from nutrient-rich conditions in the Nyaodza and Mlibizi river/estuary, low turbidity, low nitrate, rather low ammonia and low phosphate characterized the water quality at the other littoral stations (Figure 1.14). The water entering Ume basin via Ume river was very nutrient poor; total P was 12 μg P l^{-1} and total N was 0.3 mg N l^{-1}, giving a TN/TP of 25. Chlorophyll *a* was 2.7 μg l^{-1}

The nutrient inputs from the small rivers and the "wash-outs" from the shores seem to exert an internal and local effect only, since the river influence was no longer traceable once the water entered the mouth of the bay (Figure 1.14).

- In June the water quality in the littoral area was no longer influenced by suspended matter, i.e. turbidity values were below 15 (Figure 1.15). Only the water in Nyaodza showed elevated values in total P and had a chlorophyll *a* concentration of 35 μg l^{-1}. The conductivity in the Mlibizi river was still above usual lake values, and some ammonia was present in the water, although the concentration was not exceptional.

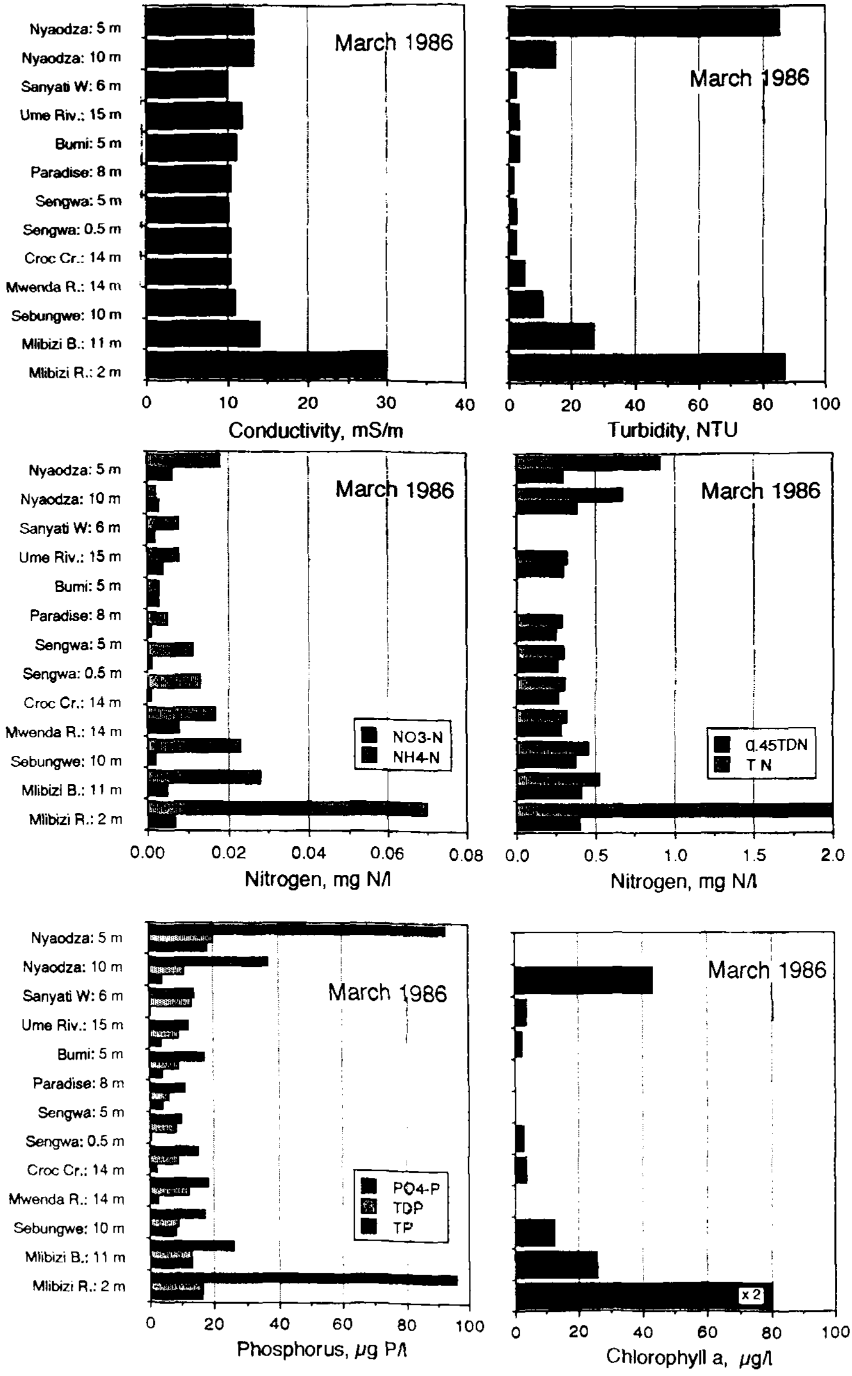


Figure 1.14 Littoral transects and stations in March 1986. Conductivity, turbidity, nitrogen, phosphorus and chlorophyll *a* in surface water (0–1 m)

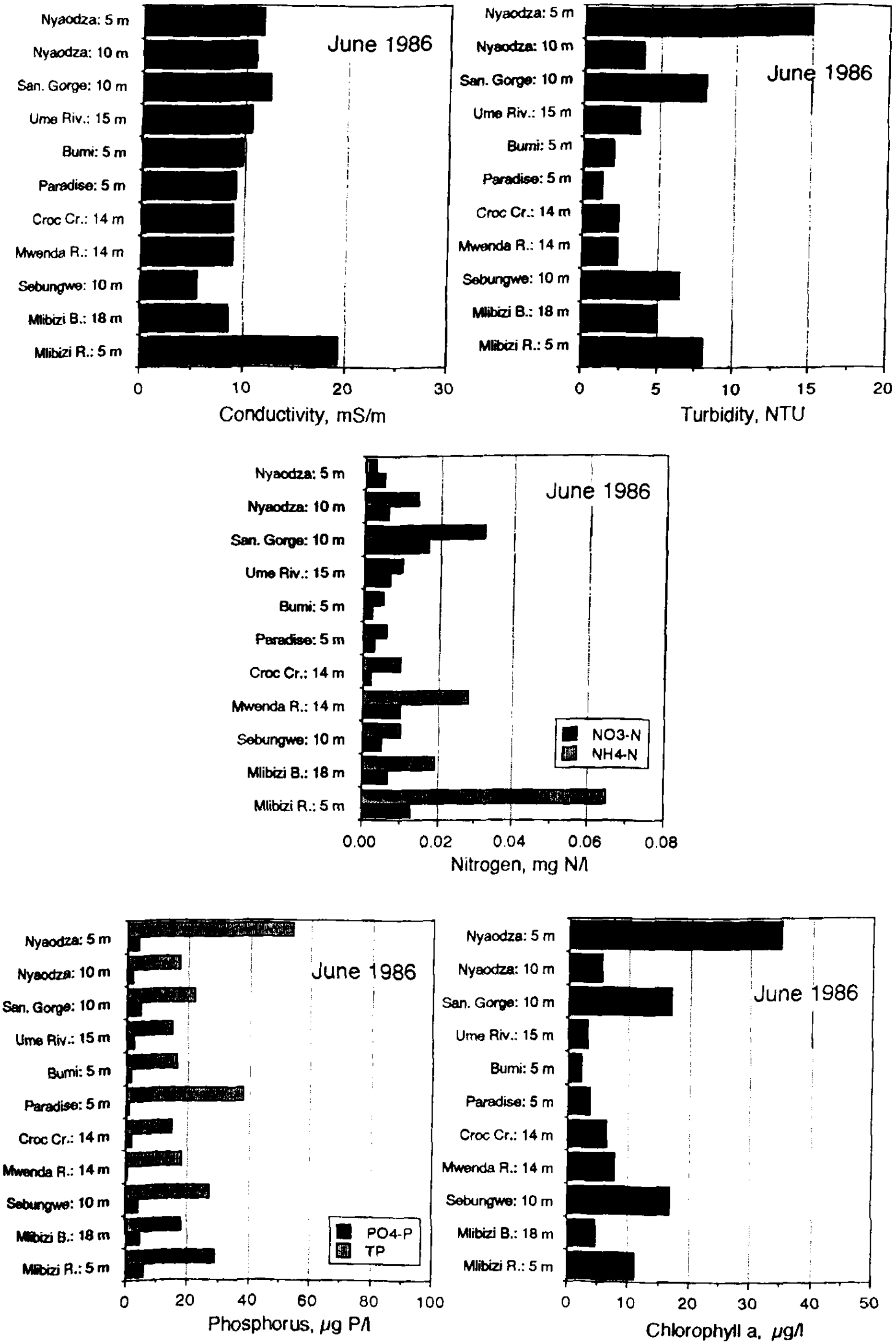


Figure 1.15 Littoral transects and stations in June 1986. Conductivity, turbidity, nitrogen, phosphorus and chlorophyll *a* in surface water (0–1 m)

- In November, at the end of the dry season, water turbidity and chlorophyll *a* values had further decreased since June. With the exception of Nyaodza river, turbidity was below 5 NTU and chl *a* below 10 (Figure 1.16).

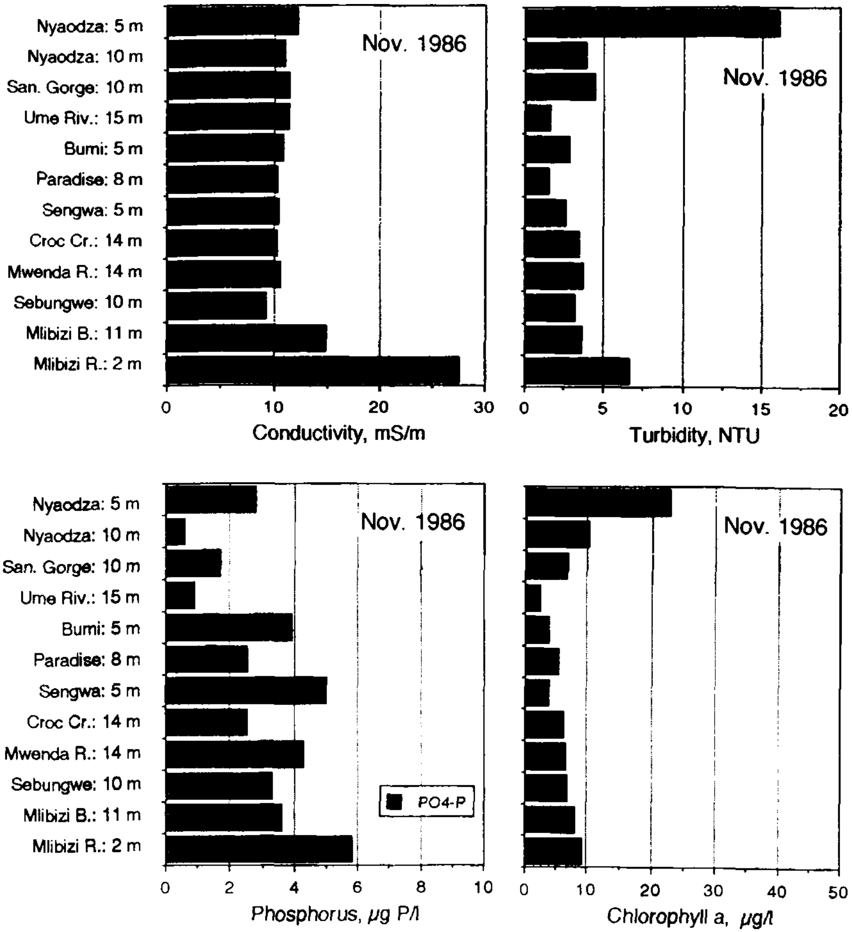


Figure 1.16 Littoral transects and stations in November 1986. Conductivity, turbidity, phosphorus and chlorophyll *a* in surface water (0–1 m)

Concerning the water overlying the sediments, the available results indicated differences in March (Figure 1.17A), in two stations only (Nyaodza and Mwenda River). They were mostly related to ammonia concentration which most probably was induced by game activity. In June, water near sediment surface showed, considering the limited values, normal and stable conditions (Figure 1.17B).

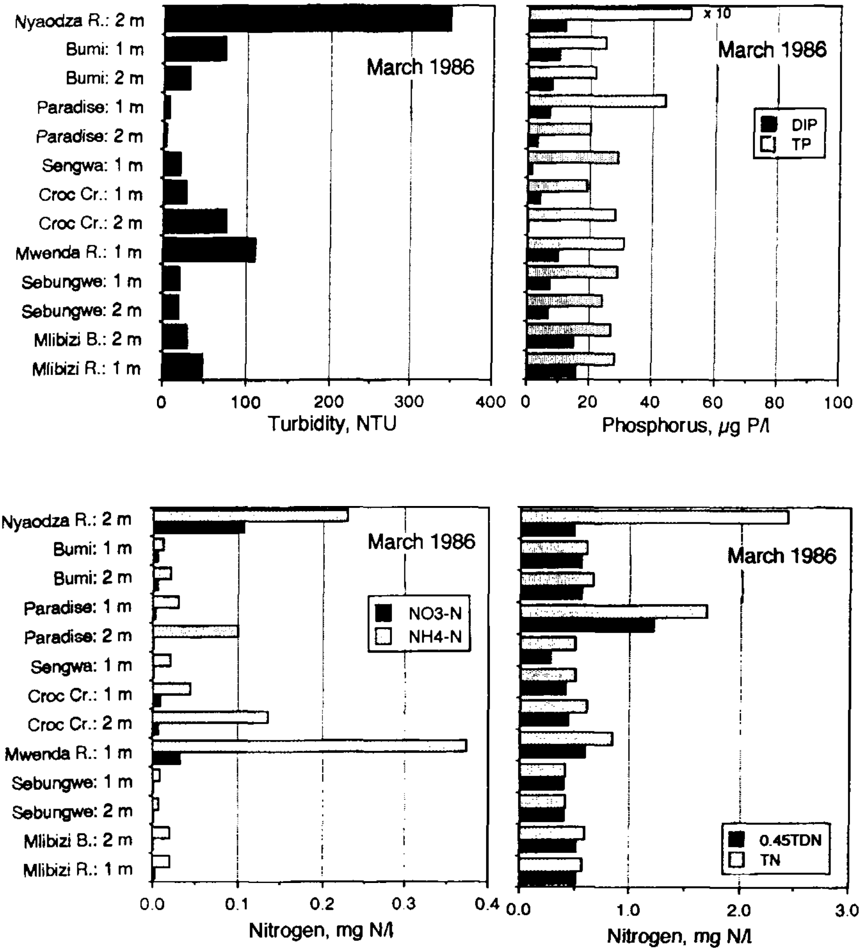


Figure 1.17A Water above sediment surface (10–0 cm) at some transects. Turbidity, nitrogen and phosphorus concentrations in March 1986

The horizontal rapid decline in nutrient concentration downstream the bays confirmed that small rivers and inundated areas were efficiently controlled by littoral plant communities. As a consequence, a nutrient depleted "dilute" water is exported downstream to offshore areas. In a separate study, productivity and metabolic activity in natural littoral communities were studied in *in situ* enclosures (Machena *et al.* 1990 and Machena this volume).

In order to compare the nutrient pool in littoral areas with conditions in the pelagic water, this study also included pelagic stations and analysis of the nutrients on same occasions as for the littoral stations to be able to relate simultaneous events to find possible correlations between them.

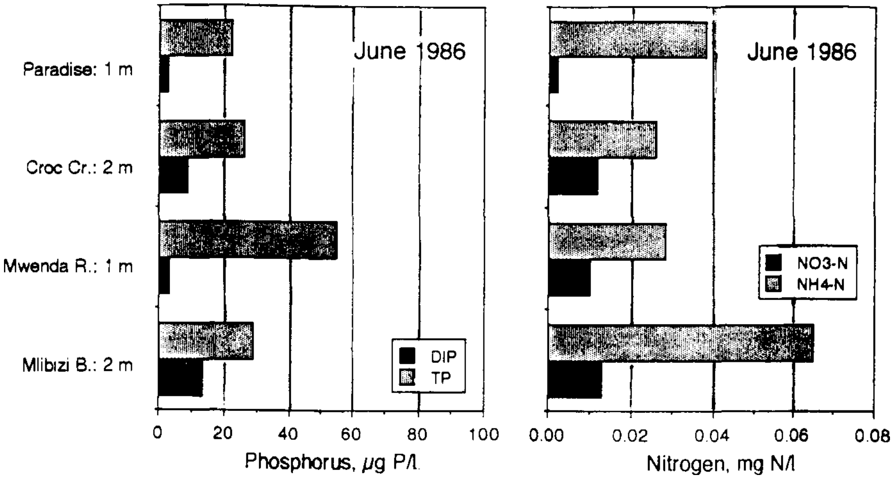


Figure 1.17B Water above sediment surface (10–0 cm) at some transects. Phosphorus and nitrogen concentrations in June1986

Physical-chemical conditions, nutrients and chlorophyll in pelagic waters

During 1986, pelagic stations in the five basins of Lake Kariba (Figure 1.1) were sampled on three occasions; in mid-March, end of June and mid-November. The samplings were coordinating water chemistry analysis with plankton studies, and aimed at investigating seasonal situations and relate the data to the three important periods in the annual lake cycle; the late period of stratification with influence from river inflows in March, the turn over period in June–July, and the stratified period at the end of the dry season in November before the rain period.

Detailed information on the thermal cycle and the oxygen cycle is presented in Balon and Coche (1974). In addition, this book includes a good description of water conductivity and ionic composition during a year cycle (*opt. cit*). Therefore, only some parameters, i.e conductivity, turbidity and pH, were investigated here since they are related to the nutrient cycle. The focus will also be on the nutrients, their composition, distribution and utilization, and chlorophyll *a*.

Secchi disc transparency was strongly reduced by the amount of suspended matter being transported with the inflow from Zambezi River into the upper Mlibizi and Binga basins (Figure 1.18) especially in March, when the effect from the flooding was at its peak in the upper basins. In June and November, there was a pronounced difference in water clarity between the upper and the lower basins. In the lower Sengwa basin, surface water was still clear in March, and Secchi disc readings reached 5 or 6 m (Figure 1.18). In June, however, river water affected the Sengwa basin and reduced transparency, whereas readings above 8 m were still recorded in the lower Ume basin.

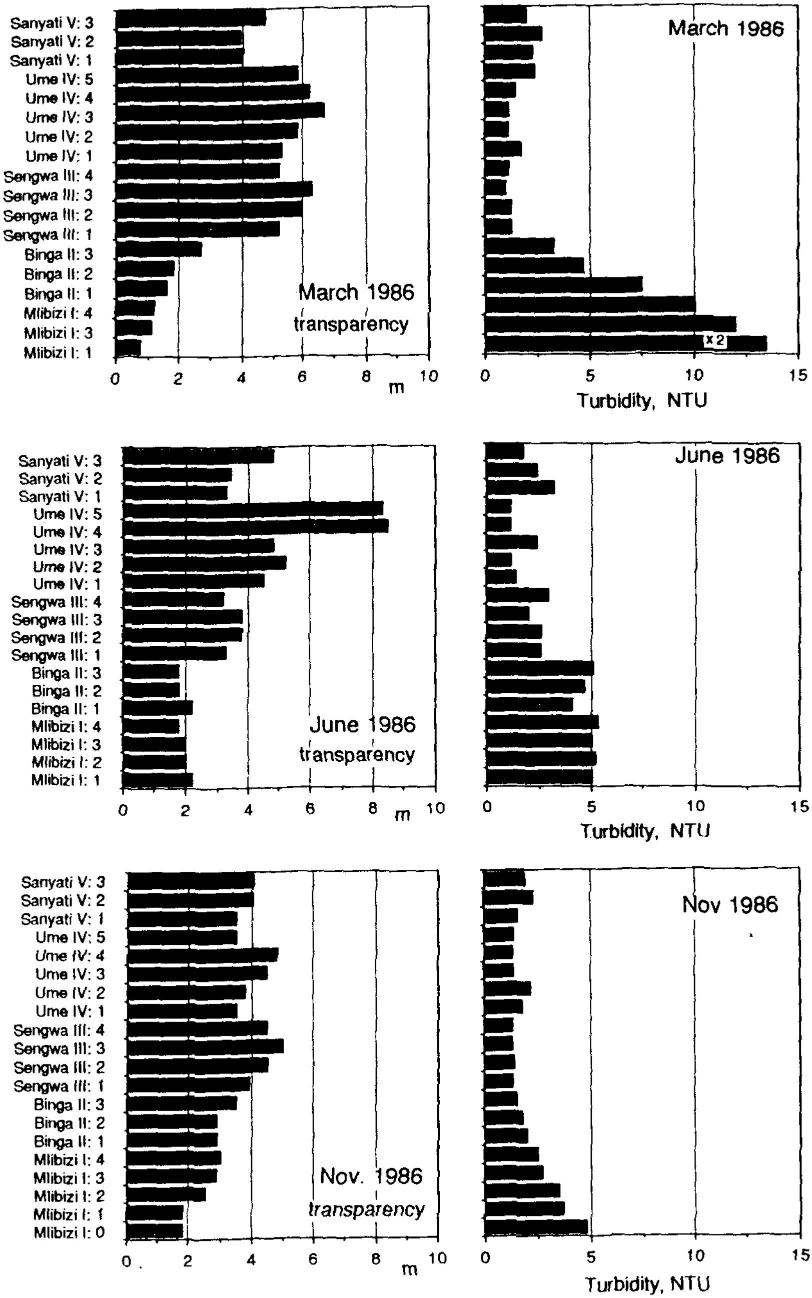


Figure 1.18 Secchi disc transparency (left) at pelagic stations, and turbidity (right) in surface water (0–5 m) at same pelagic stations in March, June and November 1986

In November, water transparency was around 4 m in a large part of the lake. Only the upper Mlibizi basin showed a transparency of about 2 m or lower during the three sampling periods.

Turbidity values were consequently the opposite to the Secchi disc readings with very high values in the Mlibizi basin, which rapidly declined in downstream basins as the suspended particles settled out and the water clarified (Figure 1.18). In general, turbidity was well below 5 NTU in the surface water 0–5 m.

pH was around 8 in the well buffered water and very stable along the lake and throughout the seasons (Figure 1.19). Conductivity was also stable and in the range of 8 to 10 mS m^{-1} at most stations (Figure 1.19). The elevated conductivity in the upper Mlibizi basin in March was due to an impact from the drainage basin. However, the lower values recorded for the upper basins in June 1986 were also observed in 1965 by Balon and Coche (1974). In general, the values in the 1986 survey were somewhat higher than in 1965, but the distribution pattern was very similar. One explanation could be the very low water level in 1986 followed upon several years of drought.

At 30 m water depth there was no change in pH values (Figure 1.20), and insignificant deviations regarding conductivity in comparison with surface water (Figure 1.20). Turbidity, however, was considerably higher in the deep water than at surface in March (see Figure 1.20 compared with Figure 1.19). The highest turbidity value (33 NTU) was in fact found in the Binga basin. Also the water in the Sanyati basin was affected by the silt particles coming from the Gorge. During the other periods, the turbidity in the deep water was very low (Figure 1.20).

The various nutrient components, their distribution pattern along the lake, and the changes in their relative importance, were primarily influenced by temperature, oxygen concentration, and silt suspension and composition as shown from some examples provided below.

The inorganic nitrogen compounds in surface water, ammonia and nitrate, were very low in March and November, i.e. below 30 μg N l^{-1} (Figure 1.21), due to biological depletion and strong stratification. In June, on the other hand, some small amounts of inorganic nitrogen were found in the Binga and Sengwa basin in particular (Figure 1.21). The inorganic N pool was dominated by ammonia in the Mlibizi and Ume basins whereas nitrate dominated in the Binga and Sengwa basins. The reason was an upwelling from deep water since the temperature stratification was on the edge to disappear. In Sengwa basin, for example, surface temperature was 23.5°C, and at 30 m water depth temperature was 23.3°C. In November, nitrate was very low, while ammonia was between 10 and 20 μg N l^{-1} (Figure 1.21). Total N varied between 0.2 and 0.5 mg N l^{-1}, with the lowest values found in the Sengwa and Ume basins (Figure 1.21).

Phosphorus concentration was related to the silt/clay import by the large rivers (see Figure 1.22 compared with Figure 1.18). As expected, the phosphate concentration was low in surface water during the non-seasonal growth, tied up in phytoplankton. Only in March and in the upper Mlibizi basin, could some significant excess in phosphate be detected. Total phosphorus in surface water was rather stable in the range 15–20 μg P l^{-1}, with a minimum in the Sengwa and Ume basin, and a maximum in Mlibizi basin and to some extent also in Sanyati basin during periods of strong input from the rivers (Figure 1.22).

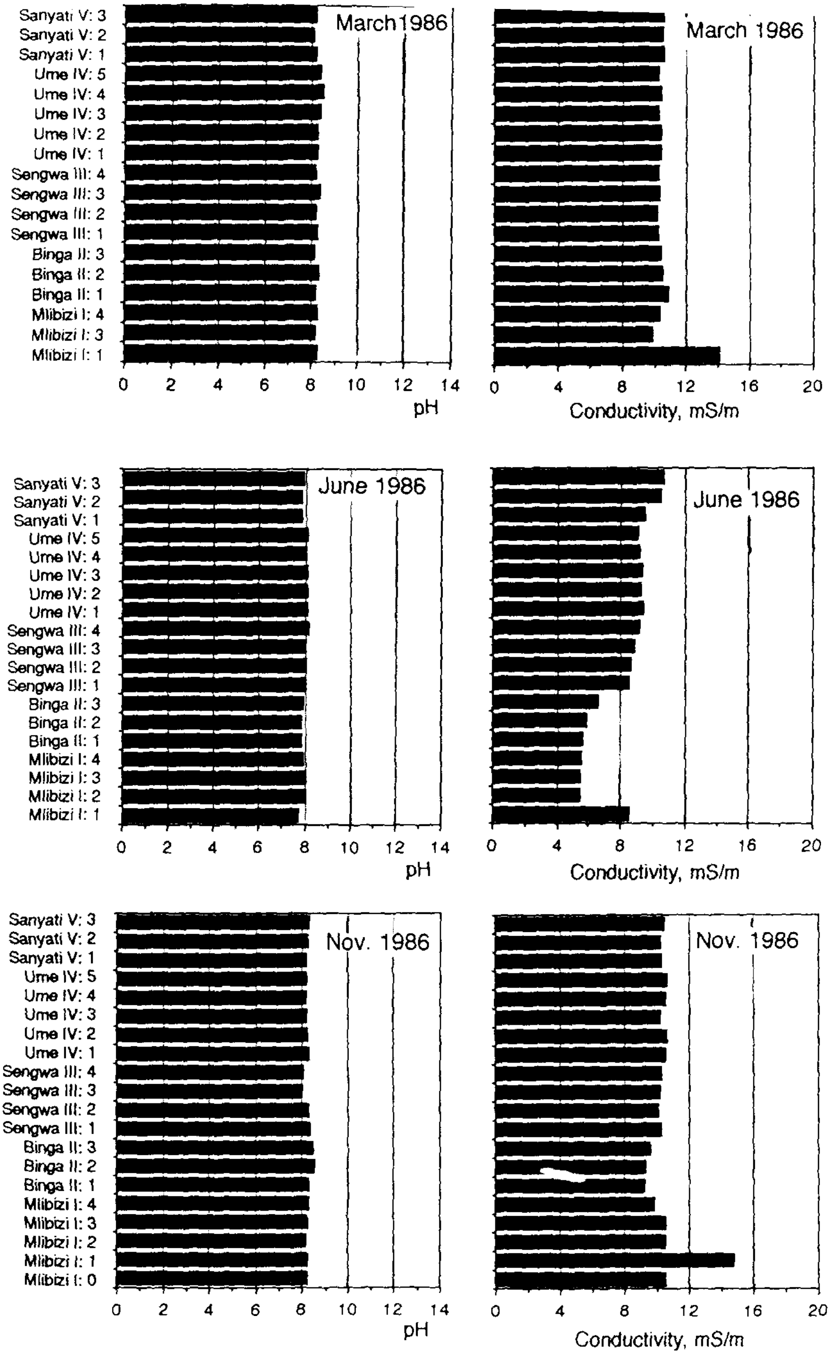


Figure 1.19 pH (left) and conductivity (right) in surface water (0–5 m) at pelagic

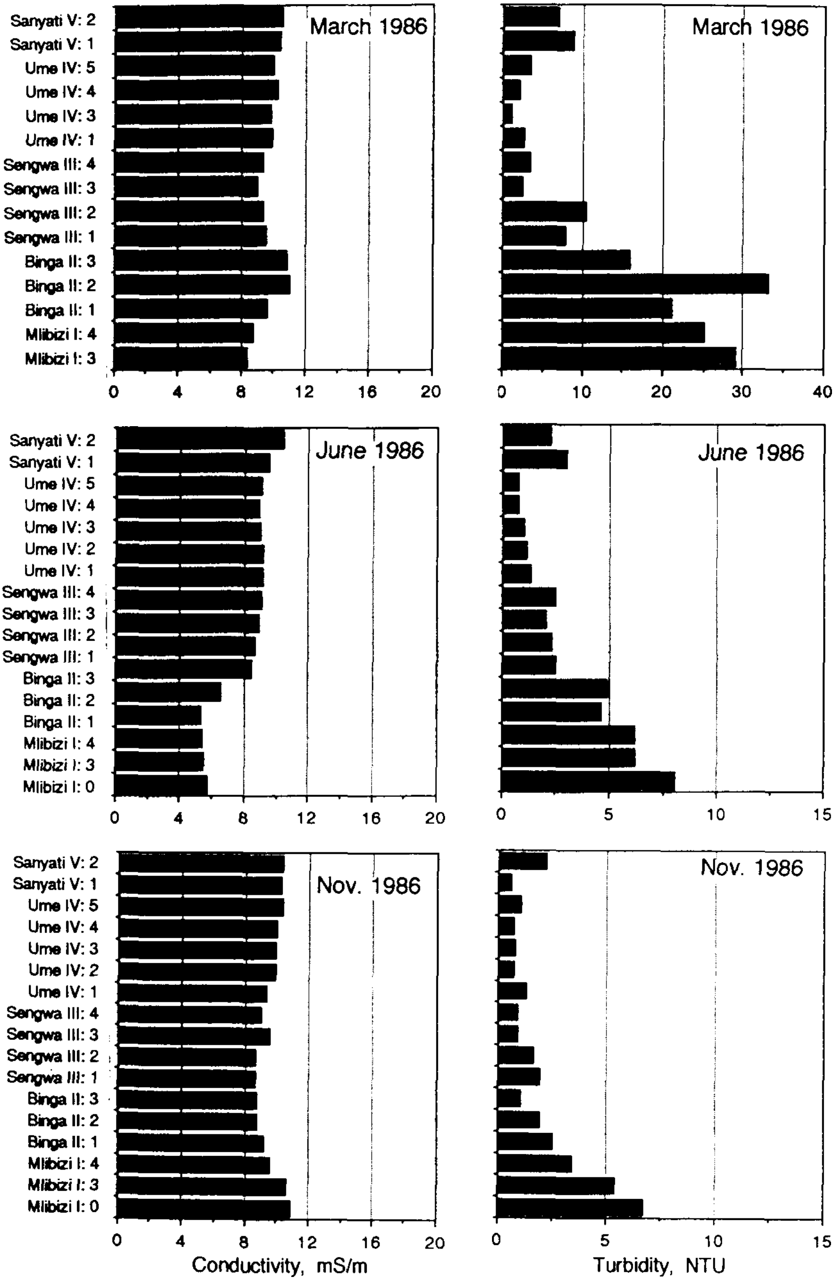


Figure 1.20 Conductivity (left) and turbidity (right) in water from 30 m depth at pelagic stations in March, June and November 1986

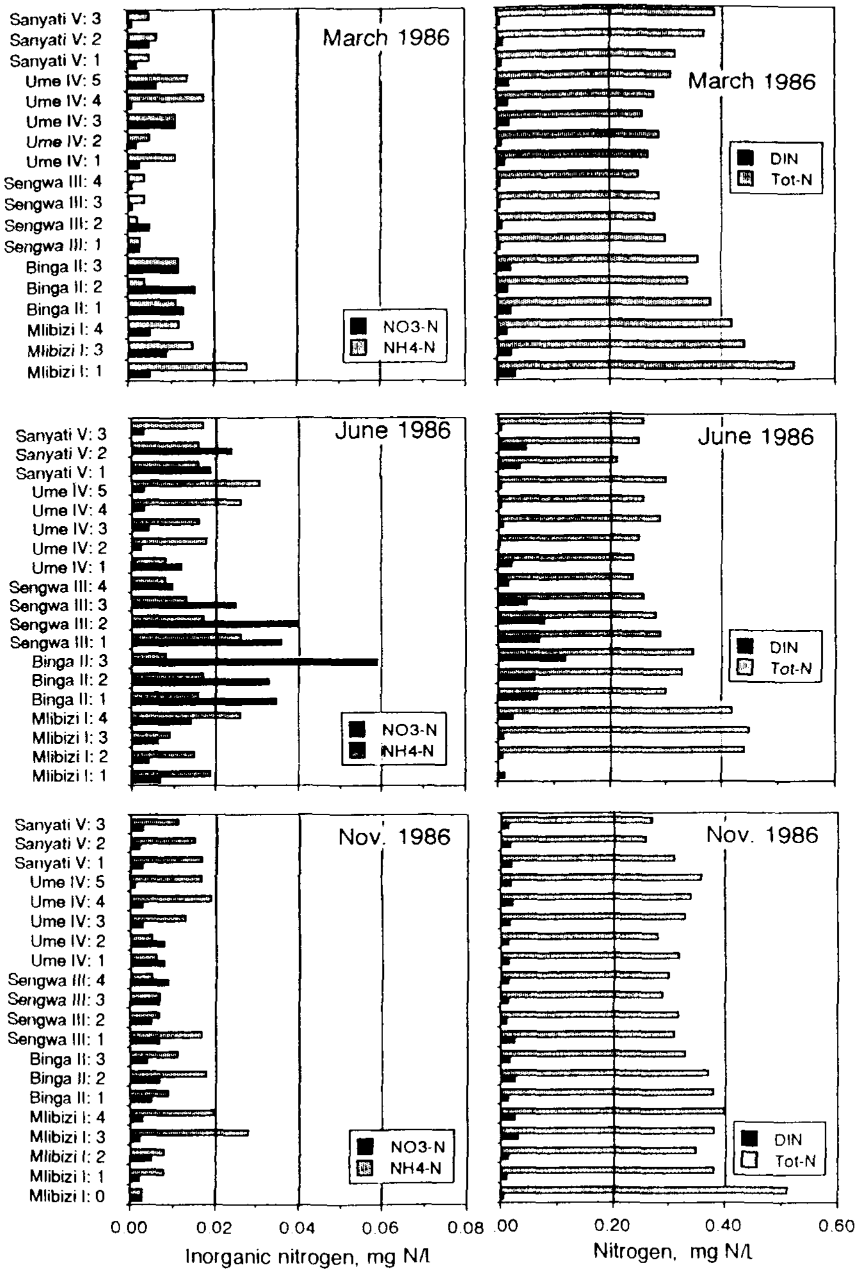


Figure 1.21 Nitrogen concentration, as NO_3-N and NH_4-N (left) and as total and inorganic (DIN) nitrogen (right) in surface water (0–5 m) at pelagic stations in March, June and November 1986

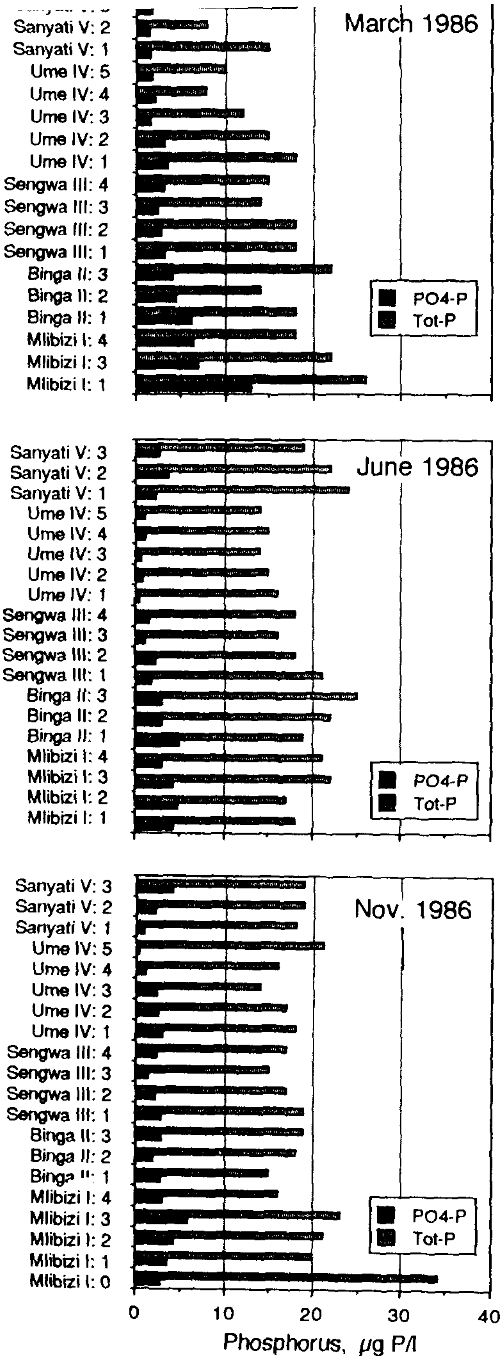


Figure 1.22 Phosphorus concentration, as phosphate-P and total phosphorus, in surface water (0–5 m) at pelagic stations in March, June and November 1986

regarding the oxygen concentration, i.e. nitrate dominated in oxic water while ammonia dominated in anoxic water. For example, in June there was sufficient oxygen at 30 m water depth, but anoxic conditions were still prevailing at 50 m with the exception of the Binga basin (see Cronberg this volume). The situation was confirmed by high ammonia and phosphate at 50 m water depth in the Sengwa and Ume basins (Figure 1.23), while the 30 m water was oxygenated and small amounts of nitrate were present (Figure 1.24). In November, the whole water column was oxygenated and nitrate dominated (Figure 1.23). The situation in March was more controlled by the silt import in the upper basins and inflow of oxygenated river water, while the lower basins had very low oxygen levels already at 30 m. Unfortunately the 50 m water depth was not sampled in March 1986.

Chlorophyll *a* concentrations in the surface water showed a distribution along the lake similar to that of total phosphorus, although there were also large deviations. In the lower basins concentrations were in the 2–6 μg chlorophyll *a* l^{-1} range. In the upper basins concentrations were higher, 5–25 μg l^{-1}, influenced by nutrient rich river waters (Figure 1.25). The values correspond well with concentrations reported for Lake Victoria by Talling and Talling (1965). Lake Victoria is the "best" of the great African lakes for such comparisons due to its physical and chemical characteristics. The other natural great lakes are far too different from Lake Kariba (Hecky and Bugenyi 1992).

A high correlation was found between chlorophyll *a* and transparency (Figure 1.26), in particular for the values from March (R = 0.92), but also the November values showed some correlation. The best correlation, however, was found for values obtained in March, when values from the turn-over period were scattered and not related, whereas the correlation between chlorophyll a and TP was not significant (Figure 1.26)

An explanation for this poor correlation between chlorophyll *a* and TP could be found in the TN/TP ratios (Figure 1.25). They indicated no clear deficiency in neither phosphorus nor nitrogen; more likely both elements were limiting factors of the production, since the ratios were in the 10–20 range. The highest correlation between chlorophyll *a* and TP was found in March and showed some links to the higher TN/TP ratios for that period (see Figures 1.25 and 1.26). An analysis on chlorophyll, P and N relations was carried out by Smith and Shapiro (1981) for individual lakes and seasons. In order to further investigate the growth controlling factors or element(s) in Lake Kariba, algal bioassays were performed in 1988.

Algal bioassays

During the survey in March 1988, the water conditions were found different from March 1986. The water flowing into Mlibizi basin from Devils Gorge was extremely turbid, carrying a large amount of suspended load: silt, clay and organic debris. Secchi disc transparency was only 0.25 m in the basin. Turbidity in surface water was high (120 NTU), i.e. ten times higher than during the sampling of March 1986 at the same station (see Figure 1.18). At 30 m water depth, a turbidity of 320 NTU was recorded, confirming the rapid transport of silt towards the bottom for deposition. Oxygen conditions at 30 m depth were still good.

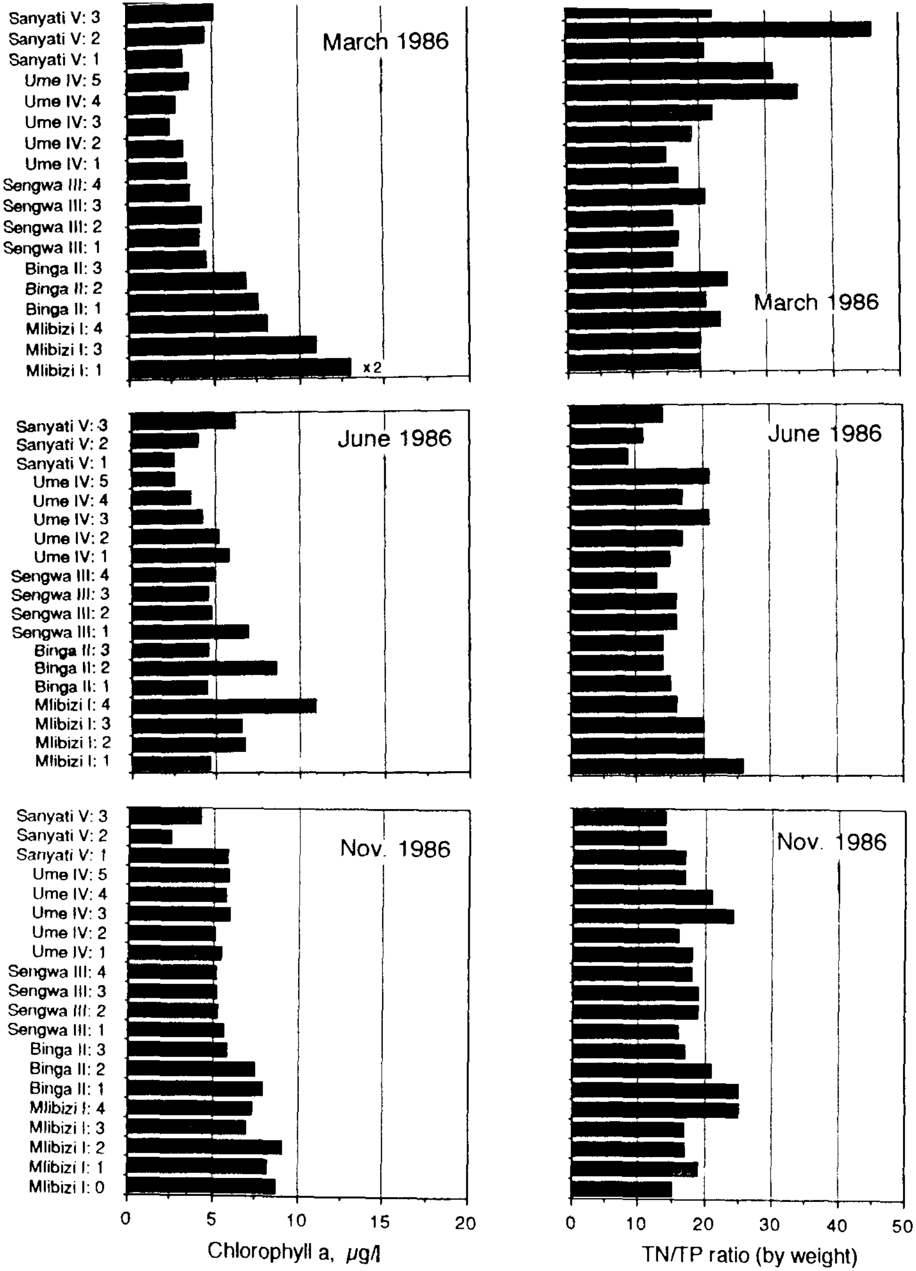


Figure 1.23 Chlorophyll *a* (left) and TN/TP ratio (by weight) (right) in surface water (0.5 m) at pelagic stations in March, June and November 1986

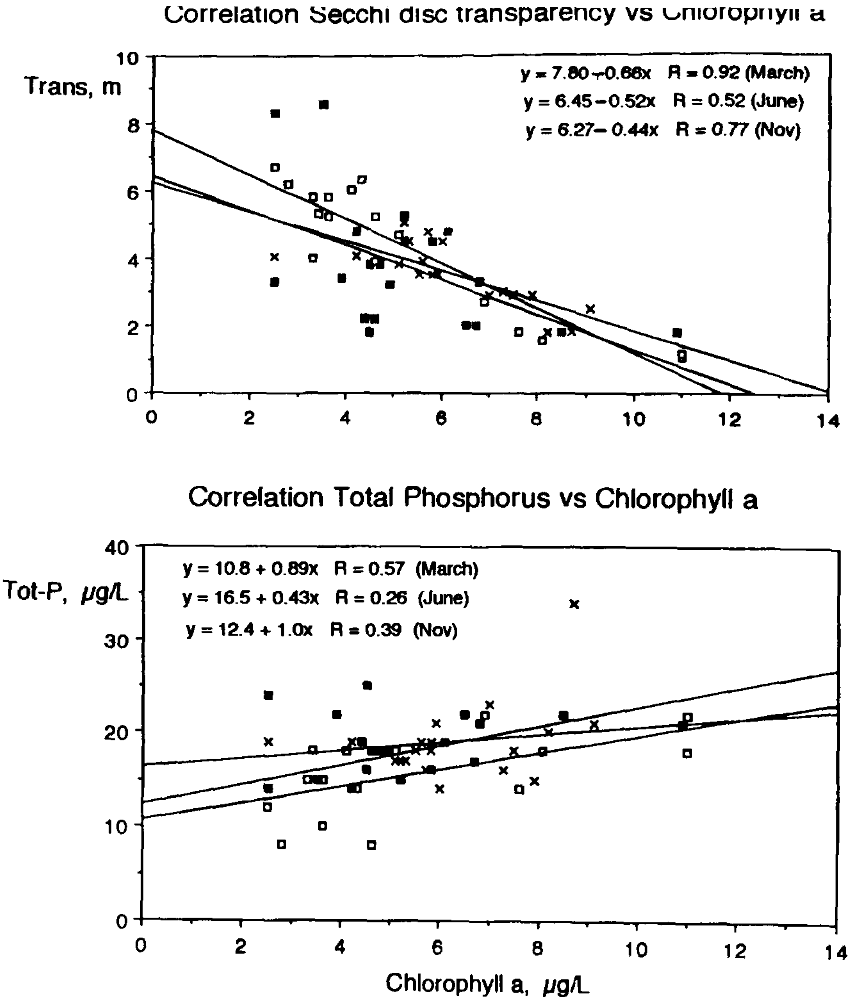


Figure 1.24 Correlation between Secchi disc transparency and chlorophyll *a* (top) and between total phosphorus and chlorophyll *a* (bottom). Values from March (□), June (■) and November (x)

A good rain season and elevated lake level could partly explain the situation. A strong year-to-year variation was also indicated. Surface water in the Binga basin was also affected by the suspended matter, although to a lesser degree (Table 1.2). Secchi disc transparency had increased to 1 m, however, still lower than in March 1986. In the Sengwa, Ume and Sanyati basins, the water was quite clear, and the values were comparable to March 1986 with a high Secchi disc transparency in the 4.5–7.5 m range. The water showed very low turbidity and nutrient levels (Table 1.2). But at a depth of 50 m in Binga basin, oxygen was depleted and H_2S was present in a "clear" water.

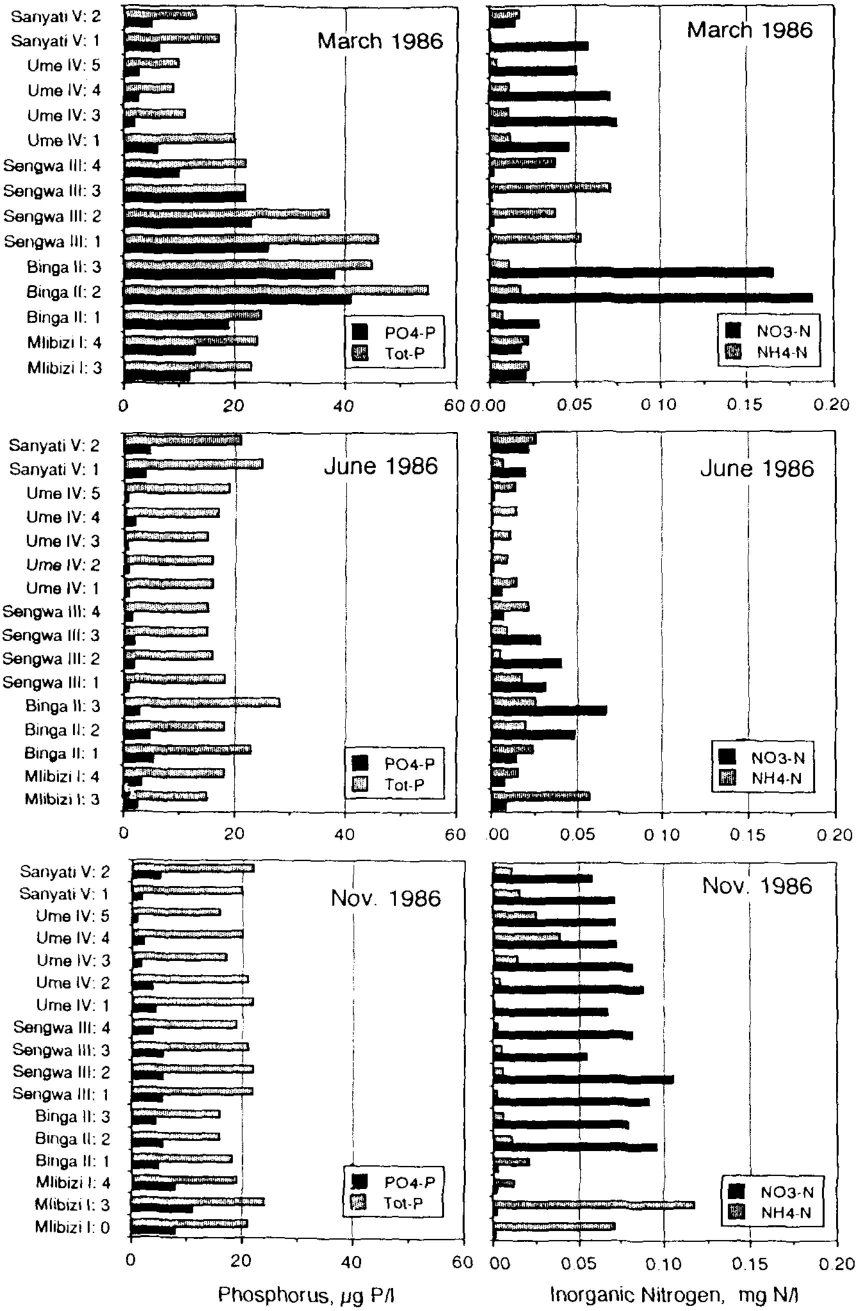


Figure 1.25 Phosphorus (left) and inorganic nitrogen (right) and concentration in water from 30 m depth at pelagic stations in March, June and November 1986

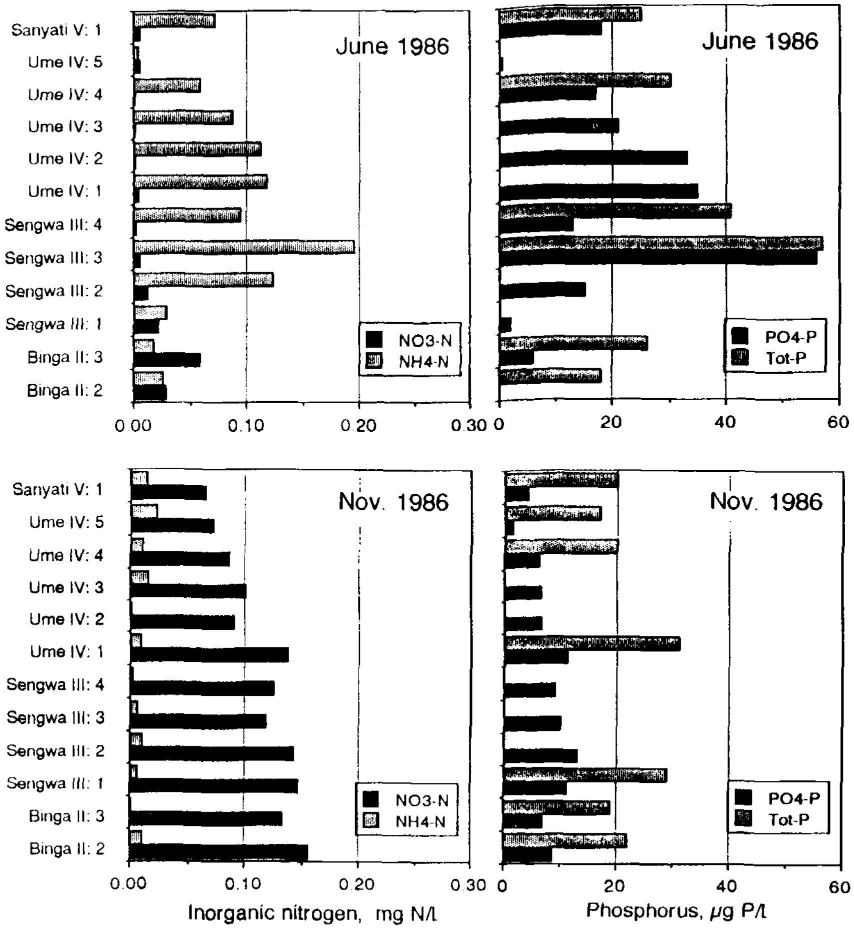


Figure 1.26 Inorganic nitrogen and phosphorus concentration in water from 50 m depth at pelagic stations in June and November 1986 (no samples in March)

In the Sengwa and Ume basin, oxygen was already depleted at 25–30 m water depth, while turbidity was very low, some 1–5 NTU. In the Sanyati basin oxygen was consumed at 20 m water depth and downward.

In the Mlibizi basin the inorganic nutrient levels were remarkably high, also in surface water (0–5 m). The concentrations of inorganic nitrogen and phosphorus were in excess for phytoplankton growth, and a limitation in light was confirmed by the low chlorophyll *a* values.

Nitrate plus ammonia (DIN) as well as phosphate (DIP) concentrations (Table 1.2) would thus represent the surplus pool of available nutrients in the water. The N/P ratios suggested that nitrogen was the primary limiting nutrient with the exception for Ume basin, once the light conditions would be improved (Table 1.2).

Table 1.2 *In situ* concentrations of chlorophyll *a*, inorganic nutrients and turbidity in March 1988

Parameter/Station	*Mlibizi I.3*	*Binga II.2*	*Sengwa III.3*	*Ume IV.4*	*Sanyati V.1*
Chl *a*, µg l^{-1}	8.8	4.3	3.6	1.2	2.6
Turbidity, NTU	120.0	23.0	1.3	2.1	1.8
DIP, µg N l^{-1}	30.0	8.0	2.5	2.7	5.3
DIN, µg N l^{-1}	165.0	63.0	12.0	33.0	8.0
DIN/DIP (w/w)	5.5	7.9	4.8	12.0	1.5

The results from the bioassays, using the natural phytoplankton community, showed a response with the expected increase in chlorophyll *a* content (Figure 1.27). The chlorophyll *a* in the control bottles increased in relation to available nitrogen. Nitrogen added to the test water further increased chlorophyll *a* concentration, whereas the addition of only phosphorus had no positive effect with the exception of a small increase in water from Ume basin.

The assays, using the test alga, *Selenastrum capricornutum*, gave another picture. The nitrogen and phosphorus available in the lake water did not stimulate algal growth for some reason. Neither nitrogen nor phosphorus had any positive impact on growth when added individually with one exception. In water from Ume basin, *Selenastrum* responded to the P addition, in conformity with an inorganic N/P ratio of 12, indicating a tendancy of phosphorus deficiency in relation to nitrogen. The combined addition of N and P stimulated the test alga and 4 of the natural communities (Figure 1.27). The better overall response from the natural phytoplankton communities was most probably influenced by a better adaptation and enhanced by a "luxury uptake" of nutrients by some algal species. For example, the chlorophyll increase in Sengwa and Binga water enriched with N exceeded by far the levels regulated by the phosphate in the water. The test alga on the other hand, was "starved" before use. Nevertheless, the assays gave some indications on nutrient supply and utilization during a period with presence of suspended silt and clay particles. Assays using the indigenous plankton community proved superior to the use of a test alga in Lago Paranoa, Brazil (Lindmark 1979). *In situ* enclosures made those experiments even more realistic, an approach not possible at the moment for the five Lake Kariba basins.

In summary, the *in situ* phytoplankton growth was severely limited by insufficient light in the water column at the time being. As far as the nutrients are concerned, there was a deficiency in nitrogen in relation to phosphorus as proved by the bioassays during the study period. However, considering the nutrient results from 1986 and the TN/TP ratios, a potential shortage in phosphorus seems more frequent than nitrogen, since the TN/TP ratios were seldom below 12. All other essential elements seemed to be in sufficient supply.

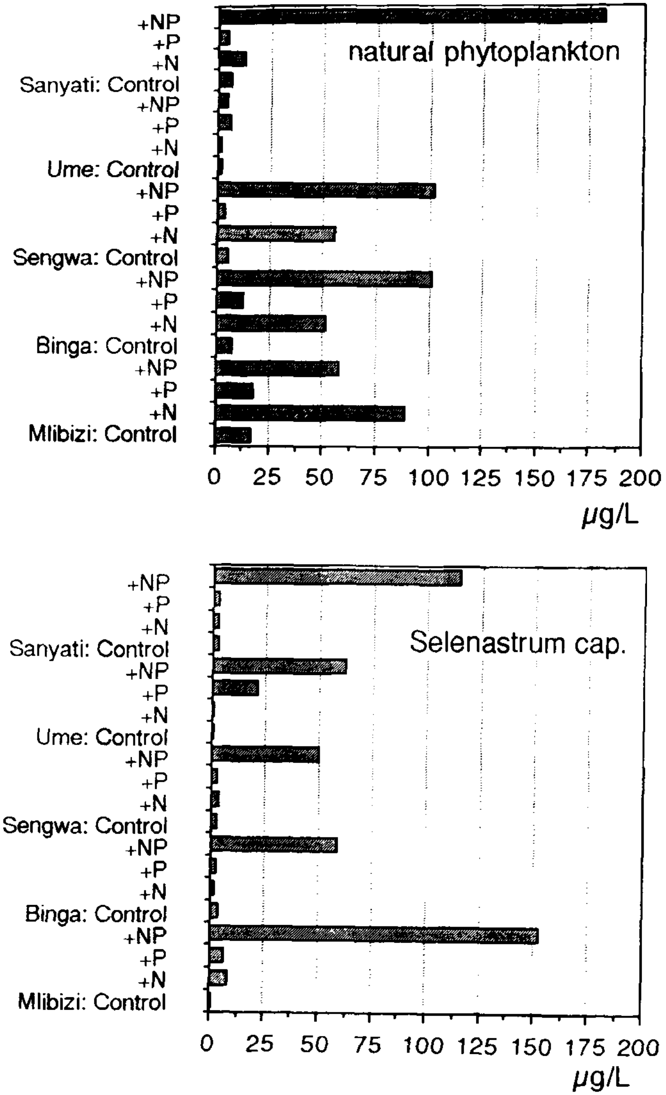


Figure 1.27 Chlorophyll *a* in bioassays with nutrient enrichment to natural phytoplankton (top) and to *Selenastrum capricornutum* (bottom), March 1988

Suspended load: characteristics and transport pattern

Indications obtained in the lake surveys and algal bioassays raised the question on the properties, the fate and value of the suspended loads and their associated nutrients imported by the large rivers, the Zambezi and the Sanyati Gorge in particular.

The period following the rainy season was the most important for the dynamics of the lake. For this reason, a horizontal and vertical survey was performed in mid-March 1989 in the Sanyati basin to follow the silt transport and to analyse what pattern of distribution and what composition the suspended load displayed in the water column. The survey covered the inlet from the Sanyati Gorge, being a major input of water, and the Nyaodza river estuary, being a dynamic but shallow tree area with less flow in terms of water input in comparison to the deep Sanyati Gorge. The water quality was then followed at 4 stations across the basin from the mouth of the Gorge to the dam.

In addition to turbidity, used as parameter for the suspended load in unfiltered and filtered water, phosphorus and nitrogen components were analysed to highlight the potential importance of the silt/clay particles and the nutrients associated to them in particular.

The results from the two inflows to the lake confirmed the differences in morphometry and behaviour (Figures 1.28A and B). The Nyaodza estuary trapped most of its suspended load locally and both turbidity and phosphorus had decreased to low values once the water entered the lake (Figures 1.28A and B). Nitrogen was less affected along the surface gradient, only the nitrate was removed and transformed. In the Gorge, on the other hand, the river water entered the bay with very high load of suspended solids (> 100 NTU) and associated phosphorus (> 150 µg P l^{-1}) (Figures 1.28A and B). The filtered fraction (GF/C) was also considerable in terms of clay particles and phosphate and nitrate. Along the water transport in the river, the large particles settled while the fine fraction stayed in suspension until the water reached the lake. Particulate phosphorus was eliminated from the surface water in connection with the sedimentation of the silt particles (Figures 1.28A and B). Nitrate and phosphate had almost disappeared from surface water at lake entrance.

Once the water entered the lake, surface water cleared and the suspended load gradually settled out (Figure 1.29). Larger silt particles sank first, while the fine clay particles, being < 4 µm (Viner 1981 and 1987) stayed in the deep water column like a "plume". The finer particles were "acccumulated" at 30 m water depth, while a large part of the silt (> 4 µm) settled when entering the Sanyati Bay (Figures 1.28 and 1.29). Turbidity was over 300 NTU at 50 m water depth at the first station (Station 1). Unfortunately the water was analysed only on unfiltered and next on GF/C-filtered water. It is therefore difficult to tell what size particles were responsible for the peak in unfiltered water at 30 m water depth at stations 2 and 4. On the other hand, the water was also filtered through membrane filters with pore size 0.45 µm and 0.2 µm. Those results showed that turbidity had decreased to values in the range of 2–5 and 0.8–1.5 NTU, respectively, giving a confirmation that a large part of the suspended clay particles actually were in the 0.45–1 µm size range.

The phosphorus and nitrogen distribution in depth was closely associated with the presence and the behaviour of the suspended matter. In particular phosphorus accompanied the deposition of silt at lake bottom at station 1 (Figure 1.29). The silt associated phosphorus was as high as 340 µg P l^{-1} at 50 m water depth. The peak at 30 m at station 2 showed that the fine clay particles were associated with more P than the silt. A close relationship between P and the surface/volume ratio of the particles was shown by Viner (1987). At the station closest to the dam the concentrations of phosphate increased in the deep water. With the exception of station 1, the total phosphorus concentration was surprisingly high in the upper 10 m.

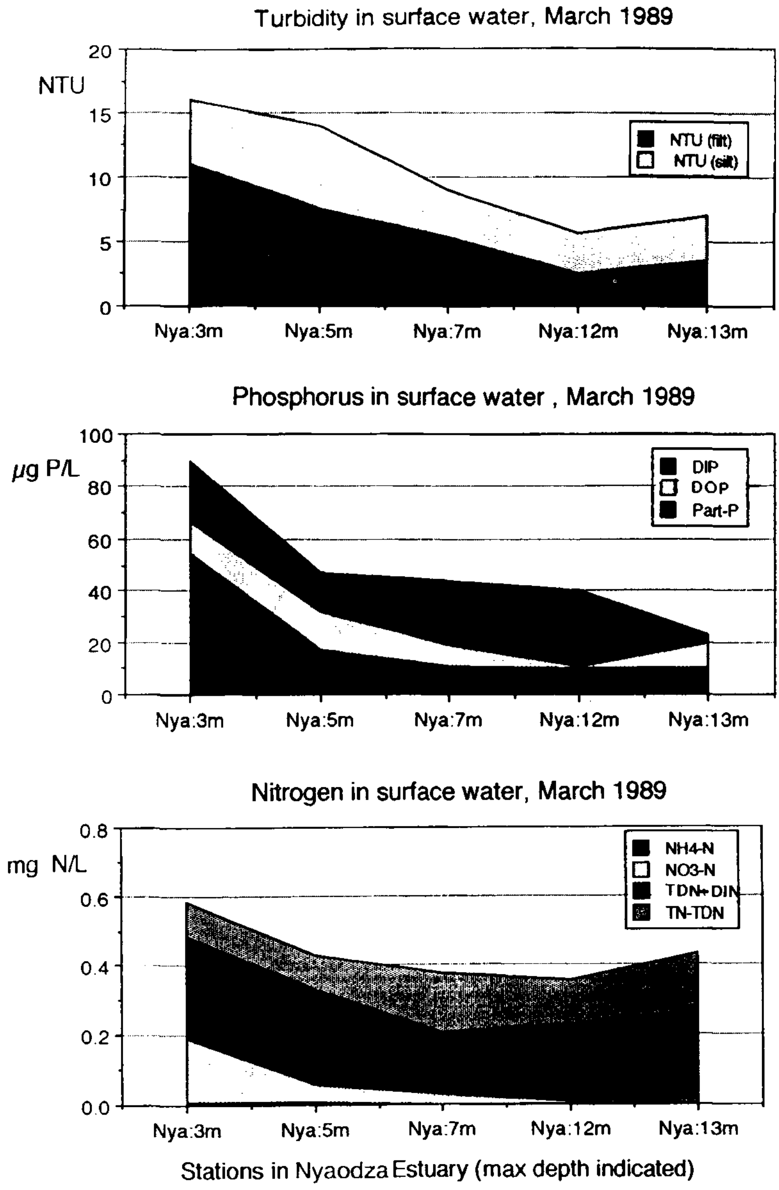


Figure 1.28A Cumulative values for turbidity (unfiltered and GF/C-filtered), phosphorus and nitrogen components and their distribution in surface water in shallow Nyaodza estuary from source (left) to mouth (right)

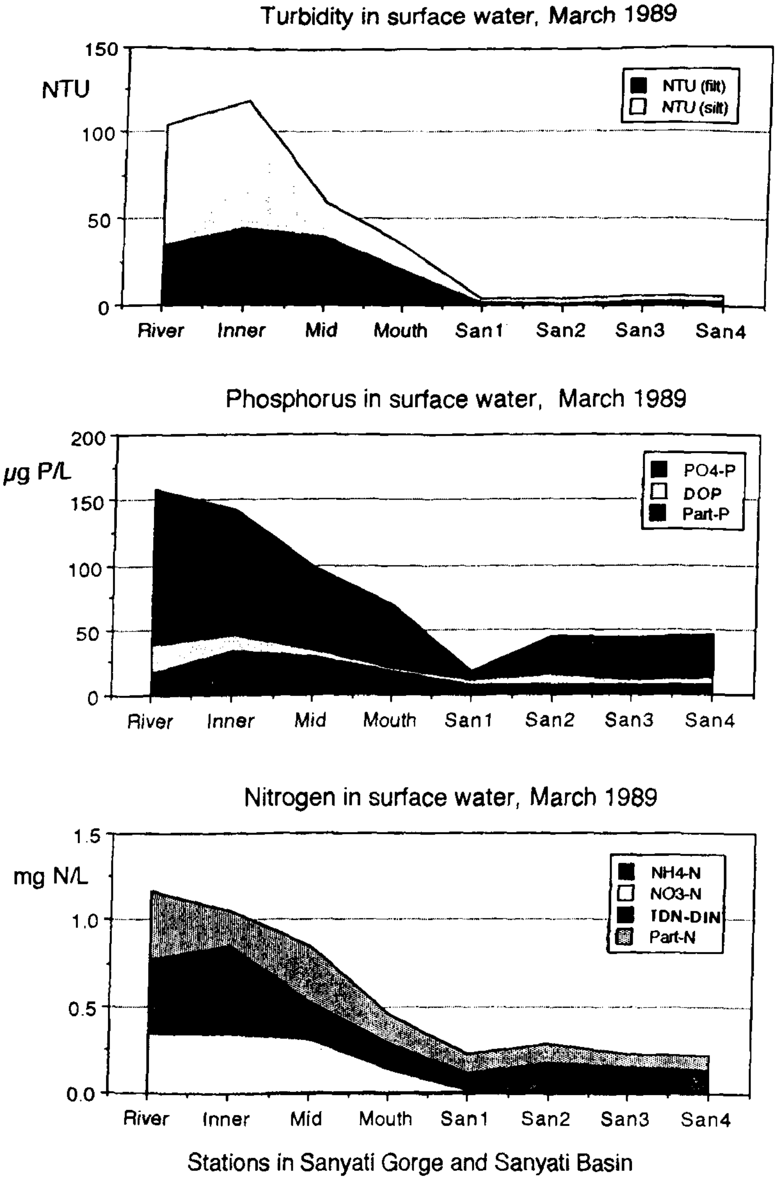


Figure 1.28B Cumulative values for turbidity (unfiltered and GF/C-filtered), phosphorus and nitrogen components and their distribution in surface water in deep Sanyati Gorge from source to mouth and across Sanyati basin to the dam. Conditions in March 1989

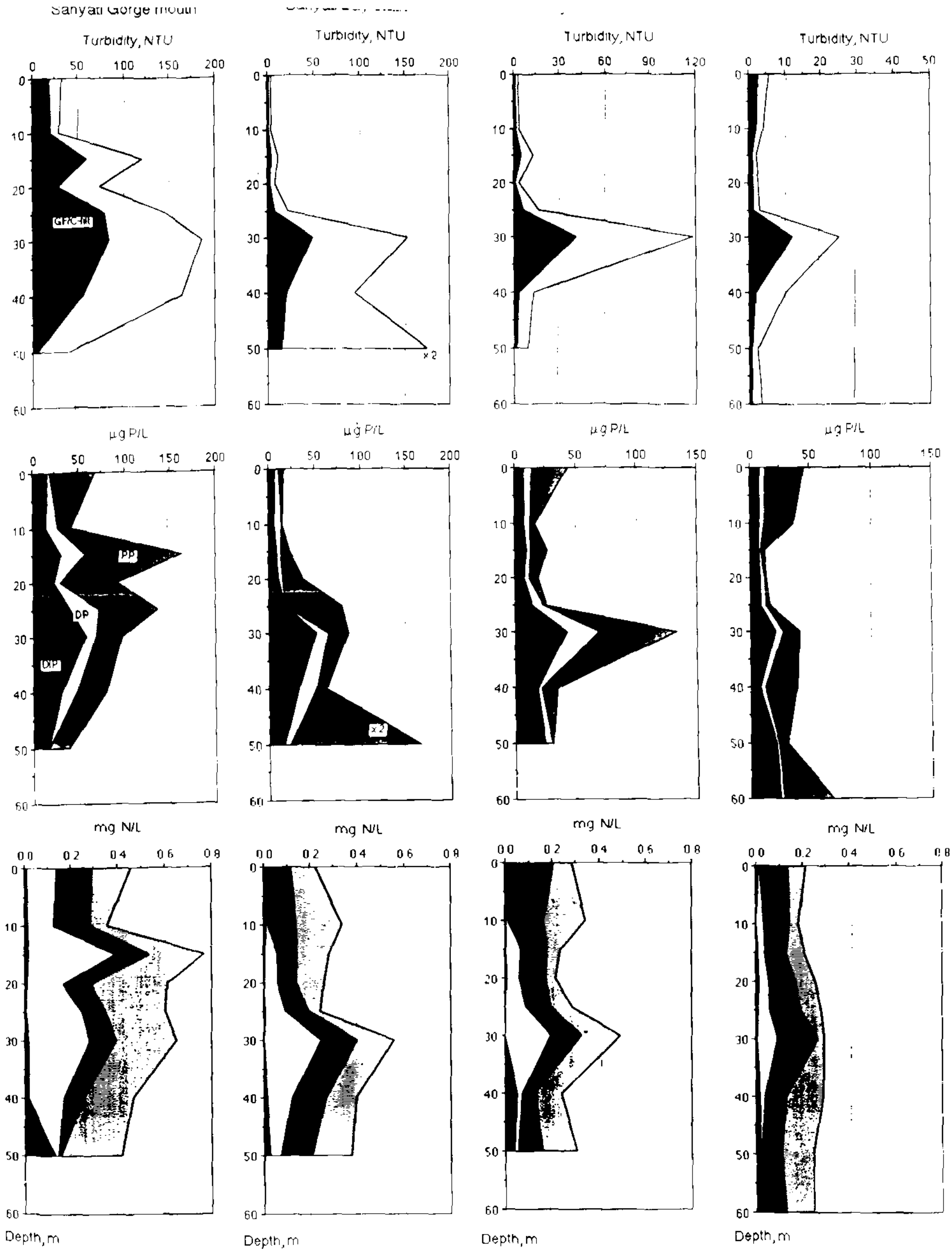


Figure 1.29 Cumulative values and concentrations in depth profiles at Sanyati Gorge mouth and at three stations across Sanyati Basin towards the dam, March 1989.

top: turbidity analysed in filtered and unfiltered samples

middle: phosphorus analysed as DIP, total dissolved P and total P,

bottom: nitrogen analysed as DIN, total dissolved N and total N.

Legends as in Figure 1.28

The large portion of nitrate transported by the river peaked at 30 m in the lake and then gradually decreased. Ammonia was low and total nitrogen was stable around 0.3 mg N l^{-1}, a value also recorded in March 1986.

The questions around the behaviour and the fate of the suspended load were thus to some extent answered, but the value of this nutrient source in terms of bioavailability remains unanswered and is still under debate (Golterman 1988). Next question will be whether the source could physically be utilized in the lake by the lake flora or whether it will be lost via the Dam outlet or maybe deposited on lake bottom. Man-made lakes are often considered as sedimentation tanks for various loads of solids from upstream watersheds, which sometimes also are loaded with heavy metals and toxicants, creating problems during deoxygenated periods (Adeniji *et al.* 1981).

DISCUSSION

In the warm monomictic Lake Kariba full water circulation occurs in mid-July in the lower basins, and somewhat earlier in the upper basins (Mlibizi and Binga) which are less stable in terms of temperature stratification. They are strongly influenced by Zambezi River, its flows and properties, as shown by data on temperature, oxygen, turbidity and conductivity etc including those of Balon and Coche (1974).

The annual water budget for the lake given by Balon and Coche (1974) indicates that 93% originates from the rivers (77% from Zambezi River and 14% from secondary rivers and flooded grassland), while direct rainfall on the lake contributes with 7%. The evaporation accounts for 14% and the outflow through the dam amounts to about 86%. The theoretical water retention time is three years and the water level fluctuates with a yearly amplitude of about 3 m.

Considering our limited occasions for sampling and our selection of stations and timing in the project (1984–89), the results are well supporting those results obtained in the intensive study period of 1965–69 (Balon and Coche 1974). In fact, regimes and values for temperature, oxygen, Secchi disc readings and conductivity have only slightly changed during the past 20 years. The conductivity values were somewhat higher in this study. Long-term natural droughts in the eighties and thus an operating lake level of 7 m below normal level could be an explanation.

Taking these events and results into consideration our choice of sampling periods seemed justified and accurate to obtain the aimed overall picture of lake components and behaviour. However, several additional and interesting aspects turned up during the project and were partly studied, i.e the nutrient bioavailability through algal assays and the silt transport and properties.

Comments directly related to the results have been presented under the result section and will thus not be repeated here. Only a few additional points will be discussed and evaluated in a summarizing perspective.

The characterization and analysis of the sediments along the lake shore gave a clear indication that exposed shores and shallow waters were very nutrient poor and consisted of sandy and gravelly sediment.

However, three main types of littoral habitats could be distinguished:

- the exposed erosion shore, often steep and with a minimum of bottom vegetation and a gravel/sand sediment among rocks.
- the sheltered bays and secondary river estuaries with inundated tree areas and dense macrophyte beds colonizing the nutrient-rich sediment with comparably high organic content and
- the very shallow grass and woodland, frequently affected also by minor water level changes, mostly covered by dense beds of plants firmly attached to a consolidated sediment.

The colonized sites were favoured by the low N/P ratio in the sediment and plant advantage to utilize sediment phosphorus. Mostly sediments serve as sinks for silt and associated nutrients, but they can also serve a dual role as sink and source as shown in sediment experiments. Game activity also induced re-suspensions of the fine clay and exposed nutrients to primary producers of different species. The results indicated further a strong controlling role by the community to trap the sediment suspensions and to utilize available nutrients within the littoral habitats. Once the water reached the outskirts of the bays and rivers, the nutrient levels were decreased considerably. Only dilute nutrient-depleted water was exported to offshore areas.

As a consequence of the low nutrient concentrations in the outskirts of the bays and rivers, the pelagic water body was mainly enriched by nutrients associated to the silt and organics entering the lake by inputs from the main rivers; the Zambezi River entering the upper basins and the Sanyati Gorge entering the lowest basin. The importance in terms of fertility of river transported silt has been known for a long time. However, such fertility transferred to an aquatic ecosystem is a loss from the terrestrial ecosystem. Heavy soil erosion with material transfer from land to water is, common in the tropical latitudes and is an overall economic loss (Viner 1987).

The period following the rainy season seemed to be the most dramatic and dynamic to the lake. Although the input of suspended load was considerable, the concentrations of nutrients in lake water were not dramatically high. At pelagic stations, total phosphorus was in the 10–30 $\mu g\ P\ l^{-1}$ range. Total nitrogen was in the 0.2–0.4 $mg\ N\ l^{-1}$ range, giving a TN/TP ratio in the interval 10–30 (by weight). The chlorophyll values were in the same range as in Lake Victoria (Talling and Talling 1965), and in relation to N and P concentrations. A horizontal rapid decline in nutrient concentrations down the lake confirmed that littoral areas efficiently controlled local nutrient inputs.

At times of insufficient light in the euphotic zone, the primary producers consumed excess of nutrients as a "luxury uptake", aimed for growth when light conditions improved. This was shown in the bioassays when the natural community was used. The TN/TP ratios in the water gave no clear answer regarding growth regulating and limiting elements.

Results from the lake surveys and algal bioassays proved the importance of investigating the value and the fate of the suspended loads and associated nutrients entering the lake. The value in terms of bioavailability of this source of nutrients is not clear-cut but remains puzzling although frequently discussed (Golterman 1988). Additional bioassays using natural communities could give some hints (Viner *et al.* 1981) as well as a more detailed analysis of composition and extractable nutrients. Another question will be what amount of silt would be deposited on lake bottom and where. Deoxygenated periods could stimulate an internal recycling not only of nutrients but also of potential accumulations of heavy metals and other toxic substances, creating future problems. A third possibility would be a loss of the silt downstream via the outlet in the dam and maybe a return transfer to a terrestrial ecosystem.

The questions around the silt behaviour, its value and distribution in the lake, are really important and open up for additional investigations. Man-made lakes have a tendency to gradually fill up since they are acting as sedimentation tanks, and due to these short-term but massive transports of upstream eroded material lake storage capacity can rapidly be reduced. For Lake Kariba the question is to find out what amount will be utilized by the lake biota, what amount will be accumulated on lake bottom and what amount will be transferred downstream via the outflow of the dam and returned to the Zambezi River.

CONCLUSION

Lake Kariba water is strongly influenced by river import of suspended solids and oxygenated water entering the lake via its two large rivers. Nutrients associated with the fine silt/clay particles are transported up the lake as sedimentation takes place. The fine clay load moves like a "plume" below lake surface and the euphotic zone clarifies and growth conditions improve. The downstream middle basins, Sengwa and Ume, are less affected by the suspended load; they show less fluctuations and lower nutrient level.

Regarding sediment influence, only river beds, estuaries and sheltered bays with trees hold sufficient organic matter and fine silt material, rich in nitrogen and phosphorus, to support vegetation. Once the water reaches the outskirts of the bays and rivers, the nutrient levels are considerably decreased, indicating an efficient internal utilization and recycling of nutrients.

The pelagic water body is thus mainly fed and refilled with nutrients via the silt and organic matter imported by the main rivers. At times with high water turbidity and insufficient light, the primary producers consume excess nutrients as a "luxury uptake" for future growth when conditions improve.

The most interesting question which is open for further investigations is what is the behaviour and the fate of the imported suspended solids. Since man-made lakes have a tendency to act as sedimentation tanks which gradually reduce their storage capacity, those situations must be clarified. These answers are needed to evaluate the nutrient capture and deposition pattern, since a present deposition may also include heavy metals and potential toxicants, which may return to water column at a later date and excert problems (Berg *et al.* 1995).

SUMMARY

Sediment and water chemistry was studied in Lake Kariba during 1984–89. Sediment composition and properties were analysed to evaluate the influence of biotic and non-biotic factors in the nutrient flux in littoral areas which was also related to nutrient levels, distribution and utilization in pelagic water. Nutrients entering littoral habitats were trapped in the sediment and utilized locally to

support dense macrophyte beds and benthic algae. Nutrient poor water was exported to offshore areas. The pelagic water body was supported by nutrients associated to the suspended solids imported by the two large rivers. Algal uptake and sedimentation "competed" for nutrients in the turbid water in the basins next to the rivers. Plumes of silt/clay particles were moving deeper into the water column while transported down the lake. The fate and value of the suspended load in terms of bioavailability and deposition remains to be further investigated.

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