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# Hydrobiological Studies of the Okavango Delta and Kwando/Linyanti/Chobe River, Botswana
## I Surface Water Quality Analysis

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### Abstract

The surface water quality of the Okavango Delta has been investigated since 1989 in a programme under the auspices of the Botswana Department of Water Affairs. These studies have mainly focused on the central section of the Delta, the Jao/Boro River with associated swamp and floodplain areas. The chemical composition of water flowing out of the Delta is different in many respects from its initial composition in the Okavango River. There is a gradient of increasing concentration towards the outlet in all chemical constituents of the main channels while spatial and temporal variations in the swamp areas are more complex, reflecting the great heterogeneity of habitats within the swamps. While evaporation contributes to concentration of all solutes, part of the changes can be attributed to biological processes. These transformations which are more clearly defined for N, P, and C components, are related to specific physical attributes of the sampled sites, such as vegetation cover and extent of flooding. Whilst a seasonal pattern in variation of water chemistry is apparent, the data suggest that modifying effects of the swamps on water chemistry are limited. River channels are mainly oligotrophic habitats. Swamps and floodplains vary between oligotrophic and mesotrophic, and isolated water bodies and outlet areas are clearly mesotrophic to eutrophic. The data further suggest differential removal of solutes and a net ion accumulation in the system during the study period. In general, channel waters, which flow considerably faster than the swamp waters, are poor in most solutes and trace elements, and moderately richer in silica, dissolved organic carbon, and organic nitrogen. Waters of the Delta's outflow at Maun are of poor quality, turbid, and affected by anthropogenic inputs. Total bacterial counts in the surface waters were in the range 0.07 to 3.89 x $10^9$ cells/l. Overall, phytoplankton concentrations were low in river channels and only a few algal groups were recorded in this habitat. By contrast, phytoplankton communities were well developed in swamp areas and isolated water bodies. Preliminary identification of the dominant zooplankton taxa showed that river channels in the upper Delta were almost devoid of zooplankton while high densities were found in terminal areas of the



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Delta. A preliminary investigation of water chemistry and microbiota of the Kwando-Linyanti-Chobe River suggest that these waters are slightly more acidic, and contain higher sulphate concentrations than the Okavango River.

## Introduction

Increasing demands of human expansion and resources exploitation, aggravated by prolonged droughts in the dry belt regions of Africa, will have ecological consequences in many ecosystems. In Botswana, and in the region as a whole, water requirements will rise in the foreseeable future, and this will necessarily increase the pressure on the few sustainable water resources across the region. The Okavango Delta and the Kwando/Linyanti/Chobe River system (hereinafter referred to as the "Linyanti") are the country's major perennial surface water sources (Fig 1). Because of their rich diversity of habitats and fauna, they belong to the world's most important wetland ecosystems. Due to its remoteness and the presence of tsetse fly (*Glossina morsitans*), the Linyanti has, fortunately perhaps, been overshadowed by the internationally better known Okavango Delta. Since historic times both systems have sustained human populations for whom the generation of income from utilisation of these systems is essential for their livelihood and continued existence. These systems are unique, not so much because they are complex (all ecosystems are, depending on scales of observation) but rather because they are still in a relatively undisturbed state. This creates an opportunity to define reference levels of various environmental variables in relation to future changes.

Over the past decades much effort has been invested in studying the hydrology and geomorphology of the Delta in an attempt to predict surface water outflows (for references on the Okavango, see UNDP/FAO, 1977, Dinçer *et al*, 1978, 1987, SMEC 1987, 1989, Shaw, 1988, Shaw and Thomas, 1992, McCarthy, 1992, IUCN, 1992). Much effort has also been directed to mapping of vegetative cover and soils in order to delineate areas of particular ecological value or risk of degradation. Considerably less is known of the Delta's ecology, hydrogeology, or hydrobiology. Information on the Linyanti is scarce. Apart from studies in the late 1970s on the limnology of Lake Liambezi (Seaman *et al*, 1978), which has been dry ever since, and sporadic monitoring exercises on water levels and quality in conjunction with the aquatic weeds control programme, little is known on the hydrology or hydrobiology of the Linyanti.

Since the late 1980s a monitoring programme on surface water quality has been carried out by the Botswana Department of Water Affairs (DWA) in collaboration with workers from the University of Botswana and Lund University, Sweden. The programme mainly focused on the central corridor of the Delta, the Jao/Boro River and adjacent swamp areas. From a water management point of view, this system is the most relevant outlet at present and its study would allow the assessment of chemical changes in water flowing through the Delta. In addition to these natural processes, a variety of human activities may have an impact on downstream areas (eg, along the Thamalakane and Boteti Rivers) and groundwaters.

It is generally perceived that use of water for households and small scale agriculture by communities in the Panhandle, the Delta, and along the fringes of the Linyanti, would have little impact on water quality. Possible effects would mainly arise from large scale water abstraction, transfer and mixing of waters of different hydrobiological composition, or return of waters enriched in agrochemicals or nutrients from commercial farming activities. In the first case, it

is believed that water abstraction, apart from reduction of the flooded areas, and outflows, would not have noticeable effects on water quality. This may not be the case, because wetland functions are almost exclusively regulated by microbiota and flowing water is of importance in providing microbial access to dissolved organic matter and nutrients, which will be transformed, stored, and exported. Moreover, processes leading to soil desiccation would occur in some areas as well as increased surficial salt accumulation. With respect to transfer of water, possible impacts would be related to changes of salinity, transfer of organisms leading to shifts in algal, invertebrate, or fish populations, or increase in the transmission of waterborne parasitic diseases. As concerns the third aspect, ie, the introduction of exogeneous chemicals or high nutrient loads, the negative impact of insecticides on biota is well known whereas the capacity of the systems to retain or export nutrients depends upon a variety of factors. It is not possible therefore, to generalise from examples available in the literature to the Okavango or Linyanti. However, the study of nutrient dynamics over several years and comparison with studies in similar wetland systems, may provide some indication of possible effects.

Less frequently recognised are impacts resulting from increasing use of boats and vehicles in the Delta. Both study areas lie in areas of medium soil degradation and wind erosion severity (UNEP, 1992). Physical effects like soil erosion or destruction of submerged aquatics are probably easy to detect. Discrete or diffuse chemical inputs, such as release of fuel by outboard engines, soluble gaseous hydrocarbons, or fuel additives (eg, tetraethyl lead) will necessarily affect water quality, but it is difficult in many instances to demonstrate causal relationships. It can be argued though, that high water temperatures would be conducive to a rapid loss of volatile organics from surface water. These compounds, however, may induce formation of microbial biofilms, complex to humics, or absorb onto suspended particles and that might explain why floating oily patches were observed in nearly all surveys.

Although some of the work has been published elsewhere, it was felt opportune to attempt to synthesise the available information on water chemistry and microbiota. The specific objectives were to describe the natural variation of the water quality in the Delta and thus outline a preliminary working scheme, based on which simple conceptual and hydrochemical models can be developed.

Given the great heterogeneity of the study areas and the different time scales on which ecological processes operate, it is noted that neither the temporal nor the spatial scales used in this study are satisfactory. For example, the residence time of the waters of the Jao/Boro system can be estimated as 7 years. In addition, drought cycles in the region recur approximately every decade. This means that a sampling series with a period of at least twenty years would ideally be required to detect average conditions or long-term trends. It would, however, have been extremely costly to have increased the resolution or frequency of the observations. The small fraction reported here may or may not be representative of key hydrobiological processes and therefore this record cannot easily be extended to other hydrological conditions. The above constraints notwithstanding, it is believed that an understanding of cause-effects relationships is a prerequisite for good management and that major processes influencing surface water chemistry can be outlined from the available data. Moreover, suggestions for supplementary studies can be made.

While the analysis in this report is centred on observed variables, it is acknowledged that latent, unobservable, or simply unavailable information (eg, aperiodic events such as fires and storms, or impacts on biogeochemical cycles brought about by animals) are likely to play equally

important roles in the interpretation of factors affecting water quality. Reporting of the data was organised along geographical criteria. One set of data considers the Jao/Boro system including observations from Seronga (Fig 1), in the Okavango River, upper Jao, upper Ngoqa, to the lower Boro at its junction with the Thamalakane. These data also include observations at Xakanaxa *lediba* (lagoon), Maxegane pools, and Khwai outflow at Bodiyo (North gate). A second set of data includes the Linyanti along the Botswana margin of the river from upstream of James Camp in the Kwando to Kasane in the Chobe River, as studied on two occasions. In addition, this report includes data on microbiota of Lake Ngami as studied on one occasion after the lake had received some freshwater inflow from the Delta.

## Study Areas and Sample Collection

### The Jao/Boro River system

Water samples were collected along the Jao/Boro River from a network of 67 to 77 sites, located in 10 transects across the main channel (Fig 2b). Flooding zonation and flood progression in the Delta are illustrated in Figures 2a and 3 respectively. Transect locations, co-ordinates, and major habitat features are given in Table 1. Water samples were collected at or below the surface (0.1-0.2 m). In locations with sufficient water depth, eg, in some lagoons and in the Okavango and Ngoqa Rivers, vertical profiles were also obtained. Specific conduction, water temperature, dissolved oxygen content and pH were measured *in situ*. Phyto-, zooplankton, and bacterial numbers were determined using standard limnological and microbiological techniques. Details of sampling, sample preservation, and analytical methods are given in Sawula *et al* (1992) and Cronberg *et al* (1995). Pore water was obtained from three sets of 9 mini-piezometers installed about 0.3 and 0.5-0.7m below the river bed. They were placed at three locations in the upper Delta in the edge of the papyrus mat: a channel near Tichira *lediba* (mostly coarse sand substratum), Moshupatsila (coarse sand with small amounts of silt), and at Jao cross-link inflow near Khwihum (sand, silt, and traces of clay). The piezometers consisted of 50 ml conical glass collectors with a sintered glass filter at the base of the collector connected to PVC tubing. The samples were obtained by suction with a syringe. Pooled samples from each site and depth were used for chemical analysis. A few seepage rate measurements at locations in the lower Boro and Tichira were also made using a technique described by Isiorho (1987). The seepage metres were placed on river beds at depths of about 0.5 to 1.0 m below the water surface.

### The Kwando/Linyanti/Chobe River

Ten surface water samples were collected on two occasions along the Kwando and Linyanti Rivers, 20 km upstream of James camp to Shaile, during October and November 1992 (Fig 4). In addition, fifteen samples were collected in each of two occasions (March and November 1992) at Ngoma bridge and in locations along the Chobe River from Chobe Game Lodge to Kasane. Shaded areas in the figure correspond to areas with various depths of flooding. Both the Makwegana and Savuti channels were dry at the time of the surveys. In addition, the course of the main channel between Horseshoe Bend and James camp had been altered due to blockage by vegetation and anastomosis. Sampling and analytical protocols were as for the Okavango Delta.

## Results and Discussion

### The Jao/Boro River system

*Temporal and spatial variability of physicochemical variables in surface waters*

The Okavango Delta exhibits a variety of landscapes and habitats, and has commonly been characterised as a mosaic-type pattern wetland, with changing aquatic, semi-aquatic, and terrestrial habitats in a range of temporal scales. This pattern, which is influenced by climate, geology and hydrology, adds to the problems of analysing the system's environmental data. Large spatial heterogeneity and temporal fluctuations of surface inflow and precipitation, result in high variability in most environmental factors. Table 2 shows the available data, sampling date, and type of sampled locations. Approximately half the number of samples was obtained in the Panhandle and perennial swamps and the remainder in seasonal swamp areas. All major physico-chemical constituents exhibited a wide range of values (Table 3), spanning over four orders of magnitude in a few variables. The coefficients of variation (CV) varied between 5.7% (pH) to over 300% for chlorophyll *a* concentration. The exceptionally high CV of turbidity resulted from a few large values: omitting these outliers reduced the CV to about 135%. In general, solutes which are controlled by physical and chemical processes such as chloride or base cations, exhibited a CV between 55 to 85% while solutes controlled by biological processes, had a CV between 100 and 210%. The probability distribution of the data is typically positively skewed: more than half of the data fall below the mean value for most variables. Consequently arithmetic means are not the most suitable parametres with which to describe the characteristics of such data. Median values and frequency distributions are probably better measures of the water chemistry.

With the spatial scale of this study, each sampling point was assumed to be representative of an area of approximately 35 $km^2$. This low resolution resulted in most locations having a variety of sub-environments. At this scale, only a few sites could be considered to represent a homogeneous space unit (or ecotone in the designation of Risser, 1990) such as some areas within the papyrus swamps or in the seasonally flooded grassland. The chemical water characteristics were therefore the end result of an array of processes, some linked to the particular environment, but all influenced by hydrological conditions at the specific locations.

The data were divided into large spatial units, each including a variety of habitats. Thus river channels and swamps constituted two such units (habitats 1 and 2, respectively) while separation into perennial and seasonal swamps (habitats 3 and 4, respectively) provided additional categories. The four habitats overlap and intercept each other to a certain extent, of course, and a sharp distinction cannot be made between them. For example, river channels in the upper Delta have different characteristics from channels in seasonal swamp areas. While the former are largely bordered by pervasive reed or papyrus stands and elevated above surrounding areas, the latter are incised channels in some reaches. A further example would be that some areas in the periphery of the perennial swamps have a vegetation cover similar to that of the seasonal swamp areas, but those areas were nevertheless included in the perennial swamp habitat type. Despite these limitations, the subdivision into four major habitats has been used here in an attempt to explain the chemical modification of swamp and channel waters.

Estimated average concentrations of major physico-chemical variables by habitat type are shown in Table 4. Differences in water composition between habitats were tested using a

median test for 27 variables (Table 5). For this exercise, the data were aggregated in two groups: group 1 compares habitats 1 and 2, and group 2, habitats 3 and 4. The test identified major differences in water chemistry between the two groups. For example, while it is apparent that there was no difference in median values of total N (TN) or total P (TP) between rivers and swamp areas, there was a significant difference in distribution of these variables in perennial and seasonal swamps. A further example would be the alkalinity (as bicarbonate), where little difference occurred whether the samples were obtained from the river channel or from swamp areas, but where significant differences were found between perennial and seasonal swamps. Conversely, the distribution of $SiO_2$ or $SO_4^{2-}$ was practically independent of the habitat type. The data indicate, therefore, that river chemistry was coupled with processes in the swamps and floodplains, while most of the chemical differences within the system could be attributed to differences between the perennial and seasonal swamp areas.

Temporal variations are shown in Fig 5 in box plots, each representing the data between the first and third quartiles, bisected by a line at the value of the median. The figure shows a clear seasonal pattern, associated with annual inflow to the Delta, despite the gaps in the data. The variance of the data depends on a number of factors. While surface water temperature is obviously coupled with the climatological cycle, other variables such as TN or turbidity are strongly associated with flowing water, whereas others, eg, chlorophyll *a* concentration, are weakly dependent on season.

The seasonal variability of composition seems to reveal both the behaviour of the entire system as well as differences in factors regulating water chemistry. Although there appears a concordant seasonal variation in chemical composition during the surveys, some differences were clearly there. For example, the concentration of $SiO_2$ (excluding the April 1990 survey which was based on only a few values) seemed to be fairly constant despite a slight dilution at high water levels. This may suggest regulating mechanisms for silicon of either chemical or biochemical origin, through precipitation-dissolution cycles and/or microbial and algal uptake processes. Likewise, algal biomass, whether it was expressed as freshweight/volume or chlorophyll *a* concentration, seemed more strongly dependent on the habitat type than on the date of surveying (Tables 4 and 5). All outliers in the normal distribution of chlorophyll *a* concentration corresponded to values observed in sites with stagnant or semi-stagnant water which suggest that physical factors, such as water flow velocity may play a greater role in controlling algal abundance than, for example, light or nutrient availability.

A pattern of change of major abiotic variables over a seasonal cycle can be obtained through normalization, interpolation and smoothing of available data (Fig 6). To normalize the data the ratio was taken of the observed values to the mean value at Sepopa/Seronga. It should be noted that the figure represents the variation observed in a rather crude spatial scale obtained by roughly dissecting the Delta into two halves (at site Xo-9), corresponding to the perennial and seasonal swamps. Higher resolution to take into account the variation in individual sites would result in small differences in the chemical component behaviour (see below), without changing the general pattern. Although the figure is only intended as a qualitative illustration of the seasonal variability of the whole system, it nevertheless shows important differences in behaviour of nutrient concentrations.

The distribution of major abiotic variables across the study area is shown in Fig 7. The numbers 1 to 12 on the vertical axis represent the transects across the Jao/Boro River (Table 1, Fig 2a). The figure shows the values of selected physico-chemical variables observed along the

Jao/Boro River and their range in the swamp areas. The perennial swamps, which roughly correspond to transects 1 to 4, are indicated as shaded fields, while seasonal swamp areas are shown as lightly shaded areas. The hydrograph at Mohembo and the total discharge in the six months preceding the date of sampling are shown in the top row of Fig 7, to illustrate the influence of hydrology on the distribution of the physico-chemical variables,. The second row in the figure shows the distribution of $\delta^{18}O$ (°/$_{oo}$ SMOW) and the approximate hydrological status at the time of sampling. Enrichment of $\delta^{18}O$ in surface water can provide an indication of total evaporation and transport efficiency of the various distributary systems within the Delta. Inflow $\delta^{18}O$ values at Mohembo-Shakawe in the Okavango River range from -4.9 to -3.9 °/$_{oo}$, with a typical value of -4.0 °/$_{oo}$ (Dinçer *et al*, 1978), while the range observed at Duba Island, in the study period, was -3.36 to -2.45 °/$_{oo}$. This indicates that significant evaporative losses are already taking place as the flood waters move down the upper Delta. With few exceptions, less enrichment was found in waters of the Jao/Boro River than in swamp waters. The same trend also appeared in the distribution of total ionic content, as characterized by specific conductance.

As noted above, the concentrations of all chemical constituents showed considerable variation along transversal gradients, but less along the main axis of the Delta. This general pattern was affected by the amount of inflow water. Particulate fractions of N and P constituted approximately 85 and 76% of the total amount of N and P components, respectively. The concentration of this fraction increased at the onset of flooding (Fig 6) to decrease as the flood progressed, partly by loss from deposition and partly by dilution. Total N concentration (mostly in reduced form as organic nitrogen) increased in the expanding flow phase, both in the perennial and seasonal swamp areas, and decreased subsequently at high water, to increase again in the stagnation period. Nitrate and ammonium showed similar increase in the expanding phase but concentrations were observed to reach a maximum prior to the high water stage and then to decrease by dilution as the Delta attained its highest water level. The nitrate concentration almost doubled as compared to that in the stagnation period while ammonium concentrations increased only slightly.

There were, however, differences in the pattern of nitrate and ammonium concentrations in specific locations in the seasonal swamps and in locations at the northeastern end of the Duba Island and Madinare transects. In general, sites which had lost all water during the drawdown period, for example the outer edges of transects downstream of Xo flats, showed higher nitrate concentrations upon return of new flood waters than those in locations which had remained inundated during the low water period. The former locations appear to be in microtopographic highs, sufficiently elevated to promote nitrification, whereas the latter sites maintained anaerobic conditions under which denitrification processes prevailed. Higher ammonium and lower nitrate concentrations therefore prevailed in these sites.

Total P concentration was practically unchanged in the perennial swamps but attained its highest level in the stagnation period in the lower Delta and then decreased by dilution with flood waters. Lower concentration gradients were observed for $SiO_2$. Dissolved oxygen values were more erratically distributed during base flow or stagnation period. At high water, oxygen saturation in the river channels was 80-120% but much lower values were observed in the swamp areas. The new flood waters, which were normally well aerated and more oxygenated than the residual waters, also removed organic matter trapped in the reed swamps. This organic load in renewed suspension resulted in increasing oxygen demand, further depressing the concentration of dissolved oxygen in the swamp waters. In the receding phase and stagnation

period, daytime dissolved oxygen concentration was usually below saturation in seasonal swamp areas and in the river channel at the Delta outlet. Dissolved oxygen concentration could, however, attain values well above saturation in some densely vegetated sites within the swamps and in water below floating vegetation cover. Like oxygen, suspended sediments also showed erratic distributions. In general, lower turbidity was observed in river channel than in swamp areas. High values were consistently observed at Boro junction probably due to mixing with the more turbid waters of the Thamalakane River.

It appears from the distribution of SC or $Cl^-$, and to a lesser degree $HCO_3^-$ (Fig 7) that waters in swamp areas located between transects 4 and 5 (which correspond to the transition between perennial and seasonal swamps), showed a higher degree of horizontal mixing than that in other transects. Salt content in Jao/Boro River waters at Xo-site-9/Xo flats was often lower or the same as that in upstream locations of the channel which suggests that fresher water was transported more rapidly through the Xo-flats than through the Jao/Boro River. This is illustrated in Fig 8 which shows contour plots for specific conductance, chloride and $\delta^{18}O$ at high water (July 1992). Lower water transfer seemed to occur in areas between the main channel and Chief's Island and in the seasonal swamps.

The scale-dependent physico-chemical pattern can be summarized in a diagram as illustrated in Fig 9. Total variability, ie, temporal plus spatial variability, was estimated from the frequency distribution of all measurements while temporal variability was evaluated from the frequency distribution in four surveys (November 1991 to October 1992). The latter measure was estimated as the difference between the 75% percentile of the observations corresponding to largest and lowest median values, divided by the mean value of the medians. In terms of the 18 physico-chemical variables, considered in the analysis, turbidity exhibited far greater temporal variability while the pH showed little spatial or temporal variation. As anticipated, chlorophyll *a* concentration exhibited the largest spatial variability. Algal abundance was strongly dependent on the habitat type: river channels were practically devoid of algae while stagnant waters exhibited up to 45 mg/l as freshweight algal biomass. Among the nutrients, total variability in nitrate- and ammonium-N concentrations was high, with a strong spatial contribution. These components, as well as $SO_4^{2-}$, are controlled by biochemical and redox reactions and their concentrations are thus strongly dependent on water depth and flooding stage.

*Relationship of solutes with discharge*

The influence of Delta inflow on the variables is illustrated in Table 6 with data from two surveys. At these dates Delta waters reflected similar conditions: base flow in the upper Delta and receding waters in the lower Delta. The total inflow at Mohembo in the 365 days preceding the dates of sampling were 6.99 and 9.37 x $10^9$ $m^3$ in Nov 1991 and Oct 1992, respectively. The short-term data obtained in the two surveys are insufficient to assess the impact of water budget changes on the variables but may provide some information on the relative importance of inflow volume on transport of major chemical constituents.

Total N and total P concentrations in the November 1991 survey should be regarded as estimates since they were based on only a few samples on. Concentration of major ions either varied inversely with the amount of inflow water or was unaffected. The exception to this trend was the concentration of $Mg^{2+}$ which seemed to increase with discharge suggesting a purging effect of this constituent, by removal and dissolution of precipitated magnesium salts. A purging effect was also observed in suspended sediments as measured by turbidity. This parameter

includes both inorganic constituents and biological material in suspension, such as algal cells and detrital material. A dilution effect was observed for TN and $NH_4^+$-N concentrations whereas TP and $NO_3^-$-N concentrations were probably conserved in relation to increased discharge.

The influence of discharge on major ion concentration (as specific conductance) is illustrated in Fig 10. In the Panhandle and upper Delta, total ionic concentration increased with discharge at low discharges (flushing or purging effect) but was inversely proportional to discharge as the discharge increased (dilution effect), with a threshold value at about 300 $m^3s^{-1}$. This pattern was progressively offset in a downstream direction. The range of solute concentrations at the Panhandle and inlet of the Delta and at outlet areas is shown in Fig 11. A ratio of about 3:1 between the total ionic content at the outlet to that of the inlet provides a guide to the effect of modification of the chemical composition as the waters move downstream. Lower ratios were found for $SiO_2$, DOC, Mg and TP concentrations, while the ratio of concentrations of N-components was more variable but still with a mean value of about 3:1.

With the data collected in the surveys it seems that the response of individual solute concentrations to discharge has a strong spatial component. A simple power function would therefore oversimplify solute response to changing flow conditions. Furthermore, it must be stressed that interpretation of ionic content variation with inflow is not as straightforward as it might appear. For example, comparison with earlier data from the 1970s and the 1980s may suggest that ionic content (SC) would not only depend on the discharge at the time of observation but also on antecedent conditions with unknown time span. This is important because it indicates that long-term hydrological records are not only crucial in the prediction of outflows but are also necessary to interpret and forecast hydrochemical and ecological changes.

*Chemical modification of inflow waters*

Discussion of pathways and processes affecting chemical composition of Delta surface waters requires extrapolations and simplifying assumptions. These are necessary because key information is either not available or insufficient to substantiate conclusions unequivocally. For example, while continuous unidirectional transport of soluble materials induced by the seasonal pulse of inflow water from the Okavango River is a major feature of the Delta, rainfall inputs, especially of transition metals and some components of N and S loads, are not negligible but cannot be quantified at present. A further example would be the transformation of chemical constituents in sediments resulting from processes governed by aquatic vegetation, processes of immense importance in wetlands for which little direct information is available. Although the effect of these individual processes cannot be assessed with the available data, it seems possible to evaluate the combined effect of all non-conservative processes on water quality at the outflows.

Surface water inflow from the Okavango River provides the main input route of chemical constituents into the Delta. The inflow is essentially a dilute bicarbonate and $SiO_2$ solution, very low in chloride, sulphate, and nutrients. The ionic load is then increased from passage through the swamps and from internal runoff in the seasonal swamp areas. Further contribution to the ionic load is brought about by atmospheric precipitation. Although these processes are imperfectly known, the few data available support the suggestion that bulk precipitation inputs of S, nutrients, and the majority of minor elements are 1 to about 5 times larger than surface input via the Okavango River.

The Delta lies in a region of anticyclonic atmospheric circulation and may therefore receive particulate fallout emitted from industrial areas in South Africa, Zimbabwe and NE Botswana. The importance of rainfall input to the chemical load in the Delta can indirectly be appreciated from published precipitation chemistry data for the region (Table 7). Although it is not possible to ascertain the sources of the elements, the data suggest non-marine atmospheric contributions of Ca, Na, K, Mn, Fe, S, Sr, and most trace metals. Most of these probably have their origin as washout from dust, whereas S and trace metals originate mainly from anthropogenic activities. A note of caution is needed here. Most of the industrial emissions with potential impact on the Delta occurred in the last 2 to 3 decades which is a short time period to detect statistically consistent changes in water quality. Unfortunately there are no historic data with which to compare present findings and earlier data from the 1970s are too few to be useful.

Sediment deposition improves water quality by decreasing turbidity and immobilising nutrients and metals. Both physical and chemical precipitation have been documented (McCarthy and Metcalfe, 1990, McCarthy *et al*, 1991a,b, Sawula and Martins, 1991), whereas solute transport to the deeper groundwater has recently been discussed by McCarthy and Ellery (1994, 1995) and Gieske (1995). A brief account of the chemical composition of suspended load (particulates, or colloidal particles in suspension) in Delta water is given here. Water samples were split into a number of analytical fractions for separate analysis. The first fraction was obtained by filtering the water through a 0.45 $\mu$m membrane filter whereas the second fraction consisted of the "raw" unfiltered water sample. The third fraction contained the particulates ranging in size from 0.45 to about 30 $\mu$m, which remained behind on the membrane filter and which were redissolved, acidified and analysed by AAS. The fourth fraction was obtained by adding strong acids to the original water sample. Analysis of this last fraction will in principle give the total concentration of the elements in the sample, ie, not only the amounts dissolved in water, but also those adsorbed to sand and clays, and contained in detritus and biological material. It should be noted at this stage that analytical procedures may influence the outcome of the chemical analysis, as discussed by McFarlane (1991) and McFarlane and Bowden (1992) (see also the discussion on aluminum in the section on water quality criteria). Results given here should be considered preliminary and are subject to further investigation.

Figures 12a and b show, on a logarithmic scale, the ratios of element concentrations in fractions two, three and four to that in fraction one. Little difference was found between the concentrations of Ca, Mg, Na, K, Si, and S in fractions 1 and 2 (Fig 12a) which indicates that these components were mostly present in a "dissolved" form or particulates of less than 0.45 $\mu$m (see Danielsson, 1982). No difference was found for $Cl^-$ either (not shown in Fig 12). Transport of Fe, Mn, and Al seems to take place mainly by particulate matter suspended in the water (Fig 12b). This fraction accounted for about 70 to 75% of the transport of Fe and Al, and for about 50 % of that of Mn. In contrast, particulates accounted for only 15 to 25% of the transport of heavy metals.

It is clear from Fig 12 that concentrations of all elements in fraction 3 are higher than in fraction 1 which seems to indicate that most of the element transport in Delta water takes place through particulate matter - of biological or inorganic nature - greater than 0.45 $\mu$m and not in "dissolved" form.

Significant differences were found between the concentrations in fractions one and four. The concentration of Ca, Mg, Si, K, and Na in fraction four was 2.0 to 3.4 times that of the filtered

fraction which may indicate that considerable amounts of these elements were adsorbed to or enclosed by particulates. Similarly, the amounts of Fe, Mn, Al, and heavy metals incorporated in particulate matter were found up to two orders of magnitude higher than that in filtered samples. Lower total amounts of Mn were found in the particulate fraction compared with Fe or Al. Since Si is not elevated in comparable fashion to the Al, this indicates that the Al is disassociated from the Si, that is, it is not simply in clay form. This is consistent with the findings of McFarlane (1991).

Nutrients (P, N and S) appear largely to be transported in the system as particulate matter. The large difference in concentration between TN and the filtered fractions of this element (Fig 12a), and between TP and soluble P (near or below detection) suggests that the detrital fraction contains the bulk of nutrients. Sulphur concentrations were also over two times higher in particulate material than in solution, probably because of surface adsorption of sulphate. The detrital fraction, deposited as sludge, appears to play a central role in nutrient storage and cycling. The sediment load carried by the Okavango River, mostly as bed load, is deposited in the upper Delta (McCarthy *et al*, 1991a) and little is transported downstream.

Sediment/water boundary interfaces are important loci of biogeochemical transformations in wetlands. These transformations are predominantly governed by micro-organisms but also controlled by the physico-chemical characteristics of water environment such as pH, redox and oxygen status, and availability of carbon compounds. Possible transformations of nutrients at these interfaces can be inferred from concentration profiles of N, and P components in pore waters, as illustrated in Fig 13. Although the profiles were generated from pooled samples (March and November, 1992) at three sites with different sediment composition, the concentration trends were consistent in individual profiles. The profile data cannot, however, be used in the evaluation of nutrient diffusive flux or residence times in sediments, since the distribution in the uppermost layers (indicated by question marks in Fig 13) could not be determined due to technical difficulties. Seepage rate values are shown in Table 8. It is difficult to assess the accuracy of the seepage data since no independent measurements were made. The data are too few for any definite conclusions and serve only as an illustration of the complex water cycle dynamics in the Delta.

Pore water pH and SC values were undistinguishable from those in the overlying water. The concentration of both TN and $NH_4^+$-N increased with depth in the profile. They were, at -0.6 m, on average about two times higher than the concentration in overlying water. In contrast, $NO_3^-$-N concentration decreased with depth and was near or below detection at -0.3 m. Total P concentration in pore water increased initially with depth and at -0.3 m it was about 1.3 times higher than that in the overlying water, to decrease at -0.6 m to almost undetectable concentrations. The concentration of DOC in pore water was unknown. However, the concentration pattern of ammonium and nitrate suggests reducing conditions in the profile which implies that only a small proportion of DOC has been oxidised. Pore water DOC concentration in the upper layers can therefore be assumed to be at least equal to that in the surface water (7 to 10 mg C/l).

Phosphorus, a more persistent element in wetlands compared with N, also seems to accumulate in the upper layers of the sediments but its concentration declined rapidly with depth suggesting that P was efficiently recycled - a trend often observed in systems where P may limit the productivity (Bowden, 1984, Walbridge *et al*, 1991). It seems likely that P was incorporated as organic P associated with detritus in the upper sediment layers. Part of this P would

eventually be released as a result of the instability of C-O-P bonds. The relative availability of the different P pools as well as the factors regulating release and retention of P are practically unknown and need further investigation.

Deposition of detritus in swamp areas will consume dissolved oxygen and will consequently decrease oxygen concentration in the water column. This situation has been observed in sites in the seasonal swamps, in deeper lagoons in the upper Delta and in Seronga lagoons in the Okavango River where the oxygen concentration in bottom layers was below 1 mg/l. The water column in these lagoons showed a slightly unstable stratification which suggests near anoxic conditions and little mixing of the water column. This stratification is probably destroyed during the night which may add a diurnal period to fluctuations of some biotic and abiotic variables. River channels were, in general, well oxygenated. An example of anoxic and reducing conditions in shallow waters was the Tichira lagoon, which is about 1 m deep and exhibits extensive sediment accumulation. Sulphate concentration in the water was below detection limit and hydrogen sulphide was easily detected by smell. However, in apparently similar areas with substantial organic accumulation, $H_2S$ could not be detected which may suggest that both microbial reduction and adsorption or incorporation in organic matter are important mechanisms for sulphate depletion and organic matter may therefore be a potential sink for sulphur.

Incorporation into biomass and decomposition of particulate organic matter are major controls of water quality. Nutrients released upon senescence of living tissue are, in general, rapidly recycled by microbiota and relatively small amounts N and P leave the system. A characteristic feature of natural wetlands is retentive and cycling capacity of nutrients and exports of dissolved organic matter under average hydrological conditions. This also seems to be the case in the Okavango Delta. Approximate input-output solute mass budgets of the Jao/Boro system suggest high turnover rates of inorganic N and TP, and less so of dissolved organic carbon and organic N. Much of the dissolved organic matter in freshwaters emanates from organic products of plant origin. Except from studies of major ion uptake and release in peat areas of the Nqoqa-Maunachira system (McCarthy *et al*, 1989), little is known of the processes controlling incorporation or release of N, P, and C components in various biomass "compartments" or of standing stocks of elements and nutrients.

Most dissolved organic carbon in the Delta´s water is in the form of humic and fulvic acid-like substances. This fraction, characterised on the basis of retention onto resin columns (Leenheer, 1981, Thurman and Malcolm, 1981), accounted for about 77.6 to 82.8 % (9-10.5 mg C/l) of the DOC load, the remainder were hydrophilic bases and acids, and neutrals. During decomposition, labile compounds are degraded much faster than humic and fulvic acid-like compounds resulting in net accumulation of the more refractory carbon. The proportion of humics increased downstream which indicates a continuous input from the swamp areas but which may also indicate that only the fraction more resistant to degradation remains to be transported to the Delta outlet. Complexation to high molecular weight DOC compounds or sorption onto particulate organic matter may be of overriding importance in processes involving N and P cycles in peat areas. These areas consist mainly of macrophyte detritus, in various degrees of degradation and consolidation, and they are rich in lignin derivatives of which humic substances seem to be a major component. Neither the origin of the different DOC components nor the relative importance of the various DOC source(s) are known at present. Source contribution cannot be specified with the available data. Chemical structure determination of

DOC fractions with NMR techniques (Martins and Drakenberg, in preparation) may, however, contribute to a better understanding of dissolved organic carbon diagenesis in the Delta.

Literally hundreds of isolated pools, ponds, and puddles, or simply water-filled depressions, with areas of less than 0.02 ha to a few ha, are found throughout the Delta. The pools receive periodic or intermittent fresh water inflows, either from the seasonal flow or from local rainfall, and some may be a surface expression of the groundwater table. The chemical and biological characteristics of these pools were extremely varied. Some pools contained diluted fresh water, certainly from rainfall, while others exhibited different loads of salts, nutrients, and dissolved organic matter. As an example, two neighbouring pools in the area between the Maunachira and Mboroga (19°12'14" S, 23°22'11" E) exhibited different characteristics. The waters in both pools were strongly evaporated and slightly alkaline but, while one pool had a SC of 1090 $\mu$S/cm, DOC concentration of about 88 mg C/l, and was devoid of algal flora, the second one, situated at about 20 m from the first pool, contained half the salt content (650 $\mu$S/cm), a lower DOC (22 mg C/l) and a fairly well developed algal flora. Ponds with peat-stained black waters with DOC concentrations over 250 mg C/l (of which 185-215 mg C/l as humics) and salt content about 4000 $\mu$S/cm are less frequent. Some are located in depressions on islands (McCarthy *et al*, 1991b) while others are located in desiccated areas (eg,, 19°12'00" S, 23°28'27" E and 19°0'41" S, 23°09'17" E). During inundation the water of some pools will mix with flood waters while others will remain isolated. The contribution of the former to the Delta surface water quality is probably negligible. The contribution to the groundwater ionic load may, however, be important but is largely unknown at present.

The outcome of all processes, in water, soil and biota, will thus be translated into water quality variation at the outflows. From analysis of the data a few conclusions can be retained. The total ionic content of water in downstream areas correlated poorly or not at all with water level. This suggests differential removal of solutes and a net accumulation of most ions in the system. The concentration of all chemical constituents increased along the main axis of the Delta as a result of the evapotranspiration, but a marked increase was found in areas downstream of the Buffalo fence. In general, while the chemical composition of the Jao/Boro River waters varied both seasonally and with amount of inflow water, their quality was always good. Conversely, waters in the Delta´s distal areas and in most swamp areas were often of a poor quality. These waters, as well as the Thamalakane River, contained high concentrations of DOC and nutrients, and were extremely turbid. Large numbers of *Euglenophytes* and *Cyanophytes* in the Thamalakane River upstream of the junction as well as in areas around Maun indicate that these waters have received considerable chemical inputs from human related activities in addition to those from natural sources.

Chemistry and microbiota of the Nqoqa/Khwai were similar to those of the Jao/Boro River. Whilst there was a gradient of increasing concentration of most chemical constituents towards the outlets of both rivers, total ionic concentration at the North gate was normally 10 to 20 $\mu$S/cm lower than that at the Buffalo fence in the Boro. Less evaporated waters, as indexed by $\delta^{18}O$, were found at North gate, in November 1992, (+4.80 ‰) compared with values at the Boro outlet (+7.12 ‰). Isotope determinations in locations in the upper Nqoqa and Jao Rivers, at approximately the same distance downstream of their confluence, showed more negative values in the Nqoqa waters than in the Jao. These findings may suggest a more efficient transport through the Nqoqa than through the Jao/Boro system.

*Bacteria assemblages and plankton communities*

Bacterial abundance, as total bacterial numbers (TBN), averaged 0.94 ($\pm$0.16) x $10^9$ cells/l, with a range of 0.07 to 3.98 x $10^9$ cells/l (n = 56). Bacterial abundance in river channels did not significantly differ from that in swamps, lagoons, or floodplains. Although the data were biased towards the upper regions of the Delta it seems that there were no significant differences in TBN between the perennial and seasonal swamps but intersite variation was considerable. Viable counts were about 1/3 of the TBN values. Viable counts averaged 0.32 ($\pm$0.34) x $10^9$ CFU/l, with a range between 0.002 and 1.0 x $10^9$ CFU/l.. Characterisation of 46 water samples showed that the majority of the strains isolated were Gram-positive aerobic rods. Gram-negative bacteria were dominant in only 7 samples. Identification of the bacterial strains is shown in Table 9. Identification of the Gram-positive species *Arcanobacterium haemolyticum*, *Bacillus insolitus*, *Corybacterium jeikeium*, *Curtobacterium citreum*, *Micrococcus luteus*, and *Streptococcus sobrinus* as well as the Gram-negative species *Brucella abortus*, *Kingella kingae* and *Moraxella atlantae* was based on a few positive tests and less confidence can, therefore, be put in their identification.

Gram-negative bacteria of public health interest are listed in Table 9. The identification system used was able to identify 15 strains to the species level (12 species), 2 strains to the genus level (1 genus), while 6 strains could not be identified. Seven of the identified strains (*Enterobacter* spp., *Enterobacter agglomerans*, *Erwinia chrysantemii*, *Plesiomonas shigelloides*, and *Serratia marcescens*) belong to *Enterobacteriaceae* while the remainder strains belong to the genera *Aeromonas*, *Alcaligenes*, *Pseudomonas*, *Shewanella*, and *Xanthomonas*. *Enterobacter*, *Erwinia*, and *Serratia* have frequently been isolated from a variety of environments. Mesophilic bacteria within the *Enterobacteriacea* family are common inhabitants of the intestinal tract of animals, including man, and some are pathogens or opportunistic pathogens. Three strains were identified as *Plesiomonas shigelloides*, which is frequently isolated from a variety of environments but is also considered as an enteric pathogen. *Enterobacter* is also regarded as opportunistic pathogen while *Erwinia* is a plant associated and sometimes plant pathogen. The genus *Aeromonas* consists of free-living bacteria as well as bacteria associated with aquatic animals. Some *Aeromonas* species are fish pathogens.

An evaluation of 340 phytoplankton samples collected during 1991-1994 suggests a rich algal population with large species diversity in the Delta waters. Although over 225 algal species were recorded, net plankton samples (10 - 45 $\mu$m mesh size) suggest a greater number of species than hitherto identified. Some species have probably not yet been recorded in the literature and therefore detailed identification with electron microscopy (EM) will be necessary to differentiate the large number of chrysophytes, diatoms, and dinoflagellates. Examples of scanning EM images of representative chrysophytes and diatoms of the Delta are shown in Plates I-III. A more detailed taxonomic characterisation of the algal flora will be reported elsewhere while a detailed assessment of the phytoplankton communities by habitat will be part of a later, companion paper.

About 75% of the recorded species are cosmopolitan whilst the remainder are typically found in tropical and inter tropical regions. A few representative tropical species of the Delta are shown in Plates IV-VI: *Aphanizomenon volzii*, *Cylindrospermopsis africanum*, *C. raciborski*, *Planktothrix raciborski*, *Asterionella thomasonii*, *Synura australiensis*, *Allorgeia incredibilis*, *Micrasterias foliaceae*, *M. sudanensis*, and *M. tropica*. Despite the rich species variety only a relatively small number of species contributed significantly to the total phytoplankton biomass.

Blue-green algae and green algae were well represented with 50 and 110 species, respectively (Table 10). Table 10 also includes, for comparison, the phytoplankton recorded in three eutrophic water bodies, the Maxegane pool, King´s pool, and Lake Ngami. Among the blue-green algae, the small-celled chroococcal blue-green algae belonging to the genera *Aphanocapsa, Aphanothece, Chroococcus, Merismopedia*, and *Microcystis* were more common than filamentous blue-greens. Among the diatoms, the genera *Aulacoseira*, *Cyclotella*, and *Synedra* were most frequent. The greenalgal flora formed an important component of the phytoplankton. They exhibited great species diversity, in particular the chlorococcal green algae and desmids. A rich blue-green algal flora, with *Microcystis aeruginosa* and *M. flos-aquae* as the dominant species, was also recorded in the polluted Maxegane pools, which host considerable numbers of crocodile and hippopotamus, and are extensively used by wildlife for drinking. Similar algal flora was also found in King´s pool in the Linyanti. Euglenophytes and chlorococcal green algae were the dominant groups in Lake Ngami waters as recorded in November 1992. On that occasion the lake was practically a shallow muddy basin about 1 m at its deepest part, and it was extremely turbid and polluted by cattle and waterfowl. In the Khwai River at North gate the channel was no more than a ditch at the time of observations and very little phytoplankton, mostly small amounts of *Cryptomonas*, was then recorded. Low biomass was also found at the inflow to the Xakanaxa lagoon, and species of the genera *Cryptomonas* and *Synedra* were dominant, while higher biomass and richer algal variety were recorded in the lagoon proper and at the outflow. The blue-green algae *Anabaena* sp, *Cryptomonas*, and the dinoflagellate *Peridinium* were common. Zooplankton taxa were identified from about 30 samples (Table 11). About 45 species or groups were recorded. Rotifers were the dominant group although cyclopoid copepods were often frequent. Cladocerans abundance was, in general, very low with *Bosmina longirostris* and *Diaphanosoma* sp as the dominant species. The absence of large cladocerans might depend on the low phytoplankton biomass in most of the studied locations, which was insufficient to sustain a large zooplankton population, or by the intensive predation by numerous small fish. In the Maxegane pools and King´s pool, *Brachionus* (Plate VII) and *Filinia*, which were, however, different from the species found in the Delta, totally dominated the zooplankton communities.

*Outline of the Delta´s hydrobiology*

The Okavango Delta encompasses a range of physiographic features with complex hydrological patterns. Inevitably, a wide range of physico-chemical and biological characteristics of surface waters is found. Most of the variance of water chemistry was related to spatial heterogeneity and seasonal inflow as described earlier. Passage of the water through the papyrus swamps in the upper Delta did not result in a consistent chemical modification pattern, except in a slight increase of TP during throughflow and the occurrence of slightly elevated levels of TN and organic N in the stagnation period. As expected, higher concentrations of all chemical constituents were observed in the seasonal swamp areas, with the exception of iron concentration, which was consistently higher within papyrus swamp areas than in the lower Delta. These findings are comparable with chemical changes observed in papyrus swamps in Kenya (Gaudet, 1979).

The present studies suggest that the effects of the swamps on nutrients, or on water chemistry in general, could be traced to physical effects, especially the effects of depth and duration of flooding. Biological effects are of course operative throughout but they are often

masked by physical effects. Transformation of N and P were more clearly defined in isolated pools and stagnant waters contained within the reed swamps, which were shielded from some of the physical effects affecting the remainder of the study area. In wetlands, concentrations of inorganic-N are typically low because of denitrification processes and assimilation in biomass of plants and decomposing organisms. The concentration of nitrate-N in the surface waters of the Delta was within the range observed in temperate and tropical wetlands while ammonium-N concentrations seem slightly elevated compared with concentrations in similar systems.

There were distinct differences in phytoplankton distribution between the major habitats. Phytoplankton was practically absent in fast running waters. Total phytoplankton biomass in this habitat was in general below 1 mg/l freshweight and only a few samples yielded higher biomass. These samples corresponded to sites near and connected to lagoons with well developed algal communities. Diatoms of the genus *Synedra* spp, cryptomonads, and dinoflagellates of the genus *Peridinium* were the dominant groups in those samples. In swamp areas the phytoplankton formed rich communities, both in diversity and in terms of the total biomass (0.001 to 45 mg/l). Green algae were well represented in this habitat and the highest biomass was observed within this group (*Spirogyra* spp, 45 mg/l). Within the chlorococcal group, *Botryococcus* was the dominant species. The desmid flora was abundant and the genera *Mougeotia, Spirogyra*, and *Staurastrun* were dominant within this group. Frequent, although not reaching high biomass, were *Peridinium* spp. cryptomonads, and *Synedra* spp. The highest biomass was recorded in isolated pools (65 mg/l) where also the greatest number of euglenophytes and cyanophytes was found. A rich flora of *Euglena* species was found in some pools giving the water a characteristic red colour of *Euglena sanguinea*. Chlorococcal green algae, in particular *Botryococcus* spp. were frequent. Desmid and diatom flora was rich and diverse. Within the diatom group, the genera *Aulacoseira*, *Cyclotella*, and *Synedra* were the most abundant. Euglenophytes and chlorococcal green algae were almost exclusively found in isolated pools.

Phytoplankton were poorly developed in river channels and only a few algal groups were recorded in this habitat. Conversely, phytoplankton communities were well developed in swamp areas and isolated water bodies. Many of these sites were a few decimetre deep, with well developed benthic and periphytic algae. In shallow areas the desmids were the most abundant group, with large species diversity. Only in deeper lagoons or isolated pools were true phytoplankton developed. During the dry season part of the seasonal swamp areas can dry out completely and characteristic algal assemblages with resting cysts, such as desmids, diatoms and chrysophytes were common. Large areas of shallow, standing waters, with profuse aquatic vegetation suggest an important role of the periphytic algal and benthic fauna communities in the Delta´s ecology. A preliminary scrutiny in a few locations indicated a rich species diversity amongst the periphytic algae but no further studies of benthic algae or benthic invertebrates were undertaken in the course of the present investigations.

Preliminary identification of dominant zooplankton taxa showed that river channels in the upper Delta were almost devoid of zooplankton. In contrast, high densities were found in terminal areas of the Delta which are strongly influenced by human activities. Rotifers and nauplius larvae were the dominant taxa and, among the former, the genera *Asplanchna, Brachionus*, *Filinia*, *Polyarthra*, and *Trichocerca* were common. Swamp areas exhibited a well developed fauna with rotifers as the dominant group but where crustaceans were also frequent. The same species were recorded in these areas as in the Thamalakane River. *Keratella* spp.,

however, seemed to be more frequent in the upper Delta. Among cladocerans, *Bosmina longirostris*, *Ceriodaphnia* sp., and *Diaphanosoma* sp. were the dominant species.

In the present data set chlorophyll *a* was well correlated with biomass ($r^2 = 0.710$, n = 74) and could, therefore, be considered a reasonable index of total phytoplankton biomass. Regressions of chlorophyll *a* with major nutrient concentrations were significant, with correlation coefficients ranging from 0.271 with TP concentration to 0.594 with ammonium-N concentration (n = 158).

Nitrogen/phosphorus ratios are often used in water quality analysis to determine which nutrient is limiting primary aquatic productivity. Generally P is considered the limiting nutrient in freshwater systems at N/P molar ratio above 10 to 15 (Hecky and Kilham, 1988). Total N and total P concentrations in channels and swamp waters were weakly correlated but they showed significant correlation in isolated pools ($r^2 = 0.770$, n = 31). Approximate TN/TP molar ratios in channels and swamp waters were in the range of 22 to 88 with an average value of $49.5 \pm 19.0$, or above the minimum for P limitation, while TN/TP ratios in isolated pools were between 6 and 16, which might suggest that N and not P was the critical nutrient in these waters. Low inorganic-N/TP ratios in some samples may also indicate enhanced denitrification and coupling of P with high load of sediments rather than a high supply rate of available P.

Classification of trophic relationships using concepts, which were originally developed for lakes and marine systems, like oligotrophy and eutrophy (Carlson, 1977, 1984, Peters, 1986) may be useful in water resources management as easily available data can be used, although quantitative measurements of nutrient concentrations and algal abundance provide a better description of trophic status. With the available data it is apparent that the waters of river channels, with low chlorophyll *a* concentration, could be classified as oligotrophic in respect to the phytoplankton but oligotrophic to mesotrophic in respect to the inorganic nutrient concentrations (Håkanson, 1980). Swamps, floodplains, and lagoons varied between oligotrophic to mesotrophic, while most of the stagnant waters, isolated pools, and backswamp areas were clearly mesotrophic to eutrophic. Bacterial numbers in unpolluted freshwater systems range from $10^7$ cells/l in oligotrophic waters up to $10^{10}$ cells/l in eutrophic waters. In the Delta waters, bacterial counts were on average about $1 \times 10^9$ cells/l, which further suggests that most habitats were oligotrophic to mesotrophic.

In summary, a tentative characterisation of the Delta´s hydrobiology would underline the low amounts of ions, trace elements, and nutrient inputs, and emphasise the retention of most inorganic nutrients within the system, which suggest an efficient utilisation of the available nutrients by aquatic autotrophs. The concentration of all solutes is progressively increased towards the terminal areas as a result of high evapo-transpiration rates (Dinçer *et al*, 1978) but differential removal of major ions by a variety of mechanisms (McCarthy, 1992) moderates the salinity at the Delta´s outlets, whereas sedimentation and plant uptake are important in maintaining low inorganic nutrients output. Decomposition processes, mostly from decay of vascular plants, are responsible for the high dissolved organic carbon and moderate organic nitrogen loads exported from the system. The Delta's fairly large bacterial biomass contributes to high mineralisation but it seems plausible that it is insufficient to completely break down all C and N components. Phytoplankton and zooplankton cannot efficiently establish in running waters but produce very rich communities in the slowly flowing swamp and floodplain areas, and in larger open water lagoons. Periphytic communities may constitute an important part of the total phytoplankton biomass.

*Water quality criteria*

Drinking-water quality standards have mainly focused on microbiological and inorganic determinands. Recently, water quality criteria have been extended to include organic compounds mostly as the result of advances in analytical instrumentation which led to considerable improvements in the detection of such compounds. Trace amounts of some xenobiotic organics (pg/g and below), such as polyaromatic hydrocarbons, organo-chlorine, and organophosphorus compounds are carcinogenic and mutagenic and therefore constitute high health risks. The present investigations did not include the study of such compounds. Effects on the Delta's fish fauna as a result of insect eradication programmes have been documented (Matthiessen *et al*, 1982) and it is believed that follow up studies are being conducted by others (G Merron, personal communication, 1990). Long-range transport of persistent contaminants may, however, also play a role in deterioration of water quality. The importance of organic contamination of water and soils of the Delta, as well as its effects on biota, remains to be evaluated.

The choice of potentially useful variables for describing the drinking-water quality of the Delta is simplified by the fact that there is no industrial or urban pollution in the Delta and that most of the low quality water is restricted to stagnant swamp areas where it is unlikely to be used. An important category of environmental contaminants is heavy metals. Their presence in surface waters continues to be one of the most pervasive environmental issues (eg, Nriagu and Pacyna, 1988). The deleterious effects of heavy metals depend on a variety of factors. The form of the soluble metal in water (ie, its speciation) and hence its bio-availability, is of central importance in the toxicity of metals to humans and biota. Estimated mean values of transition metals in surface waters of the Delta are shown in Tables 3 and 13. Guidelines and standards of water quality are given in Table 14. The concentration of filterable iron in surface waters was low (median 12.8 $\mu$g/l, range 2.4 - 91, n = 266) and considerably below guidelines of maximum level for human consumption or in protection of aquatic life. Iron is of little toxicological significance to the biota but may be moderately toxic to some species of aquatic plants, The same holds for manganese. Filterable manganese concentrations were low (3.5 $\mu$g/l, 1.0 - 98.6, 268) and at these concentrations manganese does not constitute any potential hazard to humans or biota.

Unlike Fe or Mn, the aluminum ion is extremely toxic. Aluminum has a complex chemistry and its speciation and toxicity are strongly influenced by pH and the presence of ligands. At the pH commonly found in the Delta waters, Al mainly exists as aluminate ion, $Al(OH)_4^-$, but it also may occur as colloidal $Al(OH_3)$ and as stable complex with various ligands. The filterable Al concentrations were, in general low (2.5 $\mu$g/l, 0.2 - 40.5, 247, cf 0.1 ppm is the WHO guideline). These values were obtained according to standard methods for the analysis of aluminum. The samples were filtered through 0.45 $\mu$m membrane, acidified, and subsequently analyzed. However, a slightly different procedure whereby the sample was acidified and resuspended through ultra-sound prior to filtration, often resulted in higher Al values. This may indicate that the standard method may under-estimate the true amount of filterable Al in raw water (McFarlane, 1991, 1992). Regardless of the analytical procedure used, filterable Al (as well as total Al) concentrations in surface water were, with few exceptions, below the guidelines for protection of aquatic biota or human consumption.

Chromium is an essential element but can be toxic when present in high concentrations. The principal forms of Cr in freshwater are $Cr^{3+}$, present mostly as complex, and $Cr^{6+}$, more

toxic, and present as chromate ion at pH > 6.5. Filterable Cr concentrations were determined in twelve samples randomly selected throughout the Delta. Chromium was not detected in two of the twelve samples, and it was present at an average concentration of 0.3 $\mu$g/l in the remaining ten samples. Although the standards for the protection of drinking water are based on the assumption that $Cr^{6+}$ is the dominant species, no attempt was made in the present investigations to separate the different forms of chromium. The data include therefore all forms of filterable Cr in the Delta waters. Chromium was present at low concentrations and as such does not constitute a potential environmental or health risk.

Estimated mean values of filterable Cd, Pb, Ni, Cu, Zn, and Co concentrations in one location in the upper Delta and at the outlet at Boro junction with the Thamalakane are shown in Table 13. With the exception of zinc, the concentrations of the studied metals were below $\mu$g/l level and they can reasonably be assumed as the background concentration of these metals. Heavy metal contamination may however occur locally as, for example, the result of disposing vehicle batteries and domestic sewage in the fringes of the Thamalakane, or cleansing of outboard engines and disposal of petrol/oil along the main channel in the Delta.

Impairment of water quality by micro-organisms remains the principal concern of water management. This concern has not only been focused on the potability of water but also in reflecting the importance of water in transmission of diseases. The absence of pathogenic organisms in the source does not, however, always ensure a good micro-biological quality to the end user. In effect, no other attribute of water quality is so dependent on a variety of external factors as is the micro-biological status of the water. Bacteriological contamination can occur at any stage of water utilisation, along a sequence from the source, at distribution, during storage, at disposal, to the return of the original waters and therefore the micro-biological status should be assessed at all these stages.

The overall micro-biological quality of water is, in general, determined by detecting predominantly the faecal coliform indicator *Escherichia coli* (Table 13). *E. coli* is not usually a long-term occupant of aquatic ecosystems and serves therefore only as a useful indicator of recent faecal contamination. In Delta waters, however, a continuous supply of *E. coli* can be expected from the large number of resident animals. Recent evidence suggests that other microbiological contaminants, as well as protozoan cysts and viruses, should be considered when assessing water quality (Geldreich, 1989). Consequently, revised legislation (USEPA, 1990) includes maximum levels for four microbiological contaminants in addition to faecal coliform counts, and proposes more frequent testing of every pathogen that could possibly be present in the water source. Human activities are not the sole source of pathogenic organisms of public health interest. Cattle and wildlife are not only carriers of human pathogens but can also be infected by human pathogens. Heterotrophic *Aeromonas* spp and members of the *Enterobacteriaceae* family are part of the natural bacterial flora in aquatic environments but they also cause a variety of pathologies in humans through ingestion or contact (Janda and Duffey, 1988, von Graevenitz and Althwegg, 1992). Various factors can influence bacterial numbers, dominant biotype, or species virulence, but little is known on the virulence or pathogeneity of environmental strains. Detection of opportunistic pathogens strains, eg, some *Aeromonas* spp and species belonging to *Enterobacteriaceae* family, during the present surveys, suggests that future assessment of the Delta water microbiological quality should include the screening of these bacteria. Although only one *E. coli* strain was identified, most samples from the Okavango and Linyanti waters exhibited degraded quality from faecal contamination probably

from wildlife. For example, the opportunistic *Plesiomonas shigelloides*, an enteric pathogen, was isolated from drinking water supplied from stand pipes in the Serondela camp site and it was probably also present at the North gate camp site water supply and in King's pool. Although the origin of *P shigelloides* remains uncertain, and its presence in the few samples studied does not preclude the use of the water, it suggests, nevertheless, source contamination and a potential health risk.

Deterioration of water quality as a consequence of algal blooms and release of cyanobacterial toxins are sporadic features in many natural waters (Carmichael *et al*, 1985, Codd *et al*, 1989, Carmichael, 1992) and have commonly been associated with increased eutrophication of the waters, although recent studies have documented toxic algal blooms in oligotrophic aquatic systems. Species and strains of common planktic cyanobacterial genera produce natural toxins of which the hepatotoxins are the most commonly encountered toxins involving this algal group. These toxins are produced by strains within the genera *Anabaena*, *Cylindrospermopsis*, *Microcystis*, *Oscillatoria*, but other species are also able to produce chemically related compounds. Although there are no reported cases of lethal poisoning in humans due to toxin ingestion (only because the floating scum makes the water less attractive for drinking) field poisoning involving cattle and wild animals is widespread (eg, Wicks and Theil, 1990). During the present investigations a few algal blooms were detected, mostly due to *Microcystis* and *Cylindrospermopsis*. Toxin producing species *Microcystis aeruginosa* Kütz were also found in locations throughout the Delta and Linyanti. These planktic communities were particularly well developed in eutrophic pools, such as the King's pool in the Linyanti (Table 10), the waters of which are used both by wildlife and humans (Game Scouts camp), and in Kavimba and Maxegane pools, which are mostly utilised by waterfowl and wildlife. These species, given the favourable temperature and environmental conditions that normally prevail, can quickly proliferate during the wet season constituting a potential environmental and health risk.

Suspended sediment load is an important determinand of water quality. Suspended sediments are commonly determined by sequential filtration and a cut-off value of 0.45 $\mu$m has arbitrarily been set to discriminate between dissolved and particulate matter (Danielsson, 1982). This cut-off value under-estimates the amount of particulate matter by not taking into account the amount present in the colloidal size range fraction. Suspended sediments in the Delta waters were moderately low, with a median value of 13 mg/l and a range of values between 0.2 and 130 mg/l. Turbidity is often used to characterise the solid load as it gives an indication of the weight concentration of solid particles. This latter measure cannot, however, be determined directly and accurately from turbidity unless a good correlation between suspended sediments and turbidity can be demonstrated. In the present data set turbidity was fairly correlated with suspended sediments ($r^2 = 0.477$, $n = 91$) but this correlation was lost at high sediment load. High turbidity is detrimental to water quality not only by degrading the physical characteristics of the drinking water but also by providing a substrate in which bacterial aggregates may become established. Turbidity in the Delta waters ranged from 0.3 to 289 ntu, with a median value of 1.46 ntu. As was the case with sediments, high turbidity values were observed in the lower Boro downstream of Buffalo fence. In general, within the constraints of the methods used, the waters exhibited low turbidity and could be considered of good quality with regard to suspended sediments.

Although non-specific organic determinations, such as COD and DOC, are important in defining the purity of drinking waters, naturally occurring organic compounds do not, at present, constitute priority determinands in standard or guidelines of water quality. The Delta waters contain high amounts of dissolved organic carbon of which a large proportion is in the form of humic and fulvic acid-like substances with slow biodegradation rates. The importance of these compounds to the water quality derives principally from their strong ligands and hence their effect on availability and geochemical mobility of metal ions and other elements (Schlesinger, 1977, Aiken *et al* 1985, Thurman, 1986). In addition, high DOC concentrations in the waters may also have important consequences for the maintenance of water distribution systems, design of water treatment processes, and operation of groundwater extraction.

In summary, analysis of key water quality parametres (Tables 3 and 9) indicates that turbidity exceeded 5 ntu in 19.0% of the samples, TN concentrations exceeded 1.0 mg/l in 35.3% of the samples, and TP concentrations were above 0.1 mg/l in 9.8% of the samples. Ammonium-N and nitrate-N concentrations were equal to or exceeded 0.1 mg/l in 15.3 and 8.7% of the samples, respectively. Calculated free ammonia concentrations according to Effler *et al* (1990) were in general below 0.005 mg $NH_3$-N/l but could reach 0.060 mg/l in some eutrophic pools. Non-ionized $NH_3$ is toxic to freshwater fish at concentrations above approximately 0.03 mg/l (Whitelaw and Solbé, 1989). Fluoride ion concentration was between 0.1 and 0.3 mg/l, except in the case of strongly evaporated waters, where it could reach over 3 mg/l. Swamp waters were generally of poor quality; the more stagnant the waters, the more degraded the quality, partly as a result of being more concentrated by evapotranspiration, and partly as result of processes described above. The waters in river channels were, in general, of good quality. Nevertheless, temporary deterioration of water quality may occur downstream of villages and tourist lodges. The raw water in the lower reaches of the Delta downstream of the Buffalo fence was often of low quality and therefore unsuitable for human consumption.

*Implications for management and suggestions for further studies.*

A basic premise in management of the Delta, as currently accepted, is that there will be no major alteration of the hydrology of the Delta proper as a result of human intervention. However, offtakes of up to 3% of the inflow of the Kawango River upstream of the Panhandle, and outside Botswana, may become a reality in the near future (Petitjean and Davies, 1988). Thus, management should be oriented towards the operational maintenance of an acceptable environmental quality in the face of seasonal variability and occurrence of extreme events, such as droughts. Upstream offtakes would, of course, have the largest impact during drought periods, by further increasing dry areas, lowering the water table, and increasing the surface area exposed to oxidation.

Seasonal water level variations have important and predictable consequences for the water chemistry, phytoplankton and emergent plant production, but little is known of the effects of prolonged drought on these. There are numerous studies of the wet/dry cycle effects on the water quality in wetlands but only a few studies in the temperate zone were based on field experiments (Freeman *et al*, 1993, 1994). These studies suggest a reversal of many functions in the wetlands during droughts, leading to changes in hydrochemistry but not necessarily detrimental to water quality. Relatively less organic and more inorganic solutes would be released during drought periods. These findings cannot be directly related to the Okavango but they suggest important consequences for the uses of the surface and ground waters of the region

in drought and post-drought periods.

Although it is not possible to identify and detail all impacts on the water quality, it is certain that water quality always deteriorates with increasing human use. Consequently, deterioration of the Delta water quality from previous use of insecticides is to be expected. While it is essential to further investigate their impact on biota it is equally important to evaluate the relative contribution of various long-range sources, some of which still operate.

## The Kwando/Linyanti/Chobe River

*Chemistry of the waters. Comparison with the Okavango and Zambezi Rivers*

Like the Okavango Delta, the Linyanti (Fig 4) encompasses a variety of physiographic features and aquatic habitats. Along the upper reaches of the Kwando River the main channel is confined on its right bank but forms a narrow floodplain on the Namibian side. Below about Horseshoe Bend the river divides in a number of smaller channels forming the swamps proper, with open water lagoons in a few locations. For 30 km downstream from Sajawa the channel is confined on its right margin by an incised bank, but again flows within a narrow floodplain downstream from there. Further below Shaile the channel becomes ill defined and remains so until about 5 - 10 km SW of Ngoma bridge. From that point the Chobe River flows within a floodplain, interspersed with a few sand banks until its confluence with the Zambezi below Kazungula. At the time of the surveys, most of the floodplain north of Kachekau was dry as was the floodplain in the Kavimba area. The water depth in the Kwando and Linyanti Rivers was about 2 to 3 m. The water depth in the channel at Ngoma bridge was between 1.8 and 2.0 m in April 1992, but only a few decimetres in November 1992 as the waters had by then receded, leaving only a few depressions with strongly evaporated water. The water depth at mid channel of the Chobe River at Kasane was 5.1 m and about 2.6 m at the Chobe Game Lodge river front during April 1992.

Within this largely inaccessible system of swamps and channels of the Linyanti, the processes of water flow, spilling, and sedimentation must be complex but they remain to be studied. The hydrology of the system is not well known. A schematic outline indicates that the water of the Linyanti River waters is partly derived from the Kwando and partly from spilling from the swamps, while the water of the Chobe downstream of Ngoma bridge mainly comes from the Zambezi River backflow. The geomorphological context of the Chobe/Zambezi results in the Chobe River flowing eastwards towards the Zambezi when the latter is in receding phase (October) but when the upper Zambezi floods (peak in April), the flow reverses. Information on the Linyanti and upper Zambezi is scarce (Davies, 1986). Man-made alterations to their basins, such as withdrawals from the Zambezi to supply areas further south, or drainage of the Barotse and Chobe swamps to alleviate inflow deficits to the Kariba Reservoir have been proposed (Petitjean and Davies, 1988, Pinay, 1988). The effects of the natural flow variations contributed by the various sources, on the chemistry and microbiota of the river water are not known nor are ecological consequences, as a result of the proposed alterations.

The chemical data obtained in the two surveys are summarised in Table 14. The data are too limited to allow an evaluation of water quality. They do suggest, however, that the chemical composition of the Kwando may differ from that of the Okavango River. The Kwando waters have a higher ionic content, lower pH, and higher sulphate concentrations than the Okavango River water, and both rivers were poor in nutrients. The composition of Chobe water

seemed to be similar to that of the Zambezi at Kariba inflow, based on the only available data for the upper Zambezi catchment (Balon and Coche, 1974, Davies, 1986). Both the Okavango and Kwando rivers drain mineral-poor catchments with similar lithology and land-use. The higher total ionic content observed in the latter may possibly be related to the catchment morphology which results in higher runoff from overland flow in the Kwando. The isotope data did not show a consistent pattern. For example, $\delta^{18}O$ values in the Kwando, from Horseshoe Bend to Shumamorei ranged from +1.43 to -0.11‰, increasing again to +1.88 ‰ at Sajawa. Isotope values may thus be related to the complex flow pattern of the river, which has an irregular and meandering pattern, with sinuosities and blockages where the flow is much reduced or stagnant.

It is interesting to note that the highest salt concentration ever recorded in surface waters in the Okavango or Linyanti was in one of the pools at Ngoma bridge area in November 1992. Water in this pool reached a salinity of 27500 µS/cm, was moderately alkaline (pH 8.55), and had a high concentration of sulphate (500 mg/l), total N (6.45 mg/l), and total P (0.345 mg/l).

*Bacteria assemblages and phytoplankton communities*

A preliminary screening of Gram negative fermentative bacteria of public health interest from the Linyanti waters showed the presence of species similar to that of the Okavango (Table 9), with the possible exception of a fish pathogen *Vibrio anguillarum* which was only detected in some eutrophic waters of the Linyanti system, such as King´s pool (as well as in Lake Ngami) but was not detected in the Okavango waters.

Both the Kwando and Linyanti Rivers had few phytoplankton species and low total biomass (0.02 to 0.32 mg/l). *Cryptomonas*, *Cyclotella*, and *Synedra* were the dominant species in both habitats (Table 12). The Chobe River had a higher phytoplankton biomass (0.05 to 0.86 mg/l) than the Linyanti. Blue-green algae *Microcystis aeruginosa* and the diatoms *Aulacoseira* and *Cyclotella* were the most common. Hardly any zooplankton were recorded from the running waters of the Linyanti (Table 12), whereas large numbers of zooplankton were recorded in the Chobe River at the Game Lodge river front. Nauplius larvae dominated the zooplankton fauna but cladocera *Ceridaphnia* were also abundant. Rotifers belonging to the genera *Brachionus*, *Keratella*, and *Hexarthra* were also recorded. In general, locations with high phytoplankton biomass also had rich zooplankton communities.

In summary, planktonic communities of the Kwando/Linyanti/Chobe River were similar to those found in the Okavango Delta. The relatively greater richness of the latter was probably related to the greater variety of habitats within the Delta which resulted in the development of specific communities. However, it should be noted that the swamp areas in the Linyanti system have not yet been investigated. It may well be that comparable species richness will be found in both systems when the Linyanti swamps are fully investigated.

It is interesting to compare the phytoplankton of the Okavango Delta and Kariba reservoir, two systems with widely different morphology and physiography but both located at the same latitude. Although many species are common to both systems, the composition of the phytoplankton communities are different. In particular, the Kariba phytoplankton population has fewer species. The greater species diversity of the Delta is particularly pronounced among the green-algal flora. However, a rich green-algal flora has also been recorded in Kariba shortly after filling of the reservoir, but a large number of these species has gradually disappeared (Thomasson, 1965, 1980).

## Conclusions

The work reported here has shown that the natural variation results, as anticipated, in considerable uncertainty in interpretation of environmental data. These findings are particularly important because they demonstrate that water quality indicator variables cannot be based on average values. Since rainfall varies greatly from year-to-year in climates such as Botswana, import of salts and suspended sediments into the Delta is also highly variable. This suggests, therefore, that future water quality models should be based on a probabilistic rather than deterministic approach.

Although the present report was mainly dedicated to investigation of the Okavango's water quality from a practical perspective, it also provided a glimpse of a narrow portion of the trophic chain of the system, from bacteria to invertebrates. There are, however, a few general points to be made regarding the results of this study. First, there is the question of scale which implies that the present findings are of limited value unless they are placed in the context of the long-term perspective of the hydrobiological status of the Delta. Second, the question of method, which implies that, although the composition of the populations of various organisms is essential information, simply cataloguing species does not provide a very useful insight into the system function. Finally, there is the question of representativeness of the data, which is a direct consequence of the great spatial heterogeneity within the system, and the lack of detailed hydrological information in general and on the swamp areas in particular. To the latter factors should be added the paucity of knowledge on essential links between metal biochemistry and geochemistry, as well as on the inter-relationships between chemical species and biotic communities.

The present studies also expose some of the large gaps in knowledge of the Okavango and Linyanti. As with West African wetlands (John, 1986), more attention has so far been given to descriptive studies, often confined to short periods of time, than to dynamic and functional aspects of the hydrobiology and ecology. In that regard it would be worthwhile to study the extent to which some paradigms of tropical limnology, largely established for temperate regions (Lewis, 1987, Williams, 1988, Heckman, 1994), deviate from experience in tropical wet-dry climatic zone wetlands, of which the Okavango is only one example. These aspects as well as the application of models in designing long-term monitoring strategies and in interpreting the variation of water quality will be examined in a forthcoming publication.

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Table 1: Transect Location, co-ordinates and short description of major habitat features (as in March 1994)

| Transect | nr | Transect length (km) | Number of sampling locations | Average distance between sampling locations (km) | Coordinates of locations defining the transect Lat (S) D M S | Long (E) D M S | Major habitat features |
|---|---|---|---|---|---|---|---|
| Duba Island | 1 | 12.8-14.0 | 5 | 3.4 | 19 00 47<br>18 55 29 | 22 31 54<br>22 37 16 | Main channel: Jao take off; thin papyrus margins. Floodplain: perennial, mixed papyrus/reeds,floating vegetation; thin to thick papyrus. |
| Moshupatsila | 2 | 13.3-15.2 | 6 | 2.8 | 19 10 07<br>19 05 14 | 22 34 55<br>22 39 36 | Main channel: dense papyrus margins, shallow. Floodplain: perennial; network of pools and channels; floating vegetation. |
| Madinare | 3 | 12.6-15.2 | 7 | 2.3 | 19 13 17<br>19 08 40 | 22 38 03<br>22 42 44 | Main channel: papyrus margins, floating vegetation. Floodplain: perennial, papyrus, reeds, low to dense floating vegetation; densely grassed. |
| Tichira | 4 | 21.7-22.0 | 7 | 3.6 | 19 23 20<br>19 14 37 | 22 39 23<br>22 47 38 | Channels: shallow, papyrus margins, few floating vegetation. Floodplain: perennial, shallow, reeds, papyrus, floating vegetation. |
| Xo-site 9 | 5 | 29.8-30.4 | 9 | 3.8 | 19 29 58<br>19 19 17 | 22 40 37<br>22 53 14 | Channels: open water, papyrus margins, reed beds, floating vegetation. Floodplain: seasonal, wet/dry, open pools in heavily vegetated floodplain, floating vegetation. |
| Xo flats | 6 | 32.2-36.8 | 11 | 3.4 | 19 37 59<br>19 25 41 | 22 45 41<br>23 00 12 | Channels: open water, reed beds, floating vegetation. Southermost boundary of papyrus. Floodplain: seasonal, shallow, wet/dry, reed beds, floating vegetation. |
| Xaxaba | 7 | 13.3-15.8 | 7 | 2.4 | 19 36 27<br>19 31 22 | 22 59 45<br>23 04 49 | Main channel: open water, emergent reeds. Floodplain: seasonal, wet/dry, very shallow, floodplain pools with grass and reeds. |
| Mporota | 8 | 15.8-17.5 | 6 | 3.3 | 19 41 56<br>19 34 59 | 23 08 28<br>23 14 49 | Main channel: open water, floating vegetation, emergent reeds. Floodplain: seasonal, wet/dry, shallow, dense grass cover. |
| Bokwi | 9 | 13.1-14.0 | 4 | 4.5 | 19 47 39<br>19 41 55 | 23 15 35<br>23 19 05 | Main channel: floating and submerged vegetation. Floodplain: seasonal, wet/dry, densely vegetated. |
| Thokatsebe [a)] | 10 | | 1 | | 19 47 22 | 23 19 36 | Main channel: floating and submerged vegetation. |
| Buffalo fence | 11 | 10.2-10.5 | 3 | 5.2 | 19 52 09<br>19 48 03 | 23 22 01<br>23 26 09 | Main channel: floating and submerged vegetation. Floodplain: small pools in wet/dry floodplain; grass, sedges, few reeds. |
| Boro junction [a)] | 12 | | 1 | | 19 55 00 | 23 30 59 | Main channel: floating vegetation. |

a) Boro River

| Date | 2/89 | 5/89 | 10/89 | 2/90 | 4/90 | 11/91 | 3/92 | 7/92 | 10/92 | 3/94 |
|---|---|---|---|---|---|---|---|---|---|---|
| Type a) | | | | | | | | | | |
| Channels | x | x | x | x | x | x | x | x | x | x |
| Swamps | | | | | x | x | | x | x | x |
| Isolated pools | | | | | x | x | | x | x | x |
| Available data: | | | | | | | | | | |
| Major elem. b) | x | x | x | x | x | x | x | x | x | x |
| Minor elem. c) | x | x | x | x | x | x | x | x | x | x |
| Nutrients d) | | | | | | x | x | x | x | x |
| Transition metals e) | | x | x | x | | | | | x | x |
| Dissolved org. carbon | | | | | | x | x | x | x | x |
| Phytoplankton | | | x | | | x | x | x | x | x |
| Zooplankton | | | | | | x | x | | x | |
| Bacterial numbers | | | | | | x | | | x | |

a) Type of sampled location: Channels: are defined as areas with active flow which includes river channel, secondary channels, and lagoons formed in broader parts of the main channel. Swamps are defined as swamp areas, floodplains, and lagoons and include areas of open water, with or without vagetation, which maintained hydrological continuity with surrounding areas. Swmps had usually low flow velocity or were stagnant. Isolated pools: pools, puddles, or pans with stagnant water, apparently without hydrological continuity with tneighbouring surface waters; b) Base cations, $HCO_3^-$, $Cl^-$, $SO_4^{2-}$, and $SiO_2$; c) Fe, Mn, and Al; d) Total N, total P, nitrate, and ammonium; e) $Zn^{2+}$, $Cu^{2+}$, $Pb^{2+}$, $Ni^{2+}$, $Cd^{2+}$, $Co^{2+}$, and total Cr.

**Table 2: Type of sampled location, dates of sampling, and available hydrobiological data (Jao/Boro system)**

| | Units | n | Mean | St. dev. | Min. | Max. | Median |
|---|---|---|---|---|---|---|---|
| SC | µS/cm | 367 | 86.0 | 90.9 | 29.1 | 1600 | 75.6 |
| pH | | 344 | 7.0 | 0.4 | 5.6 | 8.8 | 7.0 |
| Temp. | °C | 282 | 23.6 | 4.3 | 12.6 | 34.2 | 25.0 |
| DO a) | % sat. | 275 | 81.9 | 31.6 | 10.0 | 167 | 82.5 |
| Turb. | ntu | 253 | 5.91 | 23.9 | 0.3 | 289 | 1.46 |
| $Ca^{2+}$ | mg/l | 361 | 4.70 | 2.40 | 0.76 | 17.2 | 4.40 |
| $Mg^{2+}$ | " | 362 | 1.71 | 1.14 | 0.34 | 13.4 | 1.42 |
| $Na^{+}$ | " | 363 | 5.24 | 2.83 | 1.14 | 28.0 | 4.97 |
| $K^{+}$ | " | 358 | 3.48 | 2.78 | 0.55 | 25.0 | 2.92 |
| $HCO_3^-$ | µequiv/l | 345 | 676 | 305 | 115 | 1750 | 627 |
| $Cl^-$ | mg/l | 358 | 1.68 | 1.41 | 0.3 | 11.2 | 1.21 |
| $SO_4^{2-}$ | " | 328 | 0.29 | 0.48 | 0.02 | 6.54 | 0.17 |
| $SiO_2$ | " | 326 | 15.5 | 8.2 | 3.2 | 71.1 | 13.4 |
| DOC | " | 181 | 27.3 | 23.7 | 3.4 | 105 | 17.0 |
| Total N | " | 207 | 1.140 | 1.160 | 0.230 | 9.400 | 0.800 |
| $NO_3^-$-N | " | 230 | 0.072 | 0.147 | 0.005 | 0.910 | 0.020 |
| $NH_4^+$-N | " | 229 | 0.069 | 0.135 | 0.005 | 1.600 | 0.030 |
| Total P | " | 205 | 0.068 | 0.126 | 0.010 | 0.950 | 0.034 |
| Chlo.*a* | µg/l | 263 | 12.2 | 40.7 | 0.2 | 412 | 2.7 |
| Fe total | " | 268 | 51.5 | 42.6 | 7.5 | 175 | 28.0 |
| Fe filt. | " | 266 | 17.6 | 13.5 | 2.4 | 91 | 12.8 |
| Mn total | " | 268 | 10.6 | 9.4 | 3.0 | 78.2 | 7.1 |
| Mn filt. | " | 268 | 5.6 | 7.8 | 1.0 | 98.6 | 3.5 |
| Al total | " | 248 | 13.7 | 18.1 | 1.0 | 139 | 8.8 |
| Al filt. | " | 247 | 3.6 | 4.6 | 0.2 | 40.5 | 2.5 |

a) Daytime dissolved oxygen saturation.

**Table 3:** Summary of statistics of major physichemical variables in the Jao/Boro system

| | Habitat 1 | | Habitat 2 | | Habitat 3 | | Habitat 4 | |
|---|---|---|---|---|---|---|---|---|
| | Jao/Boro River | | Swamps and floodplains | | Perennial swamps | | Seasonal swamps | |
| | x±sd | med | x±sd | med | x±sd | med | x±sd | med |
| SC | 69.1±25.0 | 66.4 | 83.6±35.0 | 78.2 | 54.1±15.8 | 51.0 | 91.0±31.9 | 86.6 |
| pH | 6.9±0.5 | 7.0 | 7.1±2.2 | 6.9 | 6.8±0.4 | 6.9 | 6.8±0.5 | 7.0 |
| Temp. | 24.0±3.8 | 25.2 | 23.1±4.9 | 24.1 | 24.2±3.4 | 25.0 | 23.4±4.2 | 25.0 |
| DO | 78.2±33.4 | 70.5 | 83.7±29.6 | 87.0 | 68.6±31.9 | 65.0 | 90.1±28.7 | 92.0 |
| Turb. | 2.48±3.88 | 1.23 | 6.48±2.11 | 1.52 | 2.42±2.29 | 1.88 | 7.26±30.9 | 1.36 |
| $Ca^{2+}$ | 4.41±2.63 | 4.30 | 4.73±2.27 | 4.32 | 3.43±1.52 | 3.13 | 5.32±2.69 | 4.74 |
| $Mg^{2+}$ | 1.48±0.83 | 1.23 | 1.88±1.36 | 1.58 | 1.18±0.37 | 1.15 | 1.80±1.16 | 1.80 |
| $Na^{+}$ | 4.36±2.14 | 4.50 | 5.64±2.89 | 5.37 | 3.00±1.67 | 2.61 | 5.91±1.92 | 5.63 |
| $K^{+}$ | 2.92±1.91 | 2.57 | 3.59±2.63 | 3.05 | 2.41±1.00 | 2.31 | 3.77±2.74 | 3.15 |
| $HCO_3^{-}$ | 598±224 | 588 | 706±328 | 648 | 445±126 | 443 | 764±301 | 706 |
| $Cl^{-}$ | 1.47±1.97 | 1.00 | 1.73±1.25 | 1.33 | 0.94±0.44 | 0.88 | 1.76±1.11 | 1.36 |
| $SO_4^{2-}$ | 0.23±0.20 | 0.18 | 0.32±0.79 | 0.17 | 0.23±0.17 | 0.20 | 0.29±0.36 | 0.19 |
| $SiO_2$ | 15.9±8.22 | 13.0 | 14.9±7.6 | 13.2 | 16.6±9.0 | 13.0 | 15.6±8.1 | 13.4 |
| DOC | 21.2±14.6 | 15.9 | 21.0±14.5 | 17.0 | 20.9±16.9 | 15.0 | 22.5±14.9 | 17.8 |
| Total N | 1.023±0.942 | 0.640 | 0.923±1.005 | 0.800 | 0.807±1.012 | 0.450 | 1.213±0.856 | 0.970 |
| $NO_3^{-}$-N | 0.074±0.104 | 0.020 | 0.074±0.151 | 0.020 | 0.032±0.037 | 0.020 | 0.091±0.166 | 0.030 |
| $NH_4^{+}$-N | 0.079±0.237 | 0.020 | 0.050±0.062 | 0.030 | 0.064±0.170 | 0.020 | 0.071±0.163 | 0.030 |
| Total P | 0.038±0.031 | 0.030 | 0.054±0.076 | 0.034 | 0.031±0.030 | 0.023 | 0.059±0.072 | 0.038 |
| Chlo.*a* | 9.25±49.69 | 1.94 | 10.1±33.2 | 3.00 | 2.14±1.50 | 1.87 | 14.0±50.7 | 2.93 |
| Fe total | 63.3±44.9 | 57.4 | 50.3±64.5 | 25.0 | 63.7±38.9 | 54.8 | 44.3±43.3 | 24.8 |
| Fe filt. | 16.3±10.0 | 11.4 | 18.6±15.6 | 13.4 | 22.8±7.9 | 19.0 | 16.0±14.1 | 10.8 |
| Mn total | 11.0±8.5 | 6.8 | 9.9±8.6 | 6.5 | 8.1±7.1 | 5.2 | 9.4±8.1 | 6.8 |
| Mn filt. | 7.0±6.4 | 4.2 | 5.3±4.3 | 3.6 | 5.4±4.3 | 3.4 | 5.8±5.4 | 3.6 |
| Al total | 19.7±23.5 | 13.0 | 18.2±24.2 | 10.8 | 9.9±5.8 | 9.0 | 23.5±29.3 | 13.4 |
| Al filt. | 4.2±3.6 | 3.7 | 5.5±6.1 | 4.0 | 3.1±2.5 | 2.0 | 6.1±5.2 | 4.2 |

Units as in Table 3.

**Table 4:** **Estimated average concentration of major chemical constituents in the Jao/Boro River, swamps and floodplains, perennial swamp areas, and seasonal swamp areas (habitats 1 to 4, see text).**

| | Group 1 | | Group 2 | |
|---|---|---|---|---|
| Variable | Chi-square | p-value | Chi-square | p-value |
| SC | 7.54 | 0.0060 | 89.96 | 0.0000 |
| pH | 1.37 | 0.2426 | 0.08 | 0.7739 |
| Temp. | 4.19 | 0.0407 | 0.05 | 0.8318 |
| DO | 10.60 | 0.0011 | 23.51 | 0.0000 |
| Turbidity | 0.88 | 0.3492 | 0.29 | 0.5933 |
| $Ca^{2+}$ | 0.00 | 1.0000 | 1676 | 0.0000 |
| $Mg^{2+}$ | 24.72 | 0.0000 | 44.37 | 0.0000 |
| $Na^{+}$ | 16.38 | 0.0001 | 110.78 | 0.0000 |
| $K^{+}$ | 11.16 | 0.0008 | 22.89 | 0.0000 |
| $HCO_3^-$ | 4.16 | 0.0413 | 76.23 | 0.0000 |
| $Cl^-$ | 19.87 | 0.0000 | 40.95 | 0.0000 |
| $SO_4^{2-}$ | 0.60 | 0.4386 | 0.70 | 0.4039 |
| $SiO_2$ | 0.04 | 0.8430 | 0.17 | 0.6826 |
| DOC | 0.29 | 0.5908 | 1.54 | 0.2143 |
| Chlor. *a* | 7.13 | 0.0076 | 11.08 | 0.0009 |
| Total N | 1.88 | 0.1708 | 40.03 | 0.0000 |
| $NO_3^-$-N | 0.75 | 0.3881 | 0.44 | 0.5058 |
| $NH_4^+$-N | 6.10 | 0.0135 | 6.68 | 0.0097 |
| Total P | 1.61 | 0.2041 | 19.44 | 0.0000 |
| Fe total | 6.03 | 0.0140 | 4.86 | 0.0275 |
| Fe filtered | 13.64 | 0.0002 | 12.13 | 0.0005 |
| Mn total | 0.26 | 0.6135 | 3.27 | 0.0706 |
| Mn filterd | 3.61 | 0.0575 | 0.61 | 0.4355 |
| Al total | 3.43 | 0.0641 | 0.67 | 0.4128 |
| Al filtered | 0.83 | 0.3627 | 2.86 | 0.0910 |

**Table 5:** **Median test for pairs of groups. Group 1: Jao/Boro River versus Swamps and floodplains; Group 2: Perennial swamps *versus* Seasonal swamps.**

| | Nov 1991 | | Oct 1992 | | |
|---|---|---|---|---|---|
| **Variable** | **Mean ±sd** | **Median** | **Mean ±sd** | **Median** | **Effect of discharge (Q)** |
| Total N | 3.07±1.61 | 3.40 | 0.76±0.26 | 0.78 | Decrease with Q |
| $NH_4^+$-N | 0.102±0.144 | 0.040 | 0.030±0.048 | 0.010 | " |
| $Cl^-$ | 2.63±1.65 | 2.23 | 1.82±1.44 | 1.00 | " |
| pH | 7.51±0.04 | 7.50 | 6.47±0.50 | 6.20 | " |
| $Ca^{2+}$ | 4.39±1.07 | 4.67 | 2.54±1.00 | 2.33 | " |
| $K^+$ | 2.90±0.97 | 2.91 | 2.48±1.66 | 2.01 | " |
| SC | 91.1±35.3 | 85.0 | 74.2±35.2 | 69.7 | " |
| DOC | 30.6±26.8 | 20.6 | 19.5±9.5 | 17.5 | " |
| $Na^+$ | 5.15±2.35 | 5.34 | 4.56±2.54 | 4.51 | " |
| $SiO_2$ | 14.3±7.2 | 12.6 | 12.2±4.1 | 12.0 | Unaffected |
| $SO_4^{2-}$ | 0.36±0.42 | 0.30 | 0.28±0.17 | 0.23 | " |
| Total P | 0.042±0.014 | 0.042 | 0.037±0.020 | 0.031 | " |
| $NO_3^-$-N | 0.013±0.009 | 0.010 | 0.046±0.120 | 0.010 | " |
| $HCO_3^-$ | 734±301 | 686 | 727±318 | 770 | " |
| Chlor.*a* | 4.53±7.04 | 2.01 | 6.86±6.10 | 4.00 | " |
| $Mg^{2+}$ | 1.13±0.14 | 1.14 | 1.67±0.61 | 1.50 | Increase with Q |
| DO | 68.0±22.1 | 67.0 | 87.0±32.0 | 88.0 | " |
| Turbidity | 2.00±1.57 | 1.52 | 4.00±3.71 | 2.60 | " |

Units as in Table 3.

Table 6: **Effect of discharge on the concentration of selected variables. Total volumetric flow at Mohembo in the 365 days preceding the date of sampling were $6.99 \times 10^9 m^3$ (Nov 1991) and $9.37 \times 10^9 m^3$ (Oct 1992)**

| | Units | (1) Sepopa | (2) Ghanzi | (3) Kasane | (4) Maun | (5) Nata | (6) Roodeplaat | (7) E.Transvaal | (8) Namibia | (9) Kenya |
|---|---|---|---|---|---|---|---|---|---|---|
| SC | µS/cm | 38 | 25 | 15 | 16 | 14 | 22-36 | | | 31 |
| pH | | 4.3-5.3 | | | | | 3.9-4.4 | 3.9-4.8 | | 4.3 |
| Ca | mg/l | 0.30-0.34 | 0.80 | 0.90 | 0.54 | 0.73 | 0.7-2.3 | | 0.42 | 0.2-0.8 |
| Mg | " | 0.29-0.40 | 0.15 | 0.60 | 0.35 | 0.16 | 0.2-0.6 | | | 0.04-0.2 |
| Na | " | 0.27-0.88 | 0.64 | 1.40 | 0.31 | 1.11 | 0.4-1.0 | | | 0.3-1.0 |
| K | " | 0.19-0.22 | 0.81 | 2.00 | 0.32 | 0.67 | <0.1-1.0 | | 0.09 | 0.2-0.6 |
| $Cl^-$ | " | 0.26-0.3 | 0.46 | 0.36 | 0.34 | 0.53 | 0.8-1.7 | 0.1-4.1[c)] | 0.62 | 0.34-1.0 |
| S | " | 1.6-2.9 [a)] | | | | | | 11-52[d)] | 0.26 | |
| $SO_2$ | " | | | | | | | 3.4-15.9 | | |
| $SO_4^{2-}$ | " | 1.39 [b)] | 1.25 | 1.10 | 1.09 | 0.81 | 2.9-5.7 | 3.4-15.1[c)] | | 0.35-1.74 |
| $NO_3^-$-N | " | | 2.51 | 1.18 | 1.40 | 0.91 | 0.1-0.7 | 0.4-6.8 [c)] | | <0.1-0.8 |
| $NH_4^+$-N | | " | | | | | 0.3-0.6 | | | <0.1-0.23 |
| Total P | " | | | | | | 0.04-0.27 | | | |
| DOC | " | | | | | | 1.9-11.1 | | | |
| Fe | µg/l | 4.8-9.8 | | | | | 34-452 | | 0.25 | |
| Mn | " | 0.6-1.4 | | | | | 21-77 | | c. 0.004 | |
| Al | " | | | | | | 34-267 | | | |
| Zn | " | 1.8-14.8 | | | | | <1-70 | | 0.0003 | |
| Cu | " | 1-8 | | | | | 7-248 | | 0.0008 | |
| Ni | " | 0.5-6.0 | | | | | 7-447 | | 0.0015 | |
| Pb | " | 0.7-1.4 | | | | | 16-57 | | <0.0003 | |
| Br | " | 0.3-0.7 | | | | | 0.00018 | | | |
| Sr | " | 1.2-6.2 | | | | | c. 0.003 | | | |

(1) Bulk precipitation, one event Sepopa, 22.11.1991 ($\delta^{18}O$, -3.18) and one event Tichira, 17.3.1992 ($\delta^{18}O$, -1.92); (2) Ghanzi, average of bulk precipitation, 7.10.89-12.5.90 (Gieske, 1992, Selaolo et al., 1994); (3) idem, period 21.3.89-29.4.90; (4) idem, period 15.11.89-29.4.90; (5) idem, period 15.11.89-28.4.90; (6) Bulk precipitation South Africa (Bosman and Kempster, 1985); (7) Bulk precipitation (Tyson et al., 1988); (8) Background concentration in $\mu g/m^3$ (Annegarn et al., 1983); (9) Wet precipitation (Rodhe et al., 1981);

(a) Absolute mass of sulphur; (b) Maun airport, 1989; (c) Aerosol concentration in $\mu g/m^3$; (d) Unit kg/ha/yr, this value indicates that S bulk deposition could exceed up to 8 times of that of S wet deposition.

**Table 7: Comparison of precipation chemistry in Southern and East Africa**

| Location | Date | Rate (mm/day) |
|---|---|---|
| lower Boro (Prison farm) | Nov 1991 | -0.25 |
| Lake River (bund) | " | +5.00 |
| Boro junction | March 1992 | -2.76 |
| lower Boro (Prison farm) | " | -1.45 |
| Buffalo fence | " | -3.67 |
| Tichira | " | -2.90 |

Note: negative rates indicate seepage from pore water to surface water.

**Table 8: Seepage rates (mm/day) at lower Boro and Tichira**

**Table 9:** **Bacterial assemblages from the Okavango Delta and Kwando/Linyanti/Chobe River surface waters represented by strains isolated from R2A and VRBG and identified by the Biolog rapid identification system**

| Identification | Okavango from R2A | Okavango from VRBG | Linyanti from VRBG |
|---|---|---|---|
| **Gram positive isolates:** | | | |
| *Arcanobacterium haemolyticum* | 1 | | |
| *Bacillus* sp | 1 | | |
| *Bacillus insolitus* | 10 | | |
| *Curtobacterium citreum* | 1 | | |
| *Corynebacterium jeikeium* | 6 | | |
| *Micrococcus luteus* | 1 | | |
| *Streptococcus sobrinus* | 4 | | |
| **Non identified Gram positive rods**[a] | 25 | | |
| **Gram negative isolates:** | | | |
| *Acinetobacter baumannii* | | | 1 |
| *Acinetobacter* sp | | | 1 |
| *Alcaligenes xylosoxidans* | | 1 | |
| *Aeromonas hydrophila* | | 6 | 3 |
| *Aeromonas jandei* | | 19 | 1 |
| *Aeromonas media*-like | | 2 | 1 |
| *Aeromonas schubertii* | | | 1 |
| *Aeromonas veronii* | | 6 | 1 |
| *Aeromonas* spp | | 11 | 1 |
| *Brucella abortus* | 2 | | |
| *Chromobacterium violaceum* | 2 | 1 | |
| *Edwardsiella tarda* | | 4 | |
| *Enterobacter* spp | | 2 | 2 |
| *Enterobacter agglomerans* | | 3 | 1 |
| *Enterobacter cloacae* B | | 1 | 1 |
| *Enterobacter intermedius* | | 1 | |
| *Enterobacter taylorae* | | 1 | |
| *Erwinia chrysantemii* | 1 | 2 | |
| *Escherichia coli* E | | 1 | |
| *Escherichia vulneris* | | 1 | |
| *Kingella kingae* | 1 | | |
| *Moraxella atlantae* | 1 | | |
| *Pantoea agglomerans* | | 1 | |
| *Plesiomonas shigelloides* | | 12 | 1[b] |
| *Pseudomonas* sp | 1 | | |
| *Pseudomonas citronellolis* | | 1 | |
| *Pseudomonas floridana* | 1 | | |
| *Pseudomonas fluorescens* C | | 1 | |
| *Pseudomonas fuscovaginae* | | 1 | |
| *Pseudomonas mendocina* | | 1 | |
| *Pseudomonas putida* B | 2 | | |
| *Pseudomonas stutzeri* | 1 | | |
| *Xanthomonas maltophila* | | 1 | |
| *Serratia fonticola* | | | 1 |
| *Serratia marcescens* | 1 | 2 | |
| *Shewanella putrefaciens* | | 1 | |
| *Vibrio anguillarum*[c] | | 1 | 2 |
| **Non identified Gram negative rods**[a] | 11 | 23 | 4 |

[a] 50% of strains isolated from R2A and 21% from VRBG could not be identified by the Biolog system.
[b] *Plesiomonas shigelloides*, opportunistic pathogen isolated from drinking water from stand pipe at camp site.
[c] Fish pathogen isolated from Lake Ngami (Okavango) and eutrophic pools (Linyanti).

| | | | | |
|---|---|---|---|---|
| *Escherichia vulneris* | | 1 | | 1 |
| *Kingella kingae* | 1 | 1 | | |
| *Moraxella atlantae* | 1 | 1 | | |
| *Pantoea agglomerans* | | 1 | | |
| *Plesiomonas shigelloides* | | 12 | 1[b] | |
| *Pseudomonas* sp | 1 | | | |
| *Pseudomonas citronellolis* | | 1 | | |
| *Pseudomonas floridana* | 1 | | | |
| *Pseudomonas fluorescens* C | | 1 | | |
| *Pseudomonas fuscovaginae* | | 1 | | |
| *Pseudomonas mendocina* | | 1 | | |
| *Pseudomonas putida* B | 2 | | | |
| *Pseudomonas stutzeri* | 1 | | | |
| *Xanthomonas maltophila* | | 1 | | |
| *Serratia fonticola* | | | 1 | |
| *Serratia marcescens* | 1 | 2 | | |
| *Shewanella putrefaciens* | | 1 | | |
| *Vibrio anguillarum*[c] | | 1 | 2 | |
| Non identified Gram negative rods[a] | 11 | 23 | 4 | |

[a] 50% of strains isolated from R2A and 21% from VRBG could not be identified by the Biolog system.

[b] *Plesiomonas shigelloides*, opportunistic pathogen isolated from drinking water from standing pipe at camp site.

[c] Fish pathogen isolated from Lake Ngami (Okavango) and eutrophic pools (Linyanti).

**Table 9 continued**

Table 10: Phytoplankton species recorded in the Okavango Delta, Maxegane pools, King's pool, and Lake Ngami. D, dominant species.

| Localities (see below table for meaning of codes) | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| **CYANOPHYCEA** | | | | |
| **Chroococcales** | | | | |
| *Aphanocapsa delicatissima* W. & G.S. WEST | x | x | | |
| *A. elachista* W.G.S. WEST | | x | x | |
| *A. nubilum* KOM. & KLING | | x | x | |
| *A. pulchra* (KÜTZ.) RABENH. | x | | x | |
| *Aphanothece stagnina* (SPRENG) A. BR. | x | | | |
| *Chroococcus aphanocapsoides* SKUJA | | | x | |
| *Chroococcus* cf. *koordesi* STRÖM | | | x | |
| *C. limneticus* LEMM. | x | x | x | |
| *Chroococcus* sp. | x | x | | |
| *Coelomoron* cf. *pusillus* (van GOOR) KOM. | | | x | |
| *Cyanodictyon imperfectum* CRONB. & WEIB. | | | x | |
| *Cyanodictyon* sp. | x | | | |
| *Cyanonephron styloides* HICKEL | x | x | x | |
| *Epigloeosphaera* sp. | x | | x | |
| *Johannesbaptista pellucida* TAYL. & DROUET | x | | | |
| *Merismopedia glauca* (E.) NÄG. | x | | | |
| *M. tenuissima* LEMM. | x | x | D | x |
| *Merismopedia* sp. 1 (diam = 0.8 μm) | | x | x | |
| *Merismopedia* sp. 2 (diam = 2-2.5 μm) | | x | | |
| *Mycrocystis aeruginosa* KÜTZ. | x | D | D | |
| *M. botrys* TEIL. | x | | x | x |
| *M. flos-aquae* (WITTR.) KIRCHN. | | D | | |
| *M. incerta* (LEMM.) LEMM. | x | | | |
| *M. wesenbergii* KOM. in KONDR. | x | | | |
| *Radiocystis* cf. *geminata* SKUJA | x | | x | |
| *Snowella lacustris* (CHOD.) KOM. & HIND. | x | | | |
| *S. litoralis* (HÄYR.) KOM. & HIND. | | | x | |
| *Woronichinia* cf. *compacta* (LEMM.) KOM. & HIND. | x | | | |
| **Nostocales** | | | | |
| *Anabaena* sp. | x | | | |
| *Anabaena* sp. 1 | | x | | |
| *Anabaena* sp. 2 (small spirals) | | x | | |
| *Aphanizomenon gracile* LEMM. | x | | | |
| *A. volzii* (LEMM.) KOM. | | x | | |
| *Aphanizomenon* sp. 1 | | x | | |
| *Cylindospermopsis africanum* KOM. & KLING | | x | | |
| *C. philipiniensis* (TAYL.) KOM. | x | x | x | |
| *C. raciborskii* (WOLOSZ.) SENN. & SUBBA RAJU | x | x | | |
| *Gloeotrichia* sp. | x | | | |
| **Oscillatoriales** | | | | |
| *Oscillatoria* sp. | x | | | |
| *Planktolyngbya circumcreta* (G.S. WEST) ANAGN. & KOM. | x | x | | |
| *P. tallingii* KOM. & KLING | x | x | | |
| *P. undulata* KOM. & KLING | | x | x | |
| *Planktothrix agardhii* (GOM.) ANGN. & KOM. | x | x | | |
| *Planktothrix raciborskii* (WOLOSZ.) ANAGN. & KOM. | x | x | | |
| *Pseudanabaena* sp. | x | | | |
| *Raphidiopsis mediterranea* SKUJA | | | | |
| *Romeria* sp. | | x | | |
| *Spirulina* sp. | x | | | |

**TABLE 10 continued**

| Localities | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Trichodesmium sp. | x | | | |
| **Stigonematales** | | | | |
| *Scytonema* sp. | x | | | |
| **DIATOMOPHYCEAE** | | | | |
| *Acanthoceras* sp. | x | | | |
| *Asterionella thomasonii* NAUW. | x | | | |
| *Aulacoseira granulata* (E.) SIM. | x | x | x | |
| *A. granulata* var. *angustissima* (MÜLL.) SIM. | x | | | |
| *Aulacoseira* spp. | x | x | x | |
| *Cyclotella* spp. | x | x | x | x |
| *Eunotia* cf. *zazuminensis* (CAB.) KÖRNER | x | | | |
| *Fragilaria crotonensis* KITTON | x | | | |
| *Rhizosolenia* cf. *eriensis* H.L. SMITH | | | x | x |
| *Rhizosolenia* cf. *longiseta* ZACH. | x | | | |
| *Synedra* spp. | x | x | x | |
| **CHRYSOPHYCEAE** | | | | |
| *Dinobryon* cf. *crenulatum* W. & G.S. WEST | x | | | |
| *D. divergens* IMH. | x | | | |
| *D. sertularia* E. | x | | | |
| *Mallomonas akrokomos* RUTTN. | x | | | |
| *M. bangladeshica* (TAK. & HAYEK) WUJEK & TIMPANO | x | | | |
| *M. favosa* NICHOLLS | x | | | |
| *M. mangofera* HARRIS & BRADLEY | x | | | |
| *M. mangofera* f. *foveata* DÜRRSCHMIDT | x | | | |
| *M. matvienkoae* var. *grandis* DÜRRSCHMIDT & CRONBERG | x | | | |
| *M. tonsurata* TEIL. | x | | | |
| *Mallomonas* spp. | x | | | |
| *Paraphysomonas* vestita (STOKES) de SAEDELEER | x | | | |
| *Synura australiensis* PLAYF. | x | | | |
| *S. echinulata* KORSHIKOV | x | | | |
| *Synura* sp. | x | | | |
| **XANTHOPHYCEAE** | | | | |
| *Centritractus africanus* FRITSCH & RICH | | x | x | |
| *Goniochloris smithii* (BOURR.) FOTT | x | x | | |
| *Pseudostaurastrum* sp. | | x | | |
| **CHLOROPHYCEAE** | | | | |
| **Volvocales** | | | | |
| *Eudorina elegans* E. | x | x | | |
| *Gonium pectorale* O.F. MÜLL. | x | x | | x |
| *Pandorina morum* (MÜLL.) BORY | | x | | x |
| *Pleudorina californica* SHAW | x | | | |
| *Volvox* sp. | x | | | |
| **Tetrasporales** | | | | |
| *Chlamydocapsa planctonia* (W. & G.S. WEST) FOTT | x | | | |
| *Pseudosphaerocystis lacustris* (LEMM.) NOV. | x | | | |
| **Chlorococcales** | | | | |
| *Actinastrum hantschii* LAGERH. | x | | | x |
| *Ankistrodesmus bernardii* KOM. | x | | | |
| *A. bribraianum* KORSH. | x | | | |
| *A. falcatus* (CORDA) RALFS | x | | | x |
| *A. fusiformis* CORDA sensu KORSH. | | x | x | |
| *A. gracilis* (REINSCH) KORSH. | x | x | x | x |

**TABLE 10 continued**

| Localities | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| *Ankyra* sp. | x | | | |
| *Botryococcus* cf. *neglectus* | x | | | |
| *Botryococcus* sp. 1 | | x | x | x |
| *Botryococcus* sp. 2 | | x | | |
| *Botryococcus* spp. | x | | | |
| *Coelastrum cambricum* ARCH. | x | | | |
| *C. microporum* NÄG. | x | x | | |
| *C. pseudomicroporum* KORSH. | | x | x | |
| *C. reticulatum* (DANG.) SENN. | | x | x | |
| *C. sphaericum* NÄG. | x | x | | |
| *Coelastrum* sp. | x | | | |
| *Crucigenia quadrata* MORREN | x | x | x | |
| *C. tetrapedia* MORREN | x | x | x | |
| *Crucigeniella apiculata* (LEMM.) KOM. | x | x | x | |
| *C. pulchra* (W. & G.S. WEST) KOM. | x | x | | x |
| *C. rectangularis* (NÄG.) KOM. | x | | | |
| *Dictyosphaerium ehrenbergianum* NÄG. | | x | | |
| *D. indicum* IYENG. & RAMANATH. | x | x | x | |
| *D. pulchellum* WOOD | x | x | x | |
| *D. tetrachotomum* PRINTZ | x | x | x | x |
| *Dimorphococcus lunatus* A. BR. | x | | | |
| *Elakathotrix biplex* HIND. | x | | | |
| *Elakathotrix gelatinosa* WILLE | | x | | x |
| *Golenkinia radiata* CHOD. | | x | | |
| *Kirchneriella contorta* (SCHMIDLE) BOHL | x | x | x | x |
| *K. lunaris* (KIRCHN.) MÖB. | x | x | x | |
| *K. obesa* (W. WEST) SCHMIDLE | x | | | |
| *Lagerheimia citriformis* (SNOW) COLLINS | x | | | |
| *L. subsala* LEMM. | | x | | |
| *Micractinium pusillum* FRES. | x | x | | x |
| *Monoraphidium contortum* (THUR.) KOM.-LEGN. | x | x | x | |
| *M. setiforme* (NYG.) KOM.-LEGN. | x | x | x | |
| *Oocystis solitaria* WITTR. in WITTR & NORDST. | x | | | |
| *Oocystis* sp. | x | | | |
| *Nephrocytium* sp. | x | | | |
| *Pediastrum angulosum* (E.) MENEGH. | x | | | |
| *P. biradiatum* MEYEN | x | x | | x |
| *P. boryanum* (TURP.) MENEGH. | x | x | | |
| *P. boryanum* var. *longicorne* REINSCH | x | x | | |
| *P. duplex* MEYEN | x | x | x | x |
| *P. duplex* var. *gracillimum* W. & G.S.WEST | | x | | x |
| *P. simplex* MEYEN | | x | | |
| *P. tetras* (E.) RALFS | x | x | | x |
| *Scenedesmus acuminatus* (LAGERH.) CHOD. | x | x | x | x |
| *S. arcuatus* (LEMM.) LEMM. | x | | | |
| *S. armatus* CHOD. | x | | | |
| *S. brasiliense* BOHL | x | | | |
| *S. dispar* (BRÉB.) RABENH. | x | x | | x |
| *S. opoliense* P. RICHT. | x | x | | x |
| *Scenedesmus* spp. | x | x | | x |
| *Selenastrum capricornutum* PRINTZ | x | | | |
| *Sorastrum spinulosum* NÄG. | x | x | | x |

**TABLE 10 continued**

| Localities | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| *Tetrallantos* cf. *lagerheimia* TEIL. | x | x | | x |
| *Tetraedron caudatum* (CORDA) HANSG. | x | | | |
| *T. minimum* (A.BR.) HANSG. | | x | | x |
| *Tetrastrum staurogeniaeforme* (SCHRÖD.) LEMM. | x | | | |
| *Treubaria planctonica* (G.M. SMITH) KORSH. | x | | | |
| *Westella Botryoides* (W.WEST) DE-WILD | x | | | |
| **Zygnematales** | | | | |
| *Allorgeia incredibilis* (GRÖNBL, PROWSE & SCOTT) THOM. | x | | | |
| *Bambusina brebissonii* KÜTZ. | x | | | |
| *Closterium aciculare* TUFFEN WEST | x | | | |
| *C. acutum* var. *variabile* (LEMM.) KRIEG. | x | | | |
| *C. gracile* (BRÉB.) RALFS | x | | | |
| *C. incurvum* BRÉB. | x | | | |
| *C. kuetzingii* BRÉB. | x | | | |
| *Cosmarium* spp. | x | | | |
| *Cosmocladium* sp. | x | | | |
| *Desmidium bailey* (RALFS) f. *tetragonum* NORDST. | x | | | |
| *D. grevillii* (KÜTZ.) DE BARY | x | | | |
| *Euastrum* subsp. *africanum* var. *minus* NORDST. | x | | | |
| *E. didelta* RALFS | x | | | |
| *E. elegans* (BRÉB.) KÜTZ. ex RALFS | x | | | |
| *Euastrum* spp. | x | | | |
| *Gonatozygon aculeatum* HAST | x | | | |
| *Hyalotheca dissiliens* (SMITH) BRÉB. in RALFS | x | | | |
| *H. mucosa* (MERT.) E. | x | | | |
| *H. undulata* NORDST. | x | | | |
| *Micrasterias alata* WALLICH | x | | | |
| *M. americana* (E.) RALFS var. *americana* | x | | | |
| *M. apiculata* (E.) MENEGH. ex RALFS | x | | | |
| *M. crux-melitensis* (E.) HASS | x | | | |
| *M. foliacea* BAIL. ex RALFS | x | | | |
| *M. mahabuleschwarensis* HOBSON | x | | | |
| *M. novae-terrae* (CUSHM.) W. KRIEG | x | | | |
| *M. pinnatifida* (KÜTZ.) RALFS | x | | | |
| *M. radians* TURN. | x | | | |
| *M. radians* (TURN.) var. *evoluta* (TURN.) KRIG. | x | | | |
| *M. radiata* (HASS.) var. *brasiliense* GRÖNBL. | x | | | |
| *M. radiosa* RALFS | x | | | |
| *M. sudanensis* BOURR. | x | | | |
| *M. tropica* NORDST. | x | | | |
| *M. zeylanica* FRITSCH f. | x | | | |
| *Mougeotia* sp. | x | | | |
| *Phymatodocis irregulare* SCHM. | x | | | |
| *Pleurotaenium nodulosum* (BAIL.) LUND | x | | | |
| *Sphaerozosma laeve* NORDST. | x | | | |
| *Spirogyra* sp. | x | | | |
| *Spondylosium nitens* f. *tensa* TURN. | x | | | |
| *S. planum* (WOLLE) W & G.S. WEST | x | | | |
| *Staurastrum bieneanum* RABNH. var. *brasiliense* GRÖNBL. | x | | | |
| *S. fuellerbomii* SCHMIDLE | x | | | |
| *S. leptocladium* var. *cornutum* f. *crassus* GRÖNBL. | x | x | | |
| *S. ophiurum* var. *cambricum* W. & G.S. WEST | x | | | |

**TABLE 10 continued**

| Localities | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| *S. paradoxum* var. *parvum* W. WEST | x | x | | x |
| *S. setigerum* CLEVE | x | | | |
| *S. spiculiferum* BORGE | x | | | |
| *S. stelliferum* var. *africanum* FRITSH & RICH | x | | | |
| *S. tetracerum* RALFS | x | | x | |
| *S.* cf. *tetracerum* RALFS | x | x | | |
| *S. tohopekaligense* WOLLE | x | | | |
| *S.* cf. *wildemannii* GUTW. | x | | | |
| *Staurastrum* spp. | x | | | |
| *Staurodesmus extensus* (BORGE) TEIL. | x | | | |
| *S. subulatus* f. *major* THOM. | x | | | |
| *Staurodesmus* spp. | x | | | |
| *Teilingia granulata* (ROY et BISS) BOURR. | x | | | |
| *Triploceras gracilis* BAIL. | x | | | |
| *Triploceras* spp. | x | | | |
| *Xanthidium subtrilobum* W. & G.S. WEST | x | | | |
| *Xanthidium* spp. | x | | | |
| **CRYPTOPHYCEAE** | | | | |
| *Cryptomonas* sp. | x | x | x | x |
| *Katablepharis ovalis* SKUJA | x | | | |
| *Rhodomonas* sp. | x | x | x | |
| **DINOPHYCEAE** | | | | |
| *Ceratium* cf. *furcoides* SCHRÖD. | x | | | |
| *Peridinium gatunense* NYG. | x | | | |
| *Peridinium* spp. | x | | | |
| *Peridiniopsis elpatiewski* (OSTENF.) BOURR. | x | | | |
| **EUGLENOPHYCEAE** | | | | |
| *Euglena acus* E. | | x | x | |
| *E. sanguinea* E. | x | | | |
| *Euglena* spp. | | x | | D |
| *Lepocinclis* cf. *ovum* (E.) LEMM. | | x | | x |
| *Phacus caudatus* HÜBN. | x | | | |
| *P. longicauda* (E.) DUJ | x | | | |
| *P. pyrum* (E.) STEIN | x | | | |
| *P. suecicus* LEMM. | x | | | |
| *P. tortus* (LEMM.) SKV. | x | | | |
| *Strombomonas* sp. | x | | | |
| *Trachelomonas armata* (E.) STEIN | x | | | |
| *T. hispida* (PERTY) STEIN | x | x | | |
| *T. sidneyensis* PLAYF. | | | | D |
| *T. volvocina* E. | x | | | D |
| *Trachelomonas* spp. | x | x | | D |
| **RAPHIDOPHYCEAE** | | | | |
| *Gonyostomum* sp. | x | | | |
| *Merotrichia* sp. | x | | | |
| **number of samples analysed** | **340** | **3** | **1** | **1** |

1: Okavango Delta (1991-94)
2: Maxegane Pool (1992)
3: Kings Pool (1992)
4: Lake Ngami (1992)

**Taxon**

**RHIZOPODA**

*Arcella* spp.

**CILIATA**

*Difflugia* spp.

**ROTATORIA**

*Anuraeopsis fissa* (GOSSE)
*Ascomorpha ovalis* (BERGENDAL)
*A. saltans* BARTSCH
*Ascomorpha* sp.
*Asplanchna priodonta* GOSSE
*Brachionus angularis* GOSSE
*B. calyciflorus* PALLAS
*B. clayciflorus* f. *amphiceros* (EHRB.)
*B. calyciflorus* f. *anuraeiformis* (BREHM)
*B. caudatus* BARROIS & DADAY
*B. falcatus* ZACH.
*B. patulus* (MÜLL.)
*Brachionus* sp.
*Collotheca* sp.
*Conochilus* sp.
*Filinia longiseta* (EHRB.)
*F. opoliensis* (ZACH.)
*Filinia* sp.
*Gastropus* sp.
*Hexarthra* sp.
*Keratella cochlearis* GOSSE
*K. tecta* (GOSSE)
*K. tropica* (APSTEIN)
*Platylas quadricornis* (EHRB.)
*Polyarthra* cf. *remata* (SKORIKOV)
*P. vulgaris* CARLIN
*Polyarthra* sp.
*Synchaeta* sp. 1 (large)
*Synchaeta* sp. 2 (small)
*Testidunella* sp.
*Trichocerca birostris* (MINIKIWIECZ)
*T. elongata* GOSSE
*Trichocerca* sp.
Unidentified bentic rotifers

**CLADOCERA**

*Alona* spp.
*Bosmina longirostris* (MÜLL.)
*Ceriodaphnia* sp
*Chydorus sphaericus* MÜLL.
*Daphnia laevis* BIRGE
*Daphnia* sp.
*Diaphanosoma brachyurum* (LIÉVIN)

**COPEPODA**

Calanoid
Cyclopoid
Nauplius

**Table 11: Zooplankton taxa from the Okavango Delta**

**TABLE 12**

| | James Camp | 'Shuma-Morel | Sajawa | Upstream of King's Pool | Linyanti River | Kasane gauge | Chobe Game Lodge | Chobe Hippo Pool | Khwai at North Gate | Xakanaxa inflow | Xakanaxa lagoon | Xakanaxa outflow |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Relict channel | Main channel | Main channel | Main channel | Main channel | Main channel | Main channel | Salvinia infested pool | Narrow channel | Main channel | Lagoon | Main channel |
| date, 1992 | Nov. 1 | Nov. 1 | Nov. 1 | Nov. 1 | Nov. 2 | Nov. 4 | Nov. 4 | Nov. 4 | Nov. 6 | Nov. 6 | Nov. 6 | Nov. 6 |
| **PHYTOPLANKTON** | | | | | | | | | | | | |
| **Cyanophyceae** | | | | | | | | | | | | |
| *Microcystis aeruginosa* KÜTZ. | - | - | - | - | - | - | 0.169 | - | - | - | - | - |
| *Anabaena* sp. | - | - | - | - | - | - | - | - | - | - | 0.018 | - |
| **Diatomophyceae** | | | | | | | | | | | | |
| *Cyclotella* spp. | - | - | 0.022 | 0.054 | - | 0.053 | 0.268 | 0.411 | - | - | - | - |
| *Aulacoseira granulata* var. *angustissima* (MÜLL.) SIM. | - | - | - | - | - | - | 0.419 | - | - | - | - | - |
| *Synedra* spp. | - | 0.024 | 0.014 | 0.041 | 0.043 | - | - | - | - | 0.036 | - | - |
| **Cryptophyceae** | | | | | | | | | | | | |
| *Cryptomonas* spp. | 0.155 | - | - | - | - | - | - | - | 0.080 | 0.013 | 0.027 | 0.041 |
| **Dinophyceae** | | | | | | | | | | | | |
| *Peridinium* sp. | - | - | - | - | - | - | - | - | - | - | 0.078 | 0.108 |
| *Gymnodinium* sp. | - | - | - | - | - | - | - | - | - | - | - | 0.073 |
| **Raphidophyceae** | | | | | | | | | | | | |
| *Merotrichia* sp. | 0.160 | - | - | - | - | - | - | - | - | - | - | - |
| **Monads** | - | - | - | - | - | - | - | - | - | - | 0.137 | 0.091 |
| **Total biomass, mg/l** | **0.315** | **0.024** | **0.034** | **0.095** | **0.043** | **0.053** | **0.856** | **0.411** | **0.080** | **0.049** | **0.260** | **0.313** |

Table 12: Phytoplankton and zooplankton recorded in the Kwando/Linyanti/Chobe and Khwai Rivers. X, single record; C, common.

**TABLE 12 continued**

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **ZOOPLANKTON** | | | | | | | | | | | | |
| **Ciliata** | | | | | | | | | | | | |
| Difflugia sp. | X | - | - | - | - | - | C | C | - | - | - | - |
| **Rotatoria** | | | | | | | | | | | | |
| Anuraeopsis fissa (GOSSE) | - | - | - | - | - | - | - | - | - | - | - | - |
| Asplanchna sp. | - | - | - | - | - | - | 2 | - | - | - | - | - |
| Brachionus angulatus GOSSE | - | - | - | - | - | - | - | - | - | - | - | - |
| B. calyciflorus PALLAS | - | - | - | - | - | - | - | - | - | - | - | - |
| B. caudatus BARROIS & DADAY | - | - | - | - | 1 | - | - | - | - | - | - | - |
| Brachionus sp. 1 | 1 | - | - | - | - | - | 1 | - | - | - | - | - |
| Brachionus sp. 2 | - | - | - | - | - | - | - | - | - | - | - | - |
| Filinia spp. | - | - | - | - | - | 1 | 2 | - | - | - | - | - |
| Hexarthra sp. | - | - | - | - | - | 5 | 16 | 20 | - | - | - | - |
| Keratella cochlearis GOSSE | - | - | 1 | 1 | - | 7 | - | - | - | - | 2 | - |
| K. tecta (GOSSE) | - | - | - | - | - | 1 | - | - | - | - | - | - |
| K. tropica (APSTEIN) | - | - | - | - | - | 7 | 3 | 3 | 6 | 1 | - | - |
| Polyarthra vulgaris CARLIN | 1 | - | - | - | - | - | 5 | 4 | - | - | - | 3 |
| Trichocerca birostris MINIKIWIECZ | - | - | - | - | - | - | - | - | - | - | - | - |
| Trichocerca sp. | 1 | - | - | - | - | - | - | - | - | - | - | - |
| **Cladocera** | | | | | | | | | | | | |
| Bosmina longirostris (MÜLL.) | 3 | 1 | - | - | - | 4 | - | - | - | - | - | - |
| Ceriodaphnia sp. | - | - | - | - | - | 6 | 19 | 22 | - | - | - | - |
| Chydorus sphaericus MÜLL. | - | - | - | - | - | - | 9 | - | - | - | - | - |
| Daphnia sp. | - | 1 | - | - | - | - | 2 | 6 | - | - | - | - |
| Diaphanosoma sp. | 6 | - | - | - | - | 1 | 8 | 3 | - | - | - | - |
| **Copepoda** | | | | | | | | | | | | |
| Cyclopoid | 16 | 2 | - | - | - | 2 | - | 10 | - | - | - | - |
| Calanoid | - | - | - | - | - | 1 | 8 | - | - | 1 | - | - |
| Nauplius | 82 | 3 | 1 | 1 | 1 | 24 | 46 | 57 | 272 | - | - | - |
| **Total numbers per litre** | **110** | **7** | **2** | **2** | **2** | **99** | **121** | **129** | **278** | **2** | **2** | **3** |

| | Duba Island | | | | | Boro junction | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Oct 89 | 20 Feb 90 | 26 Jun 92 | 25 Oct 92 | 5 Mar 92* | 20 May 89 | 20 Oct 89 | 20 Feb 90 | 29 Jun 92 | 23 Oct 92 | 4 Mar 94* |
| $Cd^{2+}$ | 0.28±0.17 (5) | 0.24±0.22 (3) | 0.11±0.08 (3) | 0.18±0.15 (3) | <0.1 (1) | 0.22±0.11 (5) | 0.22±0.18 (5) | 0.25±0.12 (3) | 0.18±0.15 (3) | 0.08±0.12 (3) | <0.1 (1) |
| $Pb^{2+}$ | 0.17±0.13 (5) | 0.26±0.22 (3) | 0.20±0.17 (3) | 0.28±0.11 (3) | 0.3 (1) | 0.25±0.15 (5) | 0.11±0.03 (5) | 0.40±0.20 (3) | 0.30±0.15 (3) | 0.45±0.17 (3) | 0.4 (1) |
| $Ni^{2+}$ | 0.35±0.28 (5) | 0.67±0.05 (3) | 0.20±0.16 (3) | 0.30±0.25 (3) | 0.3 (1) | 0.27±0.04 (5) | 0.29±0.66 (5) | 1.18±0.29 (3) | 0.22±0.10 (3) | 0.31±0.28 (3) | 0.5 (1) |
| $Cu^{2+}$ | 0.51±0.40 (5) | 0.43±0.27 (3) | 0.40±0.30 (3) | 0.39±0.15 (3) | 0.5 (1) | 0.42±0.38 (5) | 0.28±0.31 (5) | 0.59±0.25 (3) | 0.44±0.35 (3) | 0.27±0.20 (3) | 0.3 (1) |
| $Zn^{2+}$ | 3.56±0.09 (5) | 2.91±1.13 (3) | 3.18±1.40 (3) | 4.42±1.75 (3) | 5.2 (1) | 2.78±0.98 (5) | 4.38±1.14 (5) | 4.07±2.15 (3) | 3.59±0.17 (3) | 5.15±1.80 (3) | 6.8 (1) |
| $Co^{2+}$ | nd | nd | nd | 0.12±0.06 (3) | <0.1 (1) | 0.37±0.18 (5) | 0.32±0.13 (5) | nd | nd | 0.22±0.08 (3) | <0.1 (1) |

Concentrations in µg/l; (n) number of samples; (nd) not determined
(*) Direct determination with GF AAS. Average of three replicates.

Table 13: Estimated surface water mean concentration (±1 sd) in the filtered fraction (0.45 µm) of transition metals in Duba Island and Boro junction in the Jao/Boro River.

| | MCLG [a] | MCL [b] | MCL [c] | LKE [d] | EEC [e] | WHO guideline | Jao/Boro system range (median) |
|---|---|---|---|---|---|---|---|
| **I Primary levels:** | | | | | | | |
| Cadmium | 5 | 10 | 5 | 0.15 | 5 | 5 | <0.03-0.46 (0.19) |
| Chromium | 100 | 50 | 100 | 2 ($Cr^{6+}$) | 50 | 50 | <0.1-0.75 (total Cr) |
| Copper | 1300 | | 1300 | 2 | | | <0.1-0.9 (0.4) |
| Fluoride | | 4000 | | | | 1500 | <0.05-0.3 |
| Lead | 0 | 5 | 5 | 1.5 | 50 | 0.4 | <0.1-0.7 (0.3) |
| Nickel | 100 | | 100 | 25 | | | <0.1-1 (0.4) |
| Bacteria | | 4/100 ml | | | | | |
| Coliforms | | 1/100 ml | | | 0 | 0 | |
| Turbidity (ntu) | | 1-5 [f] | | | 0-4 | <1 | 0.3-289 (1.46) |
| Susp. sediment (mg/l) | | | | | | | 0.5-130 |
| **II Secondary levels:** | | | | | | | |
| Aluminium | | | 50 | 75-100 | | | <1-139 (8.8) [g] |
| Chloride (mg/l) | | 250 | | | | | 0.3-11.2 (1.2) [g] |
| Copper | | 1000 | | | | | |
| Fluoride | | 2 | | | | | |
| Iron | | 300 | | | | | 8-175 (28) [g] |
| Manganese | | 50 | | | | | <3-78 (7) [g] |
| TDS | | 500 | | | | | 29-1600 (75.5) [h] |
| Zinc | | 5000 | | | | | 2-7 (4) |

MCLG: maximum contaminant level goal (USEPA, 1987); b) MCL: current maximum contaminant level; c) MCL: proposed maximum contaminant level; d)LKE: l known levels of effect on aquatic organisms; e) European Economic Community maximum admissible concentration; f) 1 ntu (montly avg) or 5 ntu as average or 2 consecutive
days; g) unfiltered; h) Specific conductance in $\mu S/cm$. Concentrations in $\mu g/l$ unless otherwise stated.

**Table 14:** Water quality criteria and standards summary. Maximum permissable concentrations of selected chemical parameters based on drinking water standards compared to large range of observed values (1989-1994) in the surface waters of the Jao/Boro system.

| | 31/3- 1/4/1992 | | | 30/10-5/11/1992 | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Ngoma bridge[a)] | Chobe lodge | Kasane gauge | James camp | Sajawa | Shaile | Ngoma bridge[b)] | Chobe lodge | Kasane gauge |
| SC | 1097 | 83.0 | 73.5 | 76.2 | 101.9 | 102 | 1960 | 102.5 | 87.2 |
| pH | 7.8 | 7.5 | 6.8 | 6.6 | 6.3 | 6.4 | 8.3 | 7.6 | 7.1 |
| Temp. | 26.4 | 28.1 | 28.3 | 24.4 | 24.1 | 24.1 | 24.0 | 25.1 | 25.1 |
| DO | 108 | 120 | 67 | 126 | 115 | nd | nd | 132 | 102 |
| $Ca^{2+}$ | 10.12 | 4.08 | 3.46 | 5.05 | 4.45 | 5.09 | 12.38 | 5.16 | 4.76 |
| $Mg^{2+}$ | 11.71 | 2.78 | 2.45 | 1.73 | 2.12 | 2.66 | 17.70 | 3.66 | 4.08 |
| $Na^{+}$ | 9.08 | 4.08 | 3.80 | 4.60 | 5.62 | 4.78 | 33.50 | 8.40 | 7.88 |
| $K^{+}$ | 25.68 | 1.18 | 1.44 | 1.88 | 2.25 | 1.90 | 28.20 | 2.50 | 2.20 |
| $HCO_3^-$ | 5180 | 540 | 475 | 550 | 610 | 615 | 1330 | 690 | 625 |
| $Cl^-$ | 8.50 | 3.34 | 3.58 | 0.51 | 0.57 | 0.46 | 300 | 2.19 | 1.69 |
| $SO_4^{2-}$ | 5.11 | 2.40 | 1.85 | 0.88 | 0.98 | 1.10 | >100 | 3.79 | 2.06 |
| $SiO_2$ | 24.7 | 7.7 | 9.4 | 4.8 | 6.2 | 6.8 | nd | 10.3 | 9.7 |
| DOC | 19.2 | 5.5 | 8.7 | 15.0 | 22.2 | 20.5 | >50 | 12.2 | 19.3 |
| Total N | 0.770 | 0.350 | 0.340 | 0.485 | 0.530 | 0.550 | 0.930 | 0.530 | 0.290 |
| Total P | 0.065 | 0.015 | 0.014 | 0.026 | 0.030 | 0.025 | 0.040 | 0.030 | 0.018 |
| Chlor. *a* | 78.1 | 3.6 | 4.1 | 3.3 | 4 | nd | 30 | 11 | 3 |
| Sedim.* | 73.4 | 28.4 | 11.9 | nd | nd | nd | nd | nd | nd |
| $\delta^{18}O$ | +2.89 | nd | nd | +1.43[c)]<br>-0.11[d)] | +1.83 | -2.04 | nd | -0.29 | +0.42 |

Units as in Table 3. a) Ngoma bridge, flowing water; b) Stagnant pool close to the first bridge span from the Botswana border (see text); c) Relic channel upstream of James camp; d) Flowing water in the river channel; (*) Suspended sediments in mg/l ; (nd) not determined.

**Table 15: Kwando/Linyanti/Chobe River surface water chemistry.**

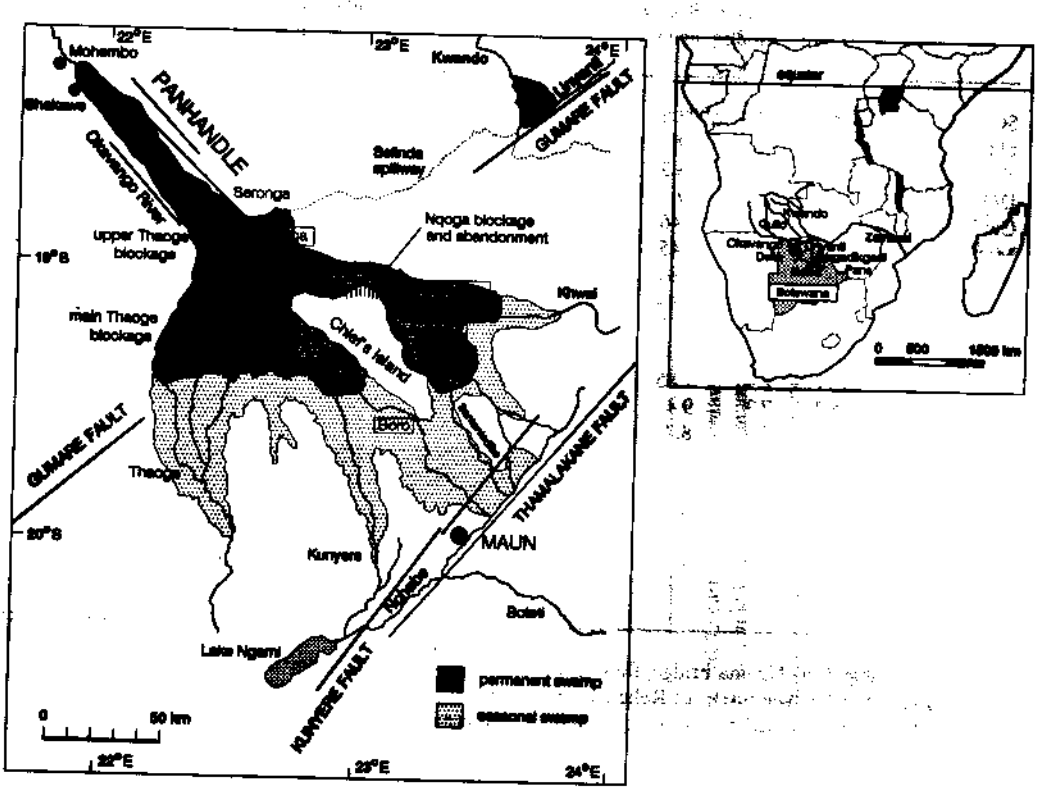



**Figure 1:** **Okavango Delta and Linyanti Swamp Location map (after UNDP/FAO, 1977)**

Fig. 2a

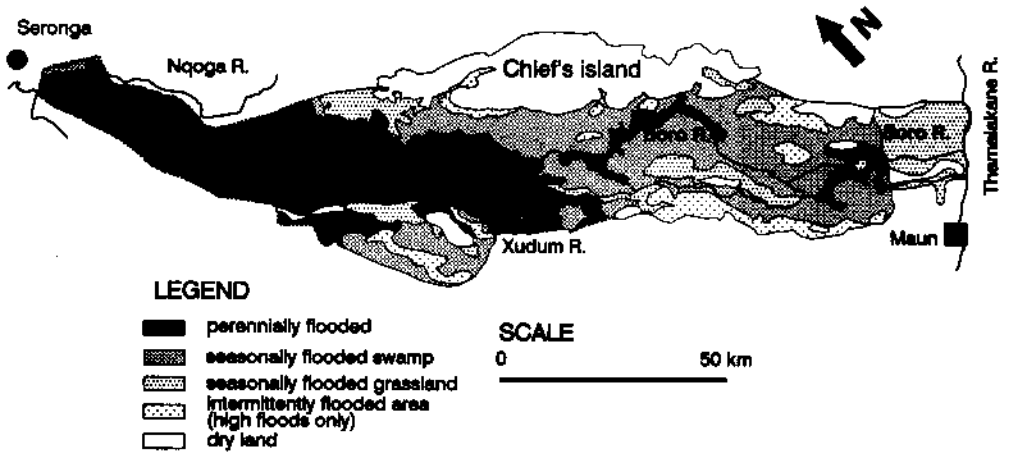



Fig. 2b

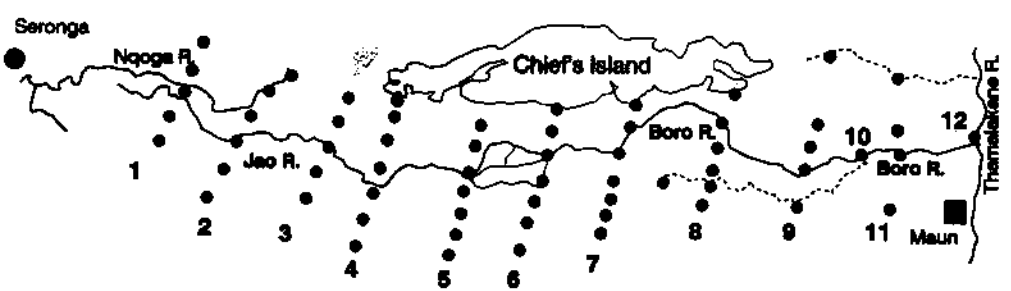



**Figure 2a:** **Flood zonation map (DWA, SMEC, 1989) of the Jao/Boro River system.**

**Figure 2b:** **Jao/Boro River system sampling locations. Numbers 1 to 12 correspond to transect number as described in Table 1.**

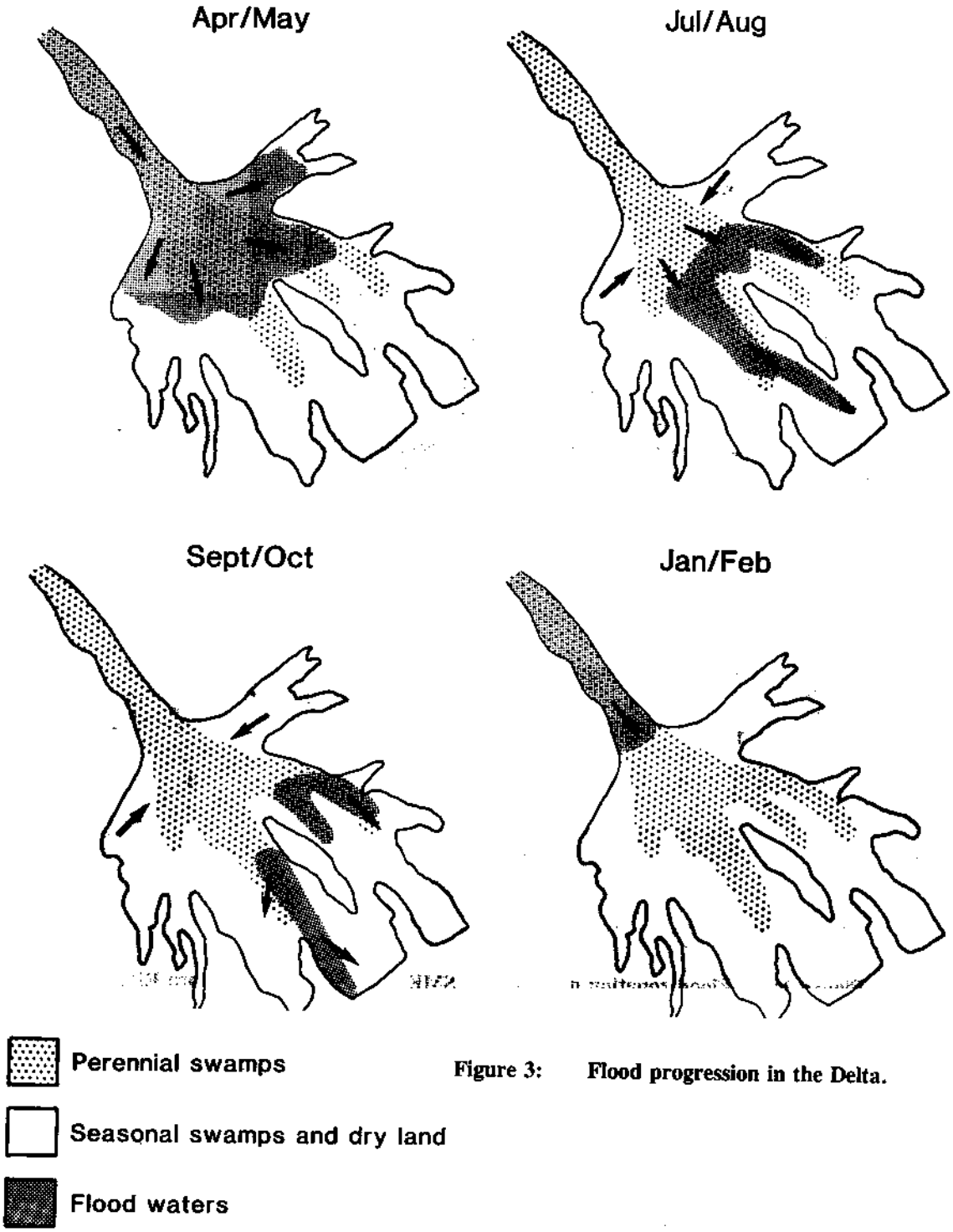



**Figure 3:** **Flood progression in the Delta.**

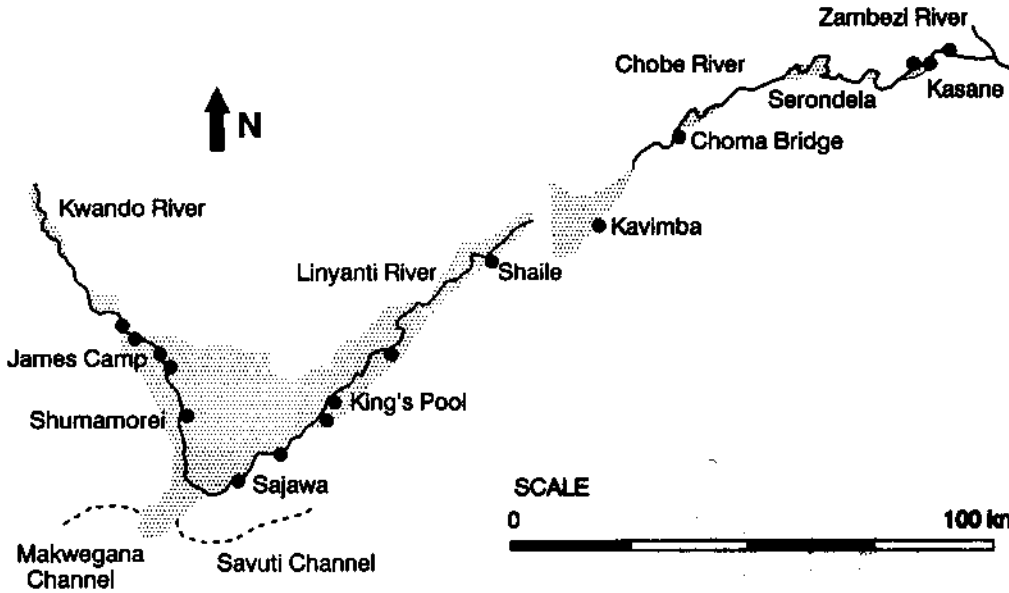



**Figure 4:** **Kwando/Linyanti/Chobe River sampling locations.**

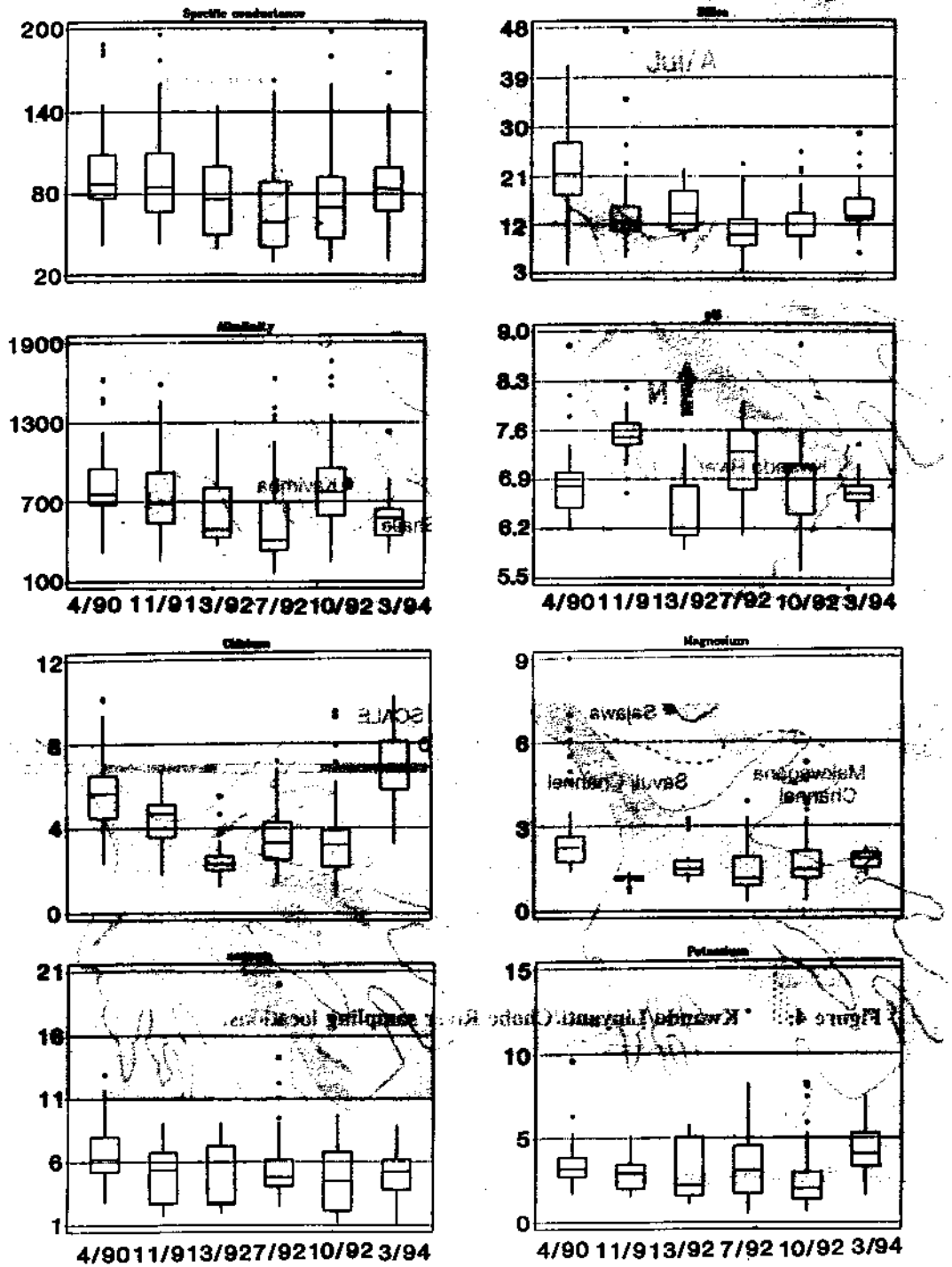



**Figure 5:** Tukey box plots of selected variables in the Jao/Boro system. Stars: possible outliers. Circles: probable outliers. Obs: data from March 1992 are biased towards the upper Delta. Units as in Table 3.

**Figure 5 cont'd**

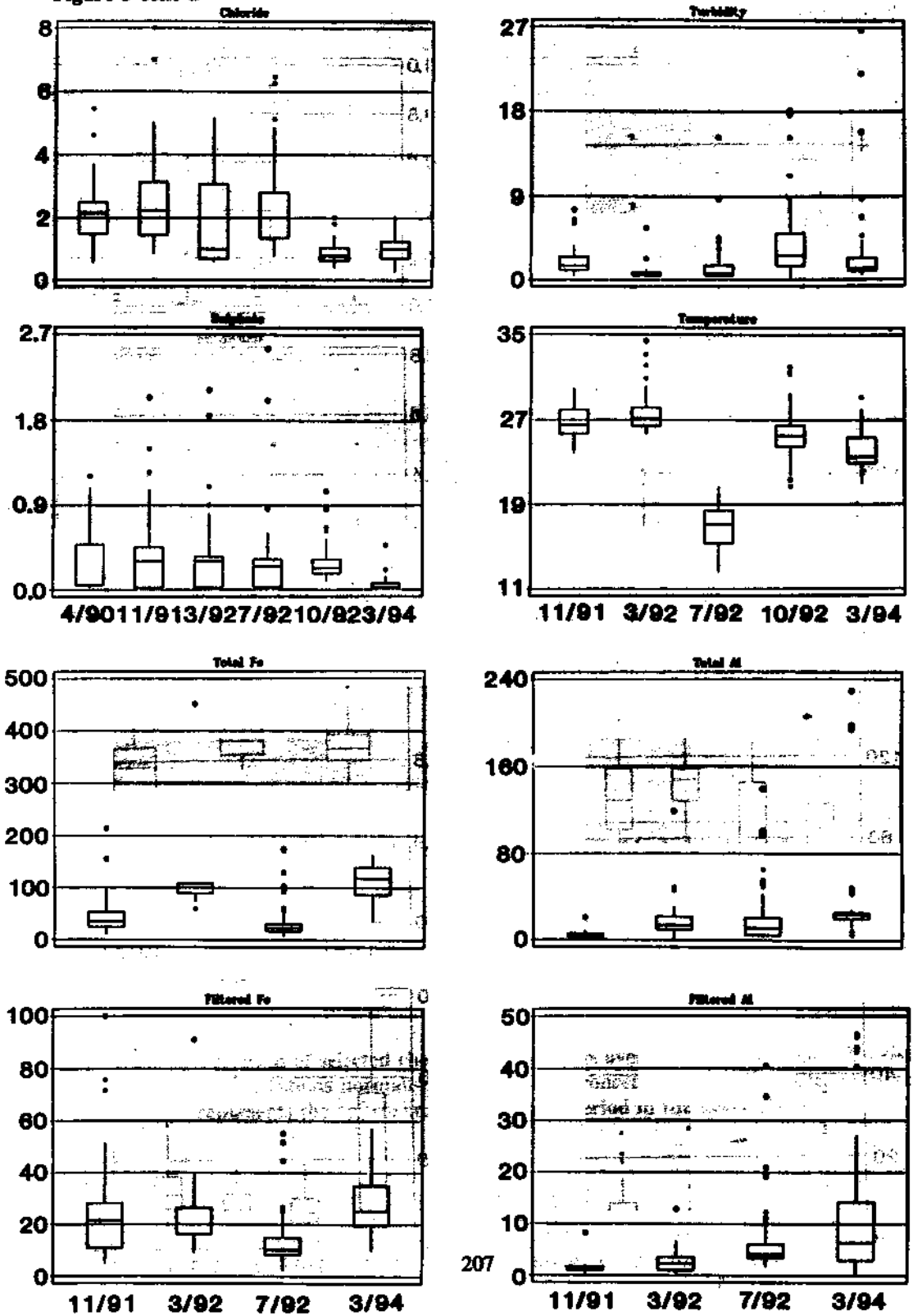
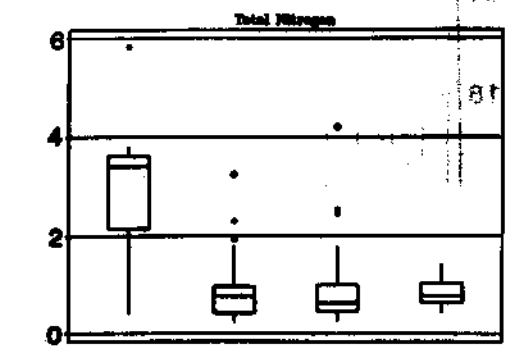
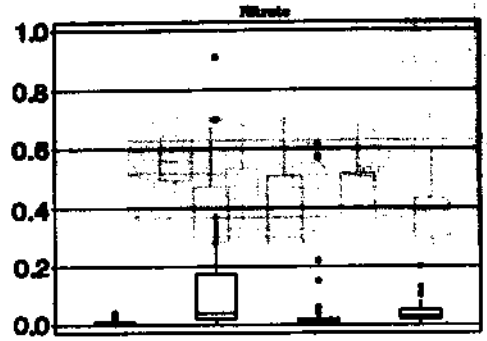
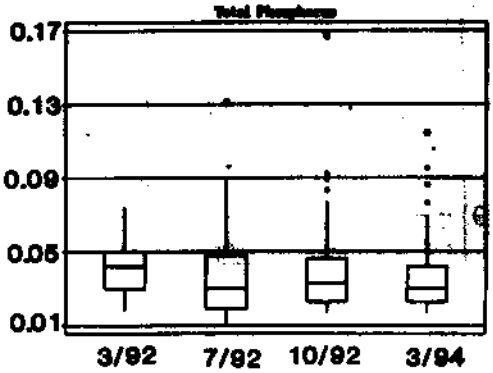
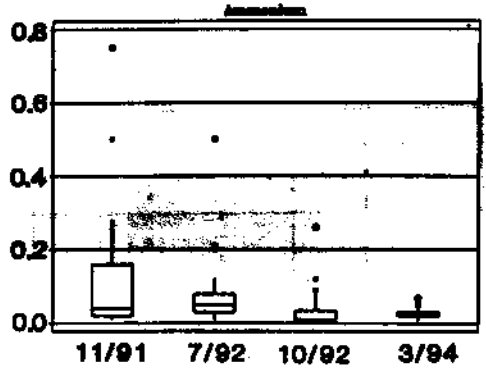


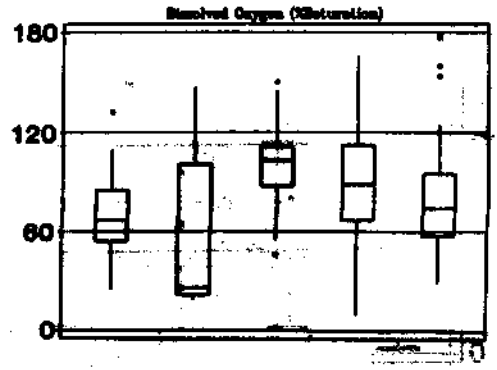
**Figure 5 cont'd**

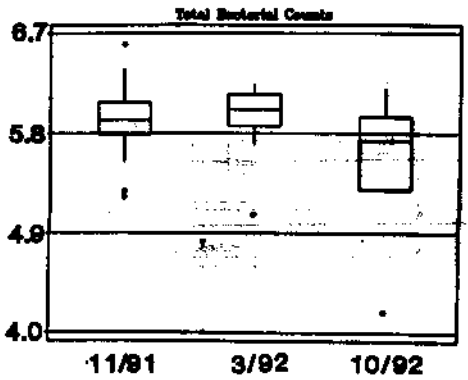


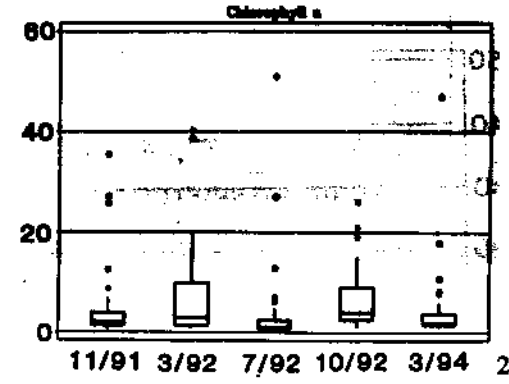



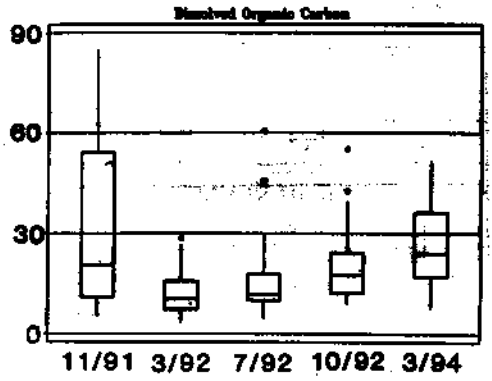



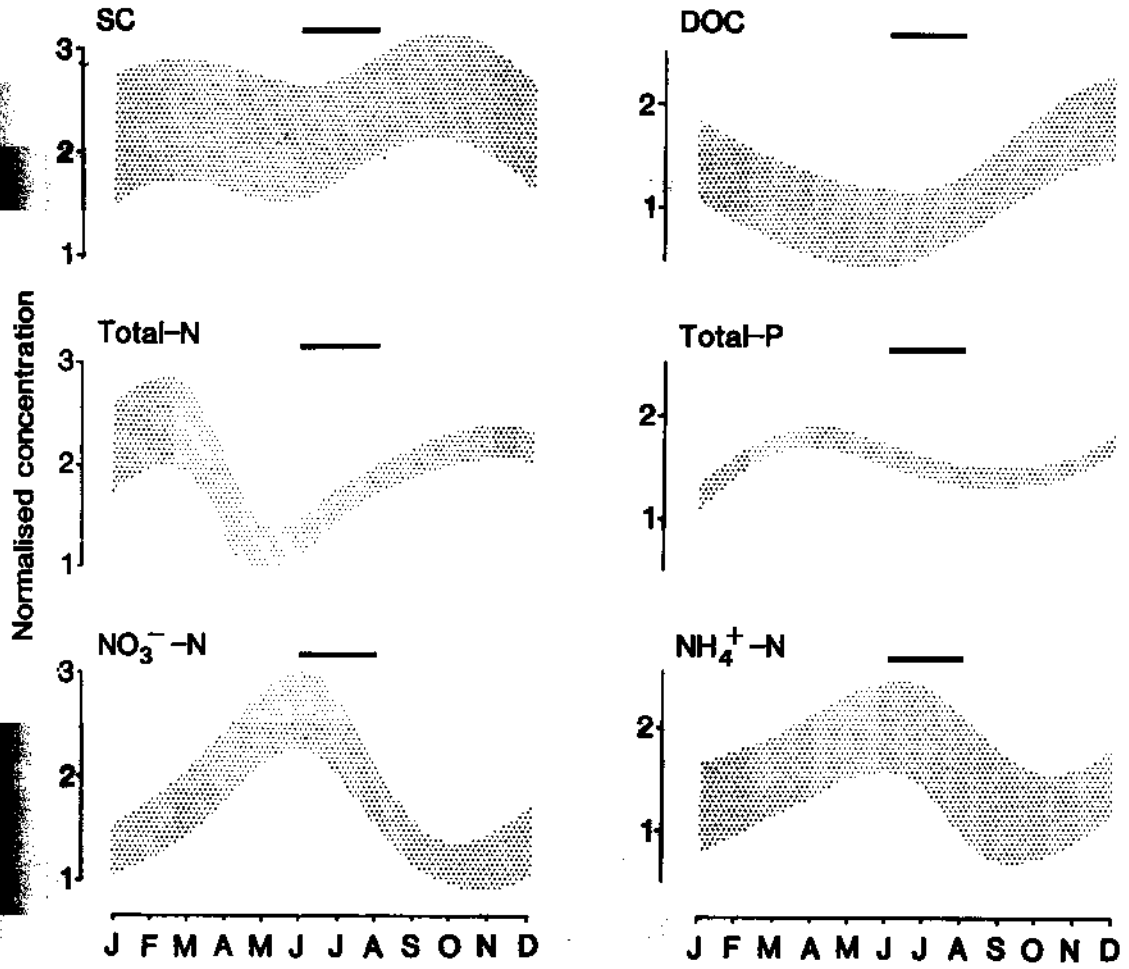



Figure 6: Variation of selected chemical constituents over one seasonal cycle. Y-axis: concentrations normalised to the inflow concentration. The horizontal line represents the approximate high water period in the lower Delta.

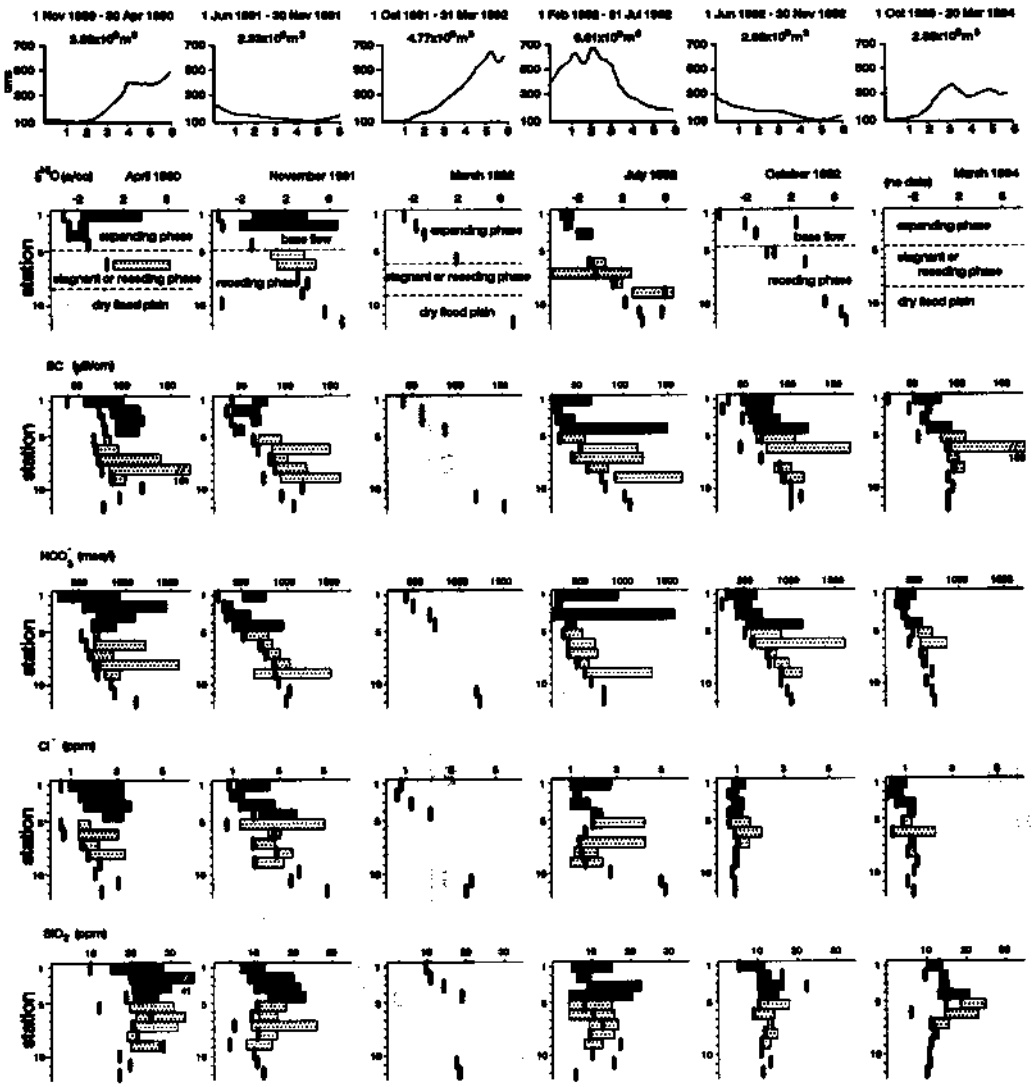



**Figure 7a & b:** Distribution of selected physicochemical variables along the Jao/Boro River (solid vertical lines) and associated swamp and floodplain areas (estimated range as shaded fields). Y-axis: transect number. Dark shaded field: perennial swamps. Light shaded field: seasonal swamps. Units as in Table 3.

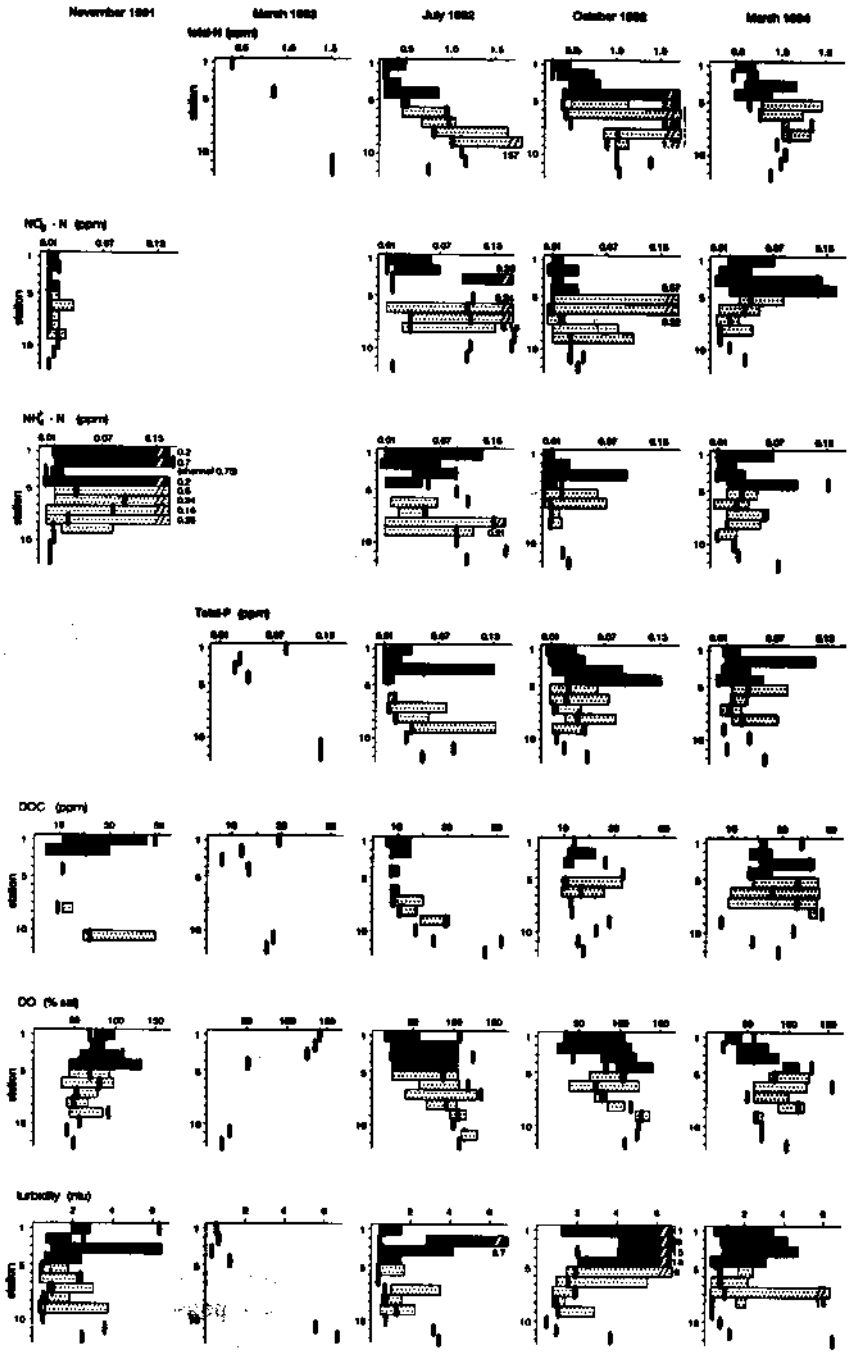

November 1991
March 1992
July 1992
October 1992
March 1994
station
DOC (ppm)
DO (% sat)
turbidity (ntu)

**Figure 7b**

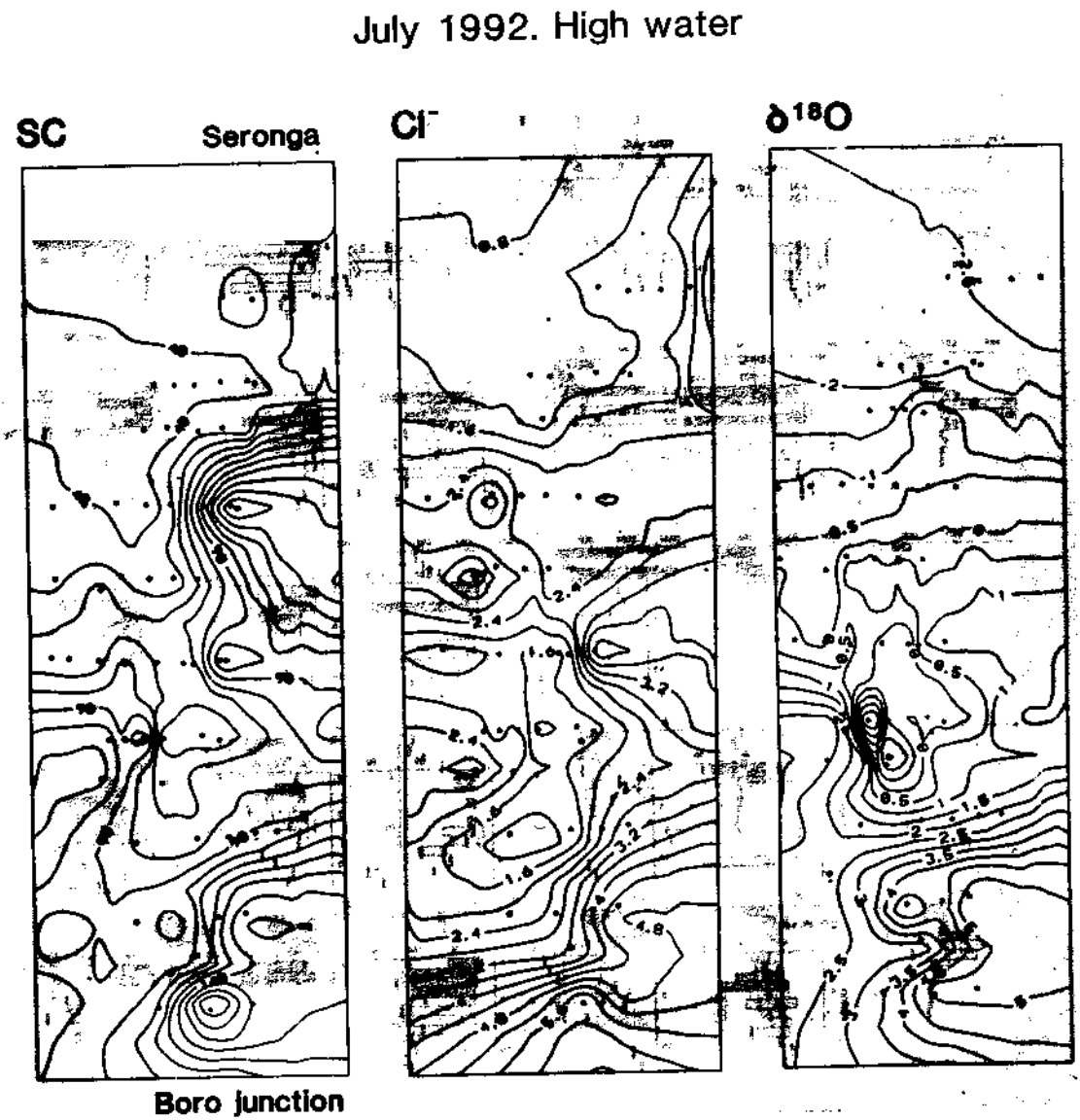



**Figure 8:** Contour plots of specific conductance (μS/cm), chloride (mg/1), and $\delta^{18}0$ (‰ relative to SMOW) at the high water phase, July 1992.

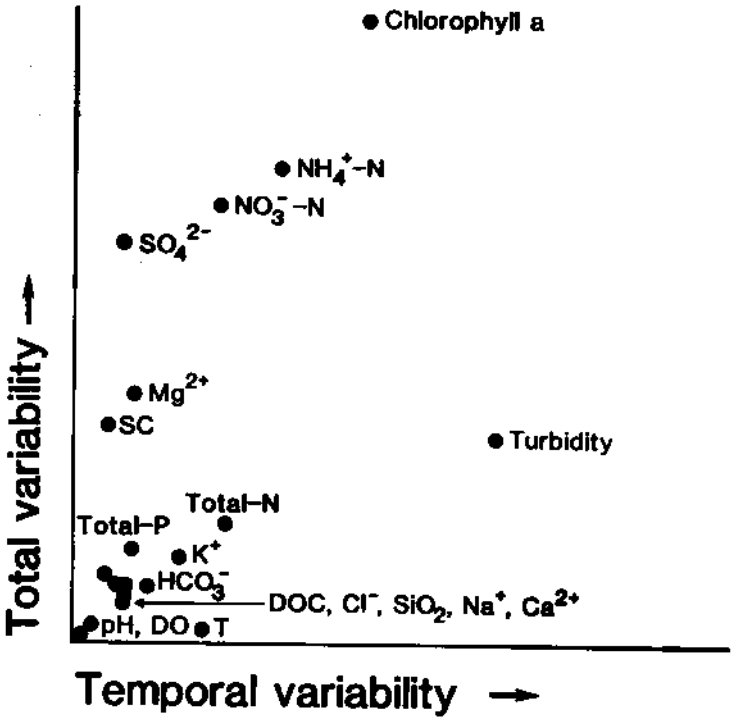



**Figure 9:** Schematic representation of total *versus* temporal variability.

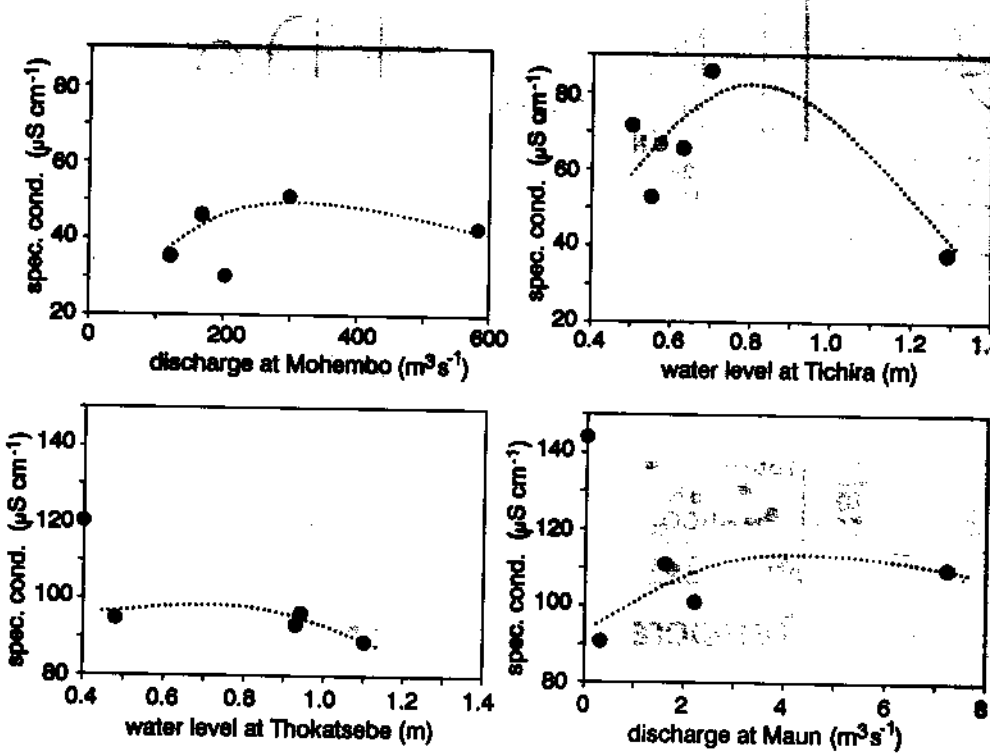



**Figure 10:** **Variation of specific conductance with discharge at Mohembo and Maun and with stage height at Tichira and Thokatsebe.**

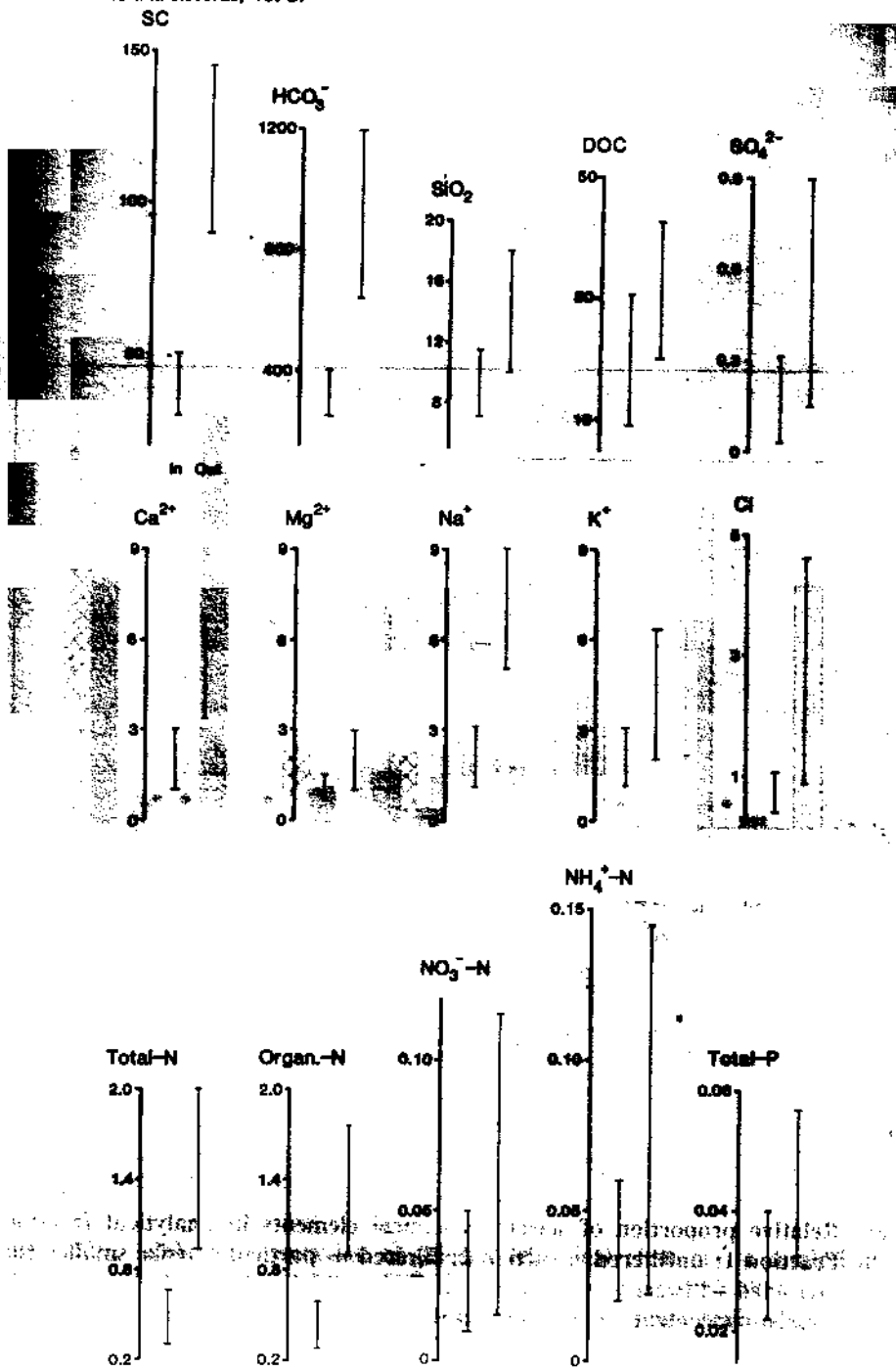



**Figure 11:** **Range of concentrations of selected physicochemical variables at the inlet (Sepopa-Seronga) and outlet (Buffalo fence-Boro junction). Units as in Table 3.**

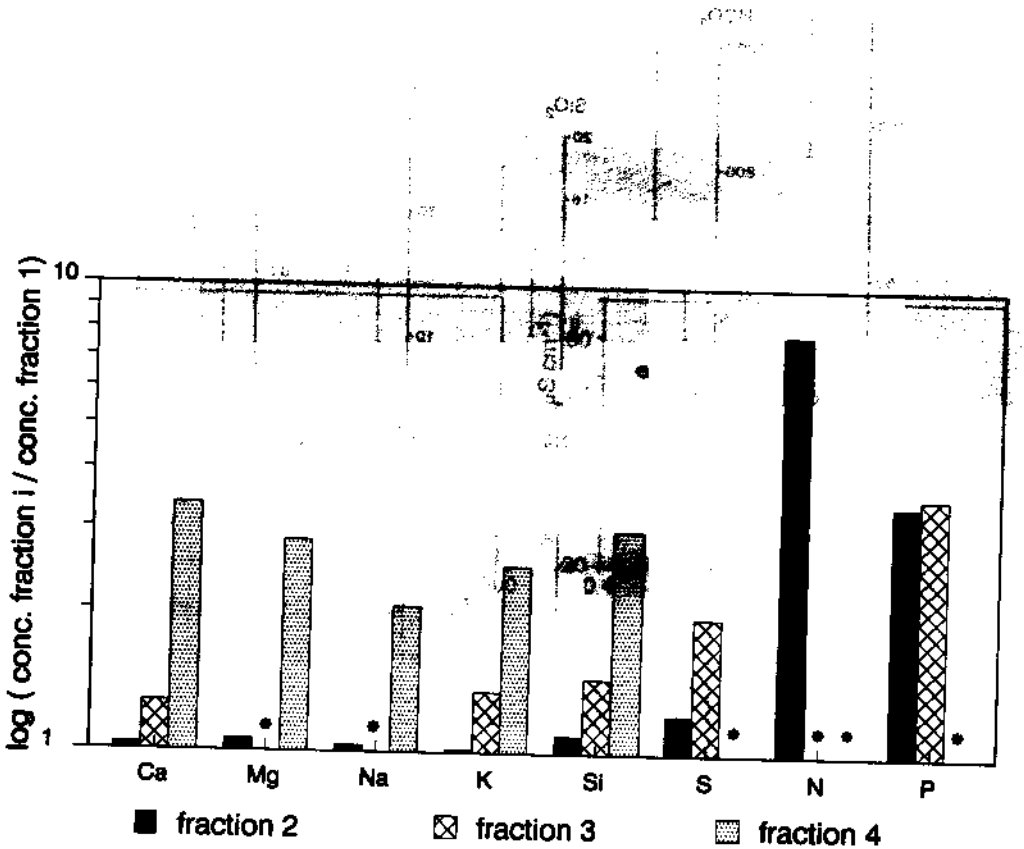



**Figure 12a:** Relative proportion of selected chemical elements in analytical fractions: Fraction 1: unfiltered; Fraction 2: filtered + particulate (size smaller than extracted with acids, evaporated to dryness and rediluted before analysis). Y-axis: concentrations normalised (log scale) to the estimated concentration in filtered sample (0.45 $\mu$m). *not determined.

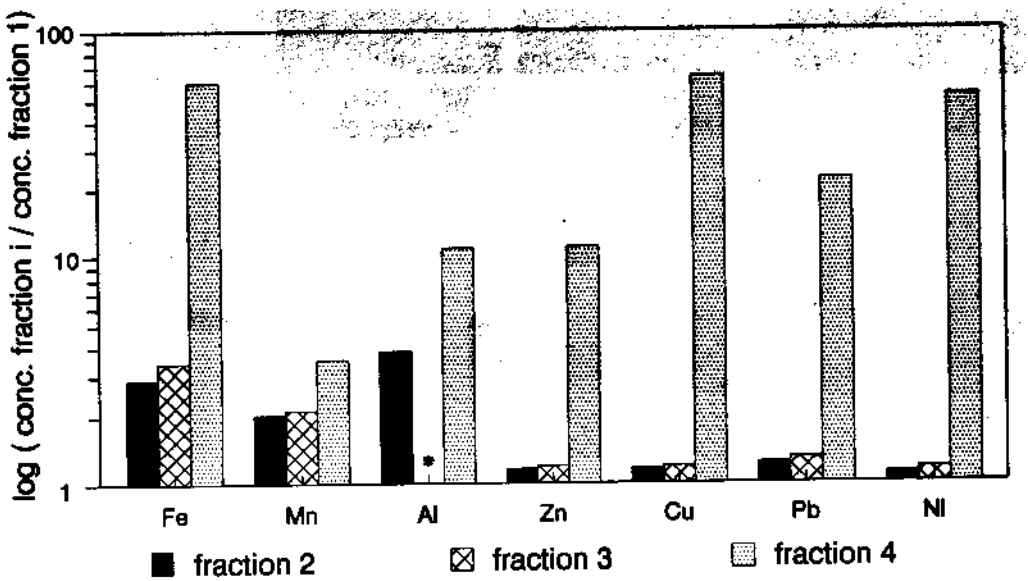



**Figure 12b:** Relative proportion of selected chemical elements in analytical fractions: Fraction 1: unfiltered; Fraction 2: filtered + particulate (size smaller than extracted with acids, evaporated to dryness and rediluted before analysis). Y-axis: concentrations normalised (log scale) to the estimated concentration in filtered sample (0.45 $\mu$m). *not determined.

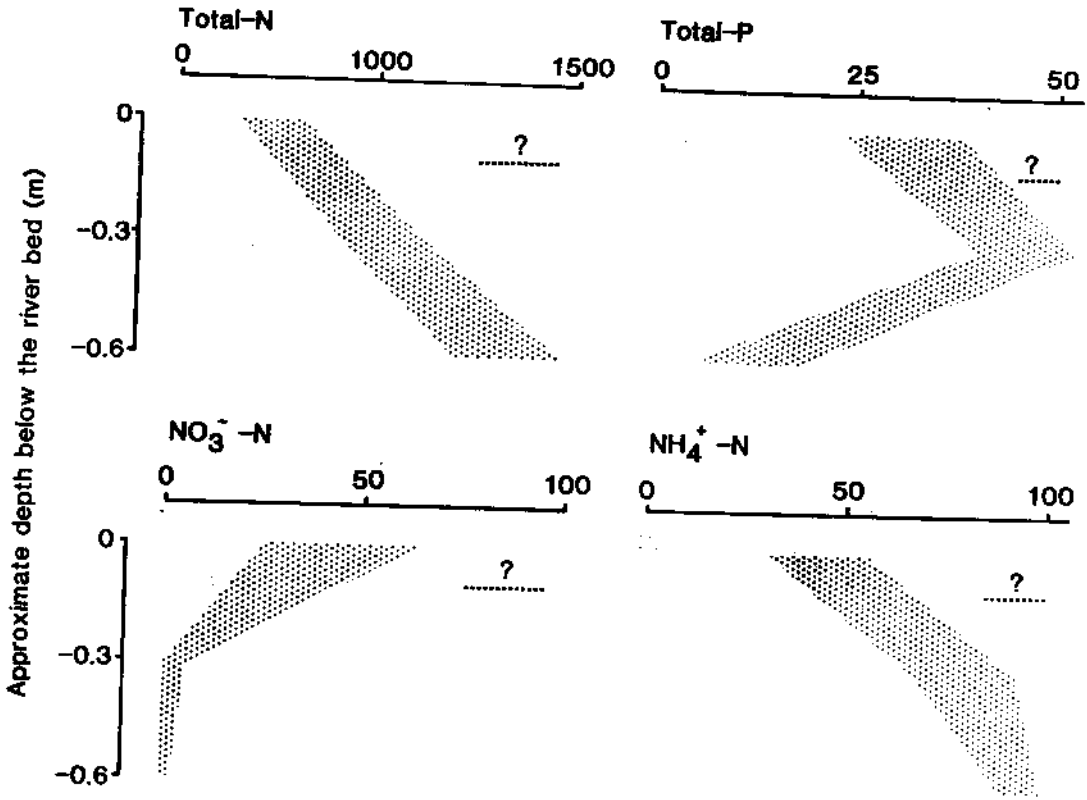



**Figure 13:** Profiles of nutrient concentrations in pore water. Pooled samples from three locations in the upper Delta. Concentrations in $\mu$g/1.

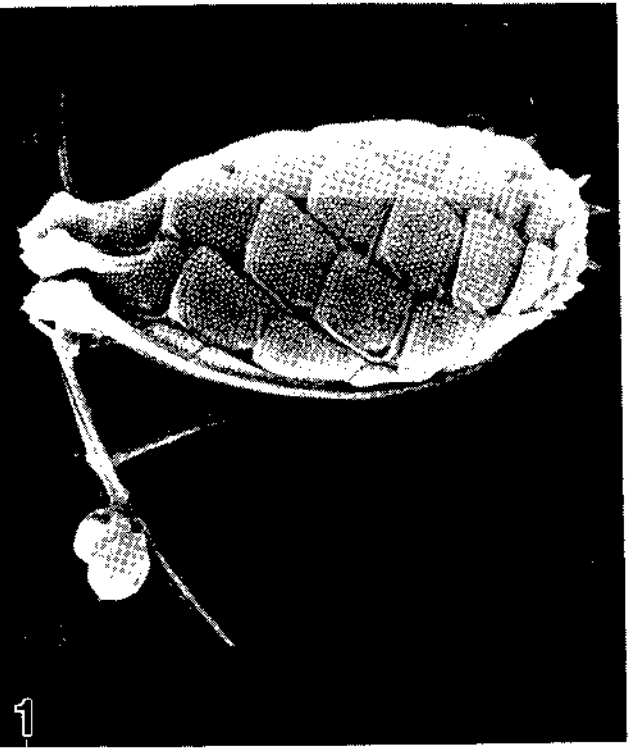


**Plate I:** **Scaled chrysophytes (scale = 1μm)**
1 *Mallomonas favosa* NICHOLLS
2 *M mangofera* HARRIS & BRADLEY

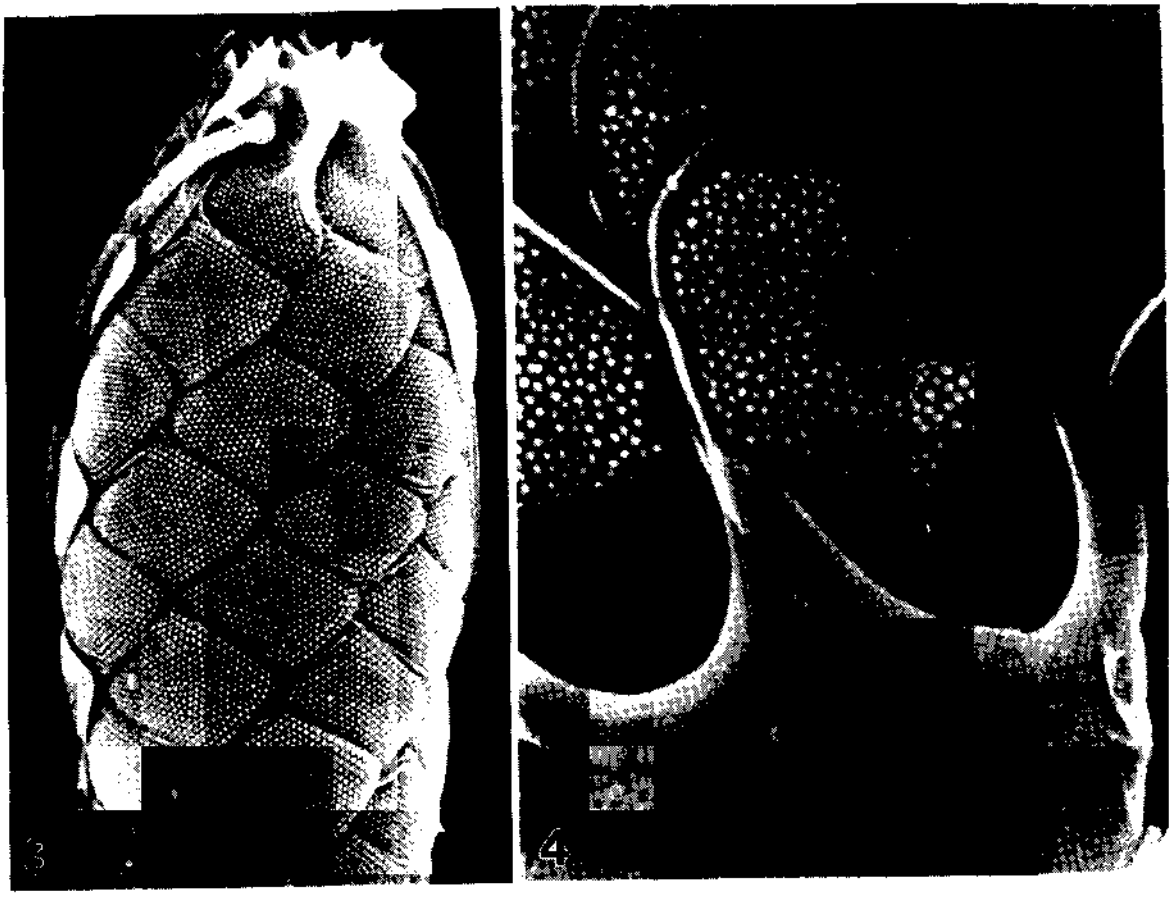
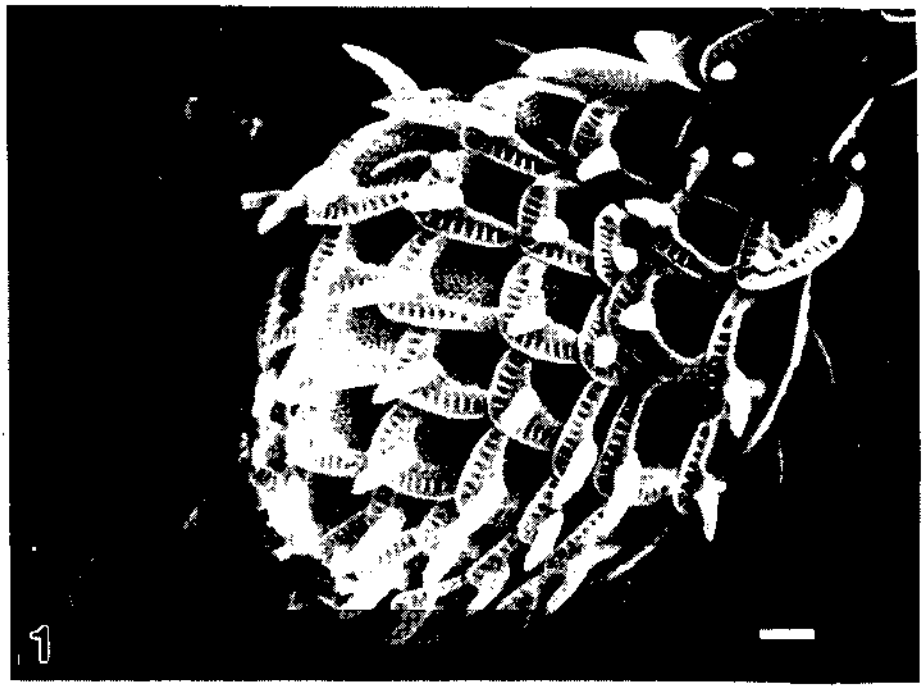



**Plate I:** **Scaled chrysophytes (scale = 1μm)**
3 *M mangofera f favoeata* DÜRRSCHMIDT
4 *M matvienkoae* var *grandis* DÜRRSCHM & CRONB



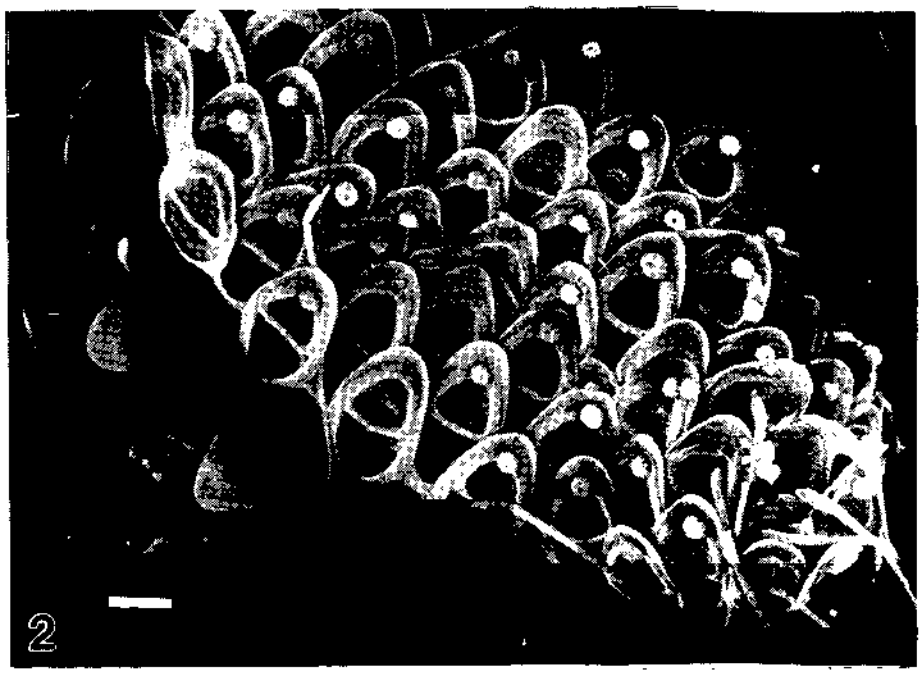
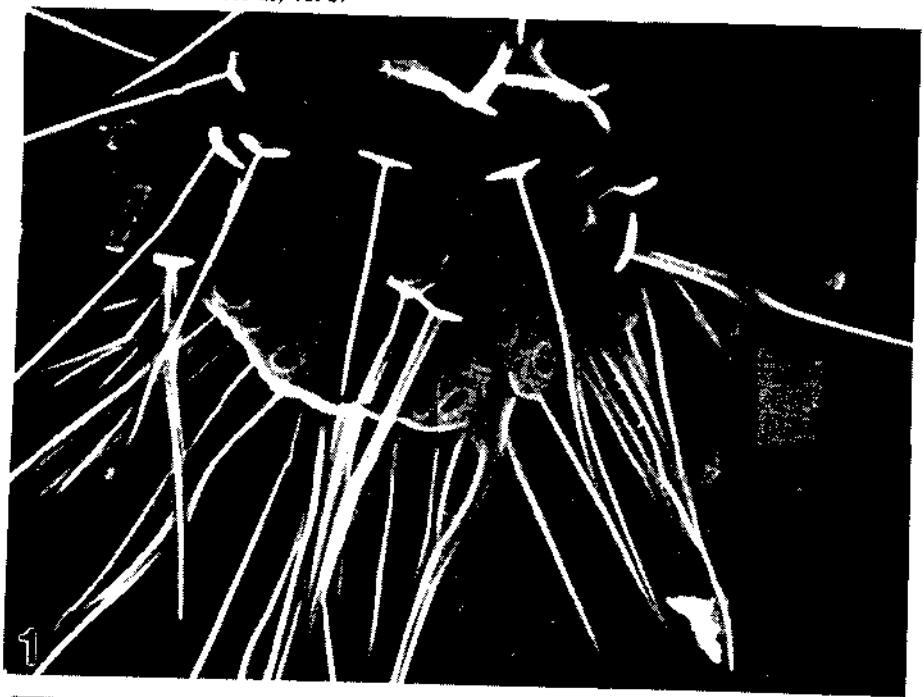
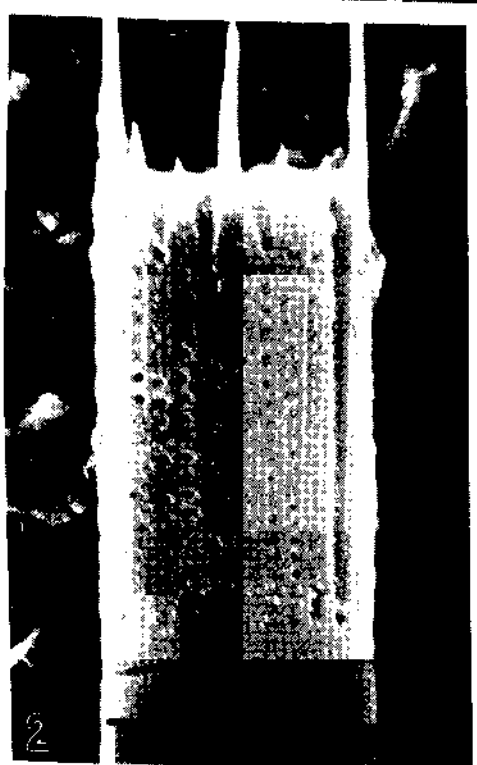




Plate II: **Scaled chrysophytes (scale = 1μm)**
1 *Synura echinulata* KORSHIKOV
2 *Mallomonas bangladeschica* (TAK. & HAYEK.) WUJEK & TIMPANO



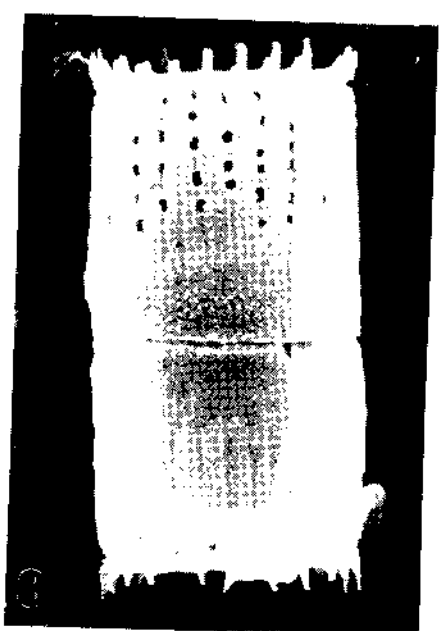




**Plate III:** **Scaled chrysophytes and diatoms (scale = 1$\mu$m)**
1 *Paraphysomonas vestita* (STOKES) de SAEDELEER
2 *Aulacoseira granulata* (E) RALFS
3 *Aulacoseira* sp

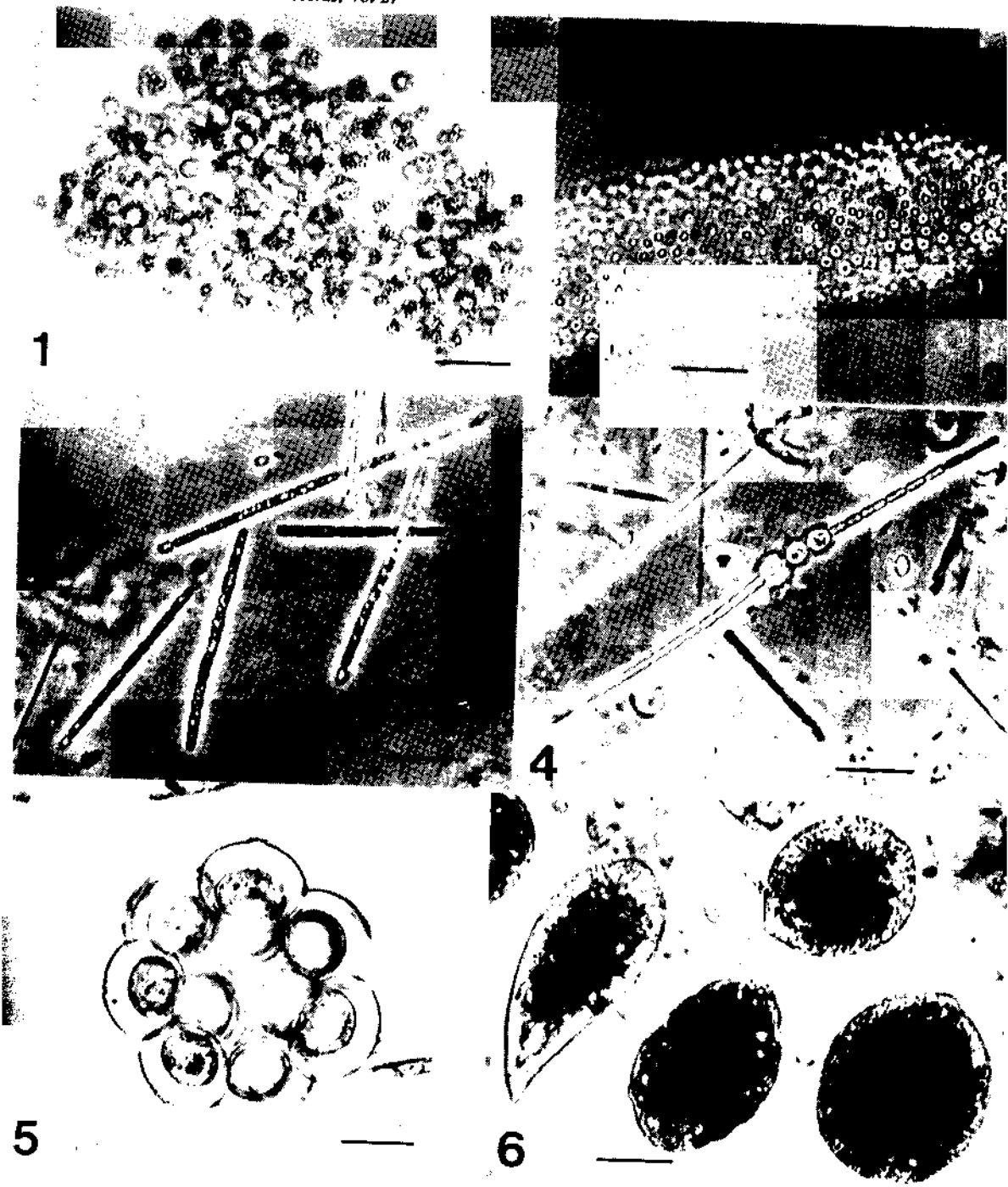
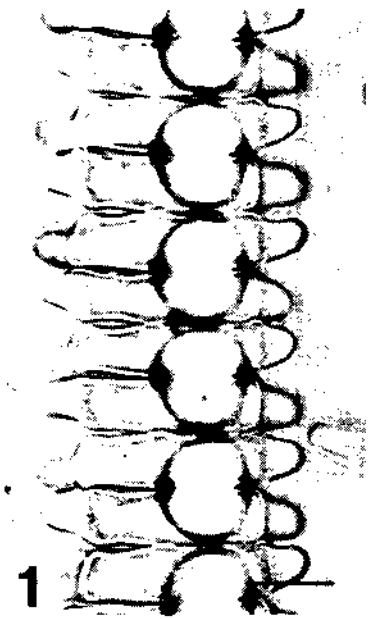
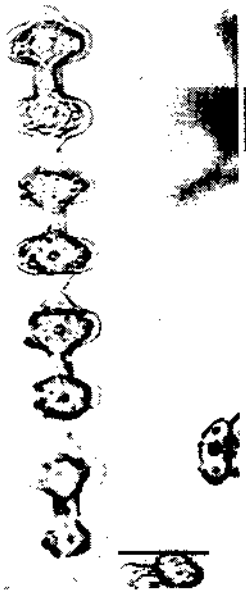


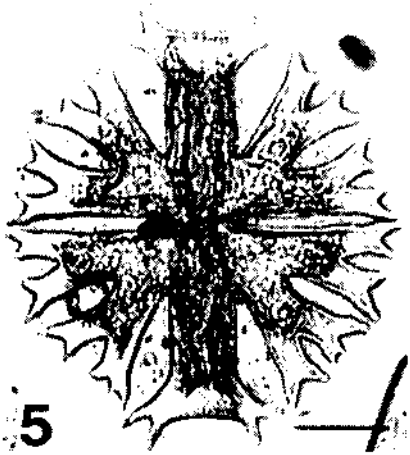

**Plate IV:** **Blue-green algae, greenalga and euglenophytes (scale = 20μm)**

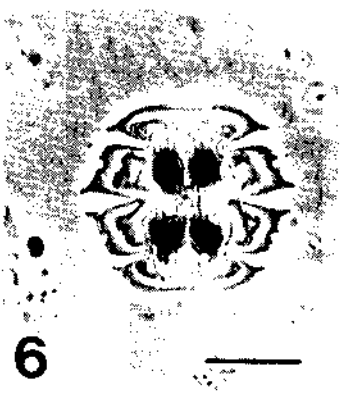
1 *Microcystis aeruginosa* KÜTZ
2 *Episphaerogloea* sp
3 *Cylindrospermopsis raciborskii* (WOLOSZ) SEEN. & SUBBA-RAJU
4 *Aphanizomenon* sp 1
5 *Coelastrum* sp
6 *Euglena sanguinea* E

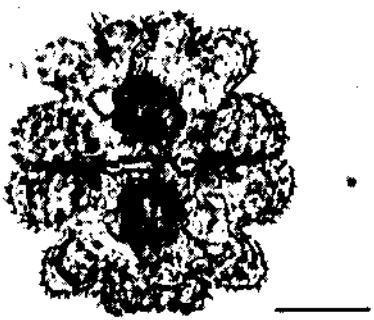
Plate V:










**Greenalgae (scale = 20)**

1 *Phymatodocis irregulare* SCHMIDLE f
2 *Micrasterias foliacea* BAIL
3 *Spondylosium* cf *nitens* f *tensa* TURN
4 *Micrasterias alata* WALLICH
5 *Micrasterias radians* TURN
6 *Micrasterias zelylancia* FRITSCH f
7 *Botryococus* cf *neglectus* W & G S WEST) DOM. & MAR
8 *Euastrum* subsp *africanum* var *minus* NORDST

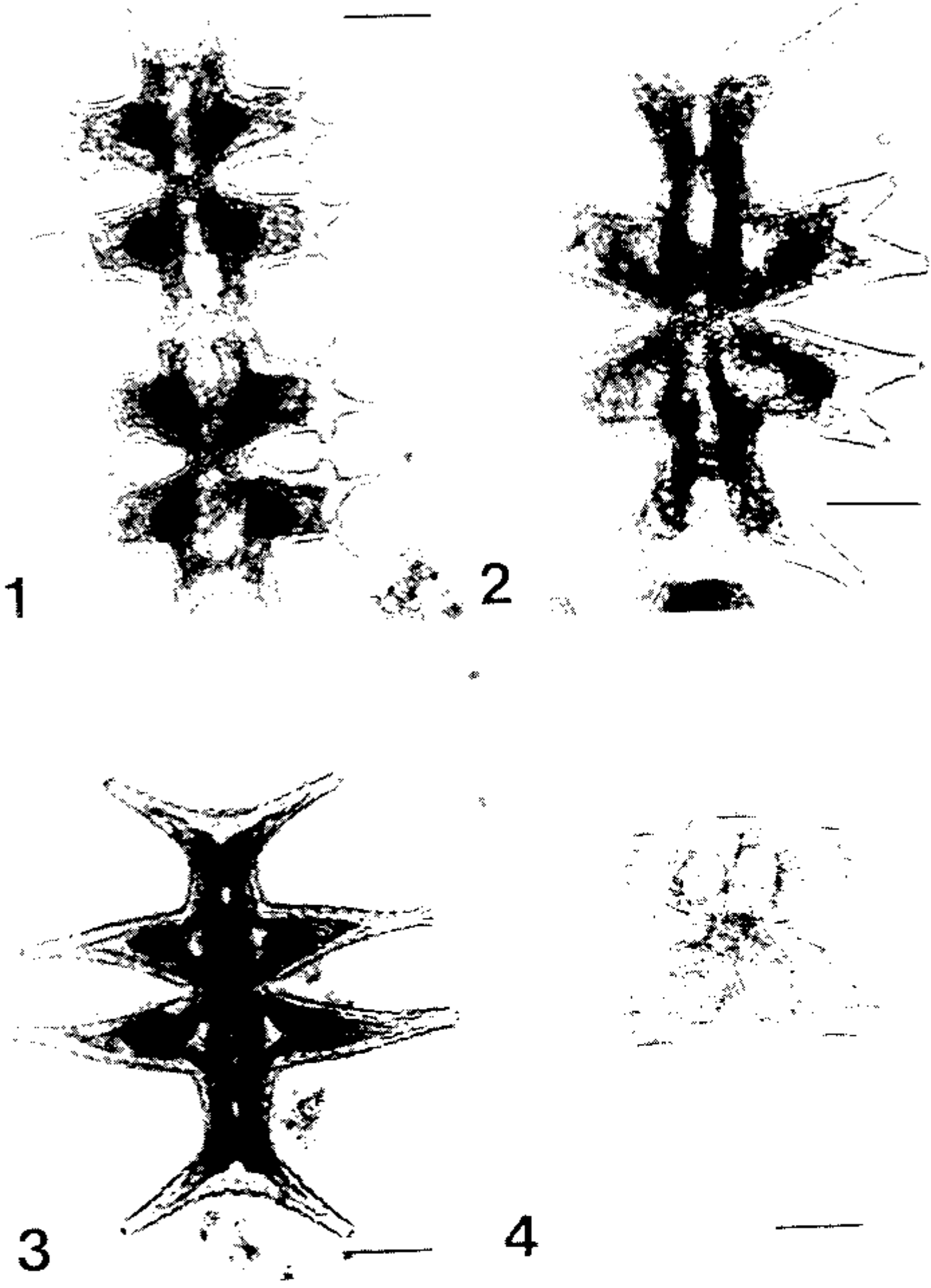



**Plate VI:** **Greenalgae (scale = 20μm)**

1 *Xanthidium subtrilobatum* W G S WEST
2 *Micrasterias mahabuleschwarensis* HOBSON
3 *Micrasterias tropica* NORDST
4 *Staurastrum* cf *wildemanii* GUTW

Plate VII:

**Rotifers (scale = 20µm)**

1 *Brachionus caudatus caudatus* BARROIS & DADAY
2 *B falcatus falcatus* ZACHARIAS
3 *B calyciflorus* PALLAS
4 *B angularis* GOSSE
5 *B calyciflorus* f *anuraeformis* BREHM
6 *Keratella tropica* (APSTEIN)