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Open Access **Water chemistry and quality of the White Nile at Khartoum**

Faisal Sinada[1] and Manal E. Abdel-Rahman[2]
Department of Botany, Faculty of Science, University of Khartoum,
Khartoum 11115, Sudan
[1]fsinada@gmail.com, [2] minoltag@yahoo.com

Abstract
Fortnightly measurements of physical and chemical variables were made on the White Nile near Khartoum from May 2000 to May 2001. Variables measured were: temperature, pH, and concentrations of dissolved oxygen, alkalinity, phosphate-phosphorus, nitrate-nitrogen, silica, calcium, magnesium, sodium, potassium, iron, and oxidizable organic matter. The seasonal variations of these factors in the White Nile are presented, and the interrelationships existing between some of them and phytoplankton growth are discussed. Comparisons are made with earlier studies on the same river and with a few tropical rivers. In the White Nile at Khartoum, changes in nutrients are largely dependent upon the flood regime, partly derived from the Ethiopian Plateau through the Sobat River and partly from utilization by seasonal phytoplankton in the upstream Jebel Aulia reservoir. Nitrate, phosphate, silicon, and iron increased considerably at Khartoum during the rainy season (July-September) when the maximum concentrations of 388 µg NO_3-N L^{-1}, 306 µg PO_4-P L^{-1}, 12.5 mg Si L^{-1} and 0.52 mg Fe L^{-1} occurred therein. The concentrations of these nutrients, except possibly nitrate, are not expected to limit phytoplankton growth in the White Nile at Khartoum although appreciable depletion occurred during periods of maximum development of diatoms and Cyanobacteria. Fall in silica concentrations, unlike falls in concentrations of nitrate, phosphate and iron, was always followed by a rapid restoration of a higher level. The seasonal variations of calcium and magnesium were irregular and without any obvious seasonal pattern. The White Nile at Khartoum is far from being polluted by heavy metals; no cadmium, lead, or nickel was detected in the surface waters.

Keywords: Sudan, White Nile, water quality, chemical composition, tropical rivers.

Introduction

Brook (1954), Brook and Rzóska (1954), Rzóska *et al.* (1955), Talling (1957), Prowse and Talling (1958), and Talling and Rzóska (1967), laid the foundation for limnological research in Sudan when they published a series of papers on the biology and chemistry of the Nile observed in the 1950s. Talling (1976, 2009) continued to update information on the physical and chemical water characteristics of the Nile.

Gay (1958) was the first to report the presence of the notorious weed *Eichhornia crassipes* (Mart.) Solms in 1957 in the White Nile. Sinada and Abdel Karim

(1984) presented detailed information on the water characteristics and the phytoplankton of the White Nile at Khartoum between 1968 and 1970, at times when chemical control programmes of this notorious weed with the use of 2,4-D (2,4-dichlorophenoxyacetic acid) was running at full scales along vast stretches of the White Nile upstream of the Jebel Aulia dam. According to Bebawi and Mohamed (1984), water hyacinth was sprayed with 2,4-D at 4.4 kg ha^{-1} to achieve temporary success in clearing waterways for navigation and irrigation. *Eichhornia crassipes* persisted in the White Nile within Sudan for many years until a successful biological control programme using two weevils (*Neochetina bruchi* and *N. eichhorniae*) launched in late 1970s gave excellent results (Beshir and Bennett 1985). In early 1980s the noxious weed started to decline in numbers; and ceased to cause any problem by the end of the decade. Since early 1990s the water hyacinth has not reached the Jebel Aulia dam.

This paper deals with the water chemistry and quality of the White Nile. The present data add to the existing information on African rivers and provide a baseline upon which the impact of any future human activities may be assessed. It was fortunate that 40 years ago Sinada and Abdel Karim (1984) did not detect any signs of eutrophication; they concluded that the water quality of the White Nile was of excellent quality and far from being polluted.

Attention is necessary to maintain the good quality of the water of the Nile within Sudan. However, in view of the expansion in agriculture and industry and the rapid social development and urbanization which were achieved within the last 20 years and that expected to take place in the coming years, contamination of the Nile water within Sudan is inevitable unless effective measures are undertaken. Possible sources of contamination of the White Nile water are numerous. These include industrial and domestic sewage effluents and surface runoff from urbanization and agricultural land. Within Sudan, the White Nile is exposed to pollution and cultural eutrophication. During the last century, some factories were built along the White Nile, and many more will be built in the future. Existing factories include cement, sugar, and tanneries. Wastewaters from these factories, as well as from a sewage treatment plant located south of Khartoum, find their way directly into the White Nile. For instance, for many years untreated wastewaters produced by the *Assalaya* and *Kenana* sugar factories near Kosti (360 km south of Khartoum) have been discharged onto the White Nile during the operating season. Moreover, agrochemicals, which are constantly applied in many *White Nile Agricultural Schemes*, are expected to reach the Nile from diffuse sources during rainy seasons.

For comprehensive descriptions of the Nile system, see Hurst (1957) and the monographs edited by Rzóska (1976) and Dumont (2009). The latter books contain a review by Talling of chemical information on the White Nile obtained before 1970.

Materials and methods

Water samples were collected between 10.00 and 11.00 a.m. at two-week intervals for over twelve months, from May 2000 to May 2001 in 2 L polythene bottles. During the period May–November 2000, the Research Vessel *Malakal*, which belonged to the Institute of Environmental Studies, University of Khartoum, was used for collection of samples of water from a fixed midstream station located 5 km upstream of the confluence with the Blue Nile. Samples of water from 0.5, 2 and 4 m were collected using a Friedinger sampler, but no significant differences between them were found. From December 2000 onwards, only sub-surface samples (0.1-0.5 m), which were considered to be representative of the water column, were taken by direct dip at about 5 m from the bank near *El Lamab District* 5 km upstream of the confluence with the Blue Nile.

Except for pH, oxygen, alkalinity and total residue, analyses were made on filtered samples, which were run through Whatman GF/C filters immediately on return to the laboratory. Chemical analyses were performed within a few hours of collection or stored at -20° C for a maximum of four weeks before analysis. The following variables were determined as described in American Public Health Association (APHA 1965): nitrate-nitrogen (phenoldisulphonic acid method), phosphate-phosphorus (stannous chloride reduction method) and silica (molybdosilicate method). Alkalinity (titration to pH 4.5 with 0.02N HCl in the field using phenolphthalein and bromcresol green-methyl red mixed indicators) and dissolved oxygen (Winkler method) were determined as described by Mackereth *et al*. (1978). Dissolved oxidizable organic matter (permanganate method) was determined as described by Mackereth (1963). Sodium, potassium, calcium, magnesium, iron, lead, nickel and cadmium were measured using a Perkin Elmer 2380 atomic absorption spectrophotometer following the methods described in its manual. Temperature was measured with mercury thermometer and pH with a Lovibond Comparator using phenol red and universal indicators in the field and checked with Hach EC 10 pH meter in the laboratory. The pH data presented in this paper are the means of two replicas. Colorimetric determinations for PO_4-P, NO_3-N, and SiO_2 were carried out using Jenway Model 6300 Spectrophotometer fitted with a 1-cm pathlength cuvette.

Results and discussion

The average, maximum and minimum values for the variables recorded in the White Nile during this study and those recorded by Sinada and Abdel Karim (1984) during 1970 are shown in Table 1. The seasonal variations of the variables measured throughout the sampling period are presented in Figs. 1-4 and discussed separately below.

Table 1. Summarized physical and chemical data. Average values (and ranges) of each factor recorded in the White Nile at Khartoum during the period May 2000-May 2001 compared with those obtained by Sinada and Abdel Karim (1984) during the period January-December 1970

Factor		Present study	Sinada & Abdel Karim (1984)
		2000/2001	1970
Temperature	(°C)	24.2(15.5-31.0)	23.8 (17.2-29.1)
pH	(units)	8.3(7.4-8.9)	8.4 (8.1-8.7)
Oxygen	(mg O_2 L^{-1})	7.3(3.9-11.5)	7.6(6.6-9.2)
Alkalinity	(meq L^{-1})	2.35(1.64-3.24)	2.49(1.94-3.40)
NO_3-N	(µg L^{-1})	191(20-388)	145 (85-270)
PO_4-P	(µg L^{-1})	129(20-306)	67 (28-108)
Si as SiO_2	(mg L^{-1})	12.7(3.5-26.7)	18.5 (15.0 22.5)
Ca^{+2}	(mg L^{-1})	17.0(7.4-30.8)	14.5 (10.2-22.4)
Mg^{+2}	(mg L^{-1})	7.0(4.2-8.8)	9.9 (5.4 13.0)
Na^{+}	(mg L^{-1})	31.9(20.2-44.7)	28.1 (20.0-46.0)
K^{+}	(mg L^{-1})	7.2(2.1-14.2)	9.1 (6.0-14.0)
Fe	(mg L^{-1})	0.21(0.03-0.52)	0.21(0.04-0.46)
Organic matter	(as mg O_2 L^{-1})	7.5(4.0-12.6)	6.4 (5.3-7.2)

Current flow

The White Nile at Khartoum does not show any flood phenomenon similar to that of the Blue Nile. According to Talling (1957a) velocities of the current in the Jebel Aulia reservoir (October 1954) declined from about 0.3 m sec^{-1} to under 0.1 m s^{-1} near the dam. Sinada and Abdel Karim (1984) found that the current velocity of the White Nile on the other side of the dam near Khartoum fluctuated between 0.9 and 1.8 m s^{-1}. The maximum velocity coincided with the release of maximal amounts of water from the Jebel Aulia Dam, 45 km upstream of the confluence with the Blue Nile at Khartoum. During July-October when the Blue Nile was at its peak, rate of flow of the White Nile at Khartoum was negligible due to minimal discharge from the dam and also due to a backing effect exerted on the White Nile by the Blue Nile for quite a distance south of their confluence. At this season, some admixture of White Nile water by Blue Nile Water occurred (Prowse and Talling, 1958). Talling (1957a) reported a good correlation between phytoplankton growth and slowing down of the current in the Jebel Aulia reservoir.

Temperature (Fig. 1a)

The water temperature of the river fluctuated in the range of 15.5-31.0 °C.

Samples taken from different depths (0.5, 2 and 4.0 m) indicated that the river was not thermally stratified. Homothermal conditions at Khartoum are attributable to complete mixing of the shallow water column where the maximum depth perhaps does not exceed four metres.

pH (Fig. 1b)

The pH in the White Nile was neither acidic nor highly alkaline. It fluctuated in an appreciable range of 7.4 and 8.9. No abrupt changes in pH occurred except at August-September 2000. This may indicate that the river possesses a relatively high buffering capacity.

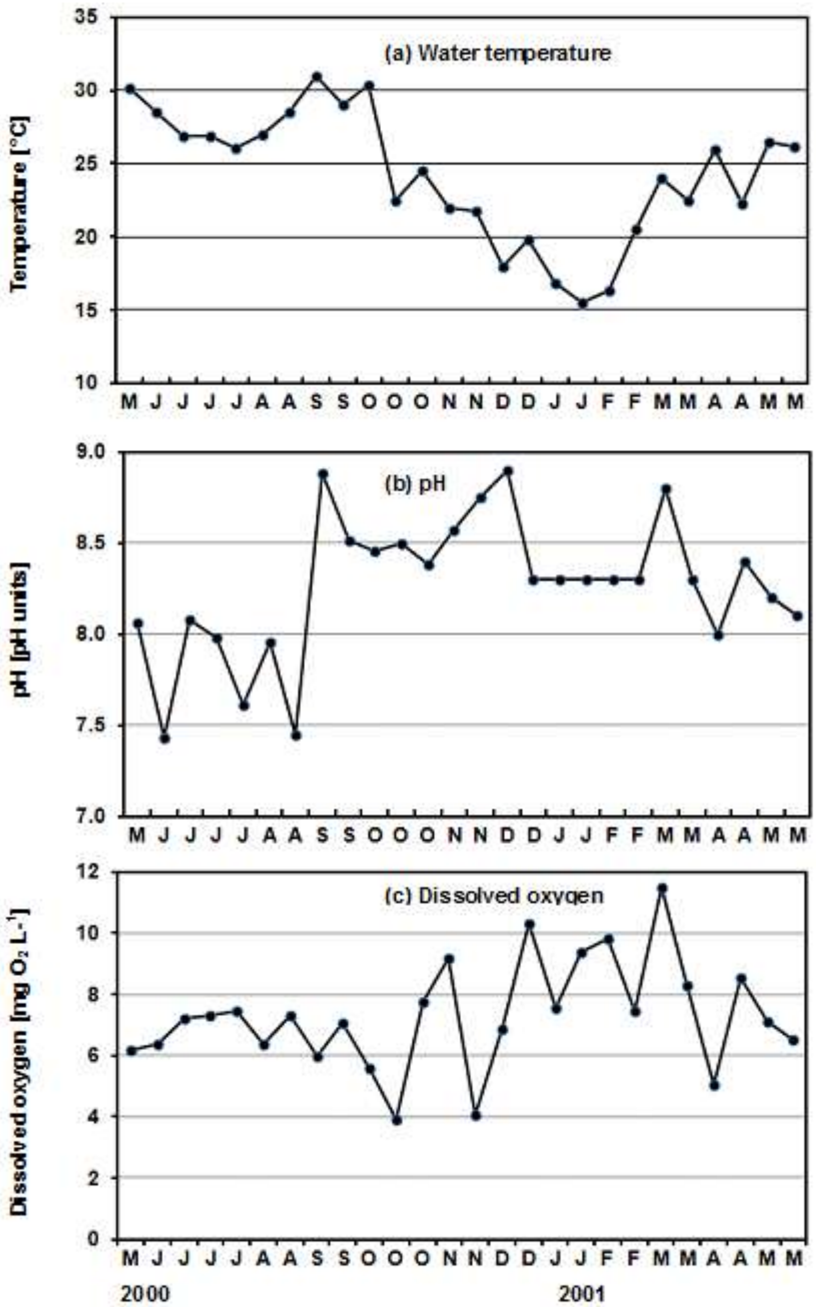

Fig. 1 Seasonal variations in (a) water temperature, (b) pH and (c) concentrations of dissolved oxygen in the surface water of the White Nile at Khartoum during May 2000-May 2001 sampled at two-week intervals

The highest pH values usually coincided with periods of high phytoplankton densities which were composed of diatoms and Cyanobacteria and a few green algae. Then diurnal changes of pH and alkalinity are likely (Talling, 1957b). As expected, minimum values of pH were maintained at times when phytoplankton growth was negligible. Many workers attributed relatively high pH values to increased photosynthetic activity of algal populations (Saad and Antonie 1978; Ahmed *et al.* 1986; Leitao and Lepetre 1998). Prowse and Talling (1958) and Talling (1957b) pointed out that the abundance of algae in the White Nile induces, by photosynthesis, more alkaline state of the water.

Dissolved oxygen (Fig. 1c)

The concentrations of dissolved oxygen occurred within a wide range of 3.9-11.5 mg O_2 L^{-1}. The White Nile was fairly oxygenated at Khartoum although the percentage saturation sometimes dropped below 60%. It is surprising that under saturation occurred at times of phytoplankton abundance when a value of 45% was recorded in mid-October when diatoms peaked. Excessive phytoplankton growth may cause a decrease in percentage saturation through the removal of oxygen from the water column as a result of microbial breakdown of decaying algae. However, supersaturation between 110-135% occurred at times of development of small peaks of diatoms. Others (e.g. Talling 1966, Hill and Rai 1984 and Talling *et al*. 2009) have noted that oxygen supersaturation is often encountered in regions with abundant phytoplankton.

Dissolved oxidizable organic matter

The concentration of dissolved oxidizable organic matter in the White Nile was greater than that in the Blue Nile. It remained in the range of 4.0-12.6 mg O_2 L^{-1}. This is not surprising; the White Nile, in passing through the *Sudd* swamps, which are infested with macrophytes, is expected to be rich in organic matter. However, the values of dissolved organic matter (Table 1) recorded during the present study were higher than those recorded by Sinada and Abdel Karim (1984) during 1968-1970. Abdellatif *et al.* (1993) reported that the sewage treatment plant at *El Qoz* south of Khartoum discharges part of its sewage through an open channel to the White Nile at *El Lamab District*. Unfortunately, no water samples were collected from the vicinity of the sugar factories in the *White Nile State*. However, it is tempting to assume that the increase in dissolved organic matter is also attributable to the direct discharge of untreated wastewaters of sugar factories into the river. It seems that the increase in dissolved oxidizable organic matter influenced the concentration of dissolved oxygen at times of low algal biomass. The lower oxygen concentrations recorded here, compared to those recorded by Sinada and Abdel Karim (1984), occurred at times of high temperature, which coincided with a reduction in dissolved oxidizable organic matter.

Nitrate-nitrogen (Fig. 2a)

The concentration of NO_3-N varied between < 20 and 388 µg NO_3-N L^{-1}. High concentrations in the range of 140–388 µg NO_3-N L^{-1} occurred during the wet season.

Two peaks of 325 and 388 µg NO_3-N L^{-1} were recorded in May and July respectively. These may result from an intrusion of the Blue Nile flood water (Prowse and Talling, 1958). The peaks of NO_3-N reported by Sinada and Abdel Karim (1984) during the wet seasons (July-September) of 1969, and 1970 were much lower being 180 and 270 µg NO_3-N L^{-1} respectively. Similarly Venkateswarlu (1969) Ahmed *et al.* (1986) reported high values of dissolved NO_3-N during the rainy season in the River Moosi (India) and in the River Nile (Egypt) respectively. Hall *et al*. (1977) suggested that NO_3-N comes mainly from the atmosphere, entering the River Zambezi with rain water.

In addition to the contribution from the Ethiopian Plateau through the Sobat River, agricultural runoff may be another source of nitrate input into the White Nile. Another possible factor for the maintenance of relatively higher concentrations of NO_3-N than those observed 40 years ago by Sinada and Abdel Karim (1984), is the disappearance of the notorious floating weed *Eichhornia crassipes* from the Jebel Aulia reservoir in early 1980s.

During the period of strong phytoplankton growth in the White Nile at Khartoum between September-November, there was – as found by Prowse and Talling (1958) – a gradual decline in NO_3-N concentration to a possibly limiting concentration of 20 µg NO_3-N L^{-1}. Limiting concentrations of NO_3-N, coupled with a shortage of carbon dioxide, perhaps checked (1966) has shown that in Lake Victoria NO_3-N possibly limits algal growth. In Amazonia Hill and Rai (1984) attributed a substantial decrease in NO_3-N to increase in its algal consumption, and considered that nitrogen possibly limited algal growth.

Phosphate-phosphorus (Fig. 2b)

The concentrations of phosphate–phosphorus varied between < 20 and 306 µg PO_4-P L^{-1}. A continuous decline in the concentrations of PO_4-P from 131 to 100 µg PO_4-P L^{-1} occurred throughout October-November 2000 when diatoms and Cyanobacteria preponderated. Minimum and relatively lower concentrations in the range of 20-107 µg PO_4-P L^{-1}, were recorded during cooler months, which coincided with the period of maximum growth of diatoms and Cyanobacteria. During the warm period, May–August, which coincided with the rainy season, phosphate maintained higher levels, in the range of 100-306 µg PO_4-P L^{-1} with the maximum value being recorded during July. During the period February-May 2001, relatively high concentrations of PO_4-P in the range of 81-238 µg PO_4-P L^{-1} were maintained without obvious trend except for sudden drops associated with high densities of the epiphyte *Cocconeis placentula* and smaller peaks of *Aulacoseira granulata*, *A. nyassensis* and *Anabaena flos-aquae*.

The present study indicated that the phosphate concentrations in the White Nile were considerably higher than those recorded by Sinada and Abdel Karim (1984) forty years ago. The peak of 306 µg PO_4-P L^{-1} recorded during the rainy season was higher than the peaks of 163 and 108 µg PO_4-P L^{-1} observed by Sinada and Abdel Karim (1984) during the wet seasons of 1969 and 1970 respectively. Talling (1957), in his longitudinal survey of the White Nile, found that phosphate increases considerably when the Sobat River joins the White Nile. It is tempting to attribute the increase in phosphate during the rainy season (may-August) to input through tributaries like the Sobat River and possibly non point sources from agricultural. The provision of higher concentrations of PO_4-P during the present study than previously recorded may be attributed to the disappearance of *Eichhornia crassipes* during the 1980s.

Silica (Fig. 2c)

The seasonal variation of dissolved silicon expressed as silica, in the White Nile

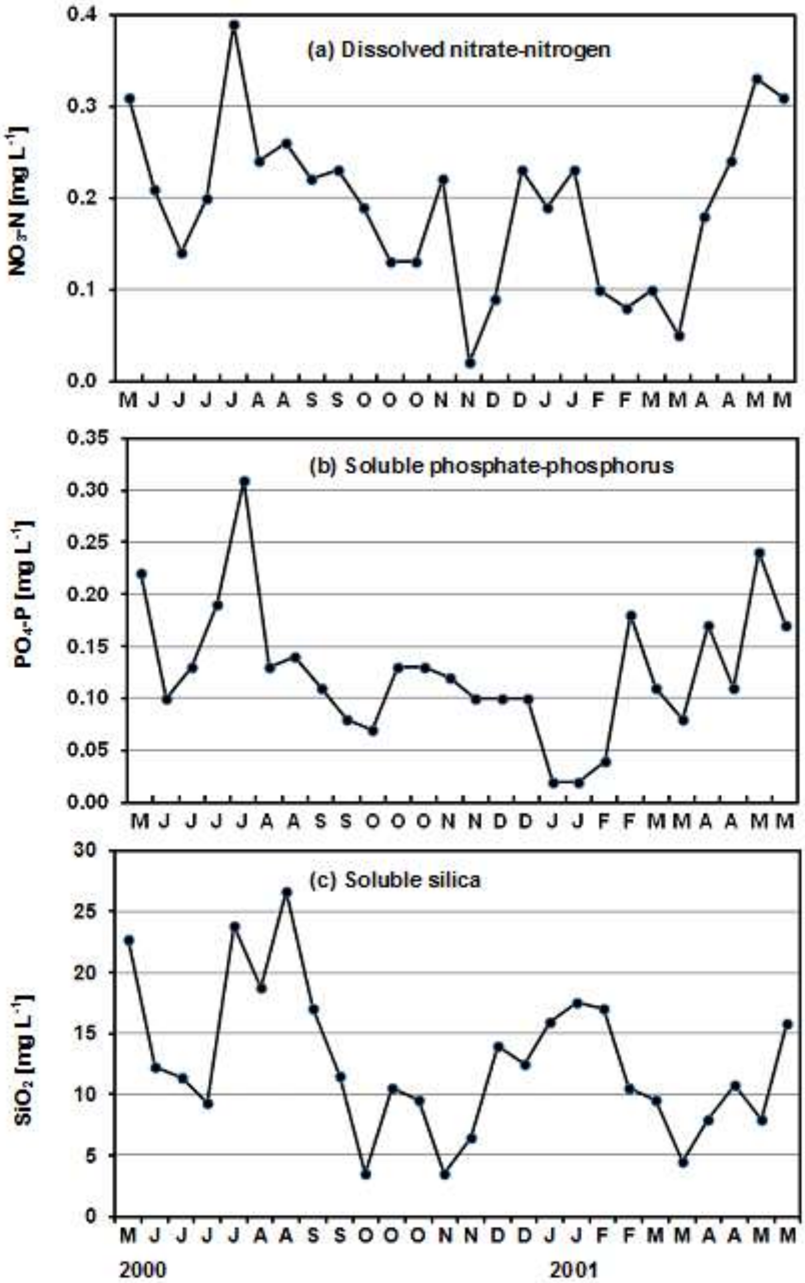

Fig. 2 Seasonal variations in the concentrations of (a) nitrate-nitrogen, (b) soluble phosphate-phosphorus and (c) soluble silica in the surface water of the White Nile at Khartoum during May 2000-May 2001 sampled at two-week intervals

during the present study varied between 3.5 and 26.7 mg SiO_2 L^{-1} (1.6-12.5 mg Si L^{-1}). The maximum value, recorded in the rainy season in August 2000, was probably partly contributed by the Sobat River whereas minimum and relatively lower concentrations, in the range of 3.5-17.5 mg SiO_2 l^{-1} (1.6-8.2 mg Si L^{-1}), were maintained during both winter and summer months. Talling (1957a), in his longitudinal survey of the White Nile, found that silica increased considerably when the Sobat River joins the White Nile. Hall *et al*. (1977) observed an increase of silica in the Zambezi River during the flood period. The fall in the concentration of silica to 3.5 mg SiO_2 L^{-1} (1.6 mg Si L^{-1}) in October occurred during the period of maximum growth of the diatom *Aulacoseira*. The relationship between active diatom growth and decline in silica content has been documented by many workers (see Talling and Lemoalle, 1998). The available evidence suggests a strong correlation between the dominance of certain diatoms and silica content of water. For instance, the spring maximum of diatom *Asterionella formosa* in the lake Windermere (England) causes silicon depletion, which limits the growth of diatoms (Lund 1950; Lund *et al*. 1963). In the present study, the decline of silica to the minimum of 3.5 mg SiO_2 L^{-1} (1.6 mg Si L^{-1}) from the maximum of 26.7 mg SiO_2 L^{-1} (12.5 mg Si L^{-1}) occurred during the period of maximum growth of diatoms between September–November. However, Talling and Rzóska (1967) did not observe any correlation between diatom increase and depletion of silica in the nearby Blue Nile River. In the White Nile near the present station Prowse and Talling (1958) did find inverse correlation. Here, during the present study, depletion of silica was followed immediately by return of higher levels. This probably indicates that high reserves of silica in the particulate fraction go rapidly in solution when dissolved silica is depleted by diatoms.

In the White Nile the concentrations of silica during the present study (3.5 and 26.7 SiO_2 L^{-1}) or any other study (Talling 1957a; Prowse and Talling 1958; Sinada and Abdel Karim 1984) never fell to levels which limit the growth of plankton diatoms. Bukaveckas *et al*. (2000) found that when silica fell to less than 0.5 mg L^{-1} in the Ohio River it limited the growth of plankton diatoms.

Alkalinity (Fig. 3a)

Phenolphthalein alkalinity was not detected at any time in the White Nile; the total alkalinity was largely or entirely due to bicarbonate ions. The maximum and minimum values of alkalinity recorded during the present survey were 3.24 and 1.64 meq L^{-1}**.** These relatively high values of alkalinity indicate a sufficient reserve of total CO_2 and an adequate supply of inorganic carbon for the support of algal photosynthesis. However, during the period of strong growth of the mixture of diatoms and Cyanobacteria in September-November 2000, alkalinity values decreased gradually to the minimum of 1.64 meq L^{-1} in mid December 2000. It is noted that, during the same period, the pH increased continuously to reach the peak of 8.9 in mid December 2000 (Fig. 1b). It is tempting to attribute the end of the growing season of the phytoplankton (a mixture of diatoms (*Aulacoseira*) and Cyanobacteria (*Anabaena*)) in the White

Nile at Khartoum to low limiting concentrations of CO_2 maintained under alkaline conditions as a result of photosynthesis. This is in conformity with Prowse and Talling (1958) and Talling *et al*. (2009) who suggested that in the White Nile and the Blue Nile, strongly alkaline conditions (near or above pH 9.0) together with low levels of nitrate (<20 µg NO_3-N L^{-1}) may check the growth of *Aulacoseira granulata* although vigorous photosynthesis by the Cyanobacteria continues. Unlike the latter observation, vigorous photosynthesis by Cyanobacteria during the present study did not continue, perhaps also limited by low concentrations

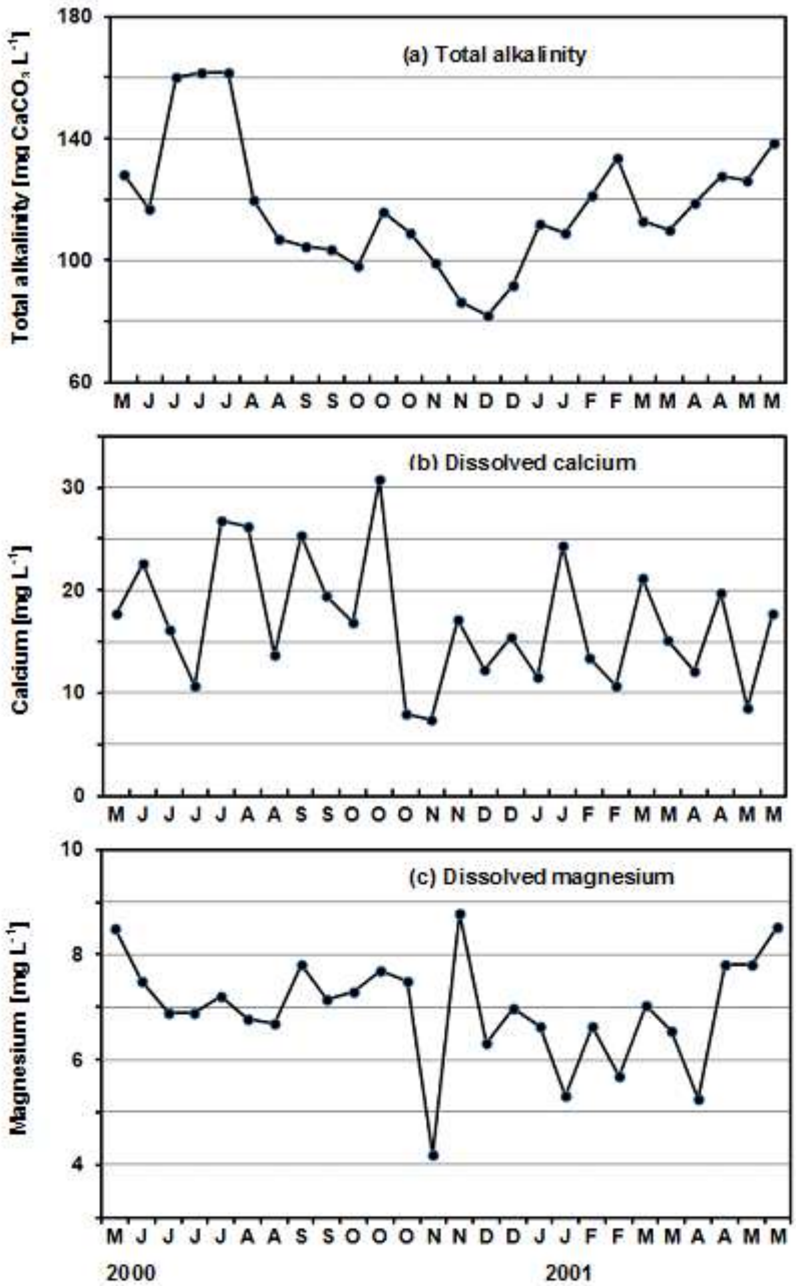

Fig. 3 Seasonal variations in (a) total alkalinity, (b) concentrations of dissolved calcium and (c) concentrations of dissolved magnesium in the surface water of the White Nile at Khartoum during May 2000-May 2001 sampled at two-week intervals

of CO_2, although lowered concentrations of PO_4-P are another possibility.

In early March 2001 when *Cocconeis placentula* suddenly peaked, and

Calcium and magnesium (Fig. 3b, c)

The average, maximum and minimum values of calcium and magnesium in the White Nile are shown in Table 1. The seasonal variations of calcium and magnesium were irregular and without any clear seasonal pattern. The concentrations of calcium were always greater than those of magnesium. The fluctuation in the concentration of magnesium during the present study did not seem to affect the growth of algae adversely. The concentrations of Ca^{2+} and Mg^{2+} dropped to their lowest concentration during the period of maximum growth of diatoms and Cyanobacteria. However, sufficient quantities of Ca^{2+} and Mg^{2+} be in excess of the requirements of the algae were maintained throughout the year.

Sodium and potassium (Fig. 4a, b)

The average, maximum and minimum values of sodium and potassium in the White Nile are shown in Table 1. The concentrations of sodium exhibited greater concentrations than those of potassium. This is in conformity with observations of Talling and Talling (1965). Neither element is likely to be a limiting nutrient for phytoplankton. Sodium and potassium concentration tended to be higher during the wet season, in agreement with Ahmed *et al.* (1986) in the Nile within Egypt and Hall *et al*. (1977) in the Zambezi River who found higher levels of sodium and potassium during the flood season. Strong

Anabaena flos-aquae maintained smaller peaks, the pH increased to the sub-maximum of 8.8 and total alkalinity showed a decline from a sub-maximum of 2.68 to 2.26 meq L^{-1}.

floods, as in the Blue Nile, are likely to reduce concentrations by dilution exceeding leaching.

Iron (Fig. 4c)

Appreciable quantities of dissolved (or very finely particulate) iron in the range of 0.11-0.30 mg Fe L^{-1} were maintained in the White Nile at Khartoum during most of the year, with peaks characterising the rainy season. The high values are attributable to increase in solubility of ferrous ions under the reducing conditions in the '*Sudd*' swamps as pointed out by Talling (1957). Lakshminarayana (1965) and Venkateswarlu (1969), working on Indian rivers, observed that the amount of dissolved iron increased with increasing discharge during the rainy season. The appreciable amounts of iron present in the White Nile throughout the year can be associated with the stabilization of iron by complexing with organic matter. According to Wetzel (1975, p. 252), an enrichment of iron is commonly found in surface waters with high contents of dissolved organic matter inasmuch as complexes of iron may be formed with certain organic molecules by which the solubility and availability of iron is increased. It seems reasonable to assume that the occurrence of appreciable quantities of dissolved iron during most of the year is due to complexing of iron with dissolved organic matter.

Heavy metals (cadmium, lead and nickel)

No attempt has been made before to detect the presence of heavy metals such as cadmium, lead and nickel in the White Nile at Khartoum. None of these heavy metals was detected during the present study. This indicates that the White Nile at Khartoum is not polluted by heavy metals.

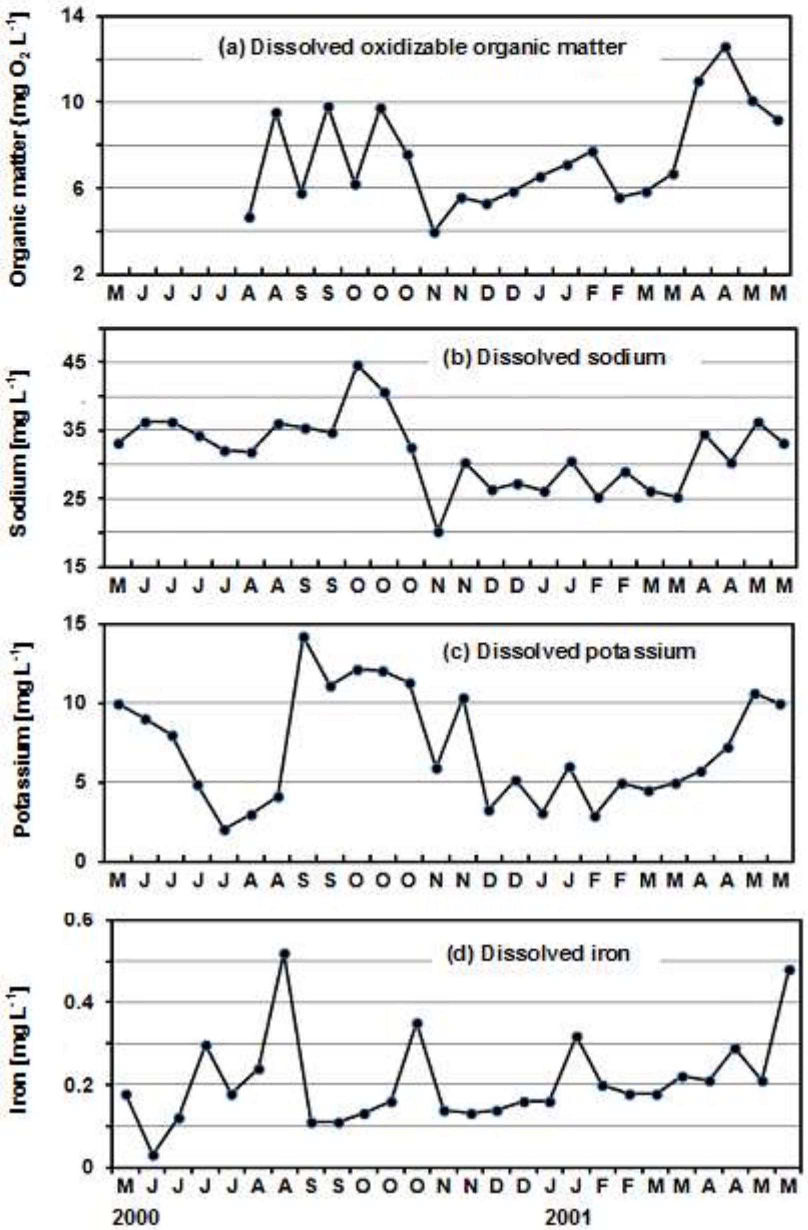

Fig. 4 Seasonal variations in concentrations of (a) dissolved oxidizable organic matter, (b) dissolved sodium (c) dissolved potassium and (d0 dissolved iron in the surface water of the White Nile at Khartoum during May 2000-May 2001 sampled at two-week intervals

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