The longitudinal succession of water characteristics in the White Nile

by

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INTRODUCTION

Successive modifications of water characteristics, both physical and chemical, can be expected to occur during the seaward flow of water in a river. Although knowledge of such changes is essential for many aspects of river biology, very few detailed studies are available, particularly for the large tropical rivers. This paper is concerned with changes in water properties along an important branch of the Nile system, the White Nile, for which little previous work exists (BEAM, 1906, 1908; LUCAS, 1908; HURST, 1925, pp. 67—73; TOTTENHAM, 1926; BROOK & RZÓSKA, 1954; BEAUCHAMP, 1956). The White Nile branch is one of the two main divisions of the upper Nile and extends for 2530 km between Lake Victoria and Khartoum, where it unites with the other division, the Blue Nile. The combined waters then flow, as the Main Nile, for a further 3080 km to the Mediterranean. This Main Nile region is not described here, and later references to the 'river' apply only to the White Nile sector.

This study was undertaken mainly as a background to a survey of river biology being made by the Hydrobiological Research Unit of the University College (now University) of Khartoum. Biological implications are therefore emphasized, and particular attention is paid to plant nutrients. Many features are also of considerable intrinsic interest, as would be expected for a river flowing northwards through several climatic and altitudinal zones, receiving the contributions of diverse drainage basins, and traversing a major African swamp system.

The data are chiefly based upon samples collected along the river in two seasons, May – June 1954 and December – January 1954-5. Results of the longitudinal survey are given here in graphical form, and interpreted in relation to the two chief modifying influences, tributary contributions and riverain swamps. In the lowest part of the river, which is a reservoir region, further modifications arise from the activities of seasonal plankton populations (cf. BROOK & RZÓSKA, 1954; RZÓSKA, BROOK & PROWSE, 1955) which will be described in a separate paper.

Detailed information on the geography and hydrology of the White Nile is readily available (HURST & PHILLIPS, 1938; NEWHOUSE, 1939; HURST, 1950, 1952). The river flows out from Lake Victoria, and passes through parts of two lakes, Kioga and Albert, before falling steeply to the Sudan plain (profile in HURST & PHILLIPS, 1938, plate 5). Here it soon enters a large swamp (the '*Sudd*') extending about 500 km along the river, in which about half of its water is lost. Near the end of the individual river at Khartoum the water is seasonally stored by the Gebel Aulia dam, whose influence extends a considerable distance upstream (BROOK & RZÓSKA, 1954). The principal tributary drainage is from Lake Albert, several torrents near the Sudan border, and the River Sobat (fig. 1); the two latter contributions show large seasonal variations.

The river water is moderately rich in dissolved salts and has a marked alkaline reaction (pH usually 7.5 to 8.5) except when locally modified by swamp drainage. Like many other African waters (but unlike those in many other regions) calcium ions make up only a small part of the total cations present, sodium and potassium being predominant. As is usual in freshwaters, bicarbonate is the principal anion.

METHODS

Most of the work was carried out between 26 May – 25 June 1954 and 11 December – 8 January 1954-5, during two cruises of the research launch 'Malakal' between Khartoum and Juba in the south Sudan. Chemical analyses were performed within a few hours of sampling, pH being determined colorimetrically immediately after collection. During 26-28 May 1954 further samples were taken between Lake Victoria and Juba and analysed after a delay of 1 to 4 days (pH excepted). Some analyses were made during a previous cruise, in December 1953, along the river stretch 1000 km southwards from Khartoum.

Analyses carried out (on filtered samples) by standard methods described by the AMERICAN PUBLIC HEALTH ASSOCIATION (1946) and TAYLOR (1949) included ammonia (direct Nesslerization), nitrate (phenol disulphonic acid, including decolorization with aluminium sulphate), silicon (ammonium molybdate), phosphate (ATKINS' modification of DENIGÈS' method), and chloride (titration with silver nitrate). Sulphate was estimated turbidimetrically after precipitation with barium chloride (WERESCHTSCHAGIN, 1931) and calcium by the versenate titration method (HERON & MACKERETH, 1955). Total iron was measured colorimetrically using ammonium thiocyanate after a preliminary oxidation with acid permanganate, the resulting colour being extracted with a mixture of amyl alcohol and amyl acetate. 'Colour' was estimated in relative units, using diluted whisky as a colour standard. Electrical conductivity (expressed as reciprocal megohms per centimetre cube at 20°C) was determined with a commercial (Evershed and Vignoles' "Dionic Water Tester") conductivity meter, and alkalinity due to bicarbonate and carbonate by titration with N/50 HCl to pH 4.5. Carbon dioxide was estimated indirectly from alkalinity and pH (MOORE, 1939); the results are reliable only where other free acids are absent. Dissolved oxygen was measured by ALSTERBERG'S (1926) modification of the WINKLER method, the samples being collected by a Ruttner sampler from which water temperatures were also read. Values for percentage saturation are based upon the data of TRUESDALE, DOWNING & LOWDEN with correction for altitude (MORTIMER, 1956). Colorimetric analyses were made using a B.D.H. Lovibond 'Nesslerizer' or 'Comparator' with coloured glass standards, the latter being calibrated against standard solutions.

Transparency was determined with a standard Secchi disc of 30 cm diameter. Light penetration was measured with an underwater photometer incorporating a selenium rectifier photocell and red, green and blue glass colour filters (numbers OR1, OG9, and OB10 manufactured by Chance Bros.). Care was taken to avoid errors due to the curvature effect in the photocell response at high light intensities (cf. ATKINS *et al.*, 1938). The results are given as mean values of the vertical extinction coefficients (defined, for example, by SVERDRUP, JOHNSON & FLEMING, 1942) for the various cell-filter combinations. The optical centres of gravity of these combinations during measurements were estimated at wavelengths of approximately 460 $m\mu$ (blue), 560 $m\mu$ (green), and 625 $m\mu$ (red).

All the analyses given refer to samples of surface water. These are considered to be representative, as temperature stratification was usually slight or absent, and occasional analyses of surface and bottom water showed no noteworthy differences. An exception exists for the lower reservoir region, which shows an intermittent stratification that will be described in detail elsewhere.

Changes in various water characteristics along the river are shown in figs. 1-5, each variable being plotted against distance by river from Lake Victoria. The river course is illustrated by an outline map (fig. 1), and by a linear diagram which is repeated in all figures so that the positions of the tributaries and swamp regions can be readily located.

The influence of a tributary water can be expected to be related to the volume and distinctive character of the water contributed. On these grounds four contributions – from Lake Albert, several torrents 380-760 km from Lake Victoria, the Bahr el Ghazal river system, and the River Sobat – are noteworthy. Measurements of their water characteristics (excluding the torrents for which data are not available) are given in table 1. Although the Bahr el Ghazal water shows several distinctive features (eg. high transparency and silicon content) its discharge is too small to modify significantly the properties studied in the main river. In its upper stretches the pH falls considerably, and a rich Desmid flora exists there (RZÓSKA *et al.*, 1955).

TABLE 1

Water characteristics of three tributary waters, measured shortly before their junction with the main river.

	L.Albert	*Bahr el Ghazal*	*Sobat*
Date of sampling	27. v. 54	30. xii. 53	10. xii. 54
conductivity (megohms-^{1} at 20°C)	675	—	112
alkalinity (N. 10^{-4})	81.6	21.4	15.2
pH	9.0	7.8	6.8
dissolved oxygen, mg/l	—	—	3.4
% saturation	—	—	44
NO_3.N (mg/l.)	0.04	—	0.015
NH_3.N (mg/l.)	—	0.1	0.02
PO_4.P (mg/l.)	0.18	0.02	0.045
Si (mg/l.)	0.6	18	12
Cl (mg/l.)	18	< 2	< 2
Ca (mg/l.)	9.0	—	8.7
SO_4 (mg/l.)	—	—	<1.5
transparency (m)	—	1.2	0.35

The contribution from Lake Albert, based upon drainage from the western Rift Valley, has probably the most profound effects. The high levels of total salts (cf. conductivity), alkalinity, pH, phosphate, sulphate, and chloride in the lake, compared with those in the inflowing Victoria Nile, lead to marked increases in these quantities downstream in the Albert Nile. This enrichment is especially notable

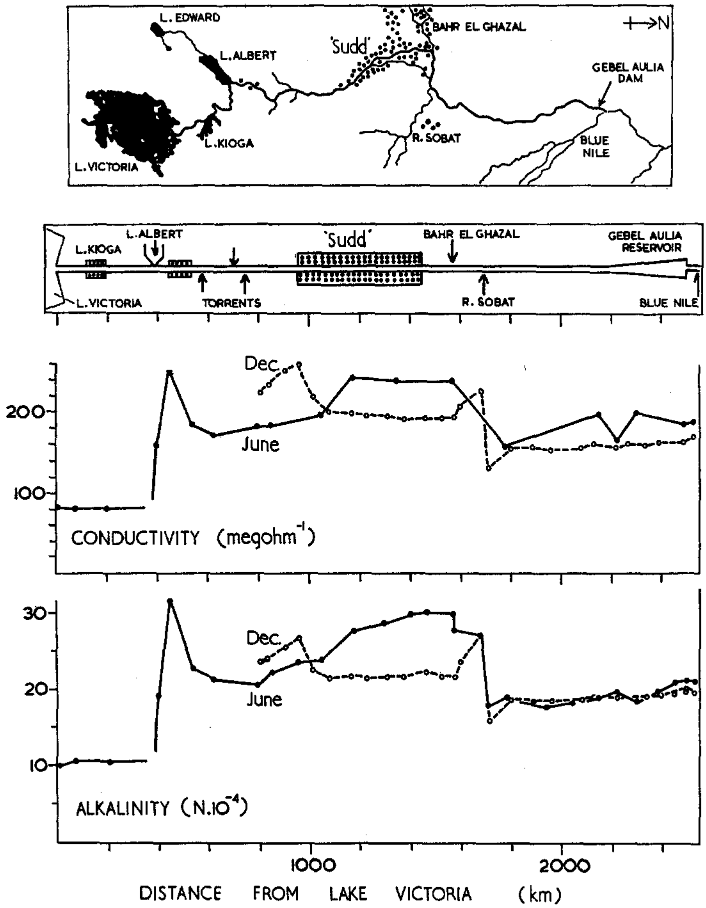

Fig. 1.

Outline map and schematic representation of the White Nile and adjacent waters, with swamp regions indicated by stippled areas; in the two lower graphs the variation in electrical conductivity and alkalinity along the river is shown.

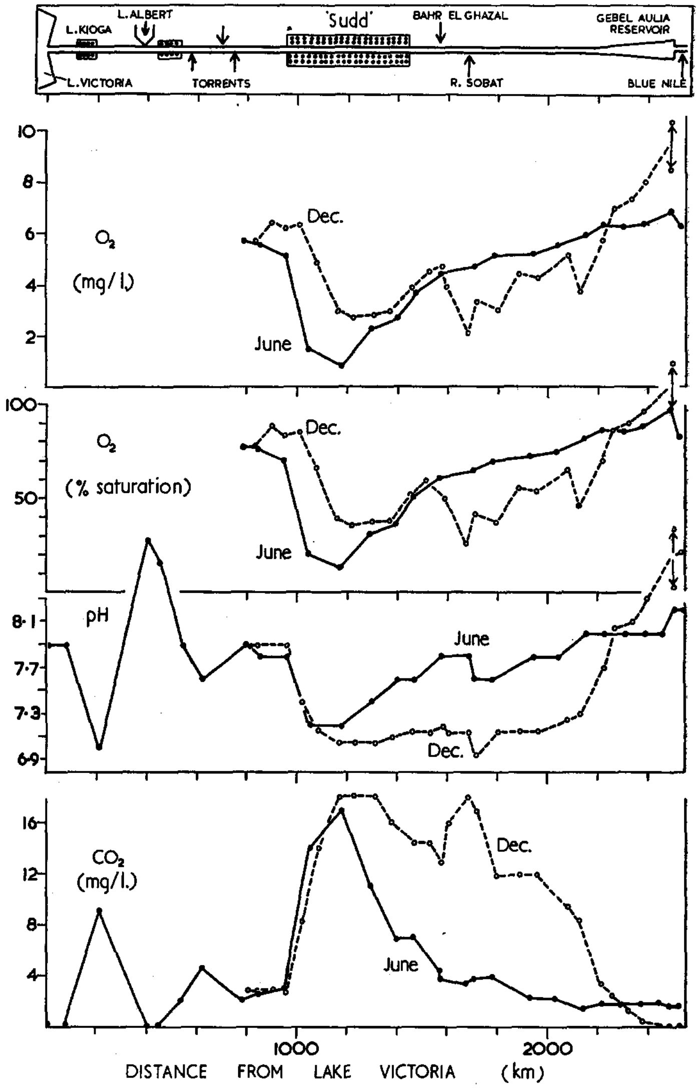

Fig. 2.

Variation in dissolved oxygen, pH, and carbon dioxide (calculated from pH and alkalinity, see p. 75) along the White Nile. At one station the daily range for oxygen and pH is shown by vertical arrows.

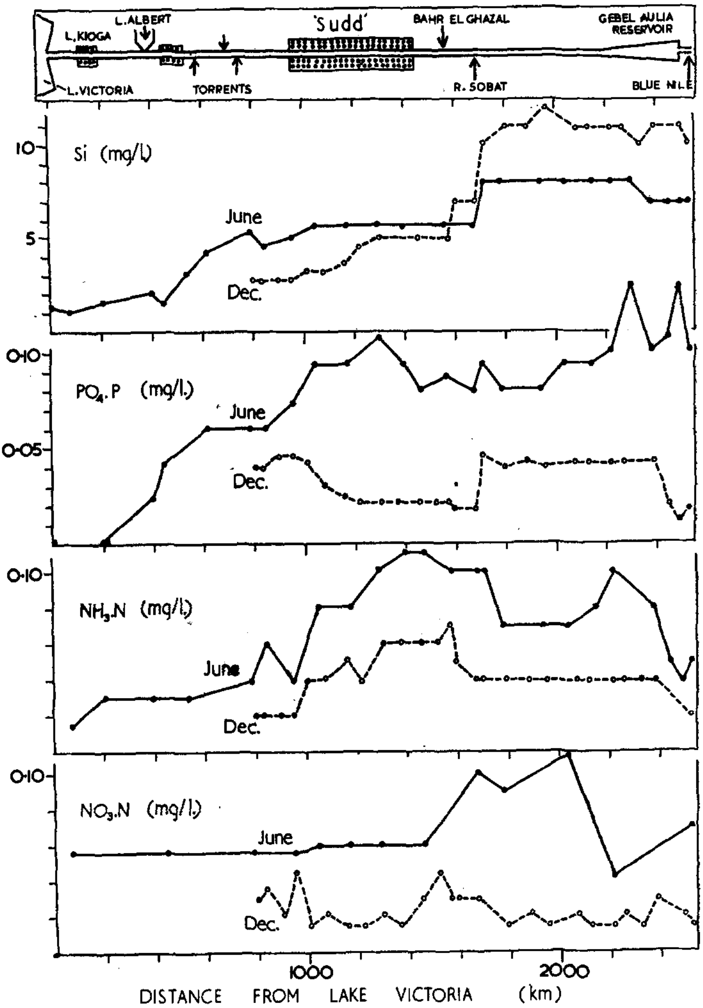

Fig. 3.

Variation in the plant nutrients silicon, inorganic phosphate, ammonia, and nitrate along the White Nile.

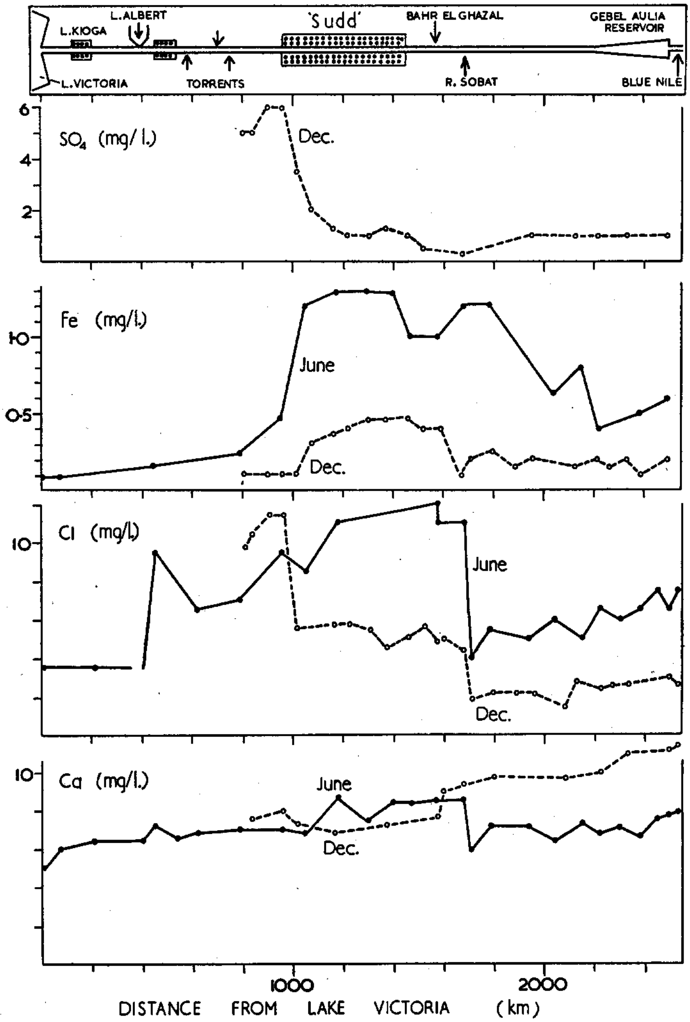

Fig. 4.

Variation in sulphate, total iron, chloride, and calcium along the White Nile.

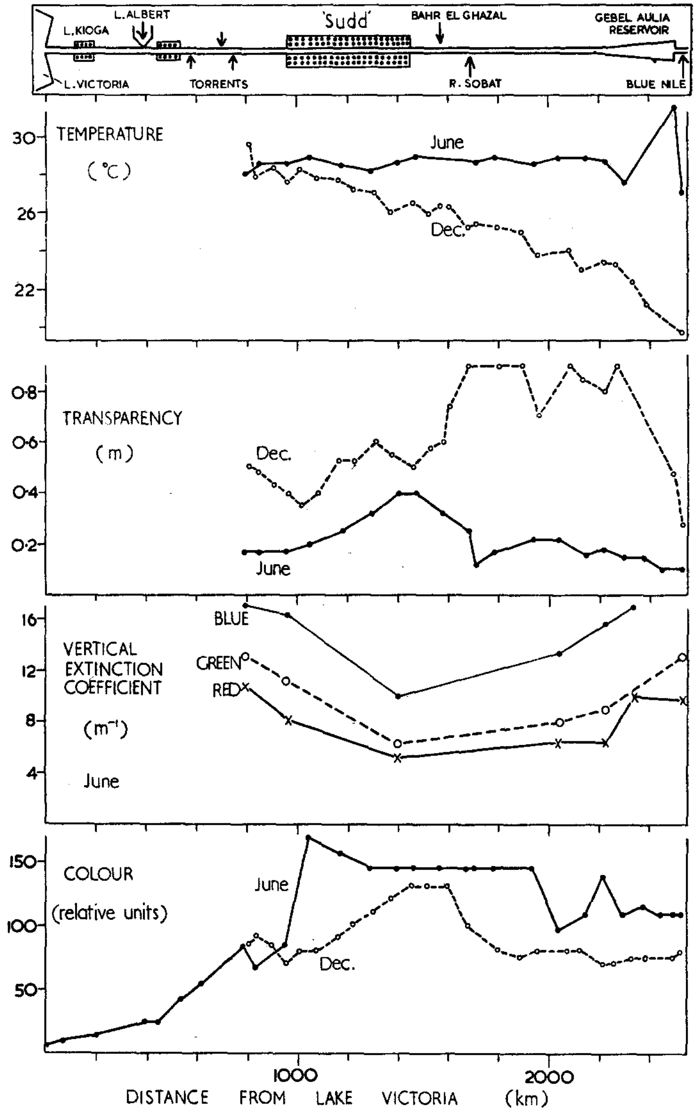

Fig. 5.

Variation in some physical quantities, surface temperature, transparency (from Secchi's disk), vertical extinction coefficients, and colour, along the White Nile. The values for colour are not directly comparable between the two seasons.

for the plant nutrients phosphate and (according to Dr G. R. FISH, private communication) sulphate, whose contents downstream appear to be almost entirely derived from the lake. The effects of Lake Albert are however complicated by the possible occurrence of large yearly fluctuations in some constituents (ANON, 1954), and by short-period variations in the volume of its contribution (HURST, 1925; TOTTENHAM 1926: NEWHOUSE, 1939, p. 27). The latter variation is reflected in large fluctuations of the conductivity of samples collected weekly in the river just below the lake (BEAUCHAMP, 1956). It also accounts for local maxima of conductivity, alkalinity, and chloride discovered in the river some 60 km below the lake (1 May 1954) and 375 km below (December 1954). The last mentioned maximum had vanished when the river region affected was resurveyed in January 1955. It appears unlikely that these temporary fluctuations have any biological significance in the river, except possibly close to the lake.

The tributary torrents, which enter the main river some distance below Lake Albert, have not been examined as to water characteristics. Consequently their influence is less easily demonstrated, but almost certainly includes an enrichment in dissolved silicon (fig. 3) and decrease in transparency (noted subjectively) that occur in this region. The silicon content and the turbidity below these tributaries near Juba (750 km from Lake Victoria) were much higher in June than in December, as would be expected from the seasonal flow of the torrents (HURST, 1952, fig. 17).

The River Sobat, the last important tributary, also produces considerable modifications in the main river. These include the decrease of conductivity, alkalinity, chloride, and transparency; an increase occurs in silicon and (during the December observations) phosphate. The Sobat discharge also shows a large seasonal variation (HURST 1952, fig. 17) which probably underlies several differences between the June and December series. A seasonal variation in the composition of the tributary water is also likely, although data are not available. At high water much Sobat water passes through parts of an adjoining swamp system, the Machar marshes. Their influence may account, at least in part, for the depressed levels of oxygen and pH found during December in the Sobat and in the main river below.

THE INFLUENCE OF RIVERAIN SWAMPS

Riverain swamps are well developed in three areas (fig. 1) within which modifications of varying degree occur in the river water. In the shallow Lake Kioga, 125 km from Lake Victoria, a dense cover of water-lilies (Nymphaeaceae) exists over much of the water surface.

In addition fringing swamps, which include abundant papyrus (*Cyperus papyrus* L.), are extensive. Further swamp regions exist along the river stretch (385-540 km from Lake Victoria) immediately below Lake Albert, and in much greater development in the southern Sudan (1000—1500 km from Lake Victoria). The latter swamp region (the '*Sudd*') has an estimated area of about 8000 km^2 and extends about 500 km along the river. Large parts are dominated by *Cyperus papyrus*, although grasses (especially *Echinochloa stagnina* P. Beauv. and *Vossia cuspidata* Griff.) are also important. The vegetation is described by Migahid (1947) and the Jonglei Investigation Team (1954). Important features of the swamp in the present connexion are the large loss of water (about half the river inflow) and the seasonal inundation of marginal land ('*toich*') by changing water levels. Within parts of the swamp area the river is split into several channels, whose size varies with season.

The influence of swamp conditions upon river-water characteristics was strongest, and was studied in most detail, in the large *Sudd* region. Here processes of decomposition caused a fall in dissolved oxygen and pH, the latter being interpreted as the result of a corresponding increase in carbon dioxide (fig. 2). The deoxygenation was much more strongly developed in June than in December. The causes of this change need more investigation, but may be connected with the displacement of swamp water by changing water levels or by the rains mainly present between April and October. An effect upon oxygen exchange from diurnal changes of thermal stratification may also be involved, as discussed for other tropical swamps by CARTER & BEADLE (1930), BEADLE (1932a), and CARTER (1934, 1955). Seasonal oxygen depletion may well be the cause of a large mortality of fish which usually occurs in this region each year about July and September.

The behaviour of several other quantities may be connected with that of oxygen. Total iron, for example, increases sharply in the swamp region owing to the solubility of ferrous iron formed under reducing conditions. The increase is greatest in the more reducing conditions of June. Inorganic phosphate shows different behaviour in the two seasons, with some increase in the swamp region during June but a marked reduction during December (fig. 3) and January. The decrease may arise from adsorption on the surface of mud under more oxidising conditions then prevailing, as is well known for muds bearing a film of ferric hydroxide. Removal of phosphate from river water flowing through a tropical swamp has also been demonstrated by BEADLE (1932b, pp. 194-6) for the Chambura river in Uganda.

The December observations showed a striking removal of sulphate soon after the river water had entered the swamp region. Less detailed measurements by Dr G. R. FISH (private communication) suggested a similar situation in June. There is good agreement with earlier observations, in 1904 or 1905, by BEAM (1906). The activity of sulphate-reducing bacteria under conditions of oxygen deficiency is presumably responsible. The concentration of sulphate in the water leaving the swamps was too low (under 1.5 mg/1.) to be determined accurately with the method used.

Swamp conditions would also be expected to modify the concentrations of ammonia and nitrate nitrogen in the river water. A noticable rise in ammonia was present in both the June and December series. Nitrate appeared to be less affected, although an irregular fall is suggested in the December series. The levels of both ammonia and nitrate nitrogen were higher in June than in December, but the difference appears largely due to changes higher up the river. In neither season were nitrites detected.

The high evaporation losses within the swamp region would be expected to increase the concentration of total salts, with which conductivity and alkalinity are closely correlated. Such increase is apparently present in the June but not the December series, although evaporation losses in the latter season are still considerable. Other modifying factors may have obscured the effect in December; the influence of oscillations in the contribution from Lake Albert has been already mentioned (p. 82).

The interpretations given above are supported by analyses of swamp waters some distance from the main river channel. They were taken in June 1954 from two points in the *Sudd* swamps 950 and 1460 km from Lake Victoria: at the first a transect was made across a marginal swamp. These swamp waters showed modifications generally parallel to – but more marked than – those found along the main river, particularly decrease in oxygen and pH and increase in ammonia and total iron. No direct evidence is available on the question of seasonal changes.

Fewer data exist for the two remaining large swamp regions, which were visited in June only. There is in both, as in the *Sudd*, a fall of pH and a corresponding rise of free carbon dioxide in the river water. Changes in ammonia, nitrate and total iron appear slight or absent; dissolved oxygen was not measured.

The figures show that some of the modifications in the swamp regions are local (eg. of oxygen in the *Sudd*) whereas others persist for considerable distances downstream (eg. total iron and sulphate below the *Sudd*).

DISCUSSION

Many characteristics previously described are of importance for plant growth. Their modifications in the river are summarized below from this viewpoint, with particular reference to phytoplankton requirements. In this river section dense populations of phytoplankton have been found only in the lowermost reservoir region near Khartoum (BROOK & RZÓSKA, 1954; RZÓSKA, BROOK & PROWSE, 1955). Further upstream densities are very low, except in local water-bodies (eg. lagoons) off the main river (PROWSE, 1954). This feature is remarkable in view of the many planktonic algae entering the river from lakes Victoria and Albert, and the appreciable time of flow (as deduced from the time of travel of hydrological disturbances) which averages about 35 days between Lake Victoria and the head of the reservoir region (MORRICE, 1956).

Of physical factors, temperature (fig. 5) is unlikely to modify directly the distribution of phytoplankton in the river. The temperature range in June was small (27—32°C), although in December there was a decline northwards from 30° to 20°C. Larger seasonal changes in the Gebel Aulia reservoir could not be correlated with the growth of phytoplankton there (PROWSE & TALLING, in prep.). Light penetration (fig. 5) would appear of greater significance, since the relatively high absorption (and hence extinction coefficients) recorded imply a correspondingly shallow photosynthetic zone. The minimum extinction coefficient over the spectrum may be taken as the best single measure (TALLING, 1955, 1957). Values of 1.5 to 3.5 (per metre), with corresponding photosynthetic zones of depth 2.5 to 1.2 m, were found in the reservoir region during October 1954 and 1955 at times of active phytoplankton growth there. Such growth may not be possible under the higher minimum extinction coefficients (c. 5 to 10) measured in the upper river region during June 1954 (fig. 5). However the situation is complicated by varying river depths and by the seasonal variation in light penetration indicated by the transparency data. It can be concluded that regional and seasonal changes in light penetration undoubtedly influence greatly the conditions of growth for phytoplankton, although an absolute limitation of growth is difficult to establish.

Of the major inorganic plant nutrients, phosphate shows a very varied history in the river. The low levels derived from Lake Victoria are suddenly increased by the contribution from Lake Albert, so that relatively high concentrations are characteristic of the later river sections. Modifications appear to be imposed by seasonal removal in the swamp region and during the growth of phytoplankton in the lower reservoir region. It is possible, though uncertain, that the latter depletion may limit the growth of certain planktonic algae (PROWSE & TALLING, in prep.). In any case the seasonal variation of phosphate phosphorus in the productive reservoir region is remarkably high, from under 0.003 to about 0.2 mg/l.

Unlike phosphate, inorganic nitrogen (as ammonia and nitrate) appears always in low concentration, although some seasonal and regional variations have been described. In these, swamp effects appear to predominate, although extreme modifications have been not found. There is some direct evidence from cell analyses (PROWSE & TALLING, in prep.) that the low concentrations may limit the densities attained by the dominant diatom of the reservoir, *Melosira granulata* (Ehr.) Ralfs.

Dissolved silicon is another nutrient which enters in relatively low concentration from Lake Victoria and is subsequently enriched by tributary waters (here the torrents and the River Sobat). During most of the year its concentration in the reservoir region is 7—11 mg/l., and never falls to the low levels (under 0.25 mg/l.) found elsewhere to limit the growth of plankton diatoms (cf. LUND, 1950). It appears, however, that there may be an appreciable reduction during the growth of *Melosira* in October.

Water from Lake Victoria also contains sulphate in low concentration (c. 0.8—1.8 mg/l.; BEAUCHAMP, 1953), and the higher values (near 6 mg/l.) found downstream in the south Sudan are largely due to the contribution from Lake Albert (p. 82). These values are soon dramatically reduced by the *Sudd* swamps to low concentrations under 1.5 mg/l., which persist along the lower river. It is not known whether these concentrations fall to the levels below 0.5 mg/l. suggested by BEAUCHAMP (1953) as limiting phytoplankton growth in other African waters.

In general, it seems unlikely that the physical and chemical features described above can account for the small development of phytoplankton above the reservoir region, compared with its great development in the reservoir during storage of water there. However, a good correlation was found between phytoplankton development and the slowing down of the current in the reservoir section. Current velocities measured at various points above the reservoir, 1400—2000 km from Lake Victoria, generally exceeded 0.5 m/sec. In the reservoir region during storage in October 1954 the velocities declined from about 0.35 m/sec to under 0.1 m/sec near the dam, so providing additional time for algal growth. It is evident, however, that the total time available for algal development between Lake Victoria and the reservoir head is still considerable, and other factors may well be involved in this upper stretch.

Little comparison can be made between longitudinal succession in the White Nile and that in other large tropical rivers, as the latter seems little known. In particular the changes in a tropical river traversing a large swamp region have been little investigated. The *Sudd* swamps described here act in some ways as a giant filter or exchange system, and the seasonal changes in their effects would repay more detailed study. Succession in the rivers of the Amazon system (SIOLI, 1951) appears different in many respects, particularly in the transition between turbid 'white water' rivers and the more acid 'black water' rivers affected by drainage from podsolic soils.

SUMMARY

The longitudinal succession of physical and chemical water characteristics in the White Nile is described, and some seasonal differences are outlined. Most successional changes are due to tributary contributions, of which the discharge from Lake Albert is particularly important, and to riverain swamps, especially in the south Sudan. Swamp effects include a partial deoxygenation and depletion of phosphate and sulphate, of which the first two vary considerably with season. The origin and extent of changes in plant nutrients, and in physical factors affecting plant growth, are discussed with reference to the growth of planktonic algae in the lower river region.

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