3. Physical and chemical characteristics of the waters

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Lake Chad shows several aspects of continuous change and therefore, permanent changes in the physical and chemical features of the lake must be expected both spatially and temporally. It is thus very difficult to describe the environment. We have subdivided the lake into a certain number of regions and considered parameters such as water turbulence, temperature, oxygenation and transparency as well as the chemical characteristics of the water. They were examined during 'Normal Chad' when the lake was not divided, with the north and south basin communicating, and when the lake became 'Lesser Chad' as a result of a lowering of water level, when the two basins were separated.

3.1 Physical characteristics of the water

The main physical features such as turbulence, temperature, oxygenation and transparency were largely determined by a combination of morphological, sedimentological and climatic features of the environment (cf. Chapter 2).

3.1.1 *Wind disturbance*

Winds blow from the northeast during winter and from the southwest in summer (cf. para. 2.1, Chapter 2). They blow mainly in the morning with an

3.1.2 *Water temperature*

The surface water temperatures in the lake were studied mainly in the Southeastern Archipelago at Bol (Roche 1973; Lemoalle 1979) and in the Northern Open Water at Malamfatori (Robinson 1968; Tobor, personal communication).

3.1.2.1 *Annual variations.* The annual variations in water temperature were low as shown by the data in Table 1. This table gives the average values of temperature measured twice a day at Bol, in the Southeastern Archipelago during different periods ranging from 2 to 3 years. These temperatures are applicable to the whole lake, because the annual average values of the two basins are quite similar (Lemoalle 1979).

3.1.2.2 *Monthly averages: influence of total radiation.* Generally, rainfall results in a slight decrease in surface water temperature during July–August, which is barely noticeable when the rainy season is slight as during the recent period from 1972 to 1975. Riou (1972) showed that the decrease in the average air temperature during the rainy season resulted mainly from a drop in maximum temperatures. Minimum air temperatures are much less influenced by rainfall (Fig. 19, Chapter 2) and follow after a slight delay the variations in total radiation, G_0. The same is true for the average water temperature (Fig. 2). At first glance solar radiation, G_0, is the main factor controlling the surface temperature of the lake.

In other words, over the year, variations in lake temperature depend upon a factor which is directly related to its geographical location. Thus Lake Chad is similar to several other African lakes in which a relationship between the latitude and the amplitude of temperature variations over the year has been shown (Talling 1969).

Table 1 Annual averages of the surface water temperature in the Southeastern Archipelago, at Bol.

Period	Temperature in °C	Authors
1956–60	27.4	Billon et al., 1963
1964–66	26.6	ORSTOM hydrology
1968–70	25.7	Roche 1973
1974–75	25.6	Lemoalle 1979
1908[a]	26	Tilho 1910

[a]Insufficient data for adequate calculation of the average temperature at Bol.

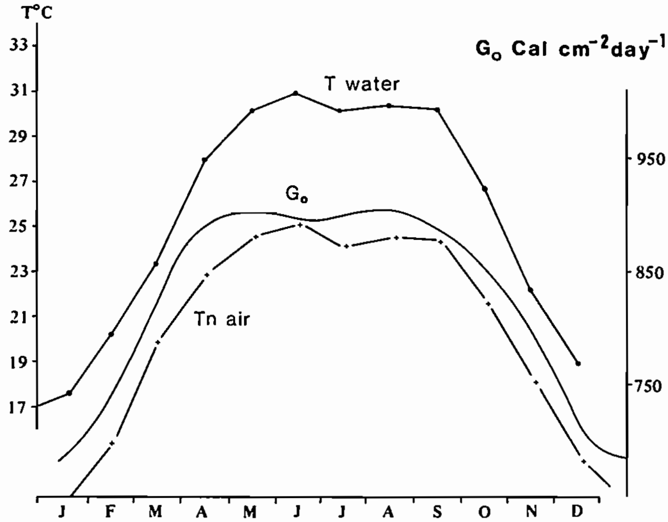

Fig. 2 Air and water temperatures and global irradiance during the year.

3.1.2.3 *Short-term seasonal variations; influence of the Intertropical Convergence Zone (ITCZ).* We have just seen that the general pattern of water temperature change over the year is mainly determined by the variations in solar radiation G_0. However, it depends upon numerous minor climatic factors such as air temperature and humidity, wind velocity and total radiation at the ground, which modulate heat transfers between the lake and the atmosphere. None of these parameters, when taken individually, can account for the variations in water temperature. So we considered the oscillations in latitude of the Intertropical Convergence Zone (ITCZ)* which include these different parameters. These oscillations, averaged over 5 days (pentads) for the year 1975 are illustrated in Fig. 15, Chapter 2. South of the ITCZ the humid winds from the southwest, the monsoon, prevails, and the dry winds from the northeast, the harmattan, prevails north of this zone. When moving over the lake, the ITCZ modifies not only the conditions for insolation and evaporation, but also the wind regime which, during the period of 'Normal Chad' changes the slope of the water surface (Toucheboeuf et al., 1969). Thermal transfers between the lake and the atmosphere are facilitated when the ITCZ moves from the north to the south of the lake.

Generally, when moving from the north to the south in September–October, the ITCZ results in an abrupt drop in temperature, but when moving from the

* The ITCZ is defined in para. 2, Chapter 2.

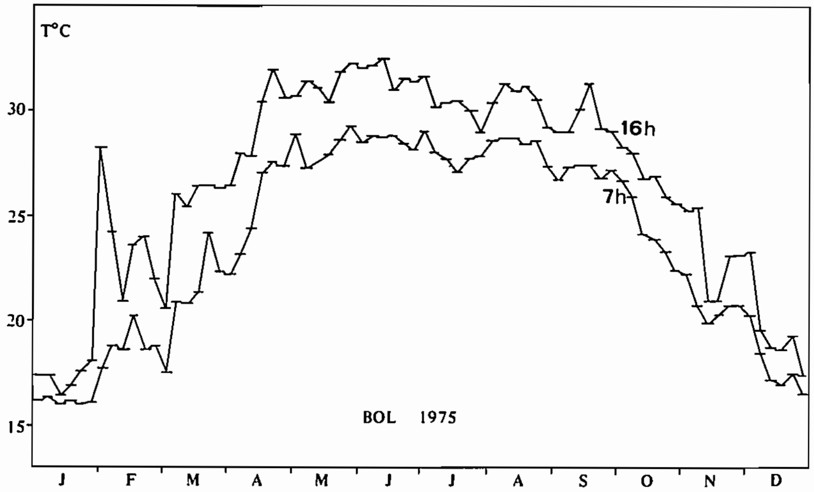

Fig. 3 Surface temperatures at 7.00 and 16.00 hr at Bol. Mean values calculated for five consecutive days.

south to the north in April–May, it prevents the water from warming, as is clearly shown in Figs. 15 (Chapter 2) and 3.

In the middle of the cool season, the oscillations of the ITCZ are felt in the far north of the convergence zone. A northern movement of the ITCZ induces a temporary decrease in the pressure gradient over the lake which results in calmer weather and a considerable diurnal increase in temperature.

During the periods of drought which sweep down the Sahel, the ITCZ is situated a few degrees further south than during the rainy periods (Dorize 1974). The dry season then appears earlier in the year and the lake is affected by northern air masses sooner, giving rise to an early water cooling and lower annual average temperatures than during normal periods.

3.1.2.4 *Diurnal variations; temperature profiles at Bol.* The diurnal variations in surface temperatures represent the heat accumulated at the surface in the daytime. Therefore, they are more important when the water is shallow and when the turbulent transfers with the underlying water layers are limited. The annual average of the diurnal variations measured by Roche (1972) for the period 1956–70 at Bol was 2.14°C, while the variations between 1967 and 1970 were lower amounting to 1.87°C. From 1972, the variations have become much greater with a maximum in 1973 (Table 2) due to a lowering of the water level and to the changed hydrological conditions.

3.1.2.5 *Vertical distribution of temperature.* Temperature profiles were measured in relation to depth at different times of the day in the Southeastern

3.1.3 *Dissolved oxygen content of the water*

The dissolved oxygen content of the water was studied mainly by Lemoalle (1979) in the Southeastern Archipelago from 1968 to 1975 and in the north Basin in 1974 and 1975, as well as by Robinson (1968) in the Northern Open Waters. The most detailed study was undertaken at Bol along with the above-mentioned study of temperatures. The main conclusions were drawn from this and allowed a more precise definition of the conditions for oxygenation in the Southeastern Archipelago and in the whole lake, for which we have very limited measurements.

3.1.3.1 *Oxygen profiles at Bol.* The oxygen profiles were determined by a galvanic probe (Mackereth type, 1964). In the same profile, sensitivity was 1% of the saturation value; and the reproducibility between the different profiles was 3%. The results, shown by the probe in % saturation have the advantage over those expressed in concentration (mg 0_2 1^{-1}) of giving a better representation of the deviation in relation to the equilibrium when temperature is not mentioned.

a) *Oxygen profiles at Bol in 1968.* The vertical distribution of oxygen concentrations was homogeneous at the beginning of the day: the values found at 7.00 hr ranged from 80 to 100% saturation. During the day, the oxygen pressure increased from the surface towards more or less important depth. During the warm season, a diurnal stratification appeared which did not exist from October to December (Fig. 6).

This temporary stratification could result from a combination of several phenomena: warming of the surface water which increased the oxygen partial pressure even if there was no change in its concentrations; photosynthetic activity of the phytoplankton which generated oxygen and finally, respirations of organisms causing a decrease in oxygen content in the water especially in the bottom layers.

Without turbulence, a saturation gradient appeared, as clearly seen in the example from May 4th, 1968 (Fig. 6). However, it was an exception because generally the water turbulence resulted in an homogenization of the upper layer down to a depth that varied with weather. Generally, this turbulence extended to the whole column during the morning while a stratification appeared in the afternoon.

b) *Oxygen profiles at Bol in 1975.* After the lowering of the water level in 1973, the water area was reduced to a pond which was surrounded by macrophytes through which water flowed, especially during floods (Fig. 4).

The vertical homogeneity appeared in the morning only during the cool season (from October to December 1974 and 1975) and unlike 'Normal Chad', the oxygen pressures were close to 0 (Fig. 6). In the course of the day, oxygen in the upper layers reached 12% saturation. At that time, water flowed through

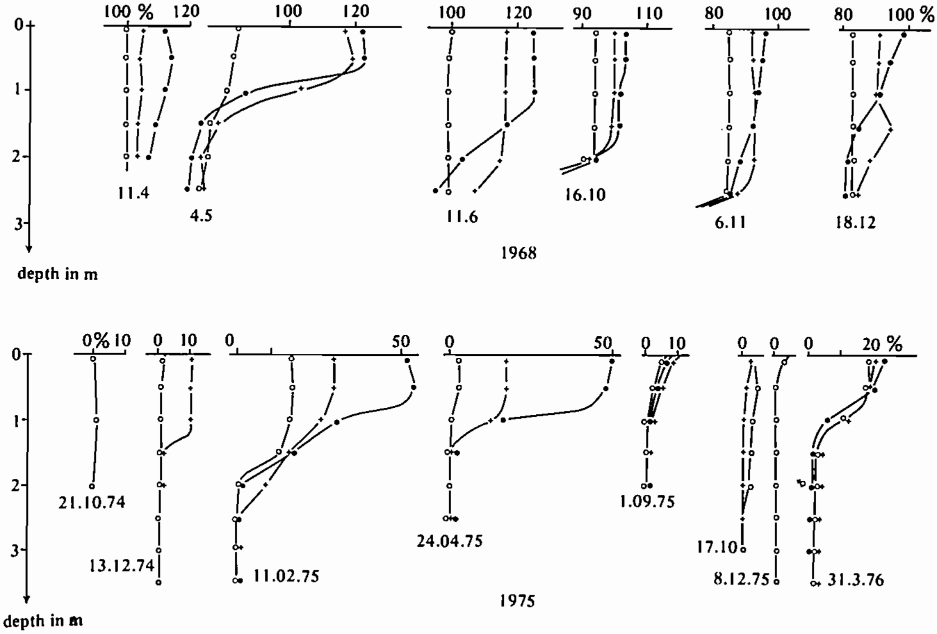

Fig. 6 Oxygen profiles at Bol.

the macrophytes which retained the oxygen-generating phytoplankton while releasing dissolved oxygen consuming organic matter.

During the warm season, the water circulation and mixing were less, so that warming of the water gave rise to a stable stratification. The oxygen pressure in the epilimnion changed considerably from 5 to 60% during the afternoon, while the hypolimnion remained anoxic. Some tornadoes such as that which occurred on August 22nd, 1978 can destroy this stratification, which reappeared quickly. Phytoplankton concentrations (1-9-75) could also be reduced by a horizontal small scale circulation of water.

Generally, the small open water zones in the archipelago were more influenced by water circulation than the larger ones which were more markedly of lacustrine type. The decrease in oxygen due to horizontal circulation was less in these larger areas.

3.1.3.2 *Oxygenation in the Southeastern Archipelago.* During the period of 'Normal Chad', the station at Bol, in the middle of the open water had no special feature compared with the rest of the Archipelago. Turbulence may have been slightly higher here than closer to the shore and lower than in the channels situated between two islands. But the difference was undoubtedly insignificant and the same phenomena were likely to occur everywhere.

conditions remained similar to those of 'Normal Chad' with some modifications appearing near the shore due to vegetation. The Southern Archipelago was characterized by very low oxygenation which varied according to the period: during the cool season, oxygen in the surface layers reached 12% saturation in the course of the day compared with 5 to 60% during the warm season. The hypolimnion generally remained anoxic. In the north basin, during the drying up period in 1974 and 1975, no stable stratification was revealed but there were variations of great amplitude which were marked by periods of frequent anoxia. In 1976, when the water level of this basin increased again, water was enriched by organic matter and the conditions for oxygenation remained very variable.

3.1.4 *Water transparency*

3.1.4.1 *Local characteristics of transparency.* Since 1964, water transparency has been measured by a Secchi disc (Gras et al. 1967; Roche 1973; Lemoalle 1979). This allowed three main environments to be distinguished: the open water of the south basin, the archipelagos of the south basin and the north basin, each characterized by seasonal and multi-annual variations.

(a) In the open water of the south basin, the seasonal change was characterized by maximum transparency in December–January during the high water period and minimum transparency in June–July during the low water period. This was true during the period of 'Normal Chad' as well as during the period of 'Lesser Chad' (Fig. 7a,b). Over the years, the lowest value recorded was related to the lowest levels observed during 1973 (Fig. 7c). Generally, the predominant transparency factor was the variation in water level. The clayey suspensions carried by the Shari at the beginning of the flood reached the lake only in July–August. So, although they contributed to the seasonal minimum transparency, they were not its main cause.

(b) In the archipelago of the south basin, water transparency increased towards the north. In other words, transparency increases with the movement of water between islands. Seasonal variations were less defined than in open water. At the station of Bol, since 1964, the change over the years has been characterized by a decrease in water transparency along with a gradual decrease of the water level up to 1973, and from that time, by an increase in transparency. This increase was related to the development of macrophytes. The considerable decrease in transparency that was continuous from 1964 to 1973 largely concealed possible seasonal changes. On the contrary, from September 1973, seasonal variations in transparency became abrupt and marked when flood water penetrated into the large vegetation banks bordering the archipelago. The transparency measured with the Secchi disc, SD, increased from 5 to 40 cm over 10 days at the end of 1973, from 15 to 35 cm in December

responsible for their turbidity and in return they take up dissolved matter. After flowing through the macrophytes, the water is therefore relatively clear but, given the conditions of agitation and the concentration of dissolved iron, a rustcoloured precipitation may form, further reducing the transparency.

(c) Throughout the north basin, the change in transparency over the years was studied from April 1968 to April 1976. This period corresponded to the gradual drying up of the basin before its water level increased again at regular intervals after 1976 (Fig. 9).

In April 1968, transparency measured with a Secchi disc, SD, was 50 cm in the open water and the region of the reed islands and 80 cm in the archipelago itself, the values being higher closer to the shore. In April 1971, SD ranged from 28 to 41 cm in the center of the basin. The difference between the open water and the archipelago, which was fairly well marked for the rest of the year was not clear at that time.

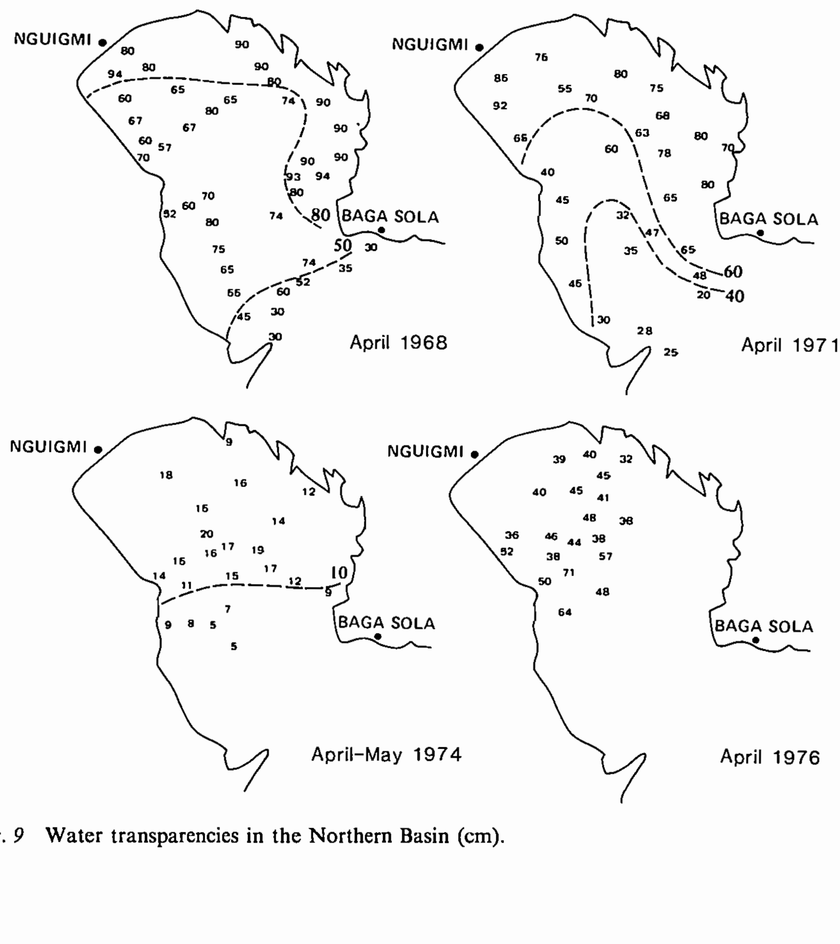

Fig. 9 Water transparencies in the Northern Basin (cm).

During April–May 1974, the north basin was isolated from the rest of the lake because of the drying up of the Great Barrier. The south basin and some parts of the archipelago with limited depth had a particularly low transparency of about 10 cm. The high phytoplankton biomass, as well as a resuspension of sediments by wave action caused short-term fluctuations of SD usually ranging from 10 to 20 cm in the center of the zone still under water.

In February 1975, SD ranged from 10 to 20 cm around Kindjéria. The water was very clayey and transparency was more reduced in the rest of the basin whose mean depth was 50 cm. Finally, in April 1976, after the complete drying up of the north basin in October 1975, water masses that percolated through the 'Great Barrier' were clearer with SD ranging from 32 to 71 cm, without any distinct zonation (Fig. 10).

3.1.4.2 *Spectral characteristics of the water.* Two series of measurements were undertaken: the first one in 1970–1971 covered the whole lake during the period of 'Normal Chad', and the second one covered only the south basin during the period of 'Lesser Chad'. For all stations, the vertical attenuation coefficient of the decreasing illumination, K_{min}, or extinction coefficient, was maximum in the blue region. However, according to the least absorbed wavelength, two extreme shapes and an intermediate one for attenuation spectra could be distinguished (Fig. 11):

— a spectrum with minimum absorption around 560 nm corresponding to grey waters, loaded with clay particles. This type of water is called clayey water;
— a spectrum with a considerable decrease from the blue to the red colour was caused by dissolved organic matter and almost no suspended material. This type of water is called organic water;
— finally, an intermediate spectrum reaching a plateau between 600 and 640 nm, was found for water rich in plankton, when water concentrated during the period of 'Lesser Chad'. This type of water is called concentrated water.

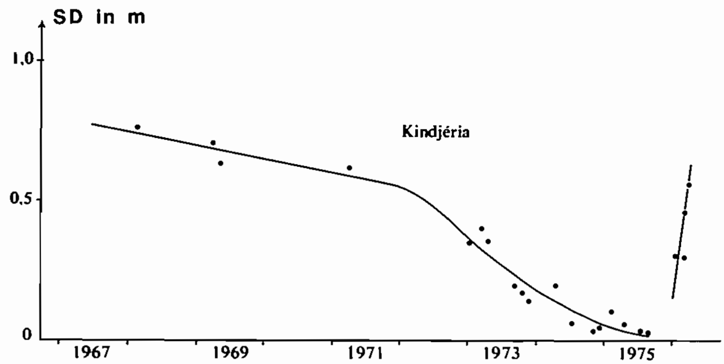

Fig. 10 Long-term changes in transparency in the Northern Basin.

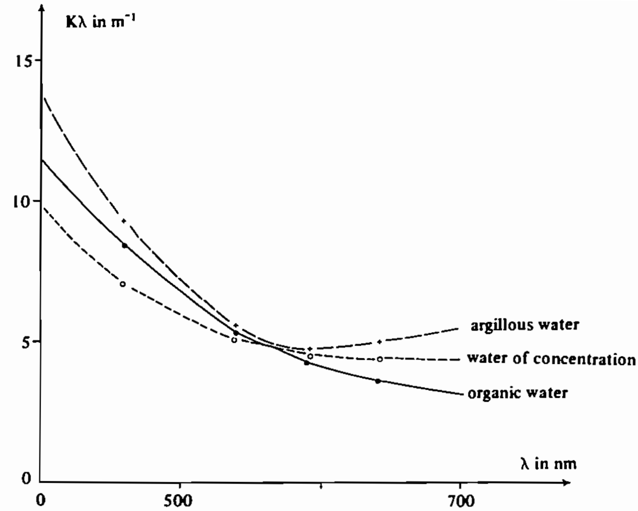

Fig. 11 Three spectral types of the attenuation coefficients Kλ of light.

Thus, the shape of the spectra as well as the values of the extinction coefficients extended over a wide range, emphasizing the heterogeneity of the lake water both in time and space. The differences in water types agreed with the results obtained in other lakes. Dokulil (1973) showed the difference between shore water occupied by *Phragmites* stands with dissolved organic matter but little suspended matter, whose K_{min} was around 700 nm, and water in the center of Neusiedlersee with significant mineral turbidity whose K_{min} was about 550 nm. For Lake George which is very rich in phytoplankton and has a marked organic colour, Ganf (1974) gives an attenuation spectrum with a plateau between 520 and 680 nm. The role played by phytoplankton in the evolution of K_{min} towards 590 nm was emphasized by Bindloss (1976) and it has also been observed elsewhere (Vollenweider 1961; Sauberer 1962). Talling et al. (1973) gave results ranging from the pure organic type Lake Aranguadi to the eutrophic organic type, Lake Kilotes (in July) with coefficients generally much higher than in Lake Chad.

As most of the transparency measurements were made with a Secchi disc, Lemoalle (1979) related the transparency values obtained with the Secchi disc to those of the attenuation coefficients from the two main types of water, the 'organic' water and clayey water. These results are shown in Table 3.

3.1.4.3 *Transparency factors.* Three main absorption factors, which are not mutually exclusive, help to account for the observed phenomena and for the three types of water.

During the period of 'Normal Chad', mineral particles were resuspended

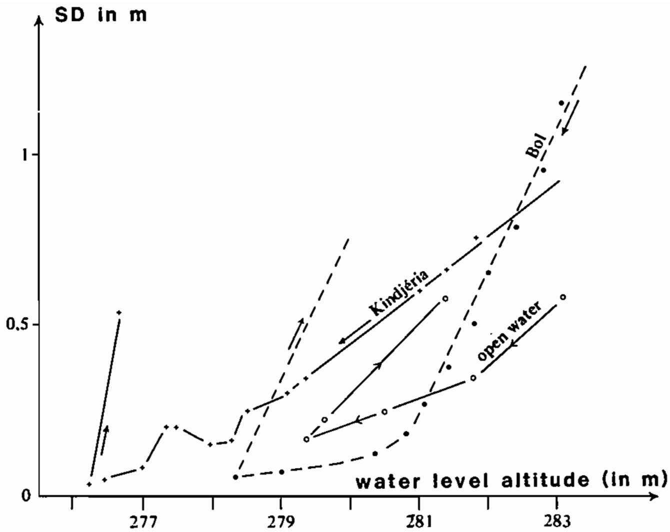

Fig. 12 Relation between transparency and lake water level at Bol and Kindjéria.

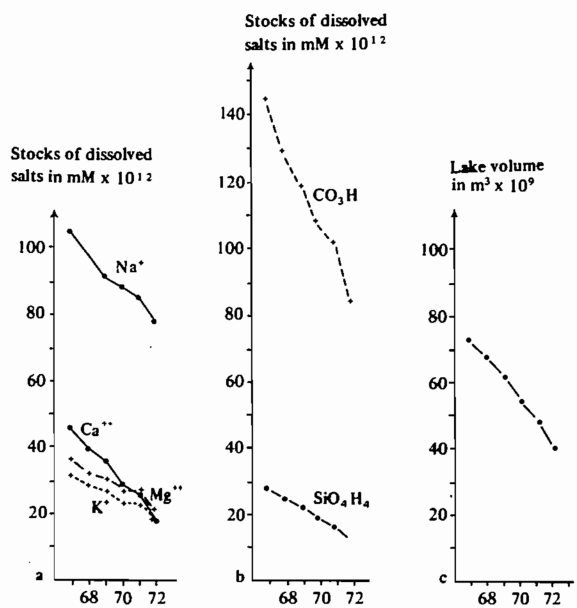

Fig. 13 Changes in the dissolved salt stocks in the lake during lake recession.

3.2.1 *The average lake or 'Normal Chad'*

The hydrochemistry was characterized by profound changes throughout the environment and by strong seasonal and annual variations at each point, and it is thus difficult to describe. However, from 1966 to 1972, the annual variations can be ignored. In fact, changes in the stock of dissolved salts were roughly similar to those of lake volume during this period of slow subsidence (Fig. 13), suggesting that there were few modifications in the dissolved salt concentrations. Moreover, spatial modifications were reduced by dividing the lake into eleven main regions (Carmouze 1976). The mean, maximum and minimum values of the main hydrochemical features were determined seasonally for eleven regions (Table 4).

Due to variations in conductivity, the water salinity increased with increasing distance from the Shari delta. Thus, water from the South-eastern Open Water near the delta was barely 1.2 times as concentrated as that of the Shari (cf. Chapter 4), while water of the Northern Reed Islands and the North-eastern Archipelago was respectively 11.8 and 11.7 times as high. More generally, the water salinities in the north basin were on average four times as high as those of the south basin which were twice as high as those of the river water (60 mg l^{-1}).

Salinity was composed of sodium, carbonates and bicarbonates, calcium, potassium and magnesium ions and dissolved silica. Its relative composition changed considerably from one region to the other*. The relative HCO_3^-–CO_3^{--} content (represented by (Alc) in Table 4) was higher in the north basin than in the south basin (91.1% compared with 75.6%). It was the reverse with dissolved silica (8.9% to 24.3%). The relative sodium content and, to a lesser extent, potassium content was higher in the north basin (35.8 to 29.9% for sodium; and 10.4 to 9.4% for potassium). It was the reverse with calcium and magnesium content (29.5 to 35.0% for calcium and 24.3 to 25.6% for magnesium). Actually, all these modifications were gradual, so that lake water was closer to the bicarbonate-sodium pole with increasing distance from the Shari delta.

The local seasonal variations gain importance as the regions concerned receive flood waters directly from the Shari. Such was the case for the South-eastern and Eastern Open Waters, the Southeastern and Southern Reed Islands, the Great Barrier, the Northern Open Water and the Northeastern Reed Islands. In this region, variations in salinity ranged from 30 to 50% with a maximum of 80% observed in the Southern Reed Islands. As far as this last feature is concerned, the archipelago regions were more stable.

Generally, the pH of water in the south basin did not exceed 8; and therefore, this water was low in alkalinity. On the contrary, in the north basin, the pH

* The relative chemical composition of water was defined as follows: the absolute concentrations (i) are expressed in mé l^{-1} or mM l^{-1}, and the relative concentrations $(i)_r$ in %.

Table 4 Hydrochemical features of the main natural regions of 'Normal Chad'. $[i]_m$ $[i]_M$ and $[\bar{i}]$ represent respectively the minimum, maximum and mean concentrations of the element, i, expressed in mé l^{-1} (except SiO_4H_4 which is expressed in mM l^{-1}). Conductivity is expressed in $\mu S\ cm^{-1}$.
$[Na]_r = [Na]/[\Sigma$ cations]; $[Ca]_r = [Ca]/[\Sigma$ Cations]; $[Mg]_r = [Mg]/[\Sigma$ cations]; $[K]/[\Sigma$ cations]; $[Alc]_r = [Alc]/[Alc] + [SiO_4H_4]$; $[SiO_4H_4]_r = [SiO_4H_4]/[Alc] + [SiO_4H_4]$. [Alc] = Alkalinity = $[HCO_3] + 2[CO_3]$

	South Eastern Open Waters				Southern Open Water			
	$[i]_m$ (Sept.)	$[i]_M$ (June)	$[\bar{i}]$	$[\bar{i}]_r$	$[i]_m$ (Sept.)	$[i]_M$ (June)	$[\bar{i}]$	$[\bar{i}]_r$
Na	0.115	0.20	0.18	24.9	0.21	0.44	0.28	30.7
Ca	0.17	0.30	0.24	37.5	0.30	0.42	0.31	33.9
Mg	0.14	0.22	0.18	28.5	0.20	0.36	0.23	25.2
K	0.045	0.07	0.055	8.7	0.08	0.13	0.09	9.8
Alkalinity	0.47	0.75	0.62	71.0	0.80	1.30	0.89	74.0
SiO_4H_4	0.20	0.25	0.25	29.0	0.34	0.30	0.31	26.0
pH	7.0	7.4	7.2	—	7.0	7.5	7.2	—
Conductivity	45	70	58	—	75	124	83	—

	Southern Reed Islands				Southeastern Reed Islands			
	$[i]_m$ (Dec.)	$[i]_M$ (June)	$[\bar{i}]$	$[\bar{i}]_r$	$[i]_m$ (Dec.)	$[i]_M$ (June–July)	$[\bar{i}]$	$[\bar{i}]_r$
Na	0.30	0.09	0.52	35.6	0.20	0.32	0.24	25.3
Ca	0.40	0.80	0.43	29.4	0.30	0.48	0.36	37.9
Mg	0.30	0.62	0.36	24.6	0.23	0.37	0.27	28.4
K	0.11	0.25	0.15	10.2	0.065	0.10	0.08	8.4
Alkalinity	1.08	2.50	1.42	78.9	0.77	1.25	0.93	73.8
SiO_4H_4	0.26	0.44	0.38	21.1	0.28	0.43	0.33	26.2
pH	7.3	7.7	7.5	—	7.2	7.7	7.4	—
Conductivity	101	234	134	—	72	118	87	—

	Southeastern Archipelago				Eastern Archipelago			
	$[i]_m$ (Dec.)	$[i]_M$ (July)	$[\bar{i}]$	$[\bar{i}]_r$	$[i]_m$ (Feb.)	$[i]_M$ (August)	$[\bar{i}]$	$[\bar{i}]_r$
Na	0.23	0.38	0.32	27.1	0.75	0.92	0.84	32.5
Ca	0.36	0.52	0.44	37.3	0.80	1.00	0.91	35.3
Mg	0.27	0.38	0.32	27.1	0.53	0.65	0.59	22.8
K	0.08	0.13	0.10	8.5	0.22	0.27	0.24	9.3
Alkalinity	0.92	1.40	1.15	74.2	2.25	2.77	2.53	78.8
SiO_4H_4	0.36	0.46	0.40	25.8	0.60	0.75	0.68	21.2
pH	7.2	7.8	7.4	—	7.5	8.0	7.7	—
Conductivity	86	133	105	—	211	259	237	—

Table 4 (Continued).

	Great Barrier				Northeastern Reed Islands			
	$[i]_m$ (Oct.–Sept.)	$[i]_M$ (May–June)	$[\bar{i}]$	$[\bar{i}]_r$	$[i]_m$ (Sept.)	$[i]_M$ (May)	$[\bar{i}]$	$[\bar{i}]_r$
Na	0.30	1.28	0.68	25.8	1.40	1.85	1.62	33.6
Ca	0.37	1.06	0.66	31.9	1.20	1.68	1.48	30.7
Mg	0.35	0.90	0.52	30.2	0.94	1.40	1.23	25.5
K	0.14	0.35	0.21	12.0	0.41	0.61	0.49	10.1
Alkalinity	1.18	3.98	2.03	81.8	3.85	5.62	4.73	89.7
SiO_4H_4	0.43	0.56	0.45	18.2	0.50	0.57	0.54	10.2
pH	7.3	8.5	8.0	—	8.0	8.8	8.5	—
Conductivity	111	373	190	—	360	526	443	—

	Northeastern Archipelago				Northern Open Water			
	$[i]_m$ (Sept.)	$[i]_M$ (July)	$[\bar{i}]$	$[\bar{i}]_r$	$[i]_m$ (Nov.)	$[i]_M$ (Sept.)	$[\bar{i}]$	$[\bar{i}]_r$
Na	2.58	2.95	2.82	36.7	1.40	1.97	1.59	35.5
Ca	1.90	2.18	2.00	27.4	1.20	1.54	1.32	29.5
Mg	1.79	2.00	1.89	24.6	0.99	1.35	1.10	24.5
K	0.78	0.92	0.86	11.2	0.38	0.52	0.47	10.5
Alkalinity	7.05	8.05	7.34	91.8	3.60	4.90	4.35	90.6
SiO_4H_4	0.59	0.69	0.65	8.1	0.43	0.53	0.45	9.4
pH	8.3	8.9	8.7	—	7.5	8.5	8.1	—
Conductivity	660	754	687	—	337	458	407	—

	Northern Reed Islands				Southern Basin		Northern Basin		Lake
	$[i]_m$ (Dec.)	$[i]_M$ (Oct.)	$[\bar{i}]$	$[\bar{i}]_r$	$[\bar{i}]$	$[\bar{i}]_r$	$[\bar{i}]$	$[\bar{i}]_r$	$[\bar{i}]$
Na	2.67	2.95	2.82	35.3	0.35	29.9	2.06	35.8	1.46
Ca	2.20	2.49	2.36	28.6	0.41	35.0	1.70	29.5	1.25
Mg	1.94	2.20	1.98	24.8	0.30	25.6	1.40	24.3	1.05
K	0.72	0.89	0.82	10.3	0.11	9.4	0.60	10.4	0.43
Alkalinity	7.15	8.30	7.74	92.4	1.15	75.6	5.63	91.1	4.06
SiO_4H_4	0.55	0.69	0.64	7.6	0.37	24.3	0.55	8.9	0.49
pH	8.3	8.9	8.7	—	7.5	—	8.4	—	8.15
Conductivity	669	777	725	—	108	—	525	—	380

Table 5 Mean hydrochemical characteristics of the Southeastern Open Water between 1973 and 1977. Na, Ca, Mg, K, and alkalinity are expressed in mé l^{-1}, SiO_4H_4 in nM l^{-1} and conductivity in $\mu S\ cm^{-1}$.

	1973	1974									1975		
	7/10	5/2	25/2	21/3	20/4	21/5	12/6	16/7	6/9	12/12	5/2	3/4	2/6
Na	0.16	0.17	0.19	0.20	0.23	0.25	0.28	0.20	0.10	0.11	0.14	0.12	—
Ca	0.20	0.30	0.35	0.41	0.45	0.42	0.50	0.30	0.17	0.28	0.31	0.32	0.40
Mg	0.18	0.24	0.29	0.28	0.32	0.30	0.33	0.26	0.15	0.19	0.25	0.30	0.41
K	0.07	0.06	0.07	0.07	0.09	0.09	0.10	0.08	0.05	0.05	0.06	0.07	—
Alkalinity	0.47	0.71	0.83	0.89	0.98	0.98	1.09	0.77	0.41	0.60	0.72	0.77	0.85
SiO_4H_4	0.20	0.12	0.14	0.13	0.13	0.15	0.16	0.11	0.16	0.17	0.12	0.16	0.17
pH	7.10	7.45	7.50	7.65	7.15	6.85	7.65	8.00	7.65	7.15	6.90	7.15	8.15
Conductivity	51	70	84	86	99	103	110	80	43	58	71	73	81

	1975				1976							1977
	1/7	14/8	10/10	31/10	26/1	27/2	5/5	17/6	28/8	21/10	11/12	31/3
Na	—	0.18	0.11	0.10	0.13	0.15	0.18	0.21	0.12	0.12	0.14	0.21
Ca	0.37	0.25	0.22	0.25	0.32	0.36	0.40	0.38	0.20	0.25	0.25	0.31
Mg	0.41	0.27	0.29	0.25	0.20	0.16	0.18	0.27	0.16	0.11	0.13	0.17
K	—	0.05	0.06	0.05	0.05	0.07	0.08	0.09	0.07	0.06	0.04	0.06
Alkalinity	0.85	0.57	0.50	0.53	0.66	0.69	0.83	0.86	0.46	0.50	0.55	0.67
SiO_4H_4	0.16	0.14	0.18	0.19	0.17	0.13	0.17	0.21	0.16	0.21	0.19	0.18
pH	7.30	7.90	7.25	7.25	7.20	7.15	7.50	7.50	7.70	7.70	7.90	6.65
Conductivity	81	61	50	52	63	70	89	97	50	53	58	73

often reached values of 8.5–8.8, especially in the northern part where water was quite alkaline.

3.2.2 *The period of 'Lesser Chad'*

Unlike the previous period when there were few variations in the chemical characteristics of the water despite the gradual reduction in water level, this new period was characterized by profound hydrochemical modifications due to considerable hydrological disturbances and vegetation development.

The appearance of the lake began to change in 1973. At that time it was divided into three distinct zones: they were the Southeastern Open Water with a connection to the river system; the Southeastern Archipelago composed of a limited number of relatively small ponds and fed seasonally by the flood of the Shari; the north basin which was nearly always isolated from the rest of the lake by the drying of the Great Barrier. The hydro-chemical characteristics of these three zones between 1973 and 1977 are shown in Tables 5, 6 and 7 (Chantraine 1978).

Table 6 Mean hydrochemical characteristics of the Southeastern Archipelago. Na, Ca, Mg, K and alkalinity are expressed in mé l^{-1}, SiO_4H_4 in mM l^{-1} and conductivity in $\mu S\ cm^{-1}$.

	1973		1974				1975	
	17/9	20/12	28/2	14/5	8/10	17/12	13/2	25/4
Na	3.70	0.33	0.42	0.61	0.30	0.19	0.24	0.47
Ca	1.02	0.78	0.91	1.69	1.20	0.53	0.59	0.91
Mg	0.95	0.57	0.66	1.13	1.18	0.42	0.43	0.70
K	0.59	0.08	0.07	0.05	0.25	0.09	0.08	0.09
Alkalinity	5.40	1.43	1.73	2.89	2.40	1.08	1.23	1.63
SiO_4H_4	0.19	0.44	0.39	0.29	0.50	0.29	0.31	0.32
pH	8.90	6.90	7.25	7.55	8.00	7.25	6.90	8.15
Conductivity	524	164	193	279	254	105	119	169
	1975		**1976**				**1977**	
	3/9	9/12	4/2	April–May	8/8	1/10	6/1	7/3
Na	0.31	0.15	0.19	0.25	0.30	0.30	0.19	0.26
Ca	0.83	0.34	0.43	0.56	0.68	0.58	0.36	0.47
Mg	0.84	0.37	0.24	0.33	0.45	0.42	0.23	0.29
K	0.05	0.08	0.08	0.07	0.07	0.09	0.07	0.08
Alkalinity	1.70	0.77	0.88	1.13	1.37	1.28	0.82	1.02
SiO_4H_4	0.25	0.21	0.22	0.25	0.32	0.31	0.7	0.32
pH	7.45	6.75	6.96	7.35	7.30	7.20	7.10	7.40
Conductivity	184	75	84	109	141	124	83	105

Table 7 Hydrochemical characteristics of the north basin from 1973 to 1976. Na, Ca, Mg, K and alkalinity are expressed in mé l^{-1}, SiO_4H_4 in mM l^{-1} and conductivity in $\mu S\ cm^{-1}$.

	1973		1974				1975				1976	
	Sept.	Nov.	May	July	Sept.	Dec.	Feb.	April	28/8	17/12	April	July
Na	4.10	5.59	8.71	13.23	17.49	34.25	3.20	3.33	22.90	0.71	1.04	1.87
Ca	1.39	1.33	1.04	0.70	0.57	0.55	1.47	0.94	0.71	2.17	2.39	2.22
Mg	1.42	1.59	2.32	1.48	1.61	1.72	1.55	1.55	1.51	1.60	1.52	1.81
K	0.75	1.06	1.55	1.93	2.46	4.10	0.86	1.33	3.48	0.75	0.57	0.76
Alkalinity	7.30	8.65	12.18	16.85	19.55	88.96	6.66	6.67	28.69	4.51	5.15	6.27
SiO_4H_4	0.32	0.35	0.06	0.18	0.20	0.25	0.17	0.28	0.63	0.56	0.55	0.42
pH	8.60	8.60	8.70	8.90	9.20	9.20	7.30	7.80	8.60	7.30	8.15	8.70
Conductivity	649	791	1120	1489	1889	3530	696	672	2568	467	508	633

was high, there was always a considerable increase in the relative sodium content (for example, it was 79% in September 1974 compared with 35.5% during the period of 'Normal Chad'). It was the reverse with dissolved silica (1.6% in September 1974 compared with 11% during the period of 'Normal Chad').

During this period of considerable recession of the water pH remained high, ranging from 8.6 to 9.2. However, in December 1975, and January 1976 when residual water mixed with flood water, it decreased to about 7.3–7.8.

3.3 Conclusions

A. Regular northeast winds blow over Lake Chad from October to April and southwestern winds from May to September. They generally blow from 6 to 12 a.m. and therefore, the environment is subjected to turbulence nearly every morning. Given the low depths, turbulence generally affects the entire water column and it is very unequal from one region of the lake to another. Obviously, it is much higher in the open water (where the fetch can reach 50 km in length) than in an archipelago (where the fetch reaches only 2 to 5 km). During the period of 'Lesser Chad', it was very reduced as a result of the decrease in open water areas and the development of vegetation.

Moreover, winds help to move the water masses that tend to accumulate on the southern and western coasts in winter and on the northern and eastern coasts in summer. This causes diurnal oscillations of the water level whose amplitude reaches 10 cm throughout the lake during the period of 'Normal Chad'. They can disappear during the period of 'Lesser Chad' when macrophytes develop.

B. Water transparency is generally low (1.20 m). This is not surprising in a turbulent and shallow environment where clayey mud and mud sediments are easily resuspended and the plankton population is relatively large. It varies considerably from one region to the other in relation to the height of the water level.

In the open water of the southern basin, water transparency measured with Secchi disc, decreased from 20–100 cm in 1964 during the period of 'Greater Chad' to 25–30 cm in 1973 during the period of 'Lesser Chad'. A seasonal minimum was recorded in July–August when the first flood waters of the Shari loaded with solid materials entered the lake. In the Southeastern Archipelago at Bol, the decrease was still more spectacular, ranging from 120 cm to 10–15 cm during the same period. But, after 1974 water transparency again increased from 25 to 100 cm due to the development of vegetation, and seasonal fluctuations in transparency remained low.

In the northern basin, water transparency ranged from 45 to 65 cm in the

vegetation. The region of open water in the southern basin which was directly fed by the Shari was the least affected by the contraction of the lake. The mean salinity of the water remained close to 50–70 mg l^{-1}.

In the archipelago of the southern basin, the water of the Bol region reached 500 mg l^{-1} during severe lake recession (1973). However, this region could be fed 'almost normally', while the northern basin dried up, resulting in salinities similar to those of a normal period.

In the northern basin when the environment dried up, the salinity of the water could reach several grams per liter with Na and HCO_3/CO_3 dominating and when normal water supply was established, salinity fell to 500 mg l^{-1}. Generally, the northern basin was chemically more stable than the southern basin during the period of 'Normal Chad' in relation to seasonal fluctuations. However it was much more unstable over several years since it could undergo a partial or even a total drying up during the period of 'Lesser Chad'. In the southern basin, the open water which had large seasonal fluctuations (salinity could double from 40 to 80 mg l^{-1}) was not subject to major chemical changes during the severe floods and contractions.

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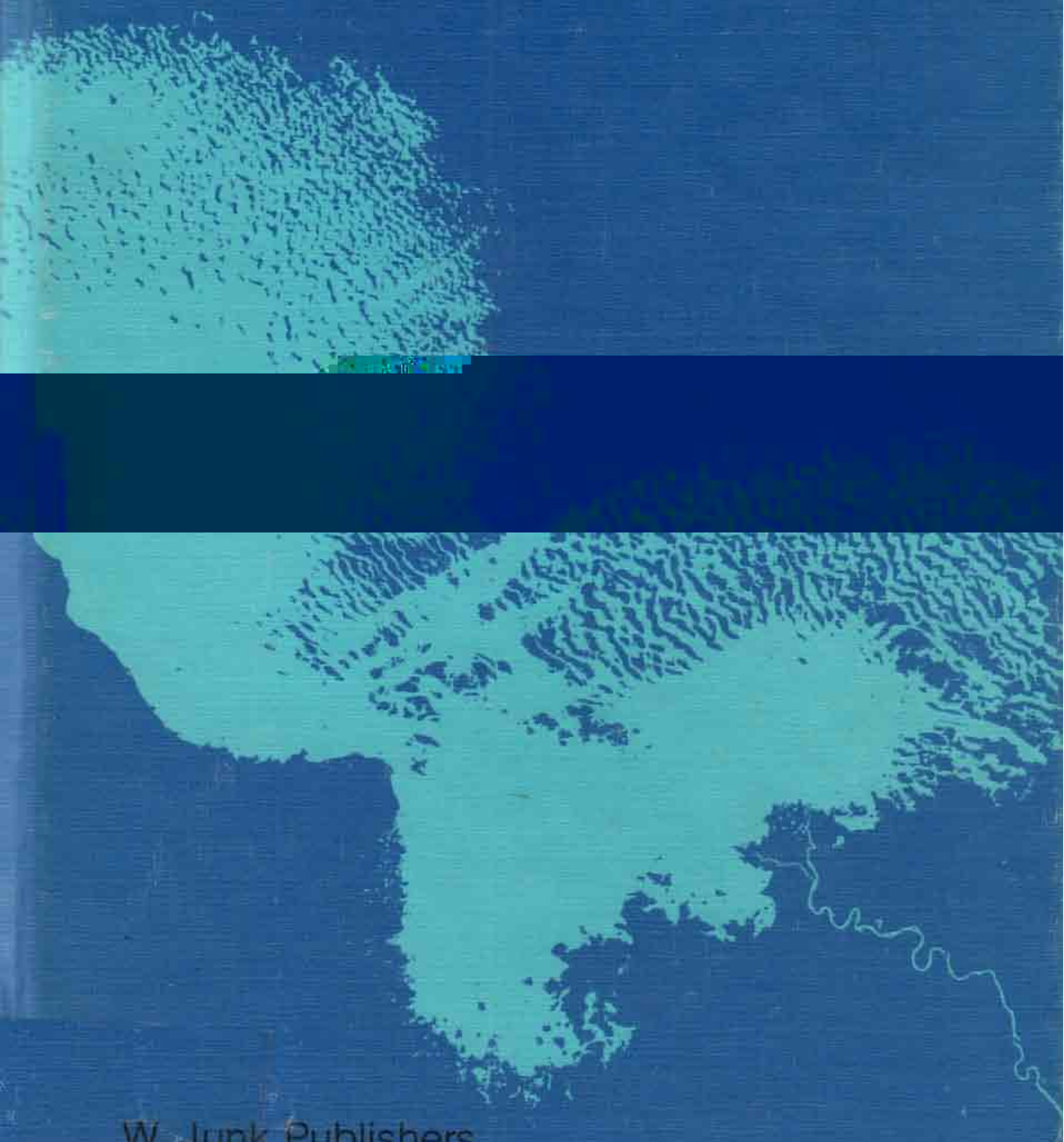

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