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**THE
HYDROCHEMICAL REGULATION
OF THE LAKE CHAD**



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THE HYDROCHEMICAL REGULATION
OF THE LAKE CHAD

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1 - INTRODUCTION

The Chad Basin is situated between 5° and 25° latitude north. It has a subarid climate, mainly characterised by strong variations of rainfall space: nowadays, the rainfall is about 1500mm/year in the south and less than 200mm in the north. This rainfall gradient is associated with a topographic gradient. Thus, the tropical waters flow from south to north towards arid zones. Collected by the river Chari, these waters spread into a large, shallow and closed basin located between $12^{\circ}5'$ and $14^{\circ}5'$ latitude north: the lake Chad (fig.1).

These waters carry dissolved materials into the lake which have been extracted up river. They are mainly Ca^{++} , Mg^{++} , Na^{+} , K^{+} , HCO_3^{-} and SiO_4H_4 arising from monosialitic alteration of crystalline rocks.

Due to its endorheism and its climate, the lake would appear to be a concentrating basin of dissolved salts. However the water salinity is *low* and relatively *stationary* in the time. Our purpose is to explain these apparent contradictions by analysing the different factors which control the dissolved constituent concentrations in the lake waters.

The Chad, although it is a geographically closed lake, is, as every aquatic environment, an open system in which material transfers take place. Therefore, the problem is to determine the different flows of water and dissolved elements which control, at every moment and in every chemically homogeneous region of the lake, the different lake stocks of dissolved salts and the volume of water, since the saline concentration is the ratio of these two parameters.

Generally, the flows vary in time and space. Therefore, especially for the lake Chad, there is local heterogeneity and temporal fluctuations of the hydrochemical state.

For this reason, two approximations were introduced :

- in order to reduce modifications, the lake was divided into two parts of less heterogeneity which represent the south and north basins of the lake.

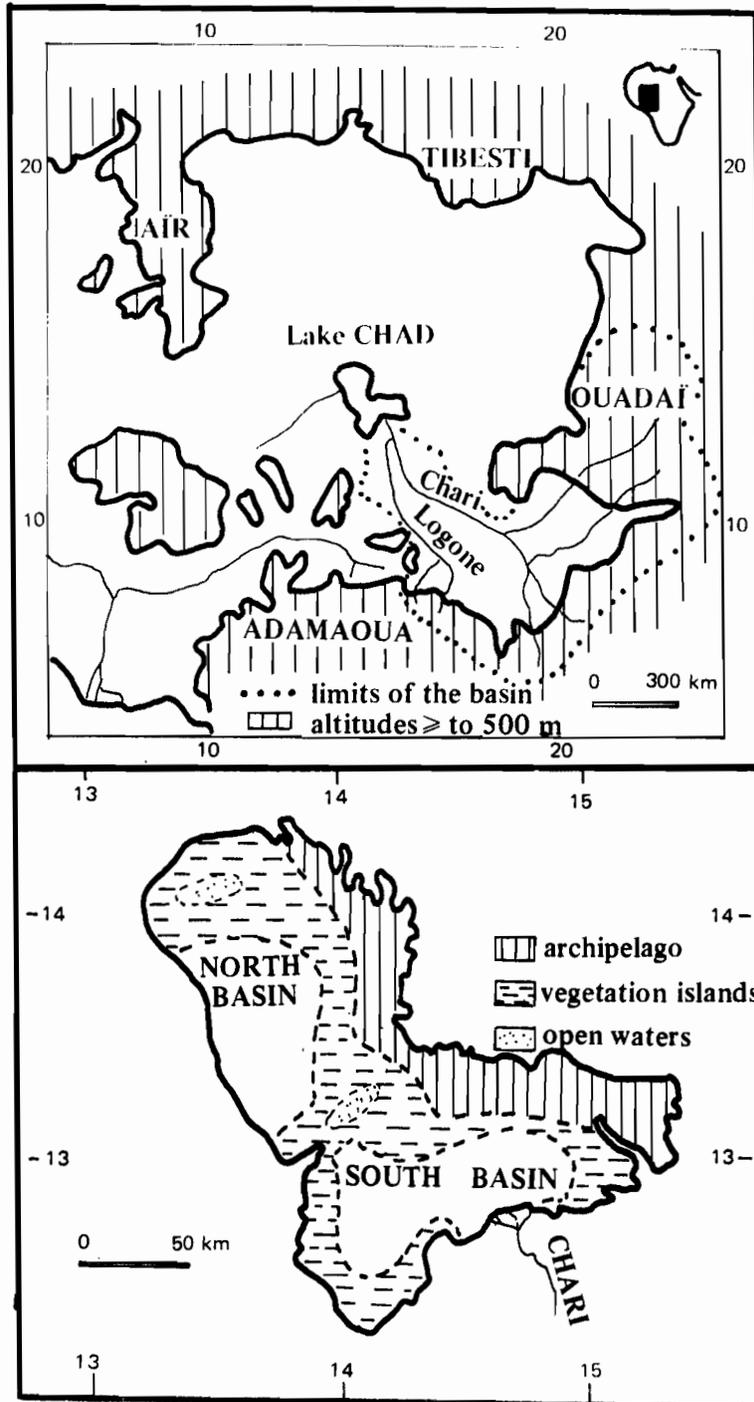


Figure 1 - The lake Chad: its localisation and its different landscapes.

- considering a large period of time the hydrochemical state of a lake oscillates around an average state because the material inputs and outputs are balanced. Neglecting these fluctuations, the environment can be considered as a steady-state system. In that case, the water chemical characteristics become time independent. For the lake Chad, a period of 18 years was considered (1954-1972).

The material flows depending in their nature, may be classified in two groups: as those associated to hydric flows and those associated to physical, chemical, geochemical or biochemical reactions (CARMOUZE and PEDRO, 1977). The water flows control primarily the "climato-geographical" dissolved salt flows (climato-geographical regulation). Depending on this pre-regulation, biogeochemical dissolved salt flows take place (biogeochemical regulation) these two flows control the total regulation.

In order to account for the low salinity of its waters, the lake will be considered as a steady-state system. For the lake and its south and north basins, the average water and dissolved salt flows and the corresponding dynamic balances for the period 1954 to 1972 will be considered. From these data, the contribution of the two hydrochemical reactions which represent the main aspect of the biogeochemical regulation will be emphasized.

Finally, the regulating mechanisms which make the salinity to be relatively stationary during the lake increase and decrease will be pointed out through the salinity evolutions.

2 - THE LAKE HYDROLOGY AND ITS CONTRIBUTION TO THE HYDRO-CHEMICAL REGULATION IN STEADY-STATE APPROXIMATION.

The lake levels have been estimated from 1895 to 1958 (ROUCHEBOEUF and *al* 1969) and measured since 1954. Complete data about climatology and hydrology have been registered from this date. So, the period 1954-1972 has been chosen to describe the mean hydrological state of the lake. This state is similar to that corresponding to

the larger period 1895-1972, according to the lake level fluctuations.

2.1. THE GLOBAL HYDROLOGY: MEAN HYDRIC BALANCE OF THE LAKE.

2.1.1. Input rates

a) Rivers inputs : almost the whole input comes from the rivers Chari and El Beïd.

The annual Chari flows are between $19,5 \cdot 10^9$ and $54,5 \cdot 10^9 \text{ m}^3$, the average value being $40 \cdot 10^9 \text{ m}^3$. The seasonal distribution is similar to a tropical one; the lake receives an average 73% of the annual input from September to December.

The river El Beïd flows from October to March. The annual flow varies between $0,6 \cdot 10^9$ and $2,7 \cdot 10^9 \text{ m}^3$ with a mean value of $1,35 \cdot 10^9 \text{ m}^3$.

b) Rainfall: the rainy season lasts from May to October. In fact, the lake receives 50% of the annual input in August. The rainfall is about 300-310mm/year. It progressively decreases from south (600mm) to north (250mm). The annual volume ranges between $2,7 \cdot 10^9$ and $8,7 \cdot 10^9 \text{ m}^3$, with a mean value, $(\bar{v})_M$ of $6,3 \cdot 10^9 \text{ m}^3$.

Overall, the annual input of water varies from $23 \cdot 10^9 \text{ m}^3$ to $61,4 \cdot 10^9 \text{ m}^3$ with a mean value of $48 \cdot 10^9 \text{ m}^3$: 87% coming from the rivers and 13% from rainfall.

2.1.2. Output rates

a) evaporation : the climate of lake Chad is subarid. It favours high evaporation rates.

Indeed, the insolation is about 280 hours/month, the average air temperature is about 27-28°C, the air humidity between 40 and 60%. Besides a northern dry wind blows from October to May (harmattan), removing the humidity loaded air masses, thus, accelerating the evaporation rate.

Different evaluations of the annual evaporation rate have

been made (RIQUIER, 1963; TURC, 1968; RIOU, 1972; TOUCHEBOEUF and *al.*, 1968; CARMOUZE 1971, 1972; ROCHE, 1973) which vary between 2,05 to 2,25m/year.

Our calculations depend on the hydric annual balance which gives the sum of the evaporation and infiltration rates, and the hydro-chemical balance which yields an estimate of the infiltration. For the period 1954-1972, the infiltration volume, evaluated in § 2.1.2.b, is equal to $3,85 \cdot 10^9 \text{ m}^3$. Assuming equal output and input volumes, on an annual average value, that is to say $47,9 \cdot 10^9 \text{ m}^3$, the evaporation is calculated by difference: $(\bar{v})_E = 44 \cdot 10^9 \text{ m}^3$. Consequently, considering a mean lake surface of 20.900 km^2 , the evaporation rate is about 2,11m/year.

The monthly evaporation rate has two maxima, one in March-April-May (17 to 18cm), and the other in October-November (20,5 to 23 cm), and a minimum from June to September (16-17cm).

b) infiltration: the lake is directly connected with a water bearing-bed of 50-70m of thickness. According to the piezometric gradients the lake is above this water bearing-bed. Infiltrations are favoured by this situation. Moreover, they are made easier because of the sandy nature of the shores and a part of the lake bottom (10 to 15%) (DIELEMAN and RIDER, 1963; PIRARD, 1963; SCHNEIDER, 1967, FONTES et *al.*, 1969; ROCHE, 1973; MAGLIONE, 1974).

The infiltrations have been indirectly estimated, using the Na balance and supposing that this element is only eliminated by infiltration. During the period 1954-1972, the Na output of $5,6 \cdot 10^{12} \text{ mM}$ /year (see § 3.2.1) has balanced the Na input. This quantity $(\bar{\text{Na}})_I$ is eliminated in a volume of infiltration equal to $(\bar{\text{Na}})_I / [\bar{\text{Na}}]_I$, where $[\bar{\text{Na}}]_I$ is the mean Na concentration in the infiltrated water. Assuming that the infiltrations occur in the whole lake, $[\bar{\text{Na}}]_I$ is close to the mean Na concentration in the lake water, $[\bar{\text{Na}}]_L$, whose value is 1,46mM/l. Then the infiltration volume can be calculated as:

$$(\bar{v})_I = 5,6 \cdot 10^{12} / 1,46 \cdot 10^3 = 3,85 \cdot 10^9 \text{ m}^3 / \text{year}.$$

The evaporation and infiltration outputs have, approximatively, been calculated for each year of the period 1954-1972, by allowing

the total outputs be roughly proportional to the lake surface. The total inputs vary between $41,3 \cdot 10^9$ and $51,8 \cdot 10^9 \text{ m}^3$. The evaporation represents 92% the infiltration 8%.

2.1.3. Hydric characteristics of the lake

The volume, surface and depths are controlled by the basin morphology and the inputs and output rates of water which have just been determined. These parameters are calculated from morphometric curves of the lake (CARMOUZE, 1976; LEMOALLE, 1979).

The lake levels were registered in the northern shore of the south basin. During the period under consideration, they changed from 281,5 to 280,5m with a maximum of 283,3m. Besides, they are modulated by seasonal changes of 0,85 to 0,80m.

The lake volumes vary between $42,5 \cdot 10^9 \text{ m}^3$ and $91 \cdot 10^9 \text{ m}^3$, with an average value, $(\bar{v})_L$, of $72 \cdot 10^9 \text{ m}^3$. These very considerable volume fluctuations are caused by very variable and aleatory inputs, while the annual output variations are less important, and by the low volume of the lake which badly palliates the output-input unbalances: 66% of the lake water is on an average removed each year.

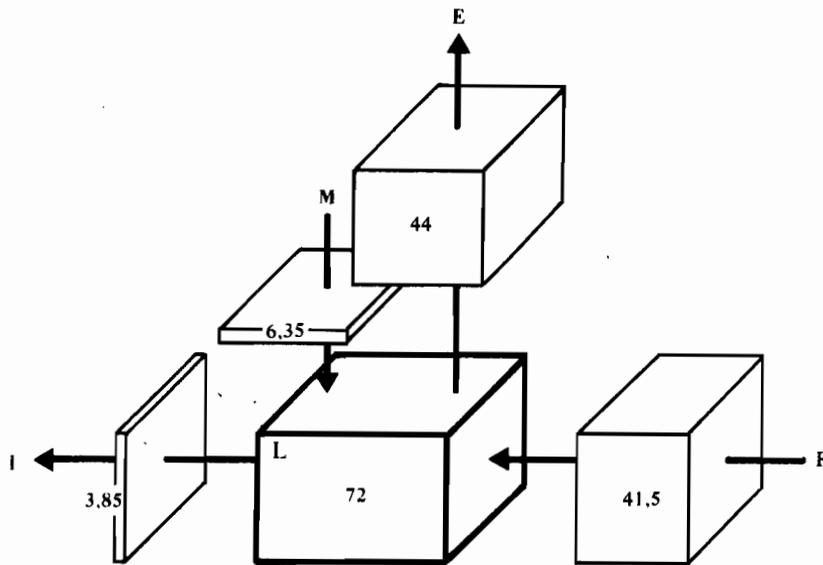
The lake surface variation range is between 22.600 km^2 (1962) and 18.000 km^2 (1972); the mean value is 20.900 km^2 .

At least, the mean annual depths vary from 4,03m (1962) to 2,35m (1972) with a mean value about 3,45m.

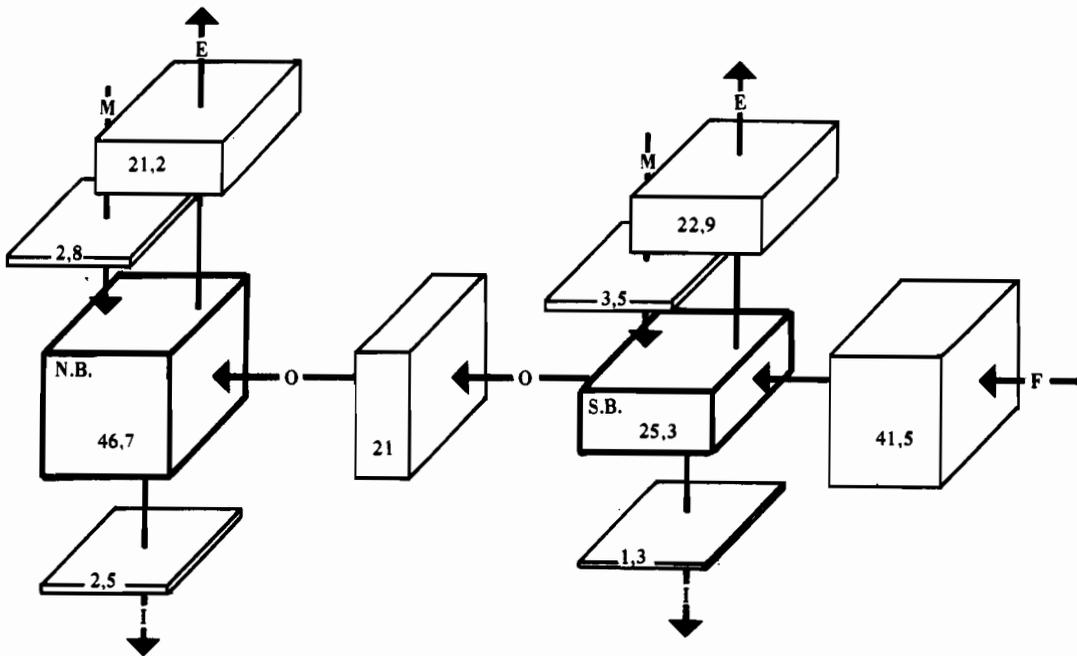
2.1.4. The mean hydric regulation and its contribution to the hydrochemical regulation.

From the data which have just been presented, it is possible to evaluate the mean hydric annual balance of the lake (fig.2a) and point out the following features :

- the inputs mainly come from the river (86,5% against 13,5% proceeding from rainfall) while the outputs by evaporation prevail over those by infiltration (92% against 8%).



a



b

Figure 2 - Mean annual hydrologic balance of the whole lake (a) and its south and north basins (b). F=fluvial input, E=evaporation, M=meteoric input, I=infiltration, O=north basin input coming from south basin. All the flows, the lake volume (L) and the north and south basin volumes (N.B. and S.B.) are given in $\text{m}^3 \cdot 10^9$.

- the input and output rates and the lake morphology control a very small lake volume: the turn-over of the lake waters is about 1,5 years.

a) Because of the first feature, the lake is a saline concentration basin whose concentration factor is easy to calculate: let us consider a dissolved element, i , whose circulation is only controlled by water flows; that means that the input of i is annually balanced by infiltration. $[\bar{i}]_F \cdot (\bar{v})_F = [\bar{i}]_I \cdot (\bar{v})_I = [\bar{i}]_I \cdot \{(\bar{v})_F + (\bar{v})_M - (\bar{v})_E\}$ (1) $[\bar{i}]_F, [\bar{i}]_I, [\bar{i}]_L, (\bar{v})_F, (\bar{v})_M$ and $(\bar{v})_E =$ river infiltration, rain fall and evaporation average annual concentrations of i and volumes.

Let us assume that the infiltration distribution is approximately uniform all over the lake. Then, $[\bar{i}]_I \approx [\bar{i}]_L =$ mean lake concentration of i . According to (1)

$$\frac{[\bar{i}]_L}{[\bar{i}]_F} = \frac{(\bar{v})_F}{(\bar{v})_I} = \frac{(\bar{v})_F}{(\bar{v})_F + (\bar{v})_M - (\bar{v})_E} = 10,8$$

This saline concentration factor controlled by the hydric or climato-geographical regulation is not very high for a closed lake because the infiltrations are relatively important.

b) The second feature of the hydric regulation denotes the lake instability in regard to the input irregularities. This feature can be illustrated as follows: let us consider the lake initially in a balanced situation, then it is submitted to an annual input-output unbalance equal to $\Delta(v)_A = \Delta(v)_F + \Delta(v)_M = \Delta(v)_L$. In order to simplify the calculations let us suppose that $\Delta(v)_M = 0$. Thus, $\Delta(v)_A = \Delta(v)_F = \Delta(v)_L$.

Let us write $\Delta(v)_F = x(\bar{v})_F$. From figure 2a, we know that $(\bar{v})_F = 0,576(\bar{v})_L$.

Therefore, $\Delta(v)_F = \Delta(v)_L = 0,576 x (\bar{v})_L$ and the new lake volume,

$(\bar{v})_L'$, is: $(\bar{v})_L' = (1 + 0,576 x) \cdot (\bar{v})_L$. The lake stock of i , $(\bar{i})_L$, changes too :

$\Delta(i)_L = \Delta(v)_F \cdot [\bar{i}]_F = 0,576 x (\bar{v})_L \cdot [\bar{i}]_F$. But $[\bar{i}]_F = 1/10,8 [\bar{i}]_L$ and therefore ,

$\Delta(i)_L = 0,053 x (\bar{v})_L \cdot [\bar{i}]_L$ and $(i)'_L = (\bar{v})_L' \cdot [i]_L (1 + 0,053 x)$ Consequently,

the new concentration of i , $[i]'_L$, is :

$$[i]'_L = \frac{(i)'_L}{(v)'_L} = [\bar{i}]_L \frac{(1 + 0,053 x)}{(1 + 0,0576 x)} \quad (2)$$

For example, when the annual excess of the river input is about 33% ($\alpha = \frac{1}{3}$), equation (2) shows a 15% decrease in the lake concentration of i . On the contrary, for a deficit of 33% ($\alpha = \frac{1}{3}$) the concentration increase of i is 21,5%. So, when the geographical regulation only takes place, the saline concentration variation, corresponding to the input-output unbalances, which frequently have these extents, are relatively important.

2.2. REGIONAL HYDROLOGY: MEAN HYDRIC BALANCES OF THE SOUTH AND NORTH BASINS.

The south and the north basins are two distinct geographical entities with different characteristics. So, to get a better hydrological knowledge of the lake the mean annual hydric balances of the two basins have been determined in the same way as those of the whole lake.

The results are shown in figure 2b. The following features can be pointed out:

- the north basin contains twice as much water as the south basin, while it roughly has the same area.
- the outputs proceeding from evaporation mainly, are almost the same in both of them because the evaporation rates are similar.
- the infiltration outputs are twice as much important in the north basin as in the south one (65% of the total infiltration against 35%).
- the turn-over of the south basin waters is very high: the residence time of the waters is 6 months. 50% of the river input flows into the north basin where the average residence-time of the waters is about 2 years.

The hydric regulation differences cause some hydrochemical modifications in the two basins :

- a) the saline concentration factor is different. For an element i , whose regulation is only climato-geographical, 8,2% of its annual inputs remains in the south basin, while 91,8% flows into the north (CARMOUZE, 1976). The increase rates on the concentration of i in

each basin can be easily calculated :

- in the south basin: $0,082[\bar{i}]_F \cdot (\bar{v})_F = [\bar{i}]_{ICS} \cdot (\bar{v})_{ICS}$, where $[\bar{i}]_{ICS}$ and $(\bar{v})_{ICS}$ are respectively the concentration of i and the volume of water infiltration in the south basin. Let us assume the $[\bar{i}]_{ICS} = [\bar{i}]_{CS}$ = south basin water concentration of i . Then :

$$\frac{[\bar{i}]_{CS}}{[\bar{i}]_F} = \frac{0,082(\bar{v})_F}{(\bar{v})_{ICS}} = 2,61$$

- in the north basin: $0,918[\bar{i}]_F \cdot [\bar{i}]_{ICN} \cdot (\bar{v})_{ICN}$
 $[\bar{i}]_{ICN}$ and $(\bar{v})_{ICN}$ are respectively the concentration of i and the volume of water infiltration in the north basin. Again, let us assume that $[\bar{i}]_{ICN} = [\bar{i}]_{CN}$ = north basin water concentration of i . Then :

$$\frac{[\bar{i}]_{CN}}{[\bar{i}]_F} = \frac{0,918(\bar{v})_F}{(\bar{v})_{ICN}} = 15,24$$

In fact, the waters which enter the north, are concentrated in the south basin while crossing it, according to a factor of 1,8. Because of this, the saline concentration factor is equal to only 8,46 in the north basin. Consequently the climato-geographical increase in salinity is 3,24 times higher in that basin.

b) the degree of stability of the two basins in regard to the annual input-output unbalances are also different.

Let us take again the example from § 2.1.4, that is to say:
 $\Delta(v)_L = \Delta(v)_F = (\bar{v})_F$

- the north receives 50,6% of the annual river input. Thus, the volume variation of this basin is : $\Delta(v)_{CN} = 0,506\Delta(v)_F = 0,506 \times (\bar{v})_F$. From figure 2b, $(\bar{v})_F = 0,888(\bar{v})_{CN}$. Then,

$$\Delta(v)_{CN} = 0,506 \times 0,888(\bar{v})_{CN} = 0,449 \times (\bar{v})_{CN}$$

And the new volume is: $(v)'_{CN} = (\bar{v})_{CN} (1 + 0,449 \times)$. The variation in the stock of for the north basin is: $\Delta(i)_{CN} = 0,918\Delta(v)_F \cdot [\bar{i}]_F$ as indicated

in § 2.2.a. Then, $\Delta(i)_{CN} = 0,918 \times (\bar{v})_F \cdot [\bar{i}]_F$

Because $(\bar{v})_F = 0,888(\bar{v})_{CN}$ and $[\bar{i}]_F = \frac{1}{15,24}[\bar{i}]_{CN}$, one gets :

$$\Delta(i)_{CN} = 0,918 \times 0,888(\bar{v})_{CN} \cdot \frac{1}{15,24} \cdot [\bar{i}]_{CN} = 0,053 \times (\bar{v})_{CN} \cdot [\bar{i}]_{CN}$$

and $(i)'_{CN} = (\bar{i})_{CN} + \Delta(i)_{CN} = (\bar{v})_{CN} \cdot [i]_{CN} (1 + 0,053\alpha)$. Consequently,

$$[i]'_{CN} = \frac{(i)'_{CN}}{(v)'_{CN}} = \frac{[i]_{CN} (1 + 0,053\alpha)}{(1 + 0,0449\alpha)} \quad (3)$$

- in the south basin, it remains 49,4% of the annual river input. Thus the volume variations is : $\Delta(v)_{CS} = 0,494 \Delta(v)_F = 0,494 \times (\bar{v})_F$ from figure 2b, $(\bar{v})_F = 1,64(\bar{v})_{CS}$. Then, $\Delta(v)_{CS} = 0,494 \times 1,64(\bar{v})_{CS} = 0,81 \times (\bar{v})_{CS}$

and $(v)'_{CS} = (\bar{v})_{CS} + \Delta(v)_{CS} = (\bar{v})_{CS} (1 + 0,81\alpha)$. The variation in the stock of i for the south basin is $\Delta(i)_{CS} = 0,082 \times (\bar{v})_F \cdot [i]_F$. Because

$(\bar{v})_F = 1,64(\bar{v})_{CS}$ and $[\bar{i}]_F = \frac{1}{2,61} [\bar{i}]_{CS}$, one gets :

$$\Delta(i)_{CS} = 0,082 \times 1,64(\bar{v})_{CS} \cdot \frac{1}{2,61} [i]_{CS} = 0,051 \times (\bar{v})_{CS} \cdot [i]_{CS} \text{ and}$$

$(i)'_{CS} = (\bar{i})_{CS} + \Delta(i)_{CS} = (\bar{v})_{CS} [i]_{CS} (1 + 0,051\alpha)$ finally,

$$[i]'_{CS} = \frac{(i)'_{CS}}{(v)'_{CS}} = \frac{[i]_{CS} (1 + 0,051\alpha)}{(1 + 0,81\alpha)} \quad (4)$$

According to (3) and (4) we can calculate that, for a river input excess of 33% ($\alpha = \frac{1}{3}$), the new saline concentration is 88,5% of the initial value in the north basin and 80% in the south one. On the contrary, for a deficit of 33% ($\alpha = \frac{1}{3}$), the saline concentration increases by 115% in the north and by 134% in the south. These data indicate that the instability in the south basin is much more important. The north basin acts more as a reservoir system.

3. THE LAKE HYDROCHEMISTRY: CONTRIBUTION OF THE BIOGEOCHEMICAL SEDIMENTATION TO ITS REGULATION IN A STEADY STATE APPROXIMATION

The mean annual dynamic balance of each constituent of the water salinity, corresponding to 1954-1972 be established for the

lake and its north and south basins. The constituents are : Na^+ , Ca^{++} , Mg^{++} , K^+ , HCO_3^- and SiO_4H_4 .

To reach this purpose, some approximations must be made because hydrochemical data are not available for the whole period.

The river salinity data are only registered since 1967 (CARMOUZE, 1969, 1972, 1976; ROCHE, 1969, 1973) but they point out that, for a given season, the salt concentrations do not change from one year to another, whatever the water flow may be. So, knowing the mean monthly concentrations, it is possible to calculate the different salt input if the monthly water flows are available.

The mean hydrochemical characteristics of the lake can be approximately obtained, by using the fact that lake saline stocks depend mainly on the lake volume. In 1967, the lake had reached a balanced situation. So, for this year the mean stock values can be extrapolated from the data of 1968 to 1972.

The total mean annual outputs can be estimated as equal to the total mean annual inputs for the whole period. Moreover, supposing that Na is only eliminated by infiltration, it becomes possible to evaluate the fraction of the other constituent outputs which sediment by biogeochemical ways.

3.1. THE GLOBAL HYDROCHEMISTRY: MEAN ANNUAL BALANCES OF THE DISSOLVED SALTS.

3.1.1. River input rates.

a) The Chari inputs :

The water chemical composition is as follows: the mean monthly values vary between : 0,41 and 0,72mM/l for HCO_3^- , 0,071 and 0,137mM/l for Ca^{++} , 0,067 and 0,115mM/l for Mg^{++} , 0,105 and 0,155mM/l for Na^+ , 0,04 and 0,06mM/l for K^+ and 0,300 and 0,425mM/l for SiO_4H_4 .

The ionised salinity of these waters is twice as much inferior to the ionised salinity of the water rivers in the world (DAVIES

and De VIEST, 1966). However the SiO_4H_4 concentration of the river Chari is 1,5 times higher.

The salt inputs of each constituent have been monthly evaluated for the period 1954-1972 using monthly concentration values and the corresponding hydric data (BILLON and *al*, 1969). The annual inputs, generally vary between 75 and 125% of the mean values which are:

$$(\overline{\text{Ca}^{++}})_{\text{Ch}} = 4,05 \cdot 10^{12} \text{ mM}; (\overline{\text{Mg}^{++}})_{\text{Ch}} = 3,1 \cdot 10^{12} \text{ mM}; (\overline{\text{Na}^+})_{\text{Ch}} = 5,25 \cdot 10^{12} \text{ mM};$$

$$(\overline{\text{K}^+})_{\text{Ch}} = 1,9 \cdot 10^{12} \text{ mM}; (\overline{\text{HCO}_3^-})_{\text{Ch}} = 20,8 \cdot 10^{12} \text{ mM}; (\overline{\text{SiO}_4\text{H}_4})_{\text{Ch}} = 15 \cdot 10^{12} \text{ mM}.$$

b) The El Beïd inputs :

The mean chemical composition of the El Beïd water is:

$$(\overline{\text{Ca}^{++}})_{\text{EB}} = 0,215 \text{ mM/l}; (\overline{\text{Mg}^{++}})_{\text{EB}} = 0,15 \text{ mM/l}; (\overline{\text{Na}^+})_{\text{EB}} = 0,35 \text{ mM/l}$$

$$(\overline{\text{K}^+})_{\text{EB}} = 0,10 \text{ mM/l}; (\overline{\text{HCO}_3^-})_{\text{EB}} = 1,15 \text{ mM/l}; (\overline{\text{SiO}_4\text{H}_4})_{\text{EB}} = 0,7 \text{ mM/l} \text{ (ROCHE, 1973)}.$$

From these chemical data and the hydrologic ones given by Billon and *al* (1974) the annual inputs for 1954-1972 have been calculated:

$$(\overline{\text{Ca}^{++}})_{\text{EB}} = 0,3 \cdot 10^{12} \text{ mM}; (\overline{\text{Mg}^{++}})_{\text{EB}} = 0,2 \cdot 10^{12} \text{ mM}; (\overline{\text{Na}^+})_{\text{EB}} = 0,5 \cdot 10^{12} \text{ mM}$$

$$(\overline{\text{K}^+})_{\text{EB}} = 0,15 \cdot 10^{12} \text{ mM}; (\overline{\text{HCO}_3^-})_{\text{EB}} = 1,6 \cdot 10^{12} \text{ mM}; (\overline{\text{SiO}_4\text{H}_4})_{\text{EB}} = 1,1 \cdot 10^{12} \text{ mM}.$$

Hence, the mean annual values of the total dissolved salt inputs which include the Chari and El Beïd inputs are:

$$(\overline{\text{Ca}^{++}})_{\text{F}} = 4,35 \cdot 10^{12} \text{ mM}; (\overline{\text{Mg}^{++}})_{\text{F}} = 3,3 \cdot 10^{12} \text{ mM}; (\overline{\text{Na}^+})_{\text{F}} = 5,6 \cdot 10^{12} \text{ mM}$$

$$(\overline{\text{K}^+})_{\text{F}} = 2,05 \cdot 10^{12} \text{ mM}; (\overline{\text{HCO}_3^-})_{\text{F}} = 22,4 \cdot 10^{12} \text{ mM}; (\overline{\text{SiO}_4\text{H}_4})_{\text{F}} = 16,1 \cdot 10^{12} \text{ mM}.$$

3.1.2. Mean annual output rates of dissolved salts

The dissolved salt outputs arise from infiltration biogeochemical sedimentation and marginal deposits. The latter output occurs when the lake size decreases. In such a case, ponds are isolated near the shores, they dry and dissolved salts precipitate. In return,

when the lake size increases, these salts are partially recovered.

We admit that, for a long period, the antagonist precipitation -dissolution phenomena are balanced and, consequently, the only effective outputs are due to infiltration and biogeochemical sedimentations.

Thus, for the period 1954-1972, the mean annual outputs, $(\bar{i})_p$, are similar to the mean annual input. Then referring to § 3.1.1. :

$$(\overline{\text{Ca}^{++}})_p = 4,35 \cdot 10^{12} \text{ mM}; (\overline{\text{Mg}^{++}})_p = 3,30 \cdot 10^{12} \text{ mM}; (\overline{\text{Na}^+})_p = 5,60 \cdot 10^{12} \text{ mM}$$

$$(\overline{\text{K}^+})_p = 2,05 \cdot 10^{12} \text{ mM}; (\overline{\text{HCO}_3^-})_p = 22,4 \cdot 10^{12} \text{ mM}; (\overline{\text{SiO}_4\text{H}_4})_p = 16,1 \cdot 10^{12} \text{ mM}.$$

The Na sedimentation, regarding the physico-chemical properties of this element and the hydrochemical environment, may be unimportant. So, the Na inputs of the river $(\overline{\text{Na}})_F$ are mainly eliminated by infiltration: $(\overline{\text{Na}})_F = (\overline{\text{Na}})_I = 5,60 \cdot 10^{12} \text{ mM}$. According to this hypothesis the infiltration volume has been calculated in § 2.1.2.b and also the factor of increasing salinity in the lake caused by the climatogeographical flows which is equal to 10,8 (§ 2.1.4.a).

This factor is lower for the other dissolved constituents because they are subject to sedimentation which can be evaluated as follows: Without sedimentation, the "climato-geographical" lake concentration of i , $[i]_{L \text{ cg}}$, would be: $[i]_{L \text{ cg}} = 10,8 [i]_F$. The annual output by infiltration would be equal to $[i]_{L \text{ cg}} \cdot (\bar{v})_I$. But, as the lake concentration i is lower than $[i]_{L \text{ cg}}$, the effective infiltration of i is equal to $[i]_L \cdot (\bar{v})_I$. The difference represents the sedimentation, $(\bar{i})_S = \{ [i]_{L \text{ cg}} - [i]_L \} (\bar{v})_I$.

Then, it is easy to calculate the mean annual outputs by infiltration :

$$(\overline{\text{Ca}^{++}})_I = 2,4 \cdot 10^{12} \text{ mM}; (\overline{\text{Mg}^{++}})_I = 1,95 \cdot 10^{12} \text{ mM}; (\overline{\text{Na}^+})_I = 5,6 \cdot 10^{12} \text{ mM}$$

$$(\overline{\text{K}^+})_I = 1,65 \cdot 10^{12} \text{ mM}; (\overline{\text{HCO}_3^-})_I = 15,6 \cdot 10^{12} \text{ mM}; (\overline{\text{SiO}_4\text{H}_4})_I = 3,0 \cdot 10^{12} \text{ mM}$$

and by sedimentation

$$(\bar{Ca}^{++})_S = 1,95 \cdot 10^{12} \text{ mM}; (\bar{Mg}^{++})_S = 1,35 \cdot 10^{12} \text{ mM}; (\bar{Na}^+)_S = 0,0$$

$$(\bar{K}^+)_S = 0,40 \cdot 10^{12} \text{ mM}; (\overline{HCO_3^-})_S = 6,8 \cdot 10^{12} \text{ mM}; (\overline{SiO_4H_4})_S = 13,1 \cdot 10^{12} \text{ mM}.$$

3.1.3. Mean hydrochemical characteristics of the lake.

Let us recall that our purpose is to describe the mean hydrochemical state of the lake during 1954-1972. The chemical data are only available since 1968. Fortunately, the hydrochemistry depends on the hydrology: the saline stocks are, to a great extent, proportional to the volume (CARMOUZE, 1976). The characteristics of 1967, which represents the mean state of the lake, have been chosen and calculated by extrapolation from 1968-72 data.

Using this procedure, the mean saline stocks of the different constituents have been calculated :

$$(\bar{Na}^+)_L = 105,2 \cdot 10^9 \text{ mM}; (\bar{Mg}^{++})_L = 36,65 \cdot 10^{12} \text{ mM}; (\bar{Ca}^{++})_L = 45,05 \cdot 10^{12} \text{ mM};$$

$$(\bar{K}^+)_L = 31,10 \cdot 10^9 \text{ mM}; (\overline{HCO_3^-})_L = 292,15 \cdot 10^{12} \text{ mM}; (\overline{SiO_4H_4})_L = 56,1 \cdot 10^{12} \text{ mM}$$

and then the concentrations of the dissolved constituents, using $(\bar{v})_L = 72 \cdot 10^9 \text{ m}^3$:

$$[\bar{Na}^+]_L = 1,46 \text{ mM/1}; [\bar{Mg}^{++}]_L = 0,509 \text{ mM/1}; [\bar{Ca}^{++}]_L = 0,625 \text{ mM/1}$$

$$[\bar{K}^+]_L = 0,432 \text{ mM/1}; [\overline{HCO_3^-}]_L = 4,057 \text{ mM/1}; [\overline{SiO_4H_4}] = 0,779 \text{ mM/1}$$

3.1.4. Conclusion : The hydrochemical regulation and the geographical and biogeochemical contribution.

The mean annual dynamic balances of the different constituents of the salinity are shown in the figures 3a and 4a, considering the lake as an homogeneous system.

Comparing these balances, we observe that each constituent has its own regulation. The climato-geographical regulation would

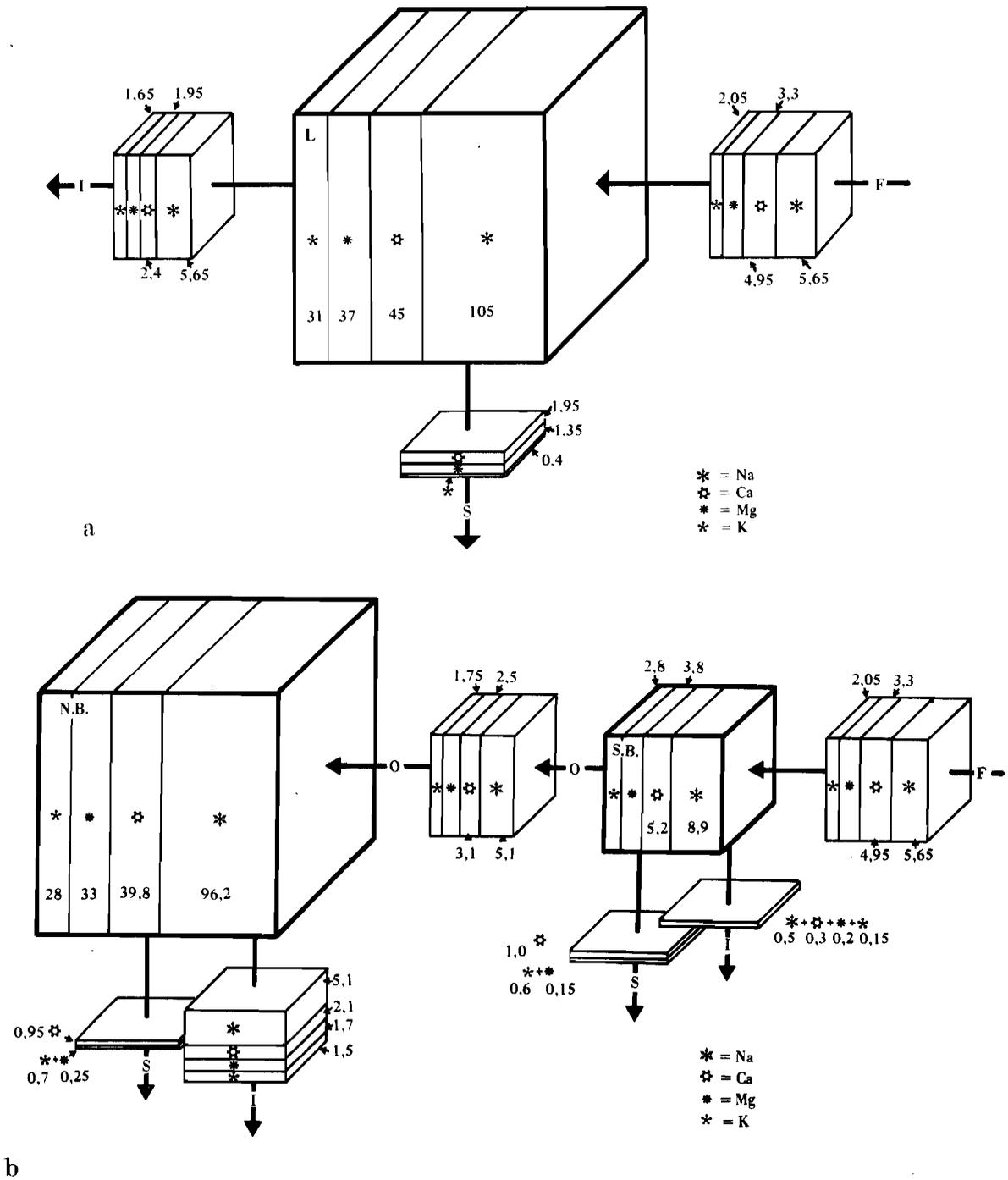


Figure 3 - Mean annual salt balances of Na^+ , Ca^{++} , Mg^{++} and K^+ in the whole lake (a) and its south and north basins (b). F= fuvial input, S= sedimation, I=infiltration, O=north basin input coming from south basin. All the flows, the lake salt stocks (L) and the north and south basin salt stocks (N.B. and S.B.) are given in Moles $\cdot 10^9$.

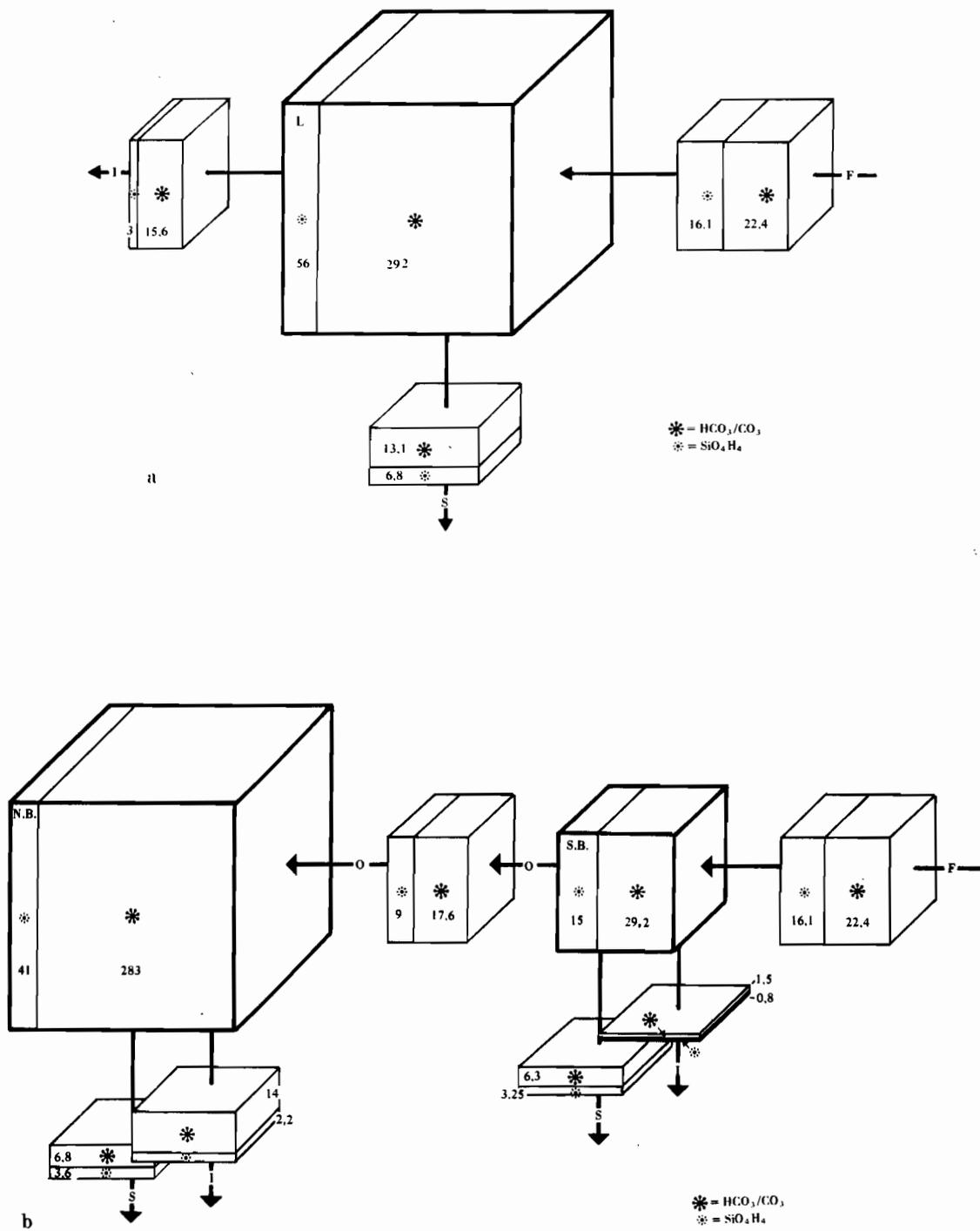


Figure 4 - Mean annual salt balances of $\text{HCO}_3^-/\text{CO}_3^-$ and SiO_4H_4 in the whole lake (a) and its south and north basins (b). F=fluvial input, S=sedimentation, I=infiltration, O=north basin input coming from south basin. All the flows, the lake salt stocks (L) and the north and south basin salt stocks (N.B.) are given in Moles $\cdot 10^9$.

have fixed the same concentration factor for each of them, which is 10,8. So the concentration of Ca^{++} , Mg^{++} , K^+ , HCO_3^- and SiO_4H_4 would have been successively equal to 1.14, 0.862, 0.527, 5.85 and 4.18mM/l, but their actual values are 0.625, 0.509, 0.432, 4.06 and 0.779mM/l. These registered diminutions are caused by intervention of biogeochemical processus.

Considering only the two extreme regulations, those of Na and SiO_4H_4 , we note that the turn-over of the Na stock represents 5,3 % while the turn-over of the SiO_4H_4 stock is 78,7%. In other words, for Na the lake is a transit place, for SiO_4H_4 mainly a sedimentation place.

Finally, the low salinity of the water is mainly explained by three reasons:

- the factor of salinity concentration in this arid region closed lake is only 10,8, a value not very high because of the infiltrations which are relatively important.

- the river salinity is low: twice as less important than the mean salinity of continental waters.

- an important sedimentation takes place in the lake. For that reason the "climato-geographical" value of the salinity is reduced by 45%.

Because of the unequal importance of sedimentation from one dissolved element to another, an evolution of the relative chemical composition of the river water is registered. It evolves to the $\text{Na}^+ - \text{HCO}_3^- / \text{CO}_3^-$ side.

The mean relative chemical compositions of the rivers and of the lake are:

$$[\overline{\text{Ca}^{++}}]_{\text{F}}^{\text{r}} = 29,5\% \quad [\overline{\text{Ca}^{++}}]_{\text{L}}^{\text{r}} = 20,8\%; \quad [\overline{\text{Mg}^{++}}]_{\text{F}}^{\text{r}} = 22,3\% \quad [\overline{\text{Mg}^{++}}]_{\text{L}}^{\text{r}} = 16,8\%;$$

$$[\overline{\text{Na}^+}]_{\text{F}}^{\text{r}} = 34,3\% \quad [\overline{\text{Na}^+}]_{\text{L}}^{\text{r}} = 47,8\%; \quad [\overline{\text{K}^+}]_{\text{F}}^{\text{r}} = 13,9\% \quad [\overline{\text{K}^+}]_{\text{L}}^{\text{r}} = 14,5\% \quad [\overline{\text{HCO}_3^-}]_{\text{F}}^{\text{r}} = 58,7\%$$

$$[\overline{\text{HCO}_3^-}]_{\text{L}}^{\text{r}} = 84\%; \quad [\overline{\text{SiO}_4\text{H}_4}]_{\text{F}}^{\text{r}} = 41,3\% \quad [\overline{\text{SiO}_4\text{H}_4}]_{\text{L}}^{\text{r}} = 16\%. \quad (*)$$

$$(*) \text{Cation}[i]^{\text{r}} = \frac{[\text{Cation } i]}{[\Sigma \text{cations}]}; \quad [\text{HCO}_3^-]^{\text{r}} = \frac{[\text{HCO}_3^-]}{[\text{HCO}_3^-] + [\text{SiO}_4\text{H}_4]}; \quad [\text{SiO}_4\text{H}_4]^{\text{r}} = \frac{[\text{SiO}_4\text{H}_4]}{[\text{HCO}_3^-] + [\text{SiO}_4\text{H}_4]}$$

3.2. REGIONAL HYDROCHEMISTRY: MEAN SALINE BALANCES IN THE NORTH AND SOUTH BASINS.

The mean balances of the dissolved constituents have also been established for the two basins (CARMOUZE, 1976). They give a better knowledge of the salt transfers at a regional scale. The results are shown in table I and figures 3b and 4b.

Table I : Characteristics of the mean saline balances in the north and south basins (N.B. and S.B.).

	Na ⁺		Ca ⁺⁺		Mg ⁺⁺		K ⁺		HCO ₃ ⁻ /CO ₃ ⁻		SiO ₄ H ₄	
	S.B.	N.B.	S.B.	N.B.	S.B.	N.B.	S.B.	N.B.	S.B.	N.B.	S.B.	N.B.
river inputs M x 10 ⁹	5.60	5.14	4.35	3.09	3.30	2.50	2.05	1.76	22.35	17.6	16.1	9.03
Infiltrations M x 10 ⁹	0.46	5.15	0.27	2.13	0.20	1.75	0.14	1.51	1.50	14.05	0.77	2.19
Sedimentations M x 10 ⁹			0.99	0.96	0.60	0.75	0.15	0.25	3.23	3.60	3.30	6.83
Lake stocks M x 10 ⁹	8.95	96.2	5.22	39.8	3.86	32.8	2.82	28.3	29.2	2.83	15.0	41.1
absolute concentrations mm x 1	0.355	2.05	2.205	0.85	0.15	0.70	0.110	0.605	1.15	5.65	0.595	0.88
relative concentrations %	42.9	48.8	25	20.2	18.5	16.6	13.5	14.3	66	86.5	34	13.5
turn-over %	62.5	5.35	83.9	8.0	85.5	7.6	88.4	7.20	76.7	6.2	107	22

The south basin is mainly a transit zone for the dissolved salts: the residence times are very short (18 months for Na, 11 months for SiO₄H₄). About 73% of the river input flows into the north basin where the residence times are ranged between 19 years for Na and 4,5 years for SiO₄H₄. Consequently the north basin is the principal container

of dissolved salt: 88,5% of the total stock against 11,5% for the other basin.

The importance of the sedimentation is the same in both basins. In the south, for $\text{SiO}_2 \cdot \text{H}_2\text{O}$ the sedimentation is 48% against 52% in the north; for Ca 51% against 49%; for Mg 44,5% against 55,5%; for K 37% against 63% and for $\text{HCO}_3^-/\text{CO}_3^{--}$ 47,5% against 52,5%.

On the contrary the salt output by infiltration is much less important in the south basin: 11% of the total against 89% in the north.

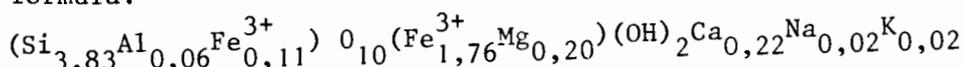
As a consequence of these different water and salt balances from one basin to the other, the salinity of the north basin is 4 times higher than that of the south basin (10,7mM/l against 1,55mM/l); this increase is accompanied by a higher relative concentration in Na and $\text{HCO}_3^-/\text{CO}_3^{--}$.

4. NATURE OF THE BIOGEOCHEMICAL SEDIMENTATION(*)

4.1. THE GEOCHEMICAL SEDIMENTATION; NEOFORMATION OF SMECTITES AND CALCITE PRECIPITATION.

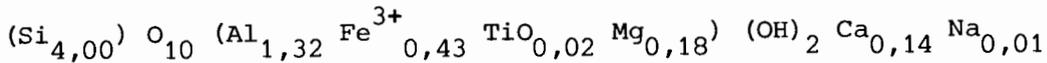
A comparative mineralogical study of the Chari discharge and of the surface sediments have shown that geochemical modifications take place in the lake itself. Three kinds of smectites are newly formed (CARMOUZE, 1976, CARMOUZE, PEDRO and BERNIER, 1977; CARMOUZE, GOLTERMANN and PEDRO, 1976, PEDRO, CARMOUZE and VELDE, 1978). They represent 65% of the total smectites included in the sediments (then 35% come from the river Chari). They are:

- a peloidal nontronite, near the delta, with the average formula:

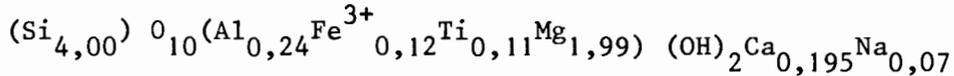


* the different ways of sedimentation cannot be quantified for the actual period using hydrochemistry data. But they have been estimated for the recent period (about two centuries) using geochemical data (CARMOUZE, 1976).

- a ferriferous beidellite in the central zone :

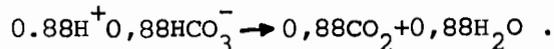
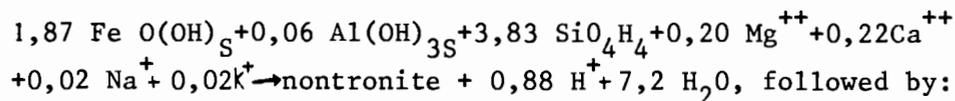


- a magnesian monmorillonite in the north:



In addition, sediments located in the north contain 5 to 10% of calcite.

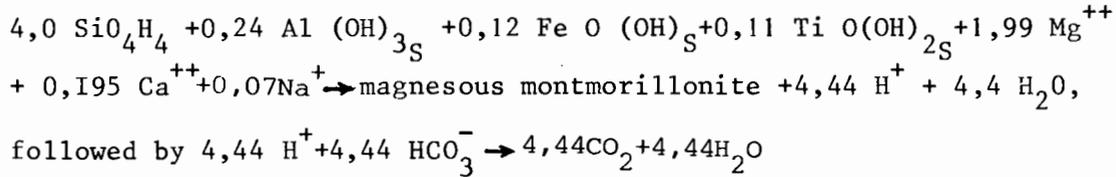
a) the sediment near the Chari delta are composed of granules (so-called pseudo-sands) whose sizes range between 0,125 and 0,500mm. They present different forms, colours and hardness, changing from black, manually unfriable and spherical to greenish-yellow, manually friable and oval. They are constituted of goethite and montronite. Black granules change into greenish-yellow ones. This evolution corresponds to a progressive silicification of goethite into montronite:



From the point of view of hydrochemistry, this reaction causes an important elimination of silice (4 moles are necessary to build up a mole of nontronite) and to a less extent, an elimination of Ca^{++} and Mg^{++} (0,20-0,22 moles). Besides, the reaction transforms a HCO_3^- fraction into CO_2 which is liberated. Consequently, the pH of the water decreases.

b) 65% of the smectite contained in the sediments located in the central zone is an autochthonous ferriferous beidellite which is build up with monocrystalline FeO_2H amorphous $\text{Al}(\text{OH})_3$ and probably free $\text{TiO}(\text{OH})_2$ coming from the Chari and with SiO_4H_4 , Mg^{++} and Ca^{++} from the aqueous solution: $4,0 \text{SiO}_4\text{H}_4 + 1,32 \text{Al}(\text{OH})_{3S} + 0,43 \text{FeO}(\text{OH})_S + 0,02 \text{TiO}(\text{OH})_{2S} + 0,18 \text{Mg}^{++} + 0,13 \text{Ca}^{++} + 0,01 \text{Na}^+ \rightarrow \text{ferriferous beidellite} + 0,63 \text{H}^+ + 8,9 \text{H}_2\text{O}$ followed by $0,63 \text{H}^+ + 0,63 \text{HCO}_3^- \rightarrow 0,63 \text{CO}_2 + 0,63 \text{H}_2\text{O}$. Then, the formation of a mole beidellite produces an impoverishment in the aqueous solution of SiO_4H_4 (4-0 moles), Mg^{++} (0,18 moles) and Ca^{++} (0,13 moles) Besides CO_2 is liberated, which decreases the pH of water.

c) the magnesian montmorillonite located in the north is build up as follows :



The neoformation of a mole of this smectite causes an important elimination of SiO_4H_4 (4 moles) and of Mg^{++} (2 moles) and to a less extent of Ca^{++} (0,20 moles) from the aqueous solution. The important quantity of CO_2 which is freed (4,44 moles) attenuates the pH increase due to evaporation.

d) In addition to the neoformation of clays, precipitation of calcite takes place in the north. Its amount in the sediments is about 5-10% . A detailed study of this phenomenon has been made (CARMOUZE, 1976) which shows that the precipitation occurs when the product of the activities of free Ca^{++} and free CO_3^{--} , $\{\text{Ca}^{++}\} \cdot \{\text{CO}_3^{--}\}$ exceeds 18 times the calcite of solubility product. The figure 5 shows in a simplified form, these four geochemical reactions.

4.2. THE BIOCHEMICAL SEDIMENTATION, MOLLUSCS AND MACROPHYTES.

A dissolved element may have an important biological sedimentation, when it largely participates in biological cycles of organisms whose biomass and production are high and when its release rate from dead organism is low.

In the case of the lake Chad, the influence of molluscs on Ca regulation and macrophytes on K, Mg and SiO_4H_4 regulation have to be taken into account. Diatoma certainly modify the SiO_4H_4 regulation as it is shown by local studies in 1974 when the lake level was very low (LEMOALLE, 1978). But we do not have enough information to fully assess their influence.

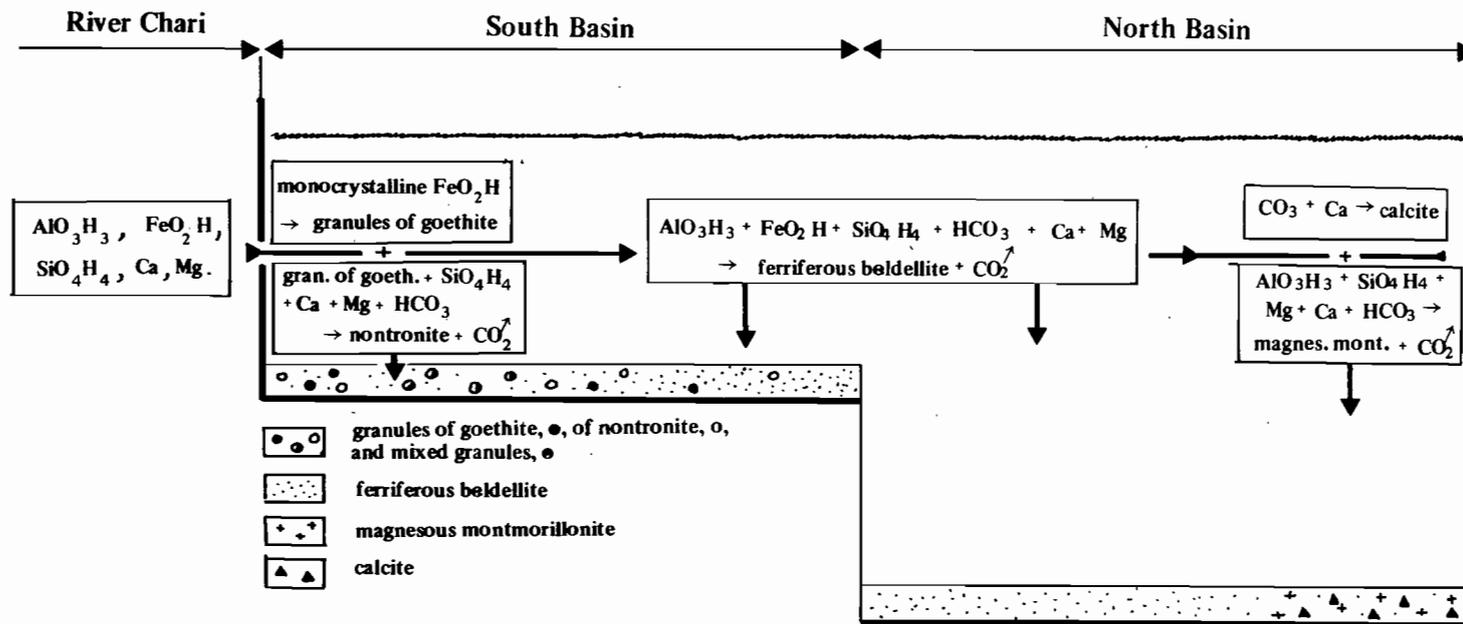


Figure 5 - Simplified geochemical reactions occurring in the lake and their localisations.

4.2.1. Molluscs

LEVEQUE (1972) has shown the mollusc importance on Ca regulation. Estimating that a population equal to that of 1970 takes up each year 700.000t of Ca, this amount represents 4 times the annual river input of Ca or the half stock of Ca in the lake. Evidently, without recycling the Ca concentration would have fastly been diminished in the lake and become null in the zones far from the delta. On the contrary, a complete recycling of Ca, considering a stationary population, would not have influenced the Ca regulation.

In fact, the biomass changes with the lake level fluctuation and the dissolution rate of shells with the water pH. LEVEQUE indicates that, during the lake decrease of 1968-70, corresponding to a lake level decrease of 0,70m, the mollusc biomass has augmented from 560.000t to 745.000t. Then, from 1970 to 1972, the decrease has continued and has been much more marked, producing, for molluscs, unfavourable ecological conditions. The biomass has therefore diminished to 15-20% of the value in 1970. According to these data the Ca uptake by molluscs and the Ca sedimentation rate have increased during the first period and diminished during the second one.

Comparing the ratio lifeless shells/life shells, LEVEQUE shows that the recycling of Ca is quite complete in the south basin and in the southern part of the north basin but incomplete in the northern part of the latter basin.

Finally, from these qualitative considerations one can conclude that when the lake decreases, the biomass of molluscs and consequently the sedimentation rate of Ca increases. (However, beyond a certain limit the ecological conditions become unfavorable, the mollusc biomass and the sedimentation rate of Ca diminish). When the lake increases, the inverse phenomenon may be observed. Whatever the lake level is, losses of Ca are more important in the northern part of the north basin.

4.2.2. Macrophytes.

The organic material of sediments proceed mainly from macrophytes (CHEVERY, 1974). *Phragmites australis*, *Cyperus papyrus*, *Vossia cuspidate* and *Typha angustifolia* represent respectively 85%, 10%, 4% and 1% of the vegetation area which is on the average about 2.400km².

The approximative quantities of K⁺, Ca⁺⁺, Mg⁺⁺, Na⁺ and SiO₄H₄ fixed and the macrophytes represents respectively 170%, 4%, 8,5% and 23,5% of the mean annual inputs of these elements or 11,2%, 0,4% , 0,8%, 0,1% and 6,8% of their corresponding lake stocks. Considering that the ration production/biomass is about one, these quantities are closed to that which are annually uptaken by the macrophytes themselves.

As organic accumulations are registered in some parts of the lake we can infer, from these data, that substantiel amounts of K and, to a less extent, of SiO₄H₄ are not recycled and then represent definitive losses.

The annual amount of dissolved salts fixed by the macrophytes change in the same proportion as the biomass. It may largely vary because the vegetation area which is about 2.500 km² at the lake level of 281,5m can double or be reduced by half respectively at the lake levels of 280 and 283m.

In conclusion, when the lake increases, the macrophyte biomass decreases, the uptake rate of dissolved salts becomes lower and the sedimentation rate through macrophytes may diminish. When the lake decreases the inverse phenomenon takes place. However for a substantial lake decrease, some regions of the lake are exondated and the vegetation is destroyed. Then when waters comme back they get enriched in K⁺ and to a less extent in Mg⁺⁺ (CHANTRAINE, 1978).

5. THE HYDROCHEMICAL REGULATION DURING THE DECREASE AND THE INCREASE OF THE LAKE.

5.1. HYDROCHEMICAL REGULATION DURING A DECREASE

From 1967 to 1972, the annual inputs have been lower than the annual outputs: the lake level has diminished by 1,35. In such a case the lake volume which has a higher turn-over than those of the saline stocks decreases faster; therefore the salt concentrations increase.

The salinity evolution can be calculated from the water and salt input deficits. During the period under consideration, the salt input deficit, $\Delta(i)_F$ which is equal to the difference between the inputs concerning the mean annual rate (see § 2.2.1) and those of 1967 to 1972, is as follows:

$$\Delta(\text{Ca}^{++})_F = 5.10^{12} \text{ mM}; \Delta(\text{Mg}^{++})_F = 3,8.10^{12} \text{ mM}; \Delta(\text{Na}^+)_F = 6,7.10^{12} \text{ mM};$$

$$\Delta(\text{K}^+)_F = 2,4.10^{12} \text{ mM}; \Delta(\text{HCO}_3^-)_F = 26.10^{12} \text{ mM}; \Delta(\text{SiO}_4\text{H}_4)_F = 19,4.10^{12} \text{ mM}.$$

or, in % of the corresponding initial stocks

$$\Delta(\text{Ca}^{++})_F = 11,1\%; \Delta(\text{Mg}^{++})_F = 10,5\%; \Delta(\text{Na}^+)_F = 6,5\%$$

$$\Delta(\text{K}^+)_F = 7,7\%; \Delta(\text{HCO}_3^-)_F = 9\%; \Delta(\text{SiO}_4\text{H}_4)_F = 34,6\%$$

These values indicate the fact that the stock changes are proportional to the stock turn-overs.

Assuming that annual outputs have not changed and that the saline stock variations arise only from input deficits, the saline stocks of 1972 could be calculated : $(i)'_L = (i)_L - \Delta(i)_F$

$$(\text{Ca}^{++})'_L = 40.10^{12} \text{ mM}; (\text{Mg}^{++})'_L = 32,8.10^{12} \text{ mM}; (\text{Na}^+)'_L = 98,5.10^{12} \text{ mM}.$$

$$(\text{K}^+)'_L = 28,8.10^{12} \text{ mM}; (\text{HCO}_3^-)'_L = 266.10^{12} \text{ mM}; (\text{SiO}_4\text{H}_4)'_L = 56.10^{12} \text{ mM}.$$

The lake volume has changed from 72.10^9 in 1967 to $45,5.10^6 \text{ m}^3$ in 1972, so the constituent concentration would be:

$$[\text{Ca}^+]_{\text{L}}' = 0,94 \text{ mM/l}; [\text{Mg}^{++}]_{\text{L}}' = 0,77 \text{ mM/l}; [\text{Na}^+]_{\text{L}}' = 2,32 \text{ mM/l};$$

$$[\text{K}^+]_{\text{L}}' = 0,667 \text{ mM/l}; [\text{HCO}_3^-]_{\text{L}}' = 4,05 \text{ mM/l}; [\text{SiO}_4\text{H}_4]_{\text{L}}' = 0,60 \text{ mM/l}$$

In fact, the actual total salinity represents 67% of the forecasted value. The stocks values in 1972 are lower than those we have just calculated:

$$(\text{Ca}^{++})_{\text{L}}'' = 18,8.10^{12} \text{ mM}; (\text{Mg}^{++})_{\text{L}}'' = 20,2.10^{12} \text{ mM}; (\text{Na}^+)_{\text{L}}'' = 78,6.10^{12} \text{ mM};$$

$$(\text{K}^+)_{\text{L}}'' = 19,7.10^{12} \text{ mM}; (\text{CO}_3\text{H}^-/\text{CO}_3^{--})_{\text{L}}'' = 172.10^{12} \text{ mM}; (\text{SiO}_4\text{H}_4)_{\text{L}}'' = 25,85.10^{12} \text{ mM}.$$

At first, this difference can be explained by an increase of the infiltration and sedimentation outputs, taking as reference the outputs which occur when the lake is in the steady-state. But the infiltration cannot notably increase: Although the salinity of the water infiltrations augment when the lake decreases, the infiltration volume diminishes because the infiltration zones are reduced and warper when they are displaced toward the middle of the lake. In the Na case, the increased output by sedimentation cannot be taken into account.

In fact, the lake morphology, which is very flat and with a bottom modulated by a dune system, facilitates the separation of many small ponds near the shore. The salts contained in these ponds deposit when they get dry.

So, for Na, we assume that the output increase $\Delta(\text{Na})_{\text{p}}$ is only due to these marginal deposits $\Delta(\text{Na})_{\text{Pm}}$. The fraction stock which deposits is equal to 18,7% of the stock of 1967. The fraction corresponding to the marginal deposits of the other elements is slightly different, depending on the stock distributions in space.

For Ca^{++} , Mg^{++} , K^+ , Na^+ , HCO_3^- and SiO_4H_4 the marginal deposits are respectively equal to 17.3, 18.1, 18.6, 18.2 and 16.4% of the initial stocks then :

$$\Delta(\text{Ca}^{++})_{\text{Pm}} = 7,8 \cdot 10^{12} \text{ mM}; \Delta(\text{Mg}^{++})_{\text{Pm}} = 6,65 \cdot 10^{12} \text{ mM}; \Delta(\text{Na}^+)_{\text{Pm}} = 19,7 \cdot 10^{12} \text{ mM};$$

$$\Delta(\text{K}^+)_{\text{Pm}} = 5,8 \cdot 10^{12} \text{ mM}; \Delta(\text{HCO}_3^-/\text{CO}_3^{--})_{\text{Pm}} = 53 \cdot 10^{12} \text{ mM}; \Delta(\text{SiO}_4\text{H}_4)_{\text{Pm}} = 9,2 \cdot 10^{12} \text{ mM}.$$

The higher the stocks are, the more important the deposits are.

The sedimentation output increase $\Delta(i)_{\text{Ps}}$ is calculated by difference: $\Delta(i)_{\text{Ps}} = \Delta(i)_{\text{P}} - \Delta(i)_{\text{Pm}}$.

$$\Delta(\text{Ca}^{++})_{\text{Ps}} = 13,45 \cdot 10^{12} \text{ mM}; \Delta(\text{Mg}^{++})_{\text{Ps}} = 6,0 \cdot 10^{12} \text{ mM}; \Delta(\text{Na}^+)_{\text{Ps}} = 0$$

$$\Delta(\text{K}^+)_{\text{Ps}} = 3,2 \cdot 10^{12} \text{ mM}; \Delta(\text{HCO}_3^-/\text{CO}_3^{--})_{\text{Ps}} = 41,0 \cdot 10^{12} \text{ mM}; \Delta(\text{SiO}_4\text{H}_4)_{\text{Ps}} = 1,70 \cdot 10^{12} \text{ mM}.$$

or in % of the corresponding initial stocks :

$$\Delta(\text{Ca}^{++})_{\text{Ps}} = 28,9\%; \Delta(\text{Mg}^{++})_{\text{Ps}} = 16,3\%; \Delta(\text{K}^+)_{\text{Ps}} = 10,3\%; \Delta(\text{HCO}_3^-/\text{CO}_3^{--})_{\text{Ps}} = 13,9\%;$$

$$\Delta(\text{SiO}_4\text{H}_4)_{\text{Ps}} = 2,9\%.$$

The hydrochemistry evolution from 1967 to 1972 is shown in figure 6.

5.2. HYDROCHEMICAL REGULATION DURING AN INCREASE.

Just two indications are available for knowing the hydrochemical evolution of the lake when the water level is increasing: one from 1945 and the other from 1957.

The lake volume in 1945 is close to that of 1972, reached after a similar lake decrease. So we can suppose that the dissolved stocks of 1945 are also similar to those of 1972, because they approximately change in the same proportion as the volume. Consequently, the total ionised salt stock of the lake in 1945, evaluated with the data of 1972, is equal to $175 \cdot 10^{12}$ mé. In 1957 the ionised salt stock, estimated from conductivity data (Guichard, 1957) was about $265 \cdot 10^{12}$ mé. So, the augment has been of $90 \cdot 10^{12}$ mé, while the lake level has risen of 2,20m.

This increase arises overplus annual inputs, from partial dissolution of salts which had precipitated during the precedent

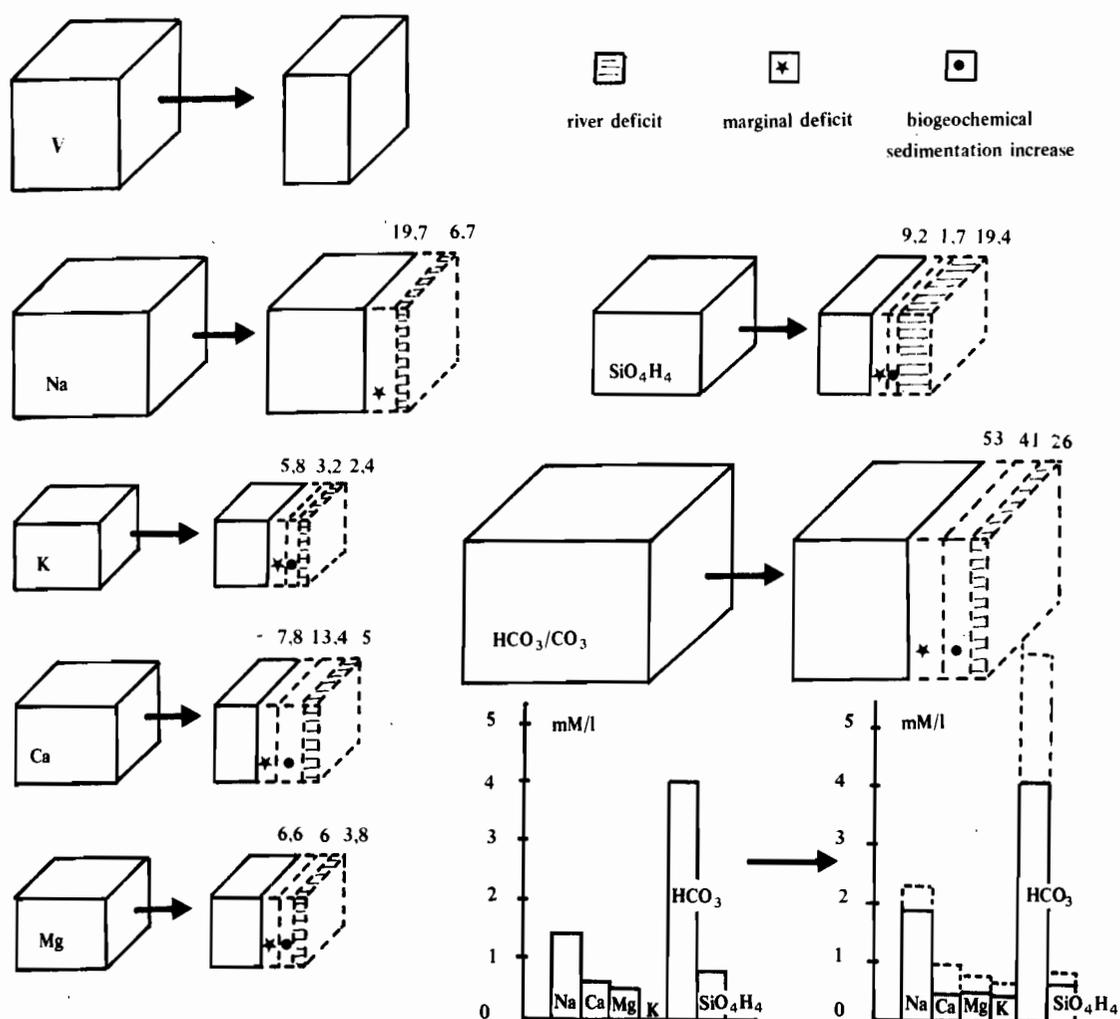


Figure 6 - Evolutions of the lake salt stocks and the chemical composition of the lake waters during the 1967-1972 decrease. The salt stock variations are given in Moles $\times 10^9$.

decrease of the lake on the marginal zones and may be from the diminution of the mean annual biogeochemical sedimentation rate. Losses by infiltration have not diminished; on the contrary they have perhaps augmented.

The excess of the ionised salt stocks coming from overplus river inputs between 1945 and 1957 is about $45 \cdot 10^{12}$ mé. That quantity represents 50% of the stock augment. Consequently, the rest, that is to say $45 \cdot 10^{12}$ mé, is attributed to the redissolution of the marginal salt deposits (*) when the lake increases, and, to a less extent, to a diminution of the biogeochemical sedimentation rate.

During the period 1945-1957, the volume of the lake has doubled: from $42 \cdot 10^9$ to $84 \cdot 10^9$ m³, while the ionised salt stock increase has been of 50%. Consequently, the mean ionised salt concentration has diminished from 4,15 mé/1 to 3,25 mé/1 (or from 365 µmhos to 290 µ mhos). However, if the salt stock had only been dependant on rates fluctuations of inputs during this period it would have been equal to about 2,60 mé/1 or 235 µ mhos (80% of the actual value).

This difference points out the importance of the dissolution processus of the marginal salt deposits and maybe, to a less extent, the diminution of the biogeochemical sedimentation rate. The both contribute to attenuate the diminution of the salinity due to the geographical factors when the lake increases.

6 - CONCLUSION

In spite of its endoreism and its subarid environment *the lake Chad is not a lake of high salinity*. Three main reasons explain this fact:

- the river salinity is *low* (about 60mg/1) twice as less important as the mean salinity of continental waters.
- the climato-geographical regulation of the salinity determines a concentration factor of the river waters of about 10,8. This

* The redissolution of salt deposits is about 60% (CARMOUZE, 1976).

value is not very high for a closed lake situated in an arid zone because the infiltrations are relatively important. This factor for the south basin, which is mainly a transit zone, is only 2,60 against 8,45 for the north one.

- the biogeochemical regulation is characterised by an important sedimentation of SiO_4H_4 , Ca^{++} , Mg^{++} , $\text{HCO}_3^-/\text{CO}_3^{--}$ and to a less extent of K^+ . The geochemical sedimentation is due to neoformations of smectites and precipitation of calcite. The neoformations of smectites are facilitated by a relatively high concentration of SiO_4H_4 in the river Chari. The salinity of waters where calcite precipitation take place is not very high because the anions are only CO_3H^- and CO_3^{--} . The mollusc and macrophyte contributions to the biochemical sedimentation are surely important because the biomasses and the productions of these two groups are substantial. Then the "climato-geographical" value of the salinity is reduced by 45%.

The salinity is relatively stationary in spite of the high instability of the lake caused by the important turn-over of the water and the dissolved salts. This is mainly due to the existence of marginal salt deposits when the lake decreases and partial redissolution of that deposits when the lake increases. These phenomena produce in the first case an additional output of salts, in the second case an additional input, in such a way the dissolved salt stocks vary approximately in the same proportion as the volume. There are favoured by the morphology of the lake, which is flat and marked by a dune system. For this reason when the lake decreases many ponds are isolated and rapidly get dry. Besides, the biochemical sedimentation rate increases when the lake decreases because the biomasses of molluscs and macrophytes augment (this ^{is} true only when the decrease is not very strong). The inverse phenomenon takes place when the lake increases.

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