THE CONTRIBUTION TO THE SALT REGULATION OF A LACUSTRINE SYSTEM BY GEOGRAPHICAL AND SEDIMENTOLOGICAL FACTORS

Jean-Pierre CARMOUZE   and   Georges PEDRO
,ORSTOM - Section d'Hydrobiolo-   INRA - Département de
gie - LA PAZ (Bolivie)   Science du Sol
                                                        CNRA - VERSAILLES (FRANCE)

This study shows that, after leaving aside the biogeochemical influences on sedimentation, the ratio of the concentration for a given dissolved element (i) between the water of a lake and the water of its tributaries : $\{\bar{\imath}\}_L / \{\bar{\imath}\}_{af}$ depends only on different hydric parameters inherent in the geographical region considered. The contribution of certain of these parameters, such as, evaporation, rainfall and infiltration relative to the inflows are quantified.

A lake is a storage vessel of rainwater, run-off water and/or resurgent waters. The later two are loaded with dissolved elements and solid particles ; the lake necessarly begins in a topographical depression which may be opened or closed. The storage process is generally <u>cumulative</u> for the solid substances ; on the contrary, it is a <u>dynamic</u> type for dissolved elements and water. Indeed, the volume of a lake and the various stocks of dissolved elements are continualy changed by the interplay of such losses and gains - the overall effect being to maintain   a more or less constant level. The lake volume and the stocks of dissolved matter are on first approximation "stationary" data. The same situation exists for the chemical composition of waters', since this is the result of dynamical equilibria which control the volume of the lake and its different salt stocks.

Thus, to unterstand or predict the chemical composition of a lacustrine "milieu", it is necessary to as_certain and quantify this various transfers of waters and dissolved salts which are connected with the lake — because, it is the mixing of these components which causes the transformation in the chemical composition of the inflows waters.

What is the nature of these transfers ? How do they contribute to the hydrochemical regulation of a lake ? We here propose some answers to these

questions, refering to our preceeding works about the regulation of lake Chad (J.P. CARMOUZE, I976 - J.P. CARMOUZE et G. PEDRO, I977).

I - TRANSFERS OF WATERS AND DISSOLVED SALTS IN A LAKE - THEIR ROLE IN THE SALT REGULATION.

I.I. - Water transfers.

In a lacustrine "milieu", the incoming water generally come from tributaries $(V)_{af}$, rains $(V)_{pl}$ and more rarely resurgent waters $(V)_{re}$, while the losses are due to outlets $(V)_{ef}$, evaporation $(V)_{ev}$ and infiltration $(V)_{in}$ (fig I)
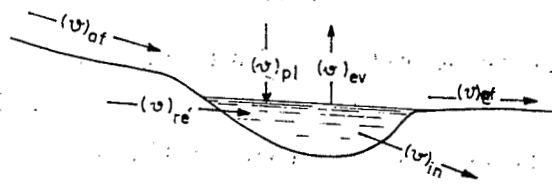

Fig I. Water transfers in a lake

In a yearly cycle, the balance between the inflows and outflows is only exceptionally realised ; this, obviously, causes variations in the volume. But, if a longer period is considered, it is very often noticed that the volume oscillates near an average value which enables one to define a mean annual hydric equilibrium for this lake ; thus, one may write :

$$(\bar{V})_{af} + (\bar{V})_{pl} + (\bar{V})_{ré} = (\bar{V})_{ef} + (\bar{V})_{ev} + (\bar{V})_{in} \quad (+) \quad (I)$$

(+) $(\bar{V})$ is the mean annual volume of various inflows and outflows

We should also notice that the volumes of waters lost by evaporation and received by rains are proportional to the surface of the lacustrine "milieu" On the other hand, those lost by infiltration and supplied by resurgent waters, both of which are regulated by the hydrogeological characteristics of the basin, are also dependent on the surface area, only this relationship is not a linear one, as in the case of the first two transfers.

Thus infiltration and resurgences are not important transfers of water compared with the other processes and it may be concluded that, for a certain supply, the various transfers of waters related to the lake determine, by their combination, a surface area which is in agrement with equation (I). The surface corresponding to this mean annual volume, we may call the "equilibrium surface" ; similarly an "equilibrium volume" is defined, this evidently depends upon the form of the basin. Thus two lakes, which have similar water transfer characteristics, may have completly different volumes.

In the case of endoreic systems occuring in arid and semi-arid climates, the hydric equilibrium described above becomes simplified : losses are only due to evaporation and to a lesser extent by infiltration.

I.2. - Transfers of dissolved salts

The influxes of dissolved salts chiefly come from tributaries $(i)_{af}$, more rarely and to a lesser extent from eolian deposits (or "dry precipitations") $(i)_{eo}$, from resurgent waters $(i)_{ré}$ and as a product of chemical dissolution etc occuring at the lake bottom $(i)_{as}$. Losses are due to outlets $(i)_{ef}$, infiltration $(i)_{in}$ and chemical sedimentations $(i)_{sé}$ (these latter account for all the transformations resulting in insoluble forms of a dissolved element ; hydrochemical, geochemical or biochemical processes are involving in these transformations) (fig 2).
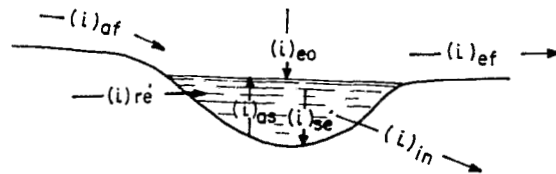

Fig 2 Transfers o issolved salts in a lake.

For every dissolved element (i), a dynamic balance tends to be maintained which may be written as follows :

$$(\bar{i})_{af} + (\bar{i})_{ré} + (\bar{i})_{é_o} + (\bar{i})_{as} = (\bar{i})_{ef} + (\bar{i})_{in} + (\bar{i})_{sé} \quad (+) \quad (2)$$

For given ratios in i and a given hydric regime, the stock of the lake in i changes to attain an importance such as equation (2) confirms. Thus, in the case of a medium which is chemically uniform, one can easily estimate the "equilibrium stock" $(\overline{Q_i})_L$ from the moment when the "equilibrium concentration" $\{ \bar{i} \}_L$ is known :

$$\{\overline{i}\}_L = \frac{(\text{salt gains in i}) - (\bar{i})_{sé}}{(\bar{v})_{ef} + (\bar{v})_{in}} \Longrightarrow (\overline{Q_i})_L = (\bar{v})_L \times \{\overline{i}\}_L$$

$(\bar{v})_L$ represents the average volume of the lake.

Refering to these relation_ships, it becomes clear that we may have two lakes which contain waters subject to the same transfer of materials and which have the same chemical reactivity, whereas they may have different stocks of dissolved salts ; these salts being related to the lake volume, that is to say the form of the basin.

To conclude, three types of transfer of materials seem to regulate the chemical composition of lacustrine waters :

- exclusive transfers of waters (or nearly) : i.e. rainfalls and evaporation;

- exclusive salt transfers, i.e. eolian deposits and various products released or bound by chemical reaction;

- mixed transfers corresponding with the flows from tributaries, by the outlets, infiltration and in the resurgent waters.

From the above, it is easy to realize that the chemical composition of waters only remains unchanged in the case where the exclusive transfers of water and dissolved salts take place according to a ratio equal to the one existing between the volume of inflowing water and the salt content of this water. This case is rare, so that generally there is an evolution in the chemistry of the inflowing waters in a lake : this evolution is related with the

---

(+) $(\bar{i})$ is the mean annual quantity of dissolved element i and $\{ \bar{i} \}$ its mean concentration.

balance of various transfers defined above. This matter will now be discussed.

I.3. - General principles of salt regulation

Choosing the ratio between the mean concentration in the lacustrine waters and in the tributaries' waters : $\{ \bar{i} \}_L / \{ \bar{i} \}_{af}$ as a parameter for study for the dissolved elements (i) and starting from a somewhat simplified lacustrine system, i.e. :

a) The eventual dissolution of salts, which are generally negligible with regard to the other transfers will not be taken into consideration $\{ (i)_{as} \simeq o \}$.

b) The "milieu" is considered as being chemically uniform.

Under these conditions :

$$\{ \bar{i} \}_{af} \times (\bar{v})_{af} = \{ \bar{i} \}_L \times (\bar{v})_{ef} + \{ \bar{i} \}_L \times (\bar{v})_{in} + (\bar{i})_{sé} \qquad (3)$$

Putting $(\bar{i})_{sé} = f_s \cdot \{ \bar{i} \}_{af} \times (\bar{v})_{af}$

(f_s being consequently the fraction of inflows which sediments out, with $0 < f_s < I$)

(3) becomes :

$$\{ \bar{i} \}_{af} \times (\bar{v})_{af} = \{ \bar{i} \}_L \cdot \{ (\bar{v})_{ef} + (\bar{v})_{in} \} + f_s \cdot \{ \bar{i} \}_{af} \cdot (\bar{v})_{af}$$

implying :

$$\boxed{ \frac{\{ \bar{i} \}_L}{\{ \bar{i} \}_{af}} = \frac{(\bar{v})_{ev} - (\bar{v})_{pl}}{(\bar{v})_{in} + (\bar{v})_{ef}} + I \cdot \{ I - f_s \} } \qquad (4)$$

Thus chemical evolution depends on two main groups of factors :

I) The atmospheric exchanges (evaporation, rain) which represent exclusive transfers of waters and the total transfers of waters charged with dissolved salts (outflows and infiltration). These exchanges of materials are thus essentially determined by the hydrological, hydrogeological and climatic characteristics of the "milieu" ; this latter may be regrouped under the title of geographical characteristics.

2) The fraction of the inflow which reacts to give insoluble compounds in the lake. This transfer thus depends on the nature of the dissolved elements present, of their mutual affinity and their aptitude to react as a function of the physicochemical and biological characteristics of the lacustrine environnement. These factors are essentially of a biogeochemical nature.

Under these conditions, an element which presents a zero chemical affinity for a given medium is uniquely controlled by the geographical charac-

teristics of the system ; we shall now elaborate upon this, before remarking upon the general contribution of the biogeochemical phenomena.

2 - INTERVENTION OF GEOGRAPHICAL FACTORS IN THE SALT REGULATION

2.I. - Contribution by climatic parameters.

When the regulation is controled only by geographical characteristics $(f_s = o)$, equation (4) simplifies to (4') :

$$\frac{\{\bar{i}\}_L}{\{\bar{i}\}_{af}} = \frac{(\bar{v})_{ev} - (\bar{v})_{pl}}{(\bar{v})_{in} + (\bar{v})_{af}} + I \tag{4'}$$

But we have :

$$(\bar{v})_{af} + (\bar{v})_{pl} \simeq (\bar{v})_{ev} + (\bar{v})_{in} + (\bar{v})_{ef}$$

It follows :

$$\frac{\{\bar{i}\}_L}{\{\bar{i}\}_{af}} = \frac{(\bar{v})_{ev} - (\bar{v})_{pl}}{(\bar{v})_{af} - (\bar{v})_{ev} + (\bar{v})_{pl}} + I \tag{5}$$

This last expression has advantage of containing only the transfer-parameters which may be directly measured (evaporation, rainfall and fluviatile inflows). Two graphical representations have been envisaged :

- The first representation takes into account only the balance of "evaporation - rainfall", expressed relatively to the contribution of the tributaries :

$$f_1 = \frac{(\bar{v})_{ev} - (\bar{v})_{pl}}{(\bar{v})_{af}}$$

f_1 may be positive, nul or negative - depending upon whether the evaporation is superior, equal or inferior to the rainfall ; thus :

$$\frac{\{\bar{i}\}_L}{\{\bar{i}\}_{af}} = \frac{I}{I - f_1} \tag{6}$$

- The second graphical representation is concerned more with the separate contributions of the two parameters : evaporation and rainfall, which are always expressed in terms relative to the inflows ; this permits us to precise the contribution of each of these transfers to the salt regulation

$$f_2 = \frac{(\bar{v})_{ev}}{(\bar{v})_{af}} \qquad \text{and} \qquad f_3 = \frac{(\bar{v})_{pl}}{(\bar{v})_{af}}$$

with f_2 and $f_3 \geqslant 0$

It follows : $f_1 = f_2 - f_3$,

$$\frac{\{\bar{i}\}_L}{\{\bar{i}\}_{af}} - \frac{I}{I - (f_2 - f_3)} \qquad\qquad (7)$$

Equations (6) and (7) represent two hyperbolae from which we are able to evaluate the role, in the salt regulation, of the climatic factors relative to fluvial hydrological parameters.

2.I.I. - The general role of the "evaporation - rainfall" balance.

Graphical representation of (6) shows an intersection of the curve with the ordinate axis when $f_1 = 0$ (fig 3)
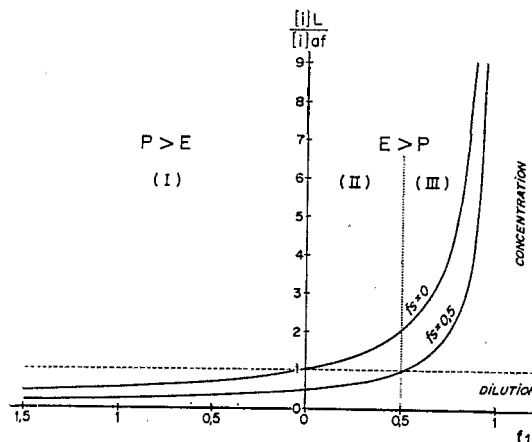

Fig 3 Variation of $\{\bar{i}\}_L / \{\bar{i}\}_{af}$ with f_1, when $f_s = 0$
(Equation 6) and $f_s \neq 0$ (Equation 9)

Three zones are recognizable :

- To the right $f_1 > 0$, a zone corresponding to E > P ; the concentration of lacustrine waters is higher than that of fluviatile waters ; this concentration rises very quickly because f_1 tends towards unity, $\{\bar{i}\}_L / \{\bar{i}\}_{af} \to \infty$ (+)

(+) e.g. when the net evaporation represents 80 % of the inflows, $\{\bar{i}\}_{af}$ is multiplied fivefold ; at 90 %, $\{\bar{i}\}_{af}$ is multiplied tenfold.

The system is a "concentration basin".

    - In the center line, $f_1 = 0$ and $E = P$; $\{ \bar{i} \}_{af}$ remains constant.

    - Finally there is the **case** : $f_1 > 0$ **(E < P), in which the concen-**tration of fluviatile waters $\{ \bar{i} \}_{af}$ diminishs very <u>slowly</u> (+ +). These conditions imply that we have a "dilution basin".

    2.I.2. - <u>The particular roles of evaporation and rainfall</u>.

From equation (7), we may deduce the separate contribution of each of these parameters. Fig 4 also permits the parameter $\{ \bar{i} \}_L / \{ \bar{i} \}_{af}$ **to be as-**certained as a function of the relative evaporation f_2 for different values of the relative rainfall f_3.
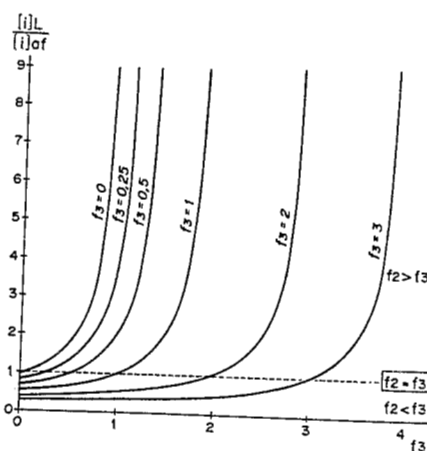

Fig 4 Variation of $\{ \bar{i} \}_L / \{ \bar{i} \}_{af}$ with f_2 for different values of f_3

    The conclusion is that the concentration is more pronounce in the case where the climatic water contribution is feeble and, for given rainfalls, when the relative evaporation of the incoming waters is high.

    2.I.3. - <u>The dynamic comparison of water and salts in these three principal climatic conditions</u>.

The introduction of a factor τ , which is the index of turn-over of

---

(+ +) For example $\{ \bar{i} \}_{af}$ diminishes to half its value when the net climatic contributions are aqual to those of the fluviatile waters, and to a quarter when this ratio is about three.

stored materials for a time interval Δt and which is generally defined for Δt equal to one year, permits us to better understand the flow characteristics of the medium. Thus, we respectively have for water and for dissolved element (i) :

$$\tau \text{ water} = \frac{(\bar{v})_{af}}{(\bar{v})_L} \qquad ; \qquad \tau_i = \frac{(\bar{v})_{af} \cdot \{\bar{i}\}_{af}}{(\bar{Q}_i)_L}$$

a) When evaporation is equal to the rainfall, $\{\bar{i}\}_L = \{\bar{i}\}_{af}$. There is no modification of the concentration in dissolved element (i) of the waters flowing into the lake.

Where $(\bar{Q}_i) = (\bar{v})_L \cdot \{\bar{i}\}_{af}$

It follows that : $\tau_i = \frac{(\bar{v})_{af}}{(\bar{v})_L} = \tau \text{ water}$

However, the lake volume and its stock of dissolved element (i) have the same index of annual turn-over, i.e. the water and the dissolved element (i) have an apparently <u>identical</u> flow rate (Rigoursly, this is only the case when $(\bar{v})_{ev} = (\bar{v})_{pl} = 0$)

b) When $E > P$, $\{\bar{i}\}_{af} < \{\bar{i}\}_L$, we have :

$$\tau_i = \frac{(\bar{v})_{af} \cdot \{\bar{i}\}_{af}}{(\bar{v})_L \cdot \{\bar{i}\}_L} \quad < \quad \tau \text{ water} = \frac{(\bar{v})_{af}}{(\bar{v})_L}$$

In such a "concentration basin", we may visualize the situation as if the flow of dissolved element in the lacustrine system has been <u>retarded</u> in proportion to the water which has a fluviatile origin.

In the limit, when f_1 tends to unity (or $f_2 - f_3 \rightarrow I$) : $(\bar{v})_{ev} - (\bar{v})_{pl} = (\bar{v})_{af}$ and it follows $(\bar{v})_{in}$ and $(\bar{v})_{ef}$ are both equal to zero.

Although, there is no loss of salts, this state implies that we have a real "saline basin" (+).

c) Finally, when $E < P$, $\{\bar{i}\}_{af} > \{\bar{i}\}_L$, we have :

$$\tau_i = \frac{(\bar{v})_{af} \cdot \{\bar{i}\}_{af}}{(\bar{v})_L \cdot \{\bar{i}\}_L} \quad > \quad \tau \text{ water} = \frac{(\bar{v})_{af}}{(\bar{v})_L}$$

However, in this type of lacustrine basin, the flow of dissolved element (i) is increased in proportion to the ratio of water coming from flu-

---

(+) The name of such basins varies with geographical position e.g. "salar" in Latin America and "sebkha" in Africa.

viatile origin.

Thus, we find that the three principal climatic conditions of the natural "milieu" may be perfectly represented (from a dynamic stand point) by comparing the respective inflows of water and dissolved substances.

2.2. - <u>Contribution from hydrological factors</u> - <u>The importance of infiltration in endoreic systems.</u>

When we have an endoreic system in which $(v)_{ef} = 0$, the dissolved salts are only able to be eliminated by infiltration. If then we put :

$$f_4 = \frac{(\bar{v})_{in}}{(v)_{af}} \qquad f_4 \geqslant 0$$

The relations (5) becomes :

$$\frac{\{\bar{i}\}_L}{\{\bar{i}\}_{af}} = \frac{f_1}{f_4} \qquad (8)$$

This is represented by fig 5, in which the variation of $\{\bar{i}\}_L / \{\bar{i}\}_{af}$ as a function of f_4, may be ascertained for different positive values of f_1.
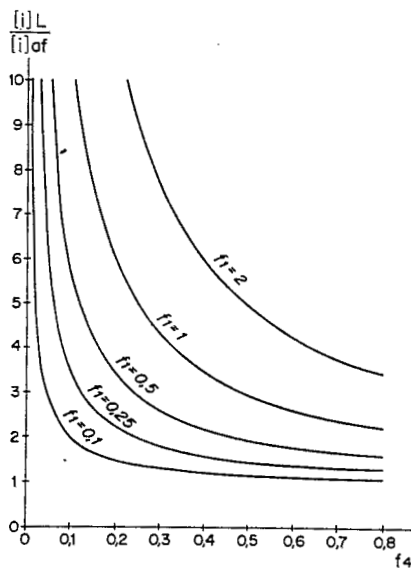

Fig 5 Variation of $\{\bar{i}\}_L / \{\bar{i}\}_{af}$ with f_4 (relative infiltration).

Thus, the concentration is elevated when the infiltrations are weak and when the evaporation rate is high.

When there are no infiltration losses, $\{\bar{i}\}_L / \{\bar{i}\}_{af} \to \infty$ and

we have the "saline situation" without losses of salts.

3 - THE GENERAL EFFECT OF THE BIOGEOCHEMICAL SEDIMENTATION ON THE MODIFICATIONS
OF GEOGRAPHICAL REGULATION.

This is the usual situation ; however, we are going to treat it in a
general manner by introducing the factor $f_s = \dfrac{(i)se}{\{\bar{i}\}_{af} \times (\bar{v})_{af}}$ and without specifying

either the nature or the importance of the chemical deposits in the lake.

Following from (4) and using equation (6), we have :

$$\frac{\{\bar{i}\}_L}{\{\bar{i}\}_{af}} = \frac{I}{I - f_1} \cdot (I - f_s) \qquad\qquad (9)$$

(9) represents a family of hyperbolae, the curves of which are all underneath
the curve corresponding $f_s = 0$ (fig 3). The presence of biogeochemical sedimen-
tation evidently diminishes the concentration of lacustrine waters in all cases ;
again three domains are delimited :

$$
\begin{array}{lll}
\text{(I)} & f_1 < 0 & (P > E) \\
\text{(II)} & 0 < f_1 < f_3 & \{\ (P < E) \\
\text{(III)} & f_1 > f_s & \{ \\
\end{array}
$$

In two of these domains, the direction of the evolution of the
"geographical regulation" is not changed : for example, in (I) the dilution
is simply more pronounced and in (III), the concentration is reduced.

However, the development of biogeochemical phenomena changes the direc-
tion of evolution in case (II), in which the concentration in (i) diminishes
in the lacustrine waters. One also notices that dispite a large hydric deficit
(E > P), the situation could arise in which consecutive desalination by
chemical sedimentation plays a more important role than the effect of evapora-
tion on concentration (cf. J.P. CARMOUZE, 1976).

Comparaison of the two parameters f_1 and f_s appears, then, to be
extremely important for predicting the variation of salinity of lacustrine
waters.

CONCLUSIONS

Three pertinent remarks may be made from these data :

a) The quantitative analysis of salt regulation permits the "weigh-
ting" of various geographical parameters in the evolution of the concentration
of any element in a lacustrine system ; these parameters are of a climatic or

a hydrological nature (respectivly due to evaporation - rainfall or fluviatile inflows, losses by outlets and by infiltration).

b) With a knowledge of concentration of fluviatile waters on one hand, and the various annual hydric characteristics of the system on the other $\{(\bar{v})_{ev} - (\bar{v})_{pl} - (\bar{v})_{af} - (\bar{v})_{ef} - (\bar{v})_{in}\}$, it is possible to calculate the <u>virtual salinity</u> of lacustine water, i.e. the salinity which is due only to factors of geographical origin and <u>without</u> influence from biogeochemical phenomena. In practise, it would suffice to compare this virtual value with the actual salinity to arrive at a general value of the fraction originating by biogeochemical sedimentation.

c) In the cases of elements such as Na^+ and Cl^- in which there are neglig.ible deposits (at least, in conditions which are not brackish), the study only of the geographical regulation allows us to determine the factor of concentration and dilution. Following from this and knowing the mean annual volume of inflows from the tributaries $\{(\bar{v})_{af}\}$ and from the rainfall $\{(\bar{v})_{pl}\}$ together with the losses from the outlets $\{(\bar{v})_{ef}\}$, it becomes possible to determine the mean annual volume lost by <u>evaporation</u> and especially <u>infiltration</u> - such measurements, particularly the latter, are generally very difficult to evaluate "in situ".

<u>REFERENCES</u>

CARMOUZE J.P. (I976) La régulation hydrochimique du lac Tchad - Thèse Paris VI - Travaux et documents ORSTOM - N° 58, 4I8 p.

CARMOUZE J.P. et PEDRO G. (I977) Influence du climat sur le type de régulation du lac Tchad ; relations avec les modes de sédimentation lacustre. Sciences Geologiques (Strasbourg) - T 30 - I (sous-presse).