Hydrodynamics of Ebrié lagoon as revealed by a chemical and isotopic study

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Abstract

To determine the origin and the circulation of waters in the different areas of the Ebrié lagoon (Ivory Coast), ionic concentrations (K^+, Cl^-) and isotopic ($\delta^{18}O$) measurements were performed. Sixty stations were sampled. Chemical and isotopic analyses were made thrice during a hydrological cycle: in May 1986, at the end of the great dry season; in October 1986, during the maximum of rainfall, in December 1987, after the Comoe river peak flow. From a hydrodynamical point of view, the results reported in this work indicate that the lagoon comprises four distinctive areas. The first is filled with freshwater all the year round and is characterized by an weak isotopic enrichment (these waters are of continental origin and annually renewed); the second corresponds to oligohaline waters highly enriched in ^{18}O (waters essentially of continental origin and poorly renewed); the third area is constituted of a mixture of waters of continental and oceanic origins. The latter group can be separated into two subgroups: a group completely renewed by oceanic water during the dry season and another group totally renewed by freshwater during the rainy and flood seasons.

Introduction

Coastal lagoons are buffer zones between continental and oceanic environments. They are characterized by a high spatial and temporal heterogeneity. Their chemical characteristics are dependent upon the origin of water masses and controlled by the hydrodynamics of the system. The hydrochemical features and the hydrodynamics play an important role in the organization, the functioning and the productivity of the biological communities living in these habitats (Guelorget & Perthuisot, 1983). The stability of the environmental conditions is one of the main factors controlling the functioning of aquatic ecosystems. Thus, the knowledge of the factors controlling the evolution of water qualities in the coastal lagoon is an essential step allowing their management

and their conservation. Lagoons are often preferential areas where men build their settlements and make multipurpose use of the environment (fishing, tourism, communications, aquaculture, etc...).

The Ebrié lagoon is an appropriate zone for hydrological study since it is the largest lagoon in West Africa. Furthermore, Abidjan the most important city (2.5 millions of inhabitants) in this subregion of Africa, is built on its banks. In general, hydrodynamical description requires the development of a mathematical model. However, current and bathymetry data are lacking for the Ebrié lagoon, hence the use or the development of a theoretical model is presently impossible. Simultaneous utilization of water ionic composition and an isotopic water molecule tracer is a pragmatic alternative (Craig & Gordon, 1965; Yurt-

sever & Payne, 1978). In this work, this approach is applied in the case of the Ebrié lagoon, using Cl^{-1} and K^{1+} concentrations to characterize ionic composition. Oxygen-18 was used as an isotopic tracer of the water molecule.

Materials and methods

With a surface area of 566 km^2 and a mean volume of 2.7 10^9 m^3, the Ebrié lagoon spreads over 130 km along the Atlantic coast (Fig. 1). In 1951, the hydrological environment was greatly modified by the man-made opening of the Vridi canal. In addition, the Ebrié lagoon is connected to the sea through the Bassam inlet opened since September 1987. This inlet was created in order to control the proliferation of aquatic plants (*Pistia stratiotes*, *Salvinia molesta*, and *Eicchornia crassipes*; Guiral & Etien, 1989) in the Ebrié lagoon.

An estimation of the hydrological budget of the lagoon was undertaken by Durand & Chantraine (1982). This work emphasized both the importance of tidal flow and annual freshwater input which represented 14 and 5 times the volume of the lagoon respectively. However, these estimations are no longer relevant to this environment. The opening of the Bassam inlet has modified the hydrology of the lagoon. Furthermore, the rainfalls greatly vary from a year to another; for example, in 1986, the rainfalls were 1338 mm compared to 2021 mm in 1987 (the latter value being close to the annual average recorded between 1950 and 1980: 2100 mm). Finally, freshwater input, essentially from the Comoe river reaching the Ebrié lagoon through its western extremity, is also characterized by an annual variability. Nevertheless, it is far more amplified than that of the rainfalls (freshwater inputs in 1986 and 1987 were estimated 3.7 10^9 m^3 and 6.6 10^9 m^3 respectively, while the average value between 1975 and 1980 was 7.1 10^9 m^3) (Tables 1a and 1b).

The Mé and Agnéby rivers also contribute to the Ebrié lagoon (Fig. 2). The catchment area of the Comoe river is of the order of 78 000 km^2, while, those of the Me and Agnéby rivers are 4300 km^2 and 8900 km^2 respectively (Durand & Chantraine, 1982). Hence, the contribution of these two rivers to the Ebrié lagoon is smaller than 25%.

In order to study the hydrochemical evolution of the Ebrié lagoon, sixty stations, chosen all over the lagoon were sampled (Fig. 2). Subsurface (0.2 m depth) water samples were collected, using a Niskin bottle. Samples were kept in dark glass bottles tightly closed. These precautions were taken to avoid evaporation of the samples before analyses.

Two surveys were undertaken during the dry season (low-water flow of the Comoé river) in May 1986 and the end of the short rainy season. The latter occurs two months after the Comoé river peak flow in December 1987. Furthermore,
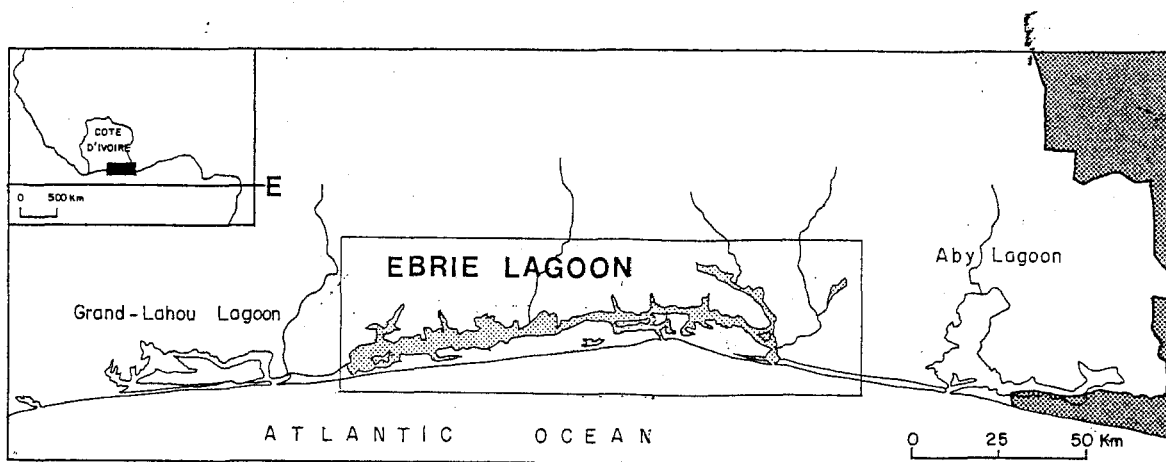

Fig. 1. Map showing the three lagoons of the Ivory Coast.

Table 1a. Climatic and hydrological data collected in 1986.

Months	Rainfall* (mm)	Evaporation* (mm)	Comoé** ($\times 10^6 \, m^3$)	Me** ($\times 10^6 \, m^3$)	Agnéby** ($\times 10^6 \, m^3$)
J	0.5	140.5	3.9	15.3	0.0
F	72.0	138.9	3.5	16.7	0.0
M	130.2	142.9	1.5	15.6	0.6
A	127.0	151.3	5.0	16.8	1.3
M	125.0	134.8	6.5	22.3	1.7
J	377.0	103.0	84.0	35.3	9.2
J	117.0	158.8	74.7	22.2	23.4
A	21.0	113.2	479.1	17.9	2.9
S	69.0	105.8	1434.2	25.5	6.4
O	142.5	123.7	1238.0	51.1	27.5
N	84.0	124.4	278.5	34.7	8.1
D	62.0	117.3	66.4	18.8	0.3
Total	1338	1555	3675	292	81

* Data collected from the bioclimatological station of Adiopodoume ($5°19'$ N, $4°13'$ W). The evaporation was estimated according to Penman formula.
** Data collected from 'la Direction des Ressources en Eau de Surface' of the Ministry of Public Works of the Ivory Coast.

Table 1b. Climatic and hydrological data for 1987.

Months	Rainfall* (mm)	Evaporation* (mm)	Comoé** ($\times 10^6 \, m^3$)	Me** ($\times 10^6 \, m^3$)	Agnéby** ($\times 10^6 \, m^3$)
J	12.5	119.0	20.2	17.9	0.1
F	47.5	136.7	9.8	14.4	0.8
M	111.0	142.2	9.6	22.2	1.0
A	135.5	143.1	21.8	20.9	10.5
M	189.5	132.4	10.0	23.7	2.0
J	323.5	109.6	123.7	39.5	6.7
J	85.5	108.0	145.8	19.2	28.4
A	159.0	85.0	946.4	48.9	50.9
S	592.5	95.1	2908.9	188.2	41.1
O	284.5	133.3	2023.7	483.5	401.8
N	51.5	137.5	284.5	69.8	29.3
D	30.0	109.4	59.8	21.4	0.9
Total	2021	1451	6564	970	573

* Data collected from the bioclimatological station of Adiopodoume ($5°19'$ N, $4°13'$ W). The evaporation was estimated according to Penman formula.
** Data collected from 'la Direction des Ressources en Eau de Surface' of the Ministry of Public Works of the Ivory Coast.

an additional survey in the western area of the Ebrié lagoon was carried out during the Comoé river peak flow and the wet season (October 1986). During this period, the discharge of freshwater in the lagoon represents about 60% of the total annual freshwater input. Figure 3 displays freshwater input during the three surveys.

Water salinity was measured using a YSI 33 conductimeter with a temperature correction device. For oligohaline waters (salinity inferior to $5 \, mg \, l^{-1}$), instead of the salinity, the conductivity was measured using the same conductimeter.

Major cations (Na^{1+}, Mg^{2+}, Ca^{2+}, K^{1+}) and Cl^{-1} were titrated during the two 1986 surveys.
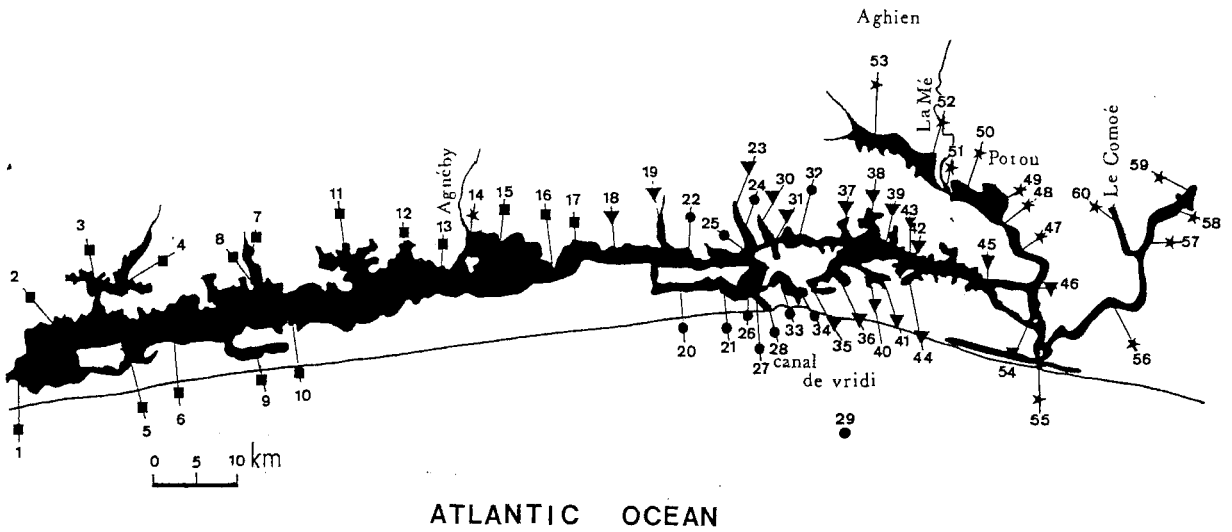
Fig. 2. Location of stations sampled in the Ebrié lagoon. Symbols stand for the different groups A (●), B (▼), C (✖), and D (■).
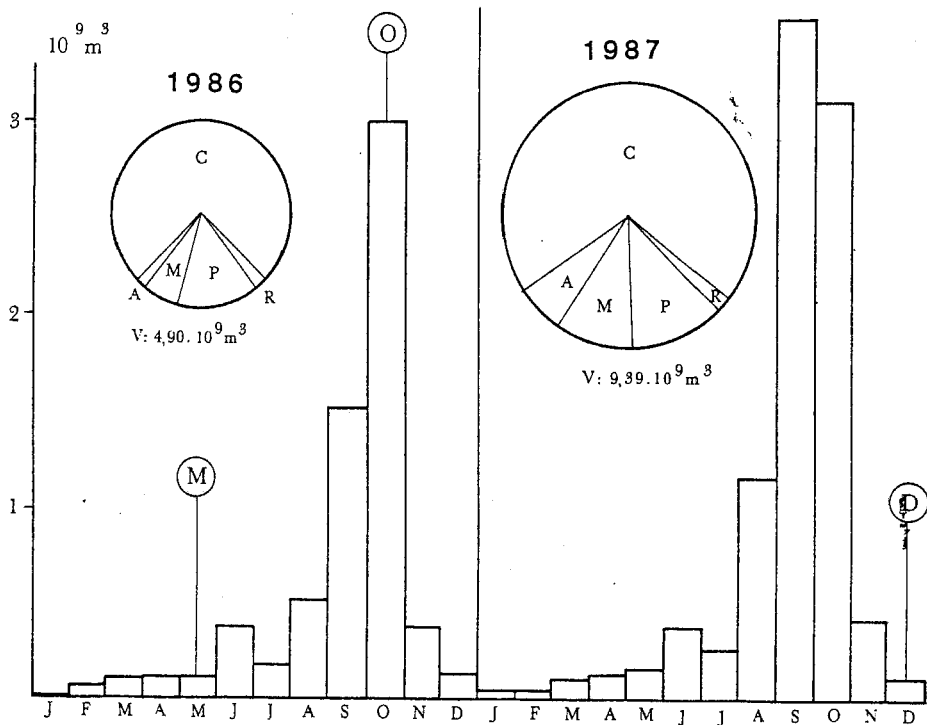

Fig. 3. Characterization of hydroclimatical condition during the three surveys undertaken in the Ebrié lagoon., M, O, and D stand for May 1986, October 1986 and December 1987 respectively. The circles represent water budget of the Ebrié lagoon in 1987–1988. Annual volumes of (A) Angnéby, (C) Comoé and (M) Me rivers inputs and (P) Precipitations and (R) Runoff.

The results from these analyses showed that Na^{1+}, Ca^{2+}, Mg^{2+} ions could very accurately be estimated from the Cl^{-1} concentration. In the contrary, K^{1+} concentrations cannot be estimated from Cl^{-1} concentration, because, potassium ions are more concentrated in the lagoon.

(Guiral & Ferhi, 1989). Hence, only Cl^{-1} and K^{1+} ions were determined in 1987. Chloride and potassium ions were determined using an auto-analyzer Technicon (ferric thiocyanate method) and a single beam flame photometer, respectively.

In addition to these chemical titrations, a ^{18}O analysis was carried out in all the samples collected. This was made, using a mass spectrometry according to the classical procedure of the isotopic equilibration (H_2O/CO_2 at 25 °C) (Epstein & Mayeda, 1953). The results are expressed in δ according to the following relationship:

$$\delta\,^{18}O = \frac{Re - Rs}{Rs}\,10^3,$$

where Re and Rs are the ratio $[^{18}O]/[^{16}O]$ in the sample and in the standard respectively. Rs is by definition the 'Standard Mean Ocean Water' ('SMOW').

Results

Data obtained during the three surveys are gathered in Table 2. Analysis of these data showed a spatial heterogeneity of the Ebrié lagoon surface waters. Furthermore, comparative analysis of ionic and isotopic composition of each survey indicated net differences between areas characterized by a great seasonal variability and more stable areas.

Good correlations between Cl^{-1} and K^{2+} concentrations were observed during the three surveys with a dry season slope significatively different from those obtained during the period of the freshwater input (Fig. 4). Moreover, the correlation coefficient between Cl^{-1} and K^{2+} slightly decreased with increasing of the amount of freshwater input ($r = 0.99$, $N = 49$ in May; $r = 0.97$, $N = 58$ in December and $r = 0.93$, $N = 28$ in October).

Depending on season, the lagoon either received marine water or continental water. However, these two sources entered the lagoon through different areas. Water near the inputs zones are hydrochemically variable. The importance of this variability decreased with increasing distance from the input zones. Figures 5, 6 and 7, displaying isotopic composition in relation to Cl^{-1} concentrations (considered as a tracer of saltwater) for the three surveys, illustrates this hydrochemical variability in relation to the sampling sites. In these figures, stations are mainly distributed according to two axes (TML, EA). The first axis corresponded to the Theoretical Mixing Line (TML) between the two types of waters (marine and fresh waters) entering the lagoon. A sample of seawater collected offshore (station 27) during the dry season (December 1987) was used as reference for marine water. The isotopic composition and Cl^{-1} concentration of this sample of seawater were + 0.47‰ and 522 meq l^{-1} respectively. For the freshwater, the reference value of Cl^{-1} concentration was taken as zero; while two values were chosen for ^{18}O contents with regard to season. In May and December, since the total amount of rainfall was less than that of the evaporation (Tables 1a and 1b), freshwater discharge was essentially due to the Comoé river. Hence, calculated mean isotopic value (equaled to −2‰) of this river was considered. In October, mean isotopic composition of rainwater was estimated from the measurement of the isotopic composition of the groundwater and is equaled to −3‰. This value is in accordance with the one defined by IAEA for this climatic zone (Forstel et al., 1975) and also corresponds to the measured isotopic composition of Comoé river during the peak flow period. From these reference data, the theoretical mixing lines were calculated for the three surveys (Figs 5, 6, 7).

The second axis corresponds to a rough fitted line and concerns low mineralization waters. These were mainly of continental origin and present a large set of isotopic compositions. The isotopic compositions ranged from freshwater characteristic values to values greater than those of marine waters. Therefore, the second axis was representative of waters which were not directly under the influence of marine inputs, but which were more or less evaporated. The second axis actually corresponded to the Evaporation Axis (EA).

Table 2. Ionic and isotopic data of subsurface waters of the Ebrié Lagoon in May and October 1986 and December 1987 (Cl^{-1} and K^{1+} expressed in meq l^{-1}).

St	May 1986					October 1986				December 1987				
	Sal.	pH	$\delta^{18}O$	Cl^{-1}	K^{1+}	Sal.	$\delta^{18}O$	Cl^{-1}	K^{1+}	Sal.	pH	$\delta^{15}O$	Cl^{-1}	k^{1+}
1	6.00	7.30	0.54	84.39	3.29	1.50	−1.42	23.52	0.52	9.00	7.60	0.61	78.40	2.24
2	6.50	6.90		81.76	3.29	4.50	0.14	64.96	1.30	5.00	6.60	0.77	75.60	2.18
3	4.50	7.60	0.67	57.12	2.60	3.00	−0.35	43.12	0.91	4.00	7.90	0.12	56.70	1.72
4	3.50	7.50	0.31	43.68	1.91	2.50	−0.44	33.60	0.65	3.00	8.10	−0.36	40.60	1.40
5										4.50	7.35	0.42	63.70	1.92
6	6.50	6.65	1.31	88.48	3.55	5.00	0.64	78.40	1.47	5.20	6.60	0.90	77.00	2.18
7	6.50	8.35	1.20	86.24	3.38	4.50	−0.01	63.84	1.17					
8						5.50	0.80	81.20	1.69	5.00	6.70	0.39	66.50	1.98
9	6.50	7.75	0.85	89.60	3.38	5.00	0.88	73.92	1.30	5.00	7.60	0.91	72.10	2.03
10	7.00	8.70	1.05	98.56	3.90	6.00	0.86	82.88	1.69	5.50	7.85	0.84	81.20	2.24
11	6.50	8.50	0.22	82.88	3.38	5.00	0.71	79.52	1.47	5.00	7.70	0.64	76.30	2.18
12										5.00	7.70	0.80	77.00	2.18
13	7.50	6.95	0.38	103.04	4.16	6.00	0.89	87.36	1.69	4.00	7.20	0.02	54.60	1.77
14	1.50	6.30	−2.19	19.04	0.16	3.00	−1.35	44.80	0.91	1.50	6.50	−1.39	18.20	0.73
15						4.00	−0.53	60.48	1.17	2.50	7.65	−0.62	32.90	1.30
16	11.50	7.30	0.58	172.48	5.63	6.00	−0.01	85.68	1.82	3.50	7.05	−0.60	43.40	1.56
17										4.00	7.00	−0.66	58.10	1.82
18	16.00	8.00	0.14	220.64	7.54	6.00	0.46	88.48	1.82	7.50	7.10	−0.51	109.20	2.96
19	21.50	8.10	0.11	286.72	9.88	7.00	0.24	96.88	2.47	9.70	7.25	−0.52	156.80	4.00
20	30.00	8.10	0.32	436.80	15.60	9.00	−1.99	133.00	2.60	17.00	7.65	−0.04	352.80	8.22
21	30.50	8.10	0.40	441.28	15.08	9.00	−2.13	129.50	2.60					
22										11.00	7.25	−0.44	190.40	4.37
23	7.00	7.00	−1.49	112.00	4.16						7.25	−0.44	190.40	4.37
24	26.50	8.50	0.34	392.00	13.86					17.00	7.65	−0.51	344.40	6.86
25	26.00	8.10	0.73	380.80	13.00	5.50	−2.20	84.00	1.69	17.00	7.70	−0.49	302.40	7.28
26	26.00	8.40	0.53	380.80	13.86	6.50	−2.49	98.00	1.82	16.50	7.50	−0.26	313.60	7.18
27	29.00	8.25	0.41	421.12	15.08	7.50	−2.24	114.10	1.95	16.00	7.91	−0.12	327.00	7.28
28										17.50	7.80	−0.12	364.00	7.80
29										34.00	8.00	0.47	522.00	12.90
30	25.00	8.20	0.19	374.08	12.48					16.00	8.20	−0.50	193.20	4.94
31	25.00	8.05	0.45	369.60	12.66	2.00	−2.61	32.48	0.52		8.20	−0.50	193.20	4.94
32	25.00	8.05	0.49	380.80	13.00					14.00	7.50	−0.74	282.80	4.68
33						7.00	−1.95	100.10	1.95	16.00	7.85	−0.37	296.80	6.14
34	27.00	8.55	0.43	403.20	14.22	8.00	−2.28	103.60	2.86	14.00	7.85	−0.58	246.40	5.25
35	21.00	8.00	0.15	315.84	10.23					11.50	8.10	−0.91	145.60	3.54
36	19.50	8.20	−0.43	286.72	9.27					11.50	7.95	−0.92	148.40	4.68
37	25.00	8.05	0.43	365.12	13.52	0.00	−2.58	3.92	0.18		7.95	−0.92	148.40	4.68
38	16.50	7.95	0.21	244.16	8.23					10.50	7.60	−1.11	187.60	4.32
39	17.00	7.95	−0.01	246.40	8.23	0.00	−2.40	1.85	0.09	10.50	7.35	−1.19	190.40	4.42
40	19.50	8.25	−0.03	282.24	9.00	0.00	−3.06	8.40	0.26	9.00	7.85	−1.17	179.20	3.54
41	19.50	7.95	0.62	280.00	9.36	0.00	−0.08	8.40	0.26	9.00	7.45	−1.04	142.80	3.80
42	15.50	7.70	−0.37	228.48	7.45					10.50	7.45	−0.89	182.00	4.26
43	15.00	7.70	−0.09	221.76	7.45						7.45	−0.89	182.00	4.26
44	14.50	7.65	−0.18	212.80	7.11						7.45	−0.89	182.00	4.26
45	9.00	7.25	−0.58	134.40	4.77					11.00	7.30	−0.95	204.40	4.21
46	9.00	7.20	−0.76	90.72	3.47					9.00	7.30	−1.12	186.20	4.32
47	4.00	6.65	−0.20	58.24	2.17					4.00	6.85	−1.35	60.20	1.92
48	2.50	7.25	−0.53	29.12	0.97					2.50	6.80	−1.41	35.00	1.25
49	1.50	7.55	−0.81	16.80	0.60					2.00	6.70	−1.47	25.20	0.94
50	1.00	6.60	−0.88	13.44	0.48					1.50	6.75	−1.23	18.20	0.73
51	0.00	6.55	−1.54	4.76	0.22					0.00	6.90	−1.71	9.38	0.16
52	0.00	7.30	−0.66	6.44	0.25					0.00	6.45	−1.83	3.53	0.10
53	0.00	8.35	−0.36	5.88	0.23					0.00	6.75	−1.77	2.52	0.10
54										12.50	7.55	−1.10	200.00	4.94
55	3.50	6.95	−1.45	49.28	1.91					12.50	7.30	−1.20	224.00	4.94
56	2.00	6.65	−2.22	14.56	0.01					4.00	7.00	−1.95	56.70	1.77
57	0.00	5.30	−2.82	0.39	0.01					2.00	6.90	−2.23	53.20	0.88
58	0.00	5.20	−2.96	4.12	0.02					0.00	7.10	−2.51	0.00	0.02
59	0.00	5.10	−2.95	0.62	0.02					0.00	5.60	−2.48	0.00	0.02
60	0.00	5.90	−1.72	0.84	0.06					0.00	7.10	−2.35	11.62	0.21

At the end of the dry season, in May 1986, four types of water in the Ebrié lagoon can be identified (Fig. 5): (1) waters with high Cl^{-1} concentration and ^{18}O value close to the oceanic water reference data (group A); (2) water exclusively under freshwater influence and characterized by a very low salinity and depleted in ^{18}O (group C); (3) waters corresponding to a mixture of oceanic and fresh waters (group B); (4) oligohaline waters with a high ^{18}O concentration (group D). It is noteworthy to point out that waters of the group B have an intermediate salinity and ^{18}O values be-
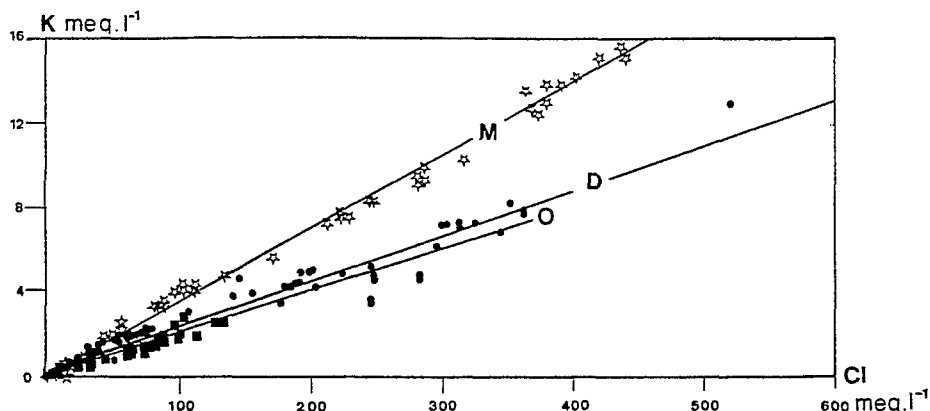
Fig. 4. Relation between of Cl^{-1} and K^{1+} concentrations expressed in meq l^{-1} during the three surveys.
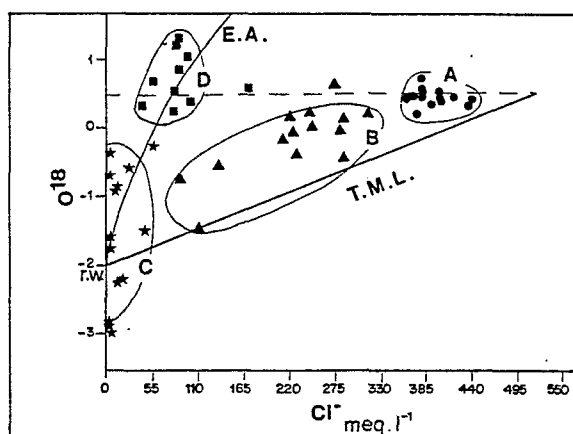

Fig. 5. Relationship between chloride concentration and oxygen-18 content of the Ebrié lagoon surface waters in May 1986. (T.M.L. Theoretical Mixing Line; E.A. Evaporation Axis).
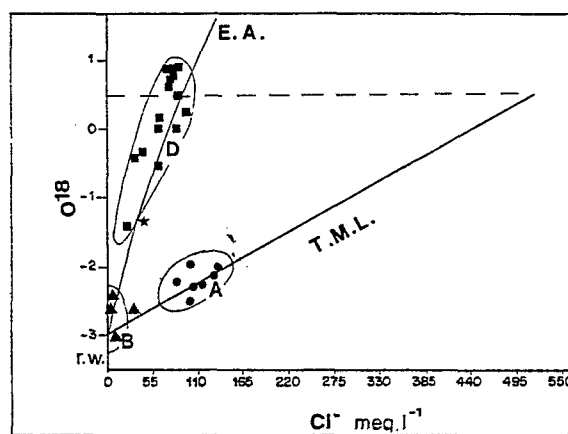

Fig. 6. Relationship between chloride concentration and oxygen-18 content of the Ebrié lagoon surface waters in October 1986. (T.M.L. Theoretical Mixing Line; E.A. Evaporation Axis).

tween those of freshwater (group C) and marine water (group A). Waters of this group were parallely distributed to the mixing line.

In December, at the beginning of the dry season (i.e. the period following the short rainy and flood seasons), another distribution of the waters was observed. Group A and B shifted toward group C along the theoretical mixing line (Fig. 7). For the group B, the difference between the observed and theoretical values was not significant. Thus, the proportion of the two water types in the mixture constituted the unique criteria allowing the differentiation of the group A and the group B.

The group C remained unchanged. Waters of

this group were, however, less dispersed and characterized by ionic and isotopic values very close to those of continental water reference data.

The group D, characterized by a less positive isotopic composition, spreaded along the evaporation axis, almost reaching the continental waters (group C). This showed a dilution effect caused by rainfall and river input during the short rainy season. In spite of this dilution effect, the group D always presented the highest isotopic value.

In October 1986, continental inputs (rainfall and river flood) are maximum. The different groups of waters described above continued their
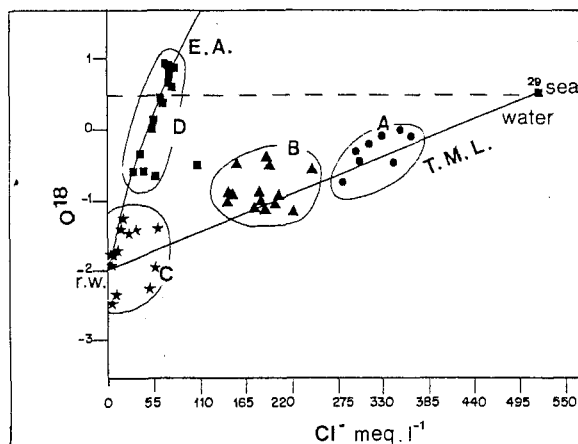
Fig. 7. Relationship between chloride concentration and oxygen-18 content of the Ebrié lagoon surface water in December 1987. (T.M.L. Theoretical Mixing Line; E.A. Evaporation Axis).

sliding along both the mixing and the evaporation lines (Fig. 6). The B and C groups formed an unique entity having the same isotopic and ionic compositions. The A group waters were highly diluted with freshwater. Waters representing this group were now located near the continental waters group on the theoretical mixing line. The D group remained isolated but extended a little more towards the continental waters.

Discussion

The different groups, constituted from chemical and isotopic composition of surface waters, correspond to four distinct geographical areas of the lagoon (Fig. 2).

The (A) group includes the stations of the estuarine area around the Vridi Canal. Waters from this area are a mixture of fresh and marine waters which, become alternatively, preponderant according to the seasons. This estuarine area appears as one of the part of the lagoon where most important variation occur during a full hydrological year. During a full year, the limits of this group are not geographically well defined, because they laterally move according to seasonal variations of freshwater and oceanic inputs.

The (B) group is formed by the stations located

to the east of the lagoon. During the wet season and the flood period, this area shows waters of typical continental origin. During the dry season, it is characterized by a mixture of marine and fresh waters.

The (D) group corresponds to the west part of the lagoon, off the Jacqueville dike. In this area, seasonal variations of different chemical and isotopic parameters remain relatively small.

The C group includes rivers mouths, and the Aghien, Potou and Ono lagoons which are far from being under marine water influence. All the year round, waters of this group are exclusively of continental origin.

During the December 1987 survey, stations located in the Ebrié lagoon estuarine zone (Group A and B) are characterized by a chemical and an isotopic compositions very close to the mixing line. This shows these waters are simple mixture of oceanic and continental inputs. During low-water flow period (May 1986), these stations reveal a more oceanic character (high Cl^{-1} concentration) and tend to depart from the theoretical mixing line. This is related to an isotopic enrichment by evaporation. Moreover, the evaporation is especially marked when the bays are confined. For example, the shift between observed and theoretical values is + 0.95‰ for the station 38 and + 0.55 for stations 35 and 40 (Fig. 2). During low-water flow (May 1986), waters of the urban zone of Abidjan (group A) show ionic and isotopic compositions very similar to those of seawater. During the river flow and rainy season (October 1986), these waters are largely diluted by freshwater entering the lagoon. In Fig. 6, these waters are exactly on the theoretical mixing line. This typically estuarine zone is thus characterized by a high hydrodynamic instability, hindering the process of the isotopic enrichment by evaporation.

Continental waters (Group C) of the east side of the Ebrié lagoon (Potou, Aghien and Ono lagoons) are characterized by low and constant ionic concentrations. In December, Aghien and Potou lagoons present a relative isotopic homogeneity with values ranging from −1.0 to 2.0‰, and close to those determined for rivers. On the

contrary, during low-water flow (i.e. in May), their isotopic compositions clearly differ from that of rivers, with, in particular, an isotopic enrichment due to an intense evaporation. Such a seasonal enrichment, occurring during the dry season, disappears during the peak flow period. Thus, this shows an important turnover rate of surface waters in these environments. Besides the peak flow periods, the Aghien and Potou lagoons are relatively stagnant. Ono lagoon waters (stations 58, 59 and 60) are acid and slightly mineralized (Guiral & Ferhi, 1989), and present a high isotopic and ionic stability. With an isotopic and ionic composition always lower than that of river waters, the Ono lagoon is in communication with the groundwater. The permanent renewal prevents the ^{18}O enrichment process by evaporation. Thus, the $\delta\ ^{18}O$ values obtained for Ono lagoon are constant and close to $-3‰$.

Stations near the new Bassam inlet are characterized by a high modification of their ionic charge. This is due to the creation of a new estuarine zone in the lagoon. The extension of this zone is very narrow during peak flow period. However, stations 56, 46 and 45, during that period, have much higher Cl^{-1} concentrations than those determined during low-water flow before the opening of the inlet.

In spite of the climatic variability of the southern region of the Ivory Coast (Durand & Chantraine, 1982), waters of the west side of the Jacqueville dyke (D group) present a high hydrochemical stability. Located far from the Vridi canal, this area does not receive any important river flow and is characterized by an isotopic composition always higher than that observed for oceanic waters. During the two surveys carried out under strong continental influence (October 1986 and December 1987), a decrease of oxygen-18 concentration is observed. In comparison with the low-water level period, the decrease in ^{18}O is more important for the stations located in the bays, because these stations are directly affected by runoff.

Waters between the Jacqueville dyke and the Vridi canal constitute a transition zone. In October, these are comparable with waters of the east

of the Vridi canal; while they become more estuarine during the low-water flow. This is due to seawater flowing into the lagoon through the Vridi canal. During the low-water level period, oceanic water penetration is necessary to maintain the hydrodynamic equilibrium between the lagoon and the open sea.

Oligohaline waters of the west side of the Jacqueville dyke, and the continental waters of the Aghien and Potou lagoons are both characterized by a high evaporation during the dry season. During periods of maximum precipitation and peak flow, continental waters are identical to rivers waters; while oligohaline waters are not modified. The Aghien and Potou lagoons are annually renewed. While, oligohaline waters are stable all the year round. Consequently, these waters are under the influence of an cumulative isotopic enrichment. Thus, it is possible to consider that major ions concentrations of these waters are also the result of evaporation. The hydrological budget, presented in Table 3b for 1986 and 1987, allows the calculation of the theoretical turnover rate. In 1986 and 1987, estimated values for the turnover rates are 0.00 and 0.18 respectively. In the present climatological conditions, the complete renewal of these waters occurs only every 11 years. According to Durand & Skubich (1982), this area is characterized by a high photosynthetic activity. The mean value of the photosynthetic production is the order of 2070 $gO_2\ m^{-2}\ year^{-1}$; while it is about 913 $gO_2\ m^{-2}\ year^{-1}$ in the estuarine area (eutrophic area under oceanic influence), and 543 $gO_2\ m^{-2}\ year^{-1}$ in the continental area (zone under river water influence). Such a high annual productivity is due to the stability of hydrochemical parameters. Furthermore, it depends upon

Table 3a. Morpho-metrical characteristics of the western zone of the Ebrié lagoon (Area located to the East of the Jacqueville dyke).

Surface of the water basin (km²)	Surface of the catchment area (km²)	Volume of the water basin (10^6 m³)
305	1200	1490

Table 3b. Water budget of the western zone of the Ebrié lagoon.

Year	**Rainfall on the water basin $(10^6 \, m^3)$	Runoff on the catchment area $(10^6 \, m^3)$	Evaporation $(10^6 \, m^3)$	Freshwater input $(10^6 \, m^3)$
1986	408	66	474	0
1987	617	99	443	273

** Deduced from rainfalls and multiplied by a runoff factor of 0.041.

the very high and permanent phytoplanktonic biomass (Dufour, 1984) constituted, at 90%, by Cyanobacteria (Iltis, 1984). From a biological point of view, the hydrochemical and hydrological stabilities can thus lead to an increase of the productivity of the environment. The high productivity is not only due to an increase of nutrients, but a strong utilization of these nutrients by primary producers (Durand & Skubich, 1982). Such an enrichment in which Cyanobacteria are involved has often been observed in the confined areas of many lagoons of the world (Guelorget & Perthuisot, 1983).

Conclusion

This study evidences the degree of hydrodynamical stability of different sectors of the Ebrié lagoon during an annual cycle; and also completes the previous work (Guiral & Ferhi, 1989) dealing with the static description of the hydrochemical characteristics of the Ebrié lagoon.

Located to the west side of the Jacqueville dyke, the group (D) is stable all year round and is not influenced by the ocean. The group (C), to the east of the lagoon, is annually renewed by waters of continental origin. The group (A) is situated close to the Vridi canal and corresponds to a typically estuarine zone. It is characterized by a high renewal frequency. Finally, the group (B) include stations with either continental or brackish waters during the year round. These waters present a weak hydrodynamics during the dry season.

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