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Hydrodynamics of the estuary of the lagoon Ebrié (Côte d'Ivoire)

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Abstract:
The estuarine bays of Abidjan are under severe anthropogenic pressure which alters the movement of water masses. In addition, these bays are showing signs of pollution. To better understand the processes that take place, morphobathymetric and dynamic approaches have been implemented. It appears that the morphology of estuarine bays is symmetrical about the central axis of the Ebrié lagoon. In narrow channels, the currents are only alternative. Current velocities in Cocody and Biétri Bays are described. The time evolution of water surface level, salinity and temperature are studied in the lagoon over days. Variations in salinity in the lagoon are related to continental and marine seasons and depend on heavy rains and river floods. It is the same for changes in water temperatures that vary according to rainfall and river flows.

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1. Introduction

An estuary is a coastal body of water partially enclosed with a free connection with the ocean and within which sea water is measurably diluted by freshwater derived from continental runoff (PRITCHARD, 1967). It is therefore the privileged environmental transition between continental and oceanic areas. PERILLO (1995) complete this definition by using the limits of the dynamic action of the tide upstream, indicating that sea water can penetrate through one or more arms open to the marine area. Estuaries and coastal areas represent a growing scientific interest based on their socio-economic impact (60% of the world population lives less than 60 km from coastline).

In West Africa, the estuary of the Ebrié lagoon (Côte d'Ivoire) is separated from the Atlantic Ocean by a sandy string crossed artificially, since 1950, through the Vridi channel. The bays of this estuary are relatively renewed since the opening of this channel (figure 1). The contributions of inland waters are formed, for two thirds, of the Comoé river. The volume of its flood, contributes to a strong annual variability (GUIRAL & DURAND, 1994).

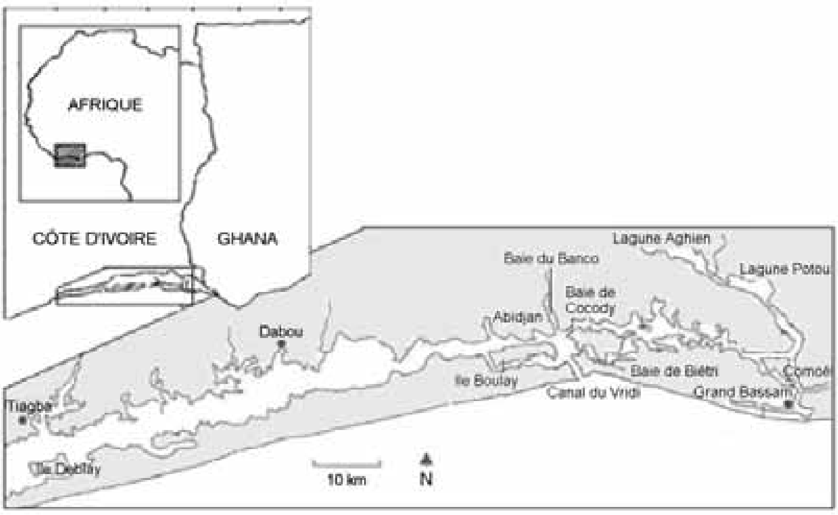

Figure 1. The lagoon and bays Ebrié estuarine Abidjan.

Estuarine bays of Abidjan are under pressure because of growing human activities since the last century. These environments are confined to major points of completion of the sewer of Abidjan. In addition, development of port activities, industrial and demographic growth of Abidjan induce the inevitable pressures on the environment. There is also road construction that requires the creation of culverts, dikes as in Koumassi and Bietri bays (figure 2). These could undoubtedly have an impact of human activities on the water circulation in the estuary.

This paper discusses the effects of natural and anthropogenic forcings on the estuary. This morphohydrodynamic approach of the estuary of Ebrié lagoon attached to the study of water circulation in the lagoon and characterization of exchange with neighboring environments.

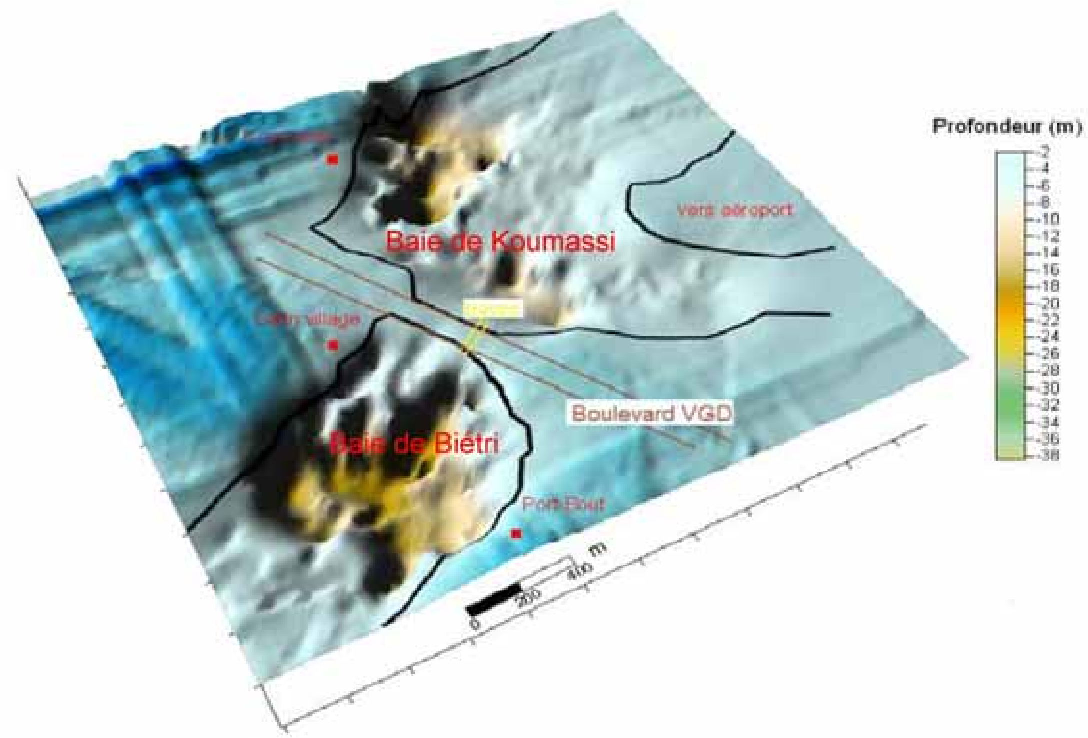

Figure 2. Landform numerical model of Bietry and Koumassi bays (Profondeur=Depth).

2. Methodology

The XYZ data (longitude, latitude and depth) of echo sounding (PAA, 1999) are exported to mapping software (Surfer) in order to produce some bathymetrics maps.

A DCM12 Type Doppler Current Meter (Aanderaa) has been used to determine the flow velocity in the water column at different depths during a tidal cycle. In addition, this current meter gives the variation of water level and the current direction in real time. Flood velocities are given positive sign, and ebb velocities negative sign.

OBS-3A have been used for the acquisition of hydrodynamic data in the port of Abidjan over a period of 20 months. It is equipped with sensors whose thresholds have been predefined (table 1) according to the hydrology of the Ebrié lagoon. The time step of measurement is 300 seconds. This represents 4320 data for 15 days (corresponding to the battery power of OBS-3A). It remains less than the real amount of data that the sounder can record (6640 data). Nevertheless, this allows acquiring 65% of data (4320 data). It is a balance between representativeness and the amount of sample to be treated. In addition, daily average and twice-monthly of water level, salinity and temperature, were determined by the conventional arithmetic method. For this calculation, a sampling interval of 1 data per 10 min was taken.

Table 1. Configuration parameters and uncertainties of sensors OBS-3A.

Sensors	***Thresholds***	***Uncertainties***
Turbidity	*NTU*	*2%*
Temperature	*20°C*	*±0,0075°C*
Pressure	*dBars*	*±0,2%*
Salinity	*0 PSU*	*±0,1 PSU*

3. Results and discussion

3.1 Bathymetric map of estuary of the Ebrié lagoon

The estuary has an average depth of 5 m, which makes it a shallow environment. Major structures have been observed in the central basin with a particular morphology. These morphostructures (figure 3) observed at the South channel Island Boulay (M1) and near the docks (South and North) from the port of Abidjan (M2 and M3). The morphostructures M2 (shoal) and M3 (depression) have a N180° direction and are located in the main navigation channel (table 2). Moreover, steep slopes are located near the docks and the lowest in the navigation channel (MONDE, 2004). This area is often dredged to facilitate maritime traffic.

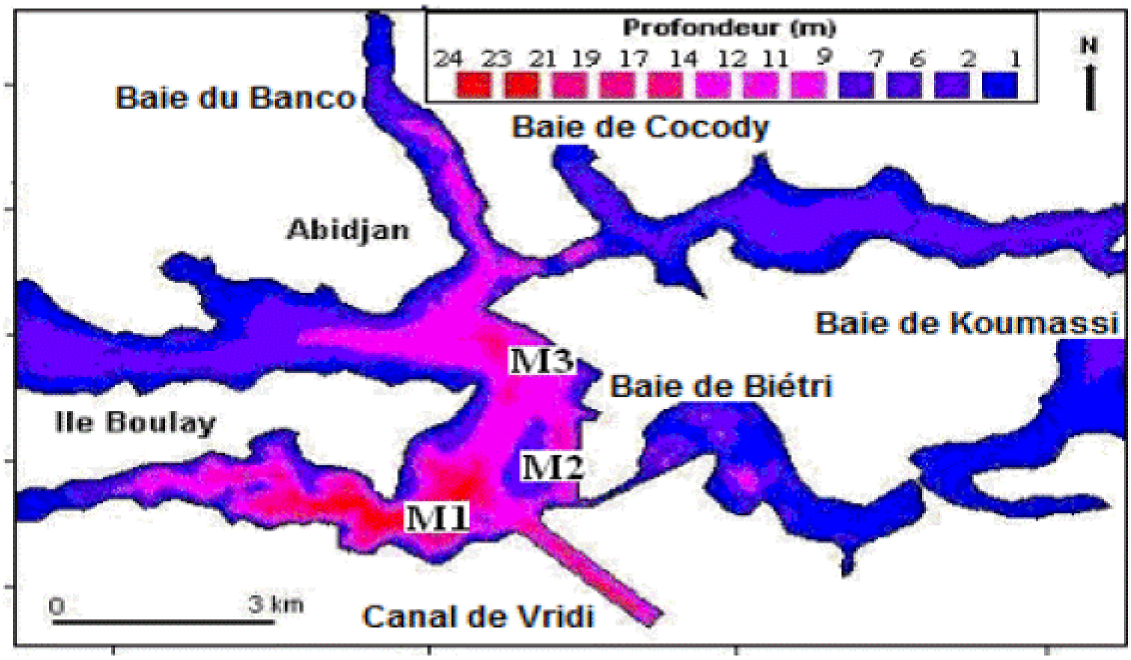

Figure 3. Morphostructures (M) in the channels of the Ebrié lagoon (Profondeur=Depth).

Table 2. Characteristics of some morphostructures in Ebrié lagoon.

	M1	***M2***	***M3***
Length (km)	*1,65*	*1,65*	*1,55*
Width (km)	*0,2*	*0,3*	*0,2 – 0,8*
Depth (m)	*4,75*	*2,35*	*4,70*

3.2 Morphobathymetry and water circulation in the bays

Analysis of morphobathymetric and water circulation will focus on two bays of Abidjan which are not only the overflow of domestic waste but also are subject to intense industrial activities (companies of fairings, metal recycling, stains, etc.).

3.2.1 Bay of Cocody

The central channel of the bay intersects perpendicularly the main channel of the Ebrié lagoon. The depths are low in the bay (0.5 to 3.5 m), except at the confluence with the lagoon, where there is a pit of -5 m (figure 4). The slopes analysis shows areas of steep slopes (3.5%) and low slopes (at the South shore, 1.75%).

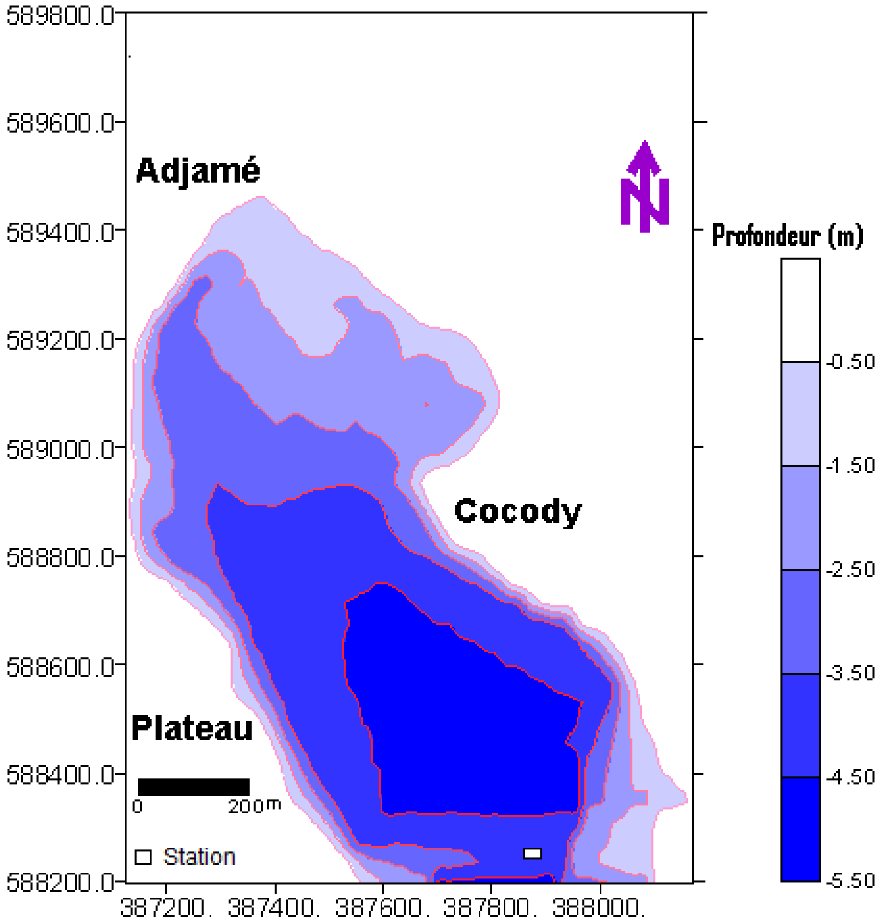

Figure 4. Bathymetric map of Cocody bay (projection UTM 30N), (Profondeur=Depth).

Figure 5 shows the temporal variation of current velocities with depth. The flood reaches its maximum in the water column surface at a speed of 0.42 m s^{-1}. In the depth (3.6 m), the speed reaches 0.50 m s^{-1}. The maximum speed of the ebb tide is 0.72 m s^{-1} (surface) and 0.68 m s^{-1} (depth). The ebb and flood have the same duration (6 h). The evolution of velocities of surface and bottom is similar. The speeds are less than 1 m s^{-1}. However, tidal currents increase gradually. In fact, they vary from 0.1 to 0.5 m s^{-1} during the flood (between 0 and 3.66 m deep) and from -0.10 to -0.60 m s^{-1} during the ebb. They reach a maximum at half-flow period (0.50 m s^{-1} for the flood current) and decreases until the fall (-0.6 m s^{-1} for the ebb tide). These variations are observed from the surface (0 m) to the bottom (3.66 m).
Currents directions in the bay of Cocody are shown in figure 6. Velocities vectors are almost aligned (ENE direction during flood and WSW in ebb), which suggest the presence of a channel.

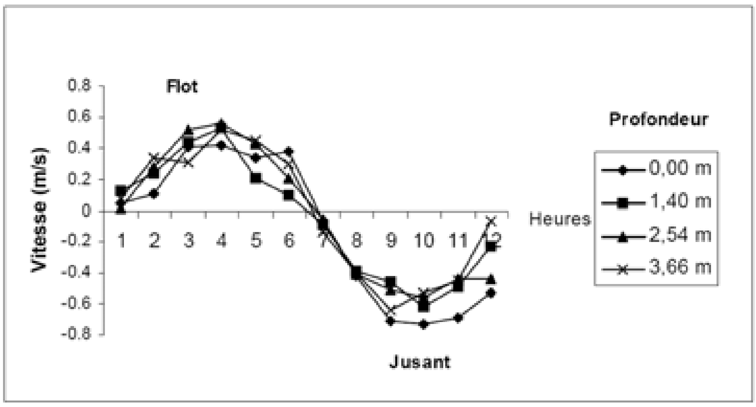

Figure 5. Temporal evolution of current speeds in the Cocody bay.

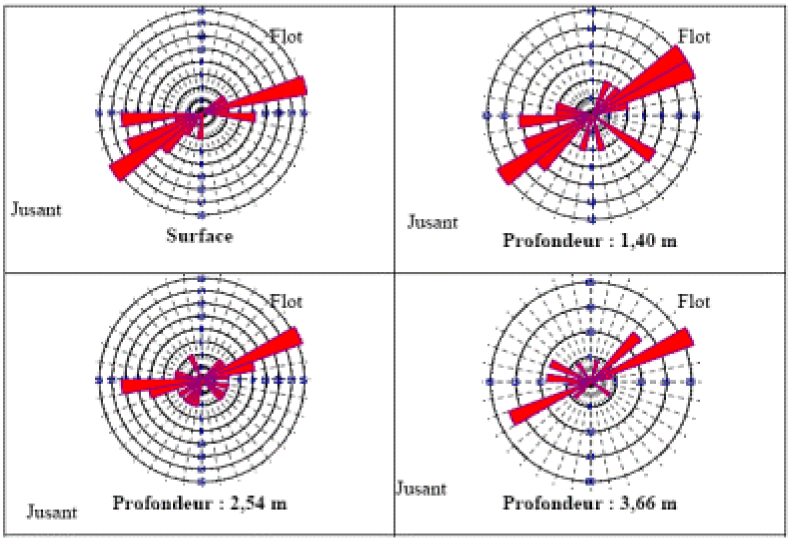

Figure 6. Currents directions in the bay of Cocody (Profondeur=Depth; Flot=Flood, Jusant=Ebb; Vitesse=Velocity).

3.2.2 Bietri bay

The bay shows different channels. The southern branch is deeper (>10 m) and joins the northern branch which has a curved shape. Depressions, with slopes ranging from 1.75 to 5%, were observed at the bottom of the bay. They could be explained by the bottom dredging (figure 7).

The flood has a maximum speed at a depth of -8.3 m (figure 8). The ebb lasts 1 h over the flood. The maximum ebb is observed at depth (8.3 m) with a speed of 0.70 m s^{-1}. There is a change in speed between bottom and surface currents. Close to the bottom, currents are always gyratories (figure 9).

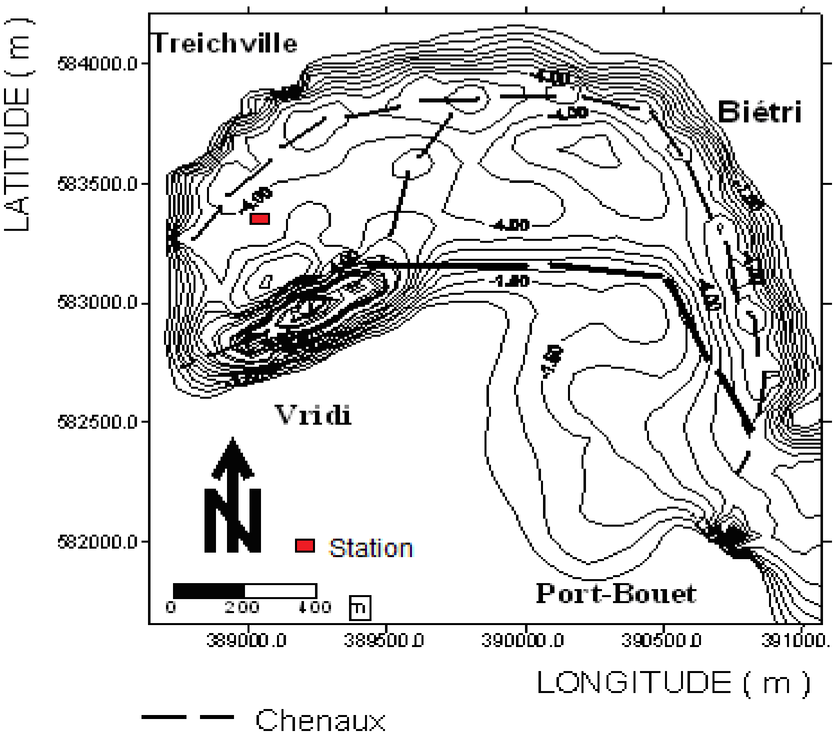

Figure 7. Bathymetric map of Bietry bay (projection UTM 30N).

Buzzards have been created between the bays of Koumassi and Bietri during the construction of the dam which was built on a road (Boulevard VGE, connecting downtown to the outskirts of Abidjan, see figure 2). Ante and post nozzles courantological study (LEMASSON *et al.*; 1981; GUIRAL & LANUSSE, 1984) helped to assess the changing currents. They show a constant spatial distribution of currents. In addition, the current increase in intensity. They increase from 0.2 to 0.9 m s^{-1} and from 0 to 1.6 m s^{-1} respectively in the Western and Eastern bay area. The most intense current are located nearby Vridi channel and the lesser ones near buzzards. In the depth, currents are rotary and the waters are not renewed (figure 9) and show the impact of the pressure due to human activities, in the hydrodynamic evolution of Bietri bay (TASTET 1979; GALLARDO, 1978)

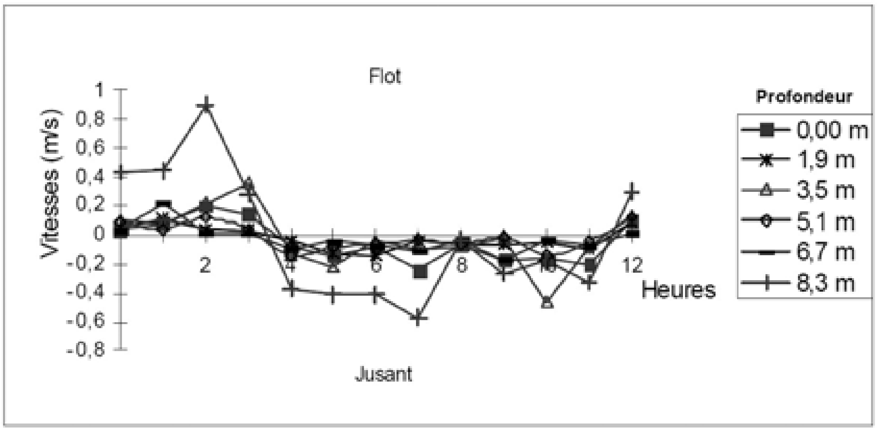

Figure 8. Velocities at spring tide in the bay of Bietri (Profondeur=Depth; Flot=Flood, Jusant=Ebb; Vitesse=Velocity; Heures=Hours).

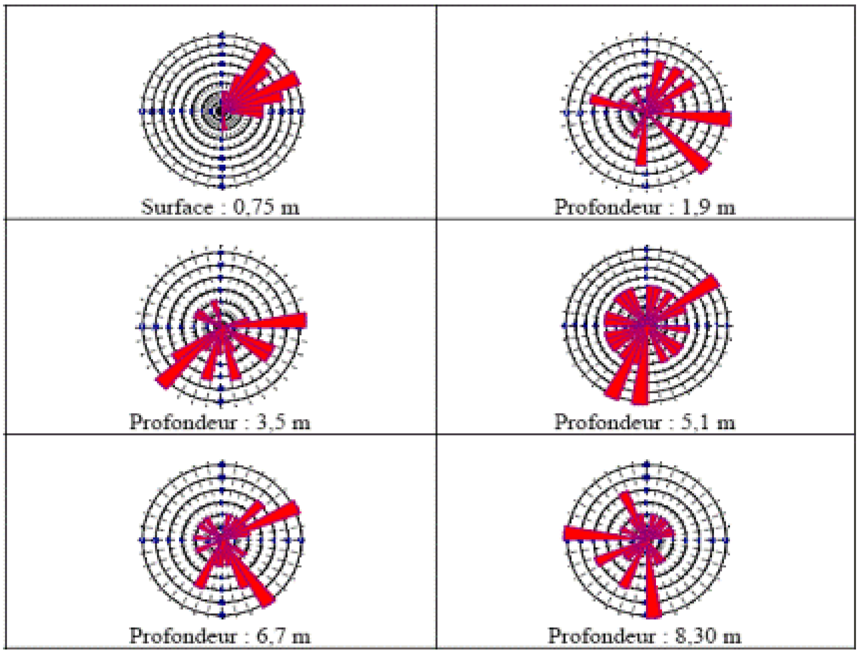

Figure 9. Frequencies of the current directions in the bay of Bietri (Profondeur=Depth).

3.3 <u>Hydrodynamics of the Ebrié lagoon</u>

3.3.1 Tidal range and depth of water

The analysis of variation in water surface level over 200 days, shows an average level of 1.01 m related to a local datum. The tidal range in spring tides varies from 0.55 to 0.80

m. In neap tide, the tidal range is smaller. It varies from 0.30 to 0.35 m. The ebb flow lasts eight days while the flood flow is shorter, it takes 7 days. The evolution curve of the average daily water level in Ebrié lagoon over 200 days has three domains (figure 10):

- From February to April (1st to 40th day), it starts from a relatively low level (0.95 m), reaches a maximum (1.05 m) and drops at a low height (0.90 m) after the 40th day. The height difference generated is 0.10 m.
- From April to June, the 40th day to 120th day, the curve is initially increasing and then it goes from 0.90 to 1.09 m after the 65th day. It stabilizes at this level until the 108th day before the value decreases to 1.00 m. The height difference is 0.15 m.
- The third area of the curve from the end of June to August is the 120th day 200th day. In this part, we observed an average level that goes from 1.05 to 1.07 m and then stabilizes at 1.06 m at the 160th day.

This curve shows a clear trend in the level of the lagoon. Water level presents anormal variations between the 70th (late April) and 80th days (early May). It is due to the premium occurred after river floods of Agnéby and La Mé (GUIRAL & DURAND, 1994). From February to June, the gradual rise in water level is linked to precipitation (transition period between rainy seasons on the mainland and lagoon) and contributions from La Mé and Agnéby. From June to August, the scarcity of rainfall induces the drop of the water level. Indeed, on the mainland, the short dry season begins during this period while the lagoon rainy season ends. The flood of Comoé allows elevated lagoon waters (0.10 to 0.50 m).

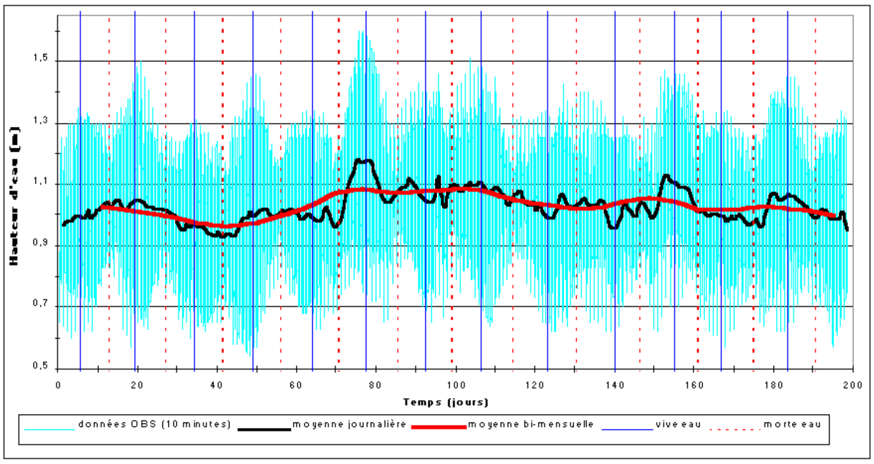

Figure 10. Evolution of water surface level over 200 days in Ebrié lagoon.

3.3.2 Salinity of the lagoon waters

The curve has an irregular shape (figure 11). It has three parts:

- From 0 to 65 days, the curve evolves in the maximum values of salinity (30.5 PSU). It increases gradually to a maximum of 30.5 PSU in the 22nd and then decreases to

16 PSU in 28th. In the range of 28 to 40 days, the salinity increases and decreases alternately to 10 PSU. Between the 40th and 64th day, it oscillates between the values of 17 to 25.5 PSU before reaching a relatively low rate of 6 PSU the 64th day.

- From the 64th to the 130th days, the shape of the curve evolves in the mean values of salinity. It oscillates between 5 and 16 PSU before falling to 6 PSU at 130th day. In this second part of the curve, the maximum of the salinity (16 PSU) is reached and the minimum is 5 PSU.
- From day 130 to day 200, the shape of the curve evolves in the lower salinity. It varies between 2 PSU (the minimum) and 6 PSU, the maximum rate.

Salinity evolution in the lagoon is similar to a "stair". Ivorian seasonal cycles (continental, lagoon and the marine) are responsible for these variations. The first level (February-April) is the highest. The high salinity is due to the lack of precipitation (dry season), low river flows (low flow of Comoé) and marine subsidies (high salinity marine season). The second level is observed from April to August. Salinity is low not only because of the abundant rainfall but also it is the flood period of Agnéby and La Mé. This final step corresponds to the great rainfall and to the flood period of Comoé which are characterized by a lower salinity (MONDE, 2004; GIRARD *et al.*, 1971; BRENON *et al.*, 2004). These results confirm the impact of rainfall and river flows (floods and low flows of streams and rivers) on the salinity of the lagoon. Indeed, heavy rains and flooding rivers reduce the salinity of their inputs (continental runoff, high water flows, etc.) in lagoon area. Scarce rainfall and low water levels of rivers increase the salinity.

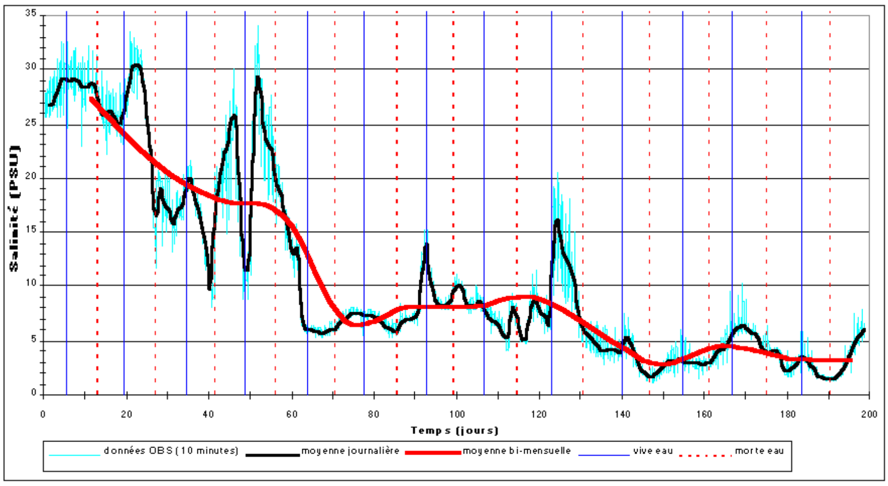

Figure 11. Salinity in Ebrié lagoon.

3.3.3 Changes in temperature

Figure 12 shows the evolution of the average daily temperatures in Ebrié lagoon. The curve shape is generally irregular. It is divided into three areas:

- 0 to 60 days, the shape of the curve evolves in an area of average temperature. She vacillates between the values of 27.5°C at values above 29.5°C.
- From day 60 to day 140, the curve reaches the maximum temperature above 30.5°C. At day 60 to day 125, the shape of the curve increase and decrease, respectively, between 28.5 and 30.5°C. At the 125th day, it decreases to below 27.5°C.
- From day 140 to day 200, the low temperature evolves between 25, 5 and 28.5°C.

The temperature increases during the first level where it spends 28 to 30.5°C. This increase is due to dry seasons. During these periods rainfall are low and the inflows of Comoé is almost nil (low water period). In the second area, the curve is decreasing. This temperature drop is due to abundant rainfall and flood of La Mé and Agnéby. The last level shows a monotonous evolution. The range of temperatures is between 26 and 27°C. This level extends from mid-July to August. The lower temperature is linked to heavy rains and flooding of Comoé (MONDE, 2004).

Besides the river inputs, the sea contributes to changing temperatures (GUIRAL & DURAND, 1994; ELDIN, 1971; PAGE *et al.*, 1979; ARFI *et al.*, 1989; AFFIAN, 2003). Indeed, in mid-March and mid-June, Southwest winds cross the Equator. They reach Côte d'Ivoire and generate the Monsoon (marine wind). These wind generators are scheduled to lift cold water upwelling to the surface. In July, the Monsoon moves to the North of the country. The rains stops, the winds and the upwelling are stabilizing. During the upwelling, deep water is taking place. After this period, the Guinean waters spread along the ivorian coast which is thus bathed in the warm waters of about 28°C (MORLIERE & REBERT, 1972).

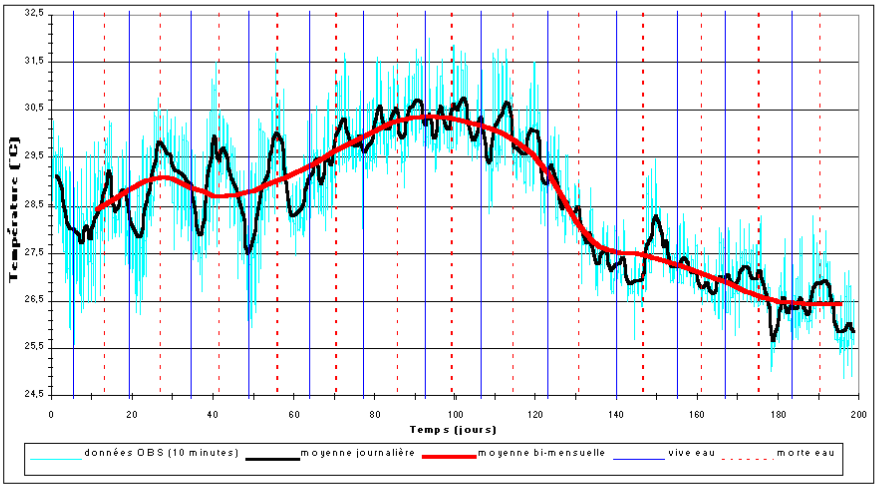

Figure 12. Ebrié lagoon temperature at different frequencies.

4. Conclusion

The Ebrié lagoon has a channel of -12 m with many morphostructures. The dynamic of the estuarine bays is very complex. The ebb predominates on the flood both in duration and intensity allowing the renewal of lagoon waters. In the bays, the currents are alternating in narrow channels and circulatory in large areas. For example, in the bay of Cocody the current velocities are proportional to the speed of the wave in a semidiurnal tide. In the bay of Bietri, the alternate character does not appear, because of its confinement and intensive industrial development.

The hydrodynamics of estuarine bays shows that the variation of salinity fits the seasonal cycles. But heavy rains and flooding rivers reduce it. Water temperatures rise in the lagoon during low rainfall and low water of Comoé. The drop in temperature in turn is due to abundant rainfall and river flows.

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