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Morphology and hydrology of an equatorial coastal swamp: Example of the Sarcelle swamp in French Guiana

ABSTRACT

The study of aerial photographs and remote sensing documents brings into relief vast amphibious spaces on the coast of the Guianas, which constitute a major feature of the Holocene coastal plain. Generally situated behind the mangrove sea front, these marshy areas are intersected by savannas and crossed by sandy ridges. By their position, the nature of their sediments, the morphological and hydrological dynamics, and by the quality of the soils, these areas constitute a privileged zone of action of marine and mainland processes, to which the evolution of these hydromorphic spaces is linked.

After a brief presentation of the physical setting of the Sarcelle swamp, the morphological analysis is approached with emphasis on its composing unities. As an indispensable complement to this approach, it will be seen how the study of the hydrological mechanisms illustrates in this context an original scenario of dynamic phenomena, to a time scale comprised between the marine and the seasonal cycles.

Two distinct unities are apparent:

- Firstly, with tide channels and mangrove, under the dynamic action of the sea and evolving to the rhythm of the ocean: semidiurnal tide and cycle between two syzygies.
- Secondly, with vast depressions and low marsh vegetation, mainly under the action of rainfall and evaporation.

This article describes the present functioning conditions of these two domains, with regard to the marine and seasonal rhythms which govern them. Then the "quality" of the limit separating these two zones will be studied, from the point of view of the mechanism of exchange between brackish and sea water, then from the aspect of the quality of the waters and their transformation according to the seasons.

RESUMEN

El estudio de fotografías aéreas y documentos de sensores

remotos pone de relieve vastos espacios anfibios de la costa de las Guayanas, los cuales constituyen un rasgo mayor de la planicie costera holocena. Generalmente situada por detrás del manglar, éstas áreas pantanosas están intersectadas por sabanas y cruzadas por crestas arenosas. Por su posición, la naturaleza de sus sedimentos, la dinámica morfológica e hidrológica, y la calidad de los suelos, estas áreas constituyen una privilegiada zona de acción de procesos marinos y continentales, a los cuales la evolución de estos espacios hidromórficos está ligada. Luego de una breve presentación de los aspectos físicos del pantano Sarcelle, el análisis morfológico se intenta con énfasis en sus unidades componentes. Como un complemento indispensable a este enfoque, se verá cómo el estudio de los mecanismos hidrológicos ilustra en este contexto un escenario original de fenómenos dinámicos a una escala temporal compuesta entre los ciclos marino

- en primer lugar, con canales de marea y manglares, bajo la acción dinámica del mar y evolucionando al ritmo del océano: marea semidiurna y ciclo entre dos cizigias.
- en segundo lugar, con vastas depresiones y vegetación de marisma baja, principalmente bajo la acción de lluvia y evaporación.

Este artículo describe las condiciones de estos dos dominios con respecto a los ritmos que los gobiernan. La "calidad" de límite que los separa será estudiada, en lo que hace al mecanismo de intercambio entre aguas saladas y salobres , la calidad de las aguas y su transformación estacional.

INTRODUCTION

All along the 300 km Guiana coast, there exists an area of transition between the continental ecosystems and the oceanic domain covering over 1000 km2. These paralic environments are vast swamps of brackish or fresh water which have developed among the sandy ridge qualified as "ancient" bearing, the road and agglomerations and the shore. This zone, which is 3 to 4 km wide and composed of marine clays, consists of amphibious spaces covered with a herbaceous fresh water vegetation or with the sea-front mangrove which is mainly **Avicennia sp.**

The coastal lagoonal environment is in fact a combination of several morphological unities whose existence and relative extension are conditioned by coastal hydrodynamics and hydro-climatic conditions.

By uniting the viewpoints of two specialities - Geomorphology and Hydrology - we shall see how certain qualitative aspects of the functioning of these ecosystems can be brought into relief through the study of a coastal swamp situated in the region of Mana: the Sarcelle swamp (Figure 1).

A first study, carried out in 1972 by M. Rossignol, clearly showed the existence of two interdependent environments whose evolution seemed very sensitive to the oceanic conditions of the moment. The morphological description is completed by the collection of measurements **in situ** which show the permanence of the unities in a better known climatic and oceanic context while, at the same time, specify the physical magnitudes which animate them. Defining the nature and the quality of the channels, their functions and the hydrological "limits" of the "marine" and brackish water domains helps to understand the mechanisms of exchange between these environments and their relationship with the ocean.

From these observations we can formulate a rough outline of the qualitative function of the swamp and define, within the framework of the morphological evolution of the region, a "sensitivity" of these domains with regard to modifications, even minor ones, of certain thresholds. We shall then discuss the various evolutive aspects, already observed in the past or more recently, which this sub-coastal environment may present under certain conditions.

1 THE PHYSICAL SETTING

1.1 Climatic conditions

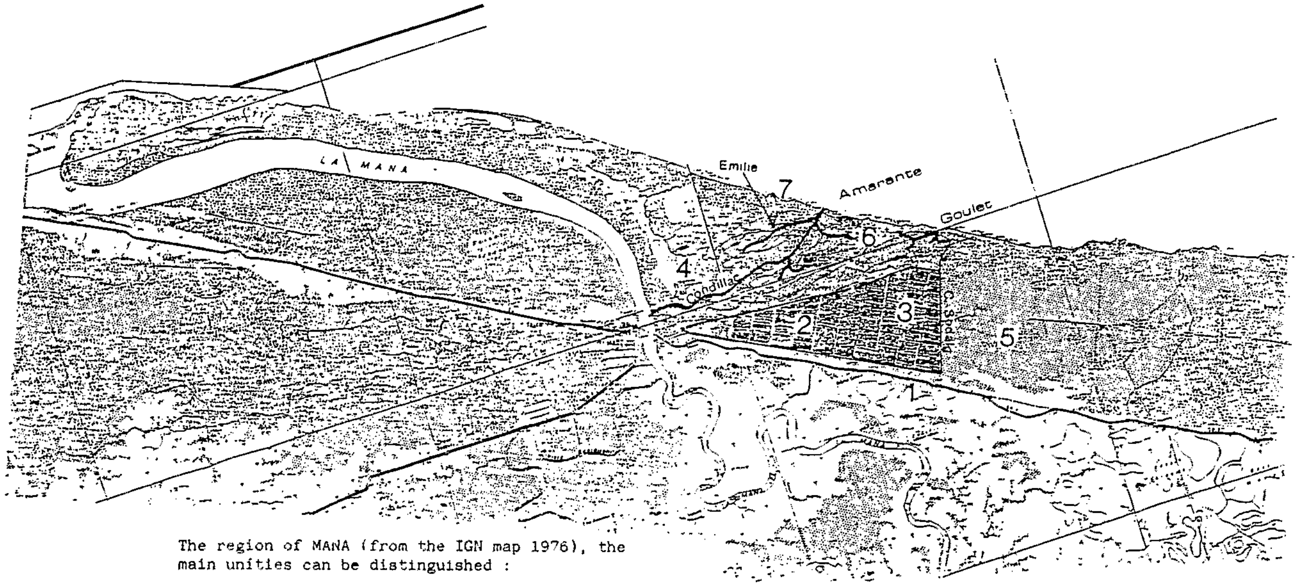
French Guiana, situated in the equatorial zone of the northern hemisphere (latitude 2 to 5°), comes under the influence of the atmospheric circulation of a general east-westerly direction. The territory is thus alternately affected by north-east or south-east trade winds according to the time of the year. The place of these two trade winds (the intertropical zone of convergence) moves up from the south towards the north from April until July and moves down in December and January towards the southern hemisphere, giving rise to frequent and violent showers. Two rainy seasons are observed, the more abundant being in May, as can be seen from the observation of the flow of the rivers.

The average temperature is 26° and remains fairly constant during the year with daily variations of air temperature between 22 and 32°C.

The average humidity on the coast is 85% and the average of the maxima and minima is about 70%. During the year, the lowest humidity is recorded in October. This period corresponds to the "dry season" and the lowest water level for all waterways.

The cloud cover is average (5,1 octas) close to that observed in the Antilles islands (Martinique 4,4 octas); there is therefore a long period of sunshine, which gives rise to considerable evaporation in the stretches of water on the coastal swamps and an increase of the temperature of shallower waters (as high as 35-37°).

The region of Mana-St Laurent presents a certain originality



The region of MANA (from the IGN map 1976), the main unities can be distinguished :

1- The "ancient" sandy bar bearing the road CD 8
2- The ricefield of the Sarcelle savanna
3- The "recent" sandy bar
4- The brackish swamp to the north of the ricefield
5- The freshwater swamp to the east
6- The seafront mangrove
7- Beach and present bar

Scale.
0 1 2 3 km

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Figure 1.

with more contrasted climatic conditions. It is the only sector of the Guianese coast where evaporation values are so high, about 900 mm/year (average value for Guiana 300 to 400 mm/ year).

The average amount of sunshine is 2100 hours/year (5,8 hours per day, and the wind conditions are stable with easterly to north-easterly winds of annual average speed of 2,5 m/s. Thus, without high winds and even less the violent tornados which occur in the Caribbean, this zone has a remarkable wind regularity. These conditions are important for the understanding of the seasonal and annual evolution of these coastal environments.

Another important factor is the rainfall, which is much lower in the region of Mana than in the other coastal regions. The interannual average is 1900 mm. The monthly maximum is in May and the two annual minima (more accentuated) in March and October. The spacial distribution of the rains is homogeneous during these two periods of high rainfall.

A more stormy period follows them with a much more heterogeneous spacial distribution during the "dry" seasons.

The climate of the region of Mana thus appears to be original not only for the whole of the Guianese littoral, but also for an equatorial region. The climatic conditions resemble those described by Marius et al . (1985) for Gabon. We shall see now the particular evolution of the interior landscape of the swamp in this type of climate.

1.2 The waters of Guiana

Analyses of the water show an identical chemical composition for the great rivers which cross the country. The ion concentrations are always fairly stable. Sodium and chlorine represent 70% of the global ion content which is on average 10 mg/l. The other ions (Mg++, Ca++, K+, Fe^{3+}, SO_4^{--}, NO_3^-) do not represent more than 1 mg/l in concentration.

Generally, these values are constant over the whole year.

The quantity of silica in solution is relatively constant with an average strength of 10 mg/l.

Thus it can be seen that the water is low in minerals, and the load in suspension is extremely low (less than 10 mg/l).

Measurements taken on the Sinnamary river (6500 km2 of catchment area and 260 m3/s annual module) show that 123000 tons of sediment are transported per year, (Fritsch, 1984), which, if spread over the entire surface of the estuary would form a deposit 1 to 2 cm thick.

The pH of river water measured in situ, on the Maroni, the Mana, the Sinnamary and the Approuague is on average 6 pH units (Hydrologie yearbook of Guiana). These waters are therefore acid; their meeting-point in estuaries and near the coasts with sea-water constitutes a buffer environment (L.R. Lafond, 1967).

The mechanical energy developed by the rivers is insufficient to transport a large quantity of particles, and the estuary beds are flooded with silt of marine origin. The influence of the Amazone is thus preponderant (Jantet, 1982) in the origin of the elements which constitute the Guianese coast. The water velocity is low (less than 1 m/s on average) as well as the slopes (0,03 m/km) and consequently numerous meanders have been formed. The main influence of this fluvial water is the dilution of the sea water, especially in the rainy season, thus considerably lowering the salinity.

On a scale of kilometres, these phenomena, which extend over the whole length of the coast, may or may not be tuned to the evolution of sub-coastal stretches of water. In the region of Mana, as we have seen, the rainfall is "low" and the evaporation high; thus, a new element comes into the sub-littoral context - the filling-in of these zones by ocean tides with sea water in the dry season and brackish in the rainy season.

1.3 The ocean environment

The marine current flows from west to east, and the coast also comes under the action of waves of direction north-east and amplitude 0,4 to 1,4 m (Demera coastal inv., 1962) as well as the mechanic action of the tide which has an average amplitude of 2 metres. The tide is of the semi-diurnal type and keeps its properties along the whole littoral.

Not far from the mouth of the small outlets of the Mana swamp, chemical measurements taken at sea show, compared with the average composition of sea-water (Sverdrup et al .), the following characteristics:

- A pH of over 7 units
- A ratio Na + K / Ca + Mg, oscillating around 5,6 to 6,6 for measures taken over seven months. This shows that, at first view, the sea water keeps its properties and is diluted by fresh water from the rivers.
- The dilution is maximal in June, i.e. during the rainy season, and the NaCl content may decrease to 60% of the nominal values. However, from September to November, a slight over-salinity can be seen (105% of reference analyses). This phenomenon is considerably less important than the dilution and most certainly due to the evaporation of sea water in shallow parts, near the coast, during the dry season.

1.4 The main morphological features of the Mana swamp

A diagrammatic section (Figure 2) orientated south-north shows the following unities:

- a sandy ridge (ancient) consisting of fine yellowish sand,

covered by mixed dense forest.
- a fresh water swamp, with mangrove vegetation consisting of **Typhaceae, Graminaceae,** ferns and shrubs. The soil is composed of de-salted marine clays. This area was chosen for the implantation of rice fields.
- the offshore bar (recent) with coarse sand: this unity constitutes a separation between the fresh water, marshy water-meadows and the brackish coastal swamps.
- a brackish swamp, shallow and partially covered by mangrove on its northern boundaries, (5 to 30 cm of water). The vegetation is mainly composed of lemna, seaweed (ruppia in the rainy season) and mangrove.
- the present offshore bar, with coarse sands crossed by small effluents from the swamp and covered with young **Avicennia sp.**
- high and low mud flats covered by loose mud constantly moved by water currents, accretion and sedimentation. This is covered by shallow sea-water at high tide (20 to 50 cm) and extends up to two kilometres out of sea from the present offshore bar.

There exists a well-defined morphological sequence, established according to the sandy accumulations forming "ancient", "recent" or "present" bars, separating accumulations of fine sediments which correspond to the two areas of marsh-land.

2 HYDROLOGY OF THE MANA SWAMP

2.1 Characteristics

The Mana swamp or Sarcelle savanna is a vast area of 5600 hectares, 1000 of which are converted into irrigated rice-fields.

The swamp extends for 20 km in the east-west direction and 4 km from north to south.

Its natural limits are the right bank of the river Mana to the south and the "present" sandy bar marking the shoreline to the north. Since 1972, the construction of a canal, now incorporated in the rice-field, has broken the continuity of this sub-littoral swampland.

The limits imposed by anthropic measures are, to the west, the canal (named Sodalg) whose northern part is in communication with the sea, and to the south of the swamp itself, the drainage canal of the rice-fields.

In the center of the swamp, there are several areas of free water, each one extending into the mangrove. The large central area of water is 450 hectares. In the rainy season, it can be found aquatic vegetation with lemna and seaweed and isolated islets of **Avicennia** and Graminaceae (**Sesuvium**). The average depth measured was 20 to 25 cm in July, 1985.

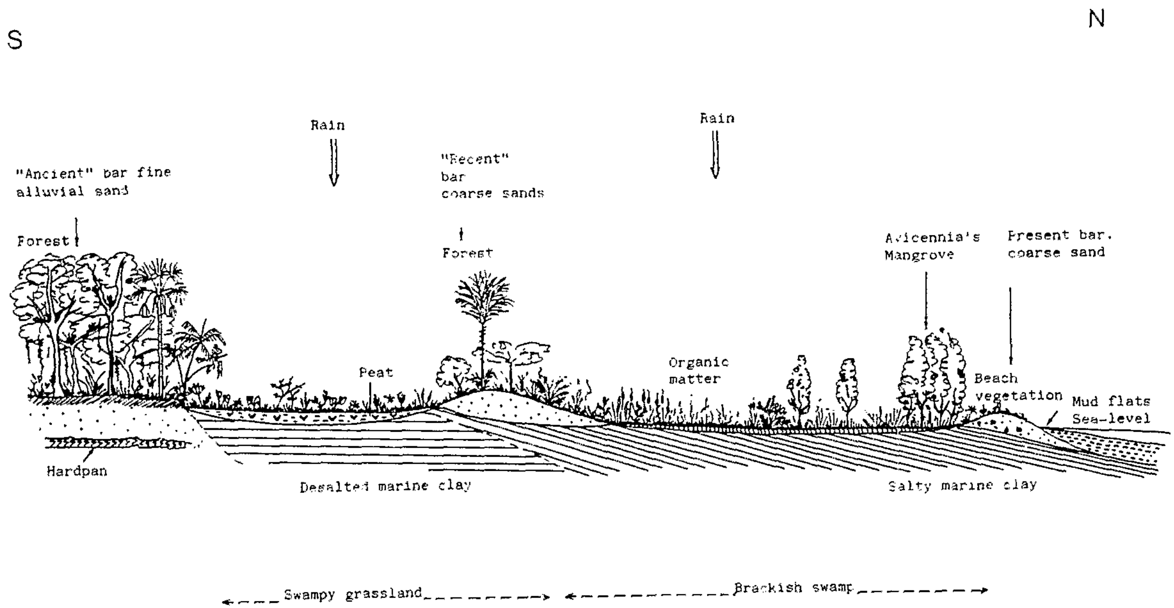


Figure 2. Diagrammatic section of swamp south-north.

2.2 The arteries

Two distinct systems ensure the ebb and flow of the water under the influence of the tide.

- The first system brings sea water to the mangrove areas. They are the tide channels of Goulet and Amarante which permit the ebb and flow of water of oceanic origin at all tides. It corresponds a zone of dead mangrove (respectively 35 and 70 hectares in area) for each channel near the outlet.

These two channels function identically. The only difference is the surface of their "catchment area" (temporary term in the tide cycle). Both possess a lateral branch on the left bank which drains the mangrove areas and does not seem to be affected by sea water. At Amarante, this small channel goes right into the heart of the swamp.

The small tributary named crique (In Guiana, small river) Emilie drains the main stretch of water of the swamp at low tide, crossing the mangrove situated behind the present off-shore bar. It also functions as a tide channel, flooding the mangrove zones with sea water, essentially during the period of spring tides. Prospecting has shown that these marine waters do not reach the stretch of brackish water of the main swamp, in the conditions of our observations, i.e. in the rainy season during which the "drainage function" is effective.

The nature of the cross-sections of these tide channels always resembles a profile U.

The second system of "arteries" originates in the river Mana, to the right of the town, at about 20 km from the mouth of the river. It is a small crique named Condillac which winds through the mangrove situated beyond the right bank of the river. Via a topographical shelf situated half-way along its course, it joins one of the branches of the Amarante tide channel.

The water of this artery is that of the river Mana. This area is strongly affected by the tide, which favours the flow of river water towards the interior of the swamp, particularly during the spring tide period. Thus, this crique resembles a tide channel, but this aspect is purely mechanical since the water is hardly salty. Furthermore, the morphology is different: a cross-section of this crique does not show the U-profile seen in the other channels, but a softer profile seen in rivers.

Thus there exist two systems which favour the outflow and perhaps the inflow of water into the brackish swamp, which reflect two different environments. The first could be qualified as purely "marine" near the effluents, under the influence of the tide and "permeable" to the ocean. The other qualified as brackish swamp, under the influence of fresh water (from the Mana) and rainfall.

2.3 Hydrometry

The comprehension of certain original phenomena, such as the decline of the mangrove near the effluents or the aspect of herbaceous or dry "tanne" (expanse with no vegetation or covered with a herbaceous carpet, situated in the depths of the mangrove) observed in the brackish swamp, needs a detailed knowledge of the hydraulic mechanisms: the effluent tide cycle, flow, fluctuating volumes, and levelling in the mud.

- Ebb and flow at an outlet: Amarante

With the rising tide, the current is cancelled out in about 5 minutes and the velocity at depth becomes irregular. The duration of the rising tide is about three or four hours. The surface velocities are about 1,2 m/s at spring tides and 0,5 m/s at still water. The duration of the ebb is generally between 8 and 9 hours sometimes 10 hours at still water.

The velocities at ebb are inferior to those at rising tide, and much more constant. The regularity of the outflow of the channels and flooded areas under the mangrove can be observed after the start of the movement of the mass of water which lasts about 1h 30'.

- Cycle of oscillating flow. Average flow in absence of rain.

At the main outlet, a continuous gauging, by independent verticals allows a precise evaluation of the flow. At spring tides the peak flow can reach 60 m3/s at Amarante, while at ebb it is less than 15 m3/s.

At ebb tide the average flow measured at Amarante oscillates between 4,5 and 0,8 m3/s during a cycle of spring tides and neap tide.

According to the measurements also taken on the crique Emilie, at Goulet and at Condillac, it can be seen that the crique Amarante plays a prime role in the present function. Its average rate of flow is 6,0 m3/s at ebb during the spring tide periods.

During these measurements, considerable modifications were observed after each tide in the profile of the gauge section. It was observed deposits and returns of banks of sand and mud 10 to 20 cm thick. This environment is thus dynamic and constantly re-shaped by the sea.

- Fluctuating volumes at Amarante

At spring tides the volume of water flowing into the swamp is twice that flowing out at ebb. For example, 400.000 m3 flows in and at ebb 190.000 m3 flows out.

There is therefore a stocking of water during the spring tides. However, at neap tide the phenomenon is reversed but the evacuated volumes are hardly superior to those flowing in (60.000 m3 at ebb for 50.000 m3 at inflow at Amarante). What then is the circulation process of these marine waters?

The phenomenon of introduction of sea water by overflow under the swamp mangrove takes place during 7 days at full moon and 5 days at new moon, corresponding to the spring tides.

Theoretically, if one spreads the volume retained during an important high tide over the surface enveloping all the "heads" of tide channels, one obtains a sheet of water 10 cm deep. This was measured during prospections in this area of swamp, which we qualified as "marine". Furthermore, the permanence of an important quantity of water in the channels at low spring tide, shows that these effluents do not allow the total evacuation by gravity of the volume of the inflow of water towards the sea. The circulation of water under the mangrove is also considerably slowed down by the large surface covered by the pneumatophores of **Avicennia sp.**

Thus a part of this ocean water is absorbed by the mangrove for a few days, and in addition to this process of evaporation, probably fairly slight under this important cover of vegetation and in absence of natural ventilation which is cut off by the coastal mangrove. The excess water drains to the sea during the period of neap tide (14 to 15 days at Amarante).

Thus -for the system observed in 1985- there is no inflow of sea water over the whole of the brackish swamp, since the "marine" mangrove slows down the natural circulation.

- Measurements of water depth. Their utilization in the determination of the heights of mud banks.

The recording of water depths with the electronic system CHLOE with piezo-resistant sounding-rod is precise to a half-centimetre.

By examining the daily water depth over a long period, the component belonging to the ocean tide can be separated from the natural flow of swamp water towards the sea. The slack water at high tide, which lasts about 30 minutes, permits a "levelling" of tide scales placed at two effluents three kilometres distant from each other.

Thus it can be determined that at the end of ebb tide, the stretches of water of Goulet and Amarante which present the same oscillations in time, are at different altitudes. The water at Goulet is 50 cm deeper than at Amarante. The mud banks situated on the high mud flats of the effluents are at the same level as these stretches of water; it can thus be shown that the silting of this maritime zone is accomplished with considerable altimetrical differences along the littoral.

The comparison of levels of slack water at high tide, which were recorded with those predicted by the Hydrographic Service for the coasts of Guiana, shows corresponding levels measured at "marine zero".

The precision of these superpositions is ± 2 cm which seemed to us to be amply enough for this type of study.

Thus it can be determined that the stretch of water of the Amarante outlet is at about average sea level. This is equally the case for the mud banks deposited in front of the outlets. The level of the Amarante bank -during the period of measurements- was about 1,90 m above the marine zero and that of the Goulet bank about 2,40 m.

The levelling of the present sandy ridge and its link to the Amarante tide scale shows that its maximum altitude is 3,80 m above the marine zero. The muddy ground with dead mangrove behind the present bar is at 2,80 m.

We also established a considerable altimetrical difference between the mud banks of the high mud flats to the right of the two swamp effluents. Furthermore, the altitude of the muddy ground of the swamp and that of the summit of the present sandy ridge, demonstrates the "sensitivity" of these paralic environments with regard to relative variations even of the order of centimetres, at sea level (maximal level at spring tides: 3,40 m.).

It seems, without any doubt, that the whole area of the Sarcelle swamp situated to the north of the rice-fields is of very recent formation. Aerial photographs taken in 1950 and 1955 show an amphibious area situated between the "recent" and "sub-present" sandy bars and the "present" shoreline bar.

We have seen that the Hydrology of the swamp is a complex system due to the dynamics of marine rhythms. But what part does rainfall play in the "interior life" of the brackish swamp?

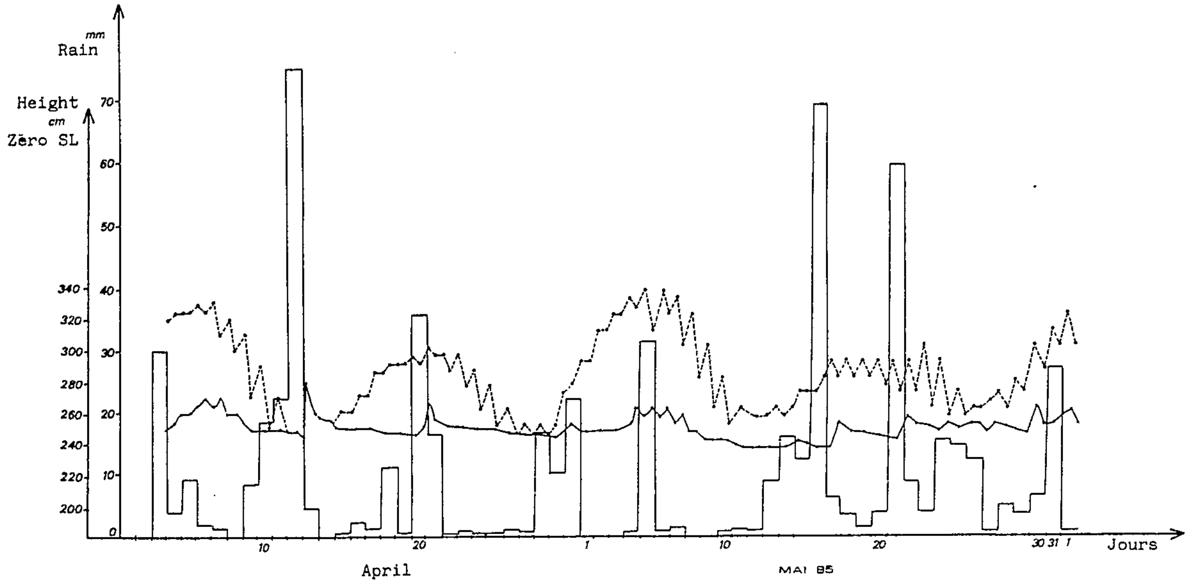
Episodes of rain explain the variations in water level (Figure 3) (after filtering of the ocean tide component), observed in particular the 13th and 21st of April 1985 and the 4th and 7th of May. In the first case, it can be seen the flooding of the catchment area after a heavy shower, especially as the first flood occurs at still water. In the second case, in May, the response is uniquely due to the oceanic momentum which"masks" the effect of a 30 mm rainfall occurring during the same period.

Analysis of this type of document shows that the observable floods are produced by showers of over 30 mm (in 24 hours) at spring tide and new moon, and over 45-50 mm at spring tide and full moon.

Moreover, we have seen that the hydraulic power of evacuation of the main effluent was about 200.000 m3 in 10 hours.

Study of the flood of 13th April supplies information on the dynamics of circulation. In comparison with the surface of the catchment area, the corresponding volume of water could have been evacuated in a half-day. Since the flood lasts almost 3 days, one can suppose that it is maintained by an exterior limited inflow. Thus it is probable that, in this case, there is draining maintained by, on the one hand, the small swamp effluent (Emilie) and on the other hand, by a lateral circulation of brackish swamp waters towards the domain of the tide channels. This phenomenon -studied purposely at neap tide- is less palpable at spring tide since, as we have seen, there is stocking of sea water in the "catchment area" part of the effluents. This is why the flooding appears, in this case, during heavier rainfall.

For showers of over 40-50 mm, the limit between the two



Level of slack water at high tide and at the end of ebb tide at Goulet, superposed on daily rainfall. Two responses of the "catchment area" can be distinguished :

- flooding after heavy rainfall (13, 21 April)
- oscillation of the sheet of water after draining of the areas flooded at spring tides (4,5,6,7 May)

Figure 3.

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domains, brackish and marine, becomes permeable in the direction swamp-sea. These elements support the field observation, which showed the existence of two very different perennial domains by the aspect of the muds and the vegetation. The hydrometric measurements indicate the hydraulic relationship between these two zones, which are separated by an "impermeable" barrier, except in the case of heavy showers (over 50 mm) when there is a transfer of water towards the tide channels, and then towards the sea.

In these conditiors, how does the water of the brackish swamp obtain its salinity?

Chemical analyses of the water of the brackish basin show concentrations of sodium chloride of 5 g/1 on average during the rainy season. This value increases with the intense evaporation during the dry season when the temperature of this water is about 32°C. Conditions of excess salinity (35 g/1 of NaCl) were even observed in certain small pools in November, 1985. The whole evolution of the brackish swamp is thus conditioned by the temporal distribution of rainfall during the dry season. In extreme cases, and as it was observed in 1969 and 1982, there can be complete drying-up and apparition of dry tanne.

The brackish origin of such a system can only be understood -under the conditions observed in 1985- by recalling the presence of salt in the marine clays of the soil. The washing of these salts by rainwater is slow and dominated by a threshold effect of rain under which the brackish swamp remains almost endorheic.

DISCUSSION

The hydrological analysis distinguishes two brackish swamp environmerts already described by Blancaneaux (1981), one by periodic marine invasion and the other dominantly brackish (Figure 4).

The "marine" environment is localized and its extension geographically small. It coincides roughly with the sub-littoral courses of the Crique (Amarante, Goulet). It has a very high oceanic permeability, and is regularly covered by the tides. On aerial photographs it appears as a series of tide channels with a U profile and by areas of dead or declining mangrove .

During the periods of ebb tide, its function resembles the catchment area; during rising tide, of short duration, there is overflowing of sea water, with temporary stocking of water.

This system may explain the decline and rapid death of the great mature mangrove situated near the outlet, behind the present sandy bar.

M. Boye (1962) thinks it is the result of the freshening of the soil. We think that the proximity of the ocean, contrary

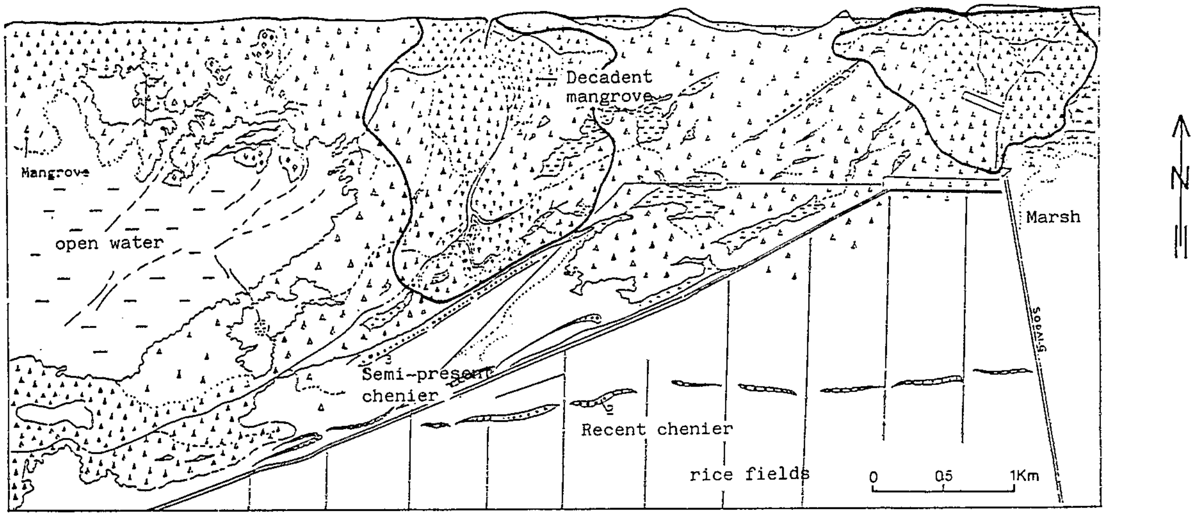

Figure 4. Limits separating "marine" and "brackish" zones around the Goulet and Amarante "criques".

to what one would expect, is in accordance with this. In fact, the short duration of rising tide (3-4 hours) and especially the large dimensions of the two tide channels do not allow the chemical and mechanical stability which is seen upstream. At rising tide, velocities are high and the mud is periodically washed. There is a sort of "mechanical asphyxia" by the tide.

- The second environment is "brackish sub-littoral", with water which is moderately salty and rich in humic acids. This environment, which is spacially the widest, is represented by the vast central basin of the swamp.

Contrary to the "marine" environment, there is practically no circulation of water here; drainage, by very insignificant effluents, is very slow.

Likewise, the small crique which flows into the river Mana only has small possibilities of inflow and outflow of river water, withdrawn from the influence of the oscillating salty part in the estuary (Lointier M., 1984).

There is a distinct limit between the two domains: there is no intrusion of sea water into the brackish basins.

However, this limit is no longer impermeable during showers of over 30-50 mm: the overflow of the brackish swamp fills the network of channels which slowly drain the water towards the sea. Thus, at this time, and only in these conditions, a one-way connection is established from the overflow of the basin towards the network of tide channels, i.e. from the "brackish" domain towards the "marine" domain. This first fact is important and contrary to the logical supposition which would be from the sea towards the swamp.

In these circumstances, how can the over-salinity of the sub-littoral swamp be explained? We are convinced that this phenomenon is linked to the soils, formed by salty marine clays. These soils have evolved themselves, according to phases of silting and unsilting, which recently seem to be a fundamental fact of the coastal dynamics. Here we touch on the problem of present and recent causes of the evolution of these environments. The present brackish sub-littoral swamp has a functioning which is certainly original, but which occurs in an environment whose evolution superposes present and recent processes. It is thus, in many aspects, an intergrade environment, in contact or in passing, where interactions occur. As regards the present dynamic, for example, it concerns an environment where the "marine" conditions diminish and the "continental" conditions become more important, due to rainwater and streams issuing from the freshwater swamp.

It is precisely in this environment that, during the years when the dry season is becoming more marked, real bare tanne are formed, as it is clearly seen on the aerial photographs. Field work has shown, on such occasions, the existence of a vast area of cracked clay and the central basin of the swamp being completely dry. The Mana swamp has thus a present dynamic as opposed to the swamps situated on the left bank of the river Mana.

This last observation allows us to go a little further in the discussion on the present and recent causes in the evolution of these environments. The swamp of the left bank of the Mana, in which a rice-field is planted, is situated behind a sandy bar which supports the track from Mana to Les Hattes. The sedimentary deposits, dating back to the Mara phase, are de-salted. They have evolved in the soils with pyrites and present at least one important layer of "pegasse". The geomorphological situation of this swamp, as well as the evolution of these soils, prove that this formation is ancient: an ancient lagoon, gradually filled in, becoming a confined environment, which has evolved behind a sandy ridge. To what extent is the present sub-littoral brackish swamp, the expresion of a stage in the evolution of the fresh-water swamp on the left bank of the Mana? The question remains. It is founded on the comparison of recent aerial photographs which show a very active dynamic. For example, the present bar of the shoreline was, in its time, part of an amphibious system, pushing the shoreline two kilometres to the North. Other documents show ancient tide channels, and even, at the level of the "recent" bar, a bend morphology of the sandy bar which resembles that of the present effluents. On the other hand, -and if we accept the preceding hypothesis- the present bar (like the Isere head at the mouth of the Mana) has isolated, by its growth, the ancient mud-flat. This environment became a lagoon and was progressively filled in. The process was thus rapid. The differences in altitude between banks, the "sensitivity" to the level of the sea, and the analysis of borings carried out by the B.R.G.M. (Geological and Mining Research Office) seem to support this thesis. However, in the absence of more detailed studies in this sector, any hypothesis of dynamic is subject to reserves, taking into account that the evolution of these zones is linked to that of the estuaries of the Mana and a more important river, the Maroni.

It is certain that the seasonal climatic variations affect the duration and the force of the winds, and thus the amplitude of the waves, and this leads to a modification of the oceanic effect on the swamp. Although the summit of the "present" sandy bar is situated 40 cm above the level of high spring tides, it is not an obstacle for waves which submerge it from time to time. The consequences are not really important if one considers the inflow into the swamp, but, on the other hand, certain lower parts of the bar can thus alter and favour the creation of potential zones of rupture. On the contrary, during "calm" cycles there should be a phenomenon of consolidation of the present bar by sedimentation and development of extensive vegetation which ensures a better cohesion of the bar.

On the whole, the sub-coastal environment appears to be very dynamic, either at the present time, or in the recent past. If the "marine" environment appears to be relatively unstable, suffering the consequences of the present coastal silting, nothing proves that, once the mud-bank has migrated towards the west, the evolution of this environment, as well as the beaches and bars in this sector, will not be modified; in fact, it is certain that this migration will bring modifications in the same way as the other coastal sectors. In the present circumstances, the sub-littoral brackish swamp appears to be rather more stable than the "marine" environment. This "stability" is, however, relative and this environment is, in reality, fragile and sensitive. Slight modifications of the hydroclimatic parameters, of the amplitude of tide are sufficient to change the brackish swamp either into bare tanne, or on the contrary, into a stretch of free water. On the other hand, the freshwater swamp appears to be the most "stable", entirely covered with vegetation. On the whole, in the hydrological as well as in the morphological domain, we pass from processes which are clear and visible to others where the environments are in evolution, ecologically balanced, with the development of soils and arrival of fresh water only. It remains to examine the role of marine dynamics in the evolution of the coast, or the variation of the shoreline, which conditions itself the evolution of the swamp.

We have seen that the different unities of this environment, as the sandy bar, are separated by altimetric differences of the order of a decimetre. A slow variation of the amplitude of the tide -without a change in the average sea level- would increase or decrease the oceanic effects in the swamp. Augustinus (1978) mentions low frequent components of the tide as an explanation for these variations in amplitude of the tide. Among the twenty-seven lunisolar components explaining the mechanism of the tide, Rouch (1948) and Gougenheim (1954) show that there exist three long periods which produce variations in amplitude in semi-annual and annual (182 and 365 days) and pluriannual (18,6 years) cycles. This last cycle affects the amplitude by ± 4%, which would produce an oscillation of about ± 10 cm for the coasts of Guiana.

In these conditions, the limits of the "marine" and brackish domains would be shifted, as well as the hydro-pluviometric values which condition the "response" of the environment. Thus there should be the extension of one unity to the detriment of the other, with probable repercussions on the functioning of the freshwater swamp.

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