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Evidence of dynamics reversal in tropical estuaries, geomorphological and sedimentological consequences (Salum and Casamance Rivers, Senegal)

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ABSTRACT

South Dakar Senegambian estuaries are subject to an unusual hydrodynamical regime caused by weak or absent run-off. In the Salum delta, each distributary lacks fresh water during most of the year. Only the tidal flows are responsible for geomorphological and sedimentological effects. The current distribution shows a net discharge upstream due to the extensive evaporation and evapotranspiration in mangrove swamps and tidal flats. Consequently the salinity is always higher towards the river than near the sea. A high salinity bottom layer suggests the occurrence of a supersaline wedge of reverse sense to the salt wedge of a normal estuary. Such an inverse pattern is similarly displayed by sedimentological features (double upstream turned spits) and by the external location of the turbidity maximum. A coherent reverse estuary model is suggested from our field observations.

INTRODUCTION

The South Dakar, Senegal and Gambia coasts are marked from North to South by outlets of three fluvial networks: the Salum, Gambia and Casamance rivers. Only the first ends in a deltaic system, the other two open into wide estuaries (Fig. 1). This region is subjected to the Sudanese climate with two distinct seasons. During the 8–10 months long, dry season, evaporation phenomena are well developed, especially in March–April. Temperature are usually low in the beginning of the dry season (15°–24°C in December–January) and rise to 27°–31°C in May–June (Diop, Sall & Barusseau, 1983). The rainy season is shorter with maximum precipitation generally in August.

The research presented here mainly deals with the study of the hydrodynamics of the Salum delta distributaries. Nevertheless, various sedimentological and geomorphological observations in the Salum and Casamance mouths are used to emphasize the incidence of these mechanisms on material transport and deposition. Lower Casamance presents a normal estuary regime with freshwater discharge all the year long; though it is weak it generally exists at the end of the dry season. The 'salinity tide' affects the lower part of the river over a length of 250 km.

In the Salum region, the meteorological regime is characterized by a lack of freshwater inflow during 9

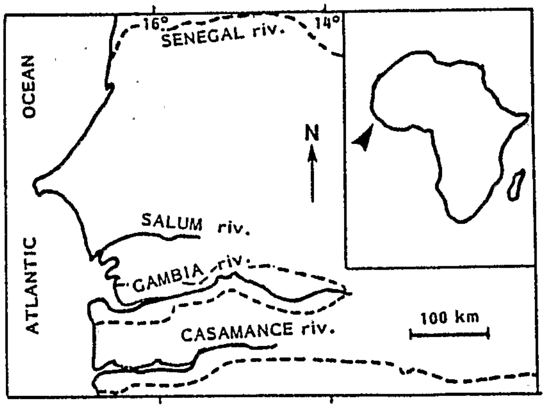

Fig. 1. Location map of the studied area.

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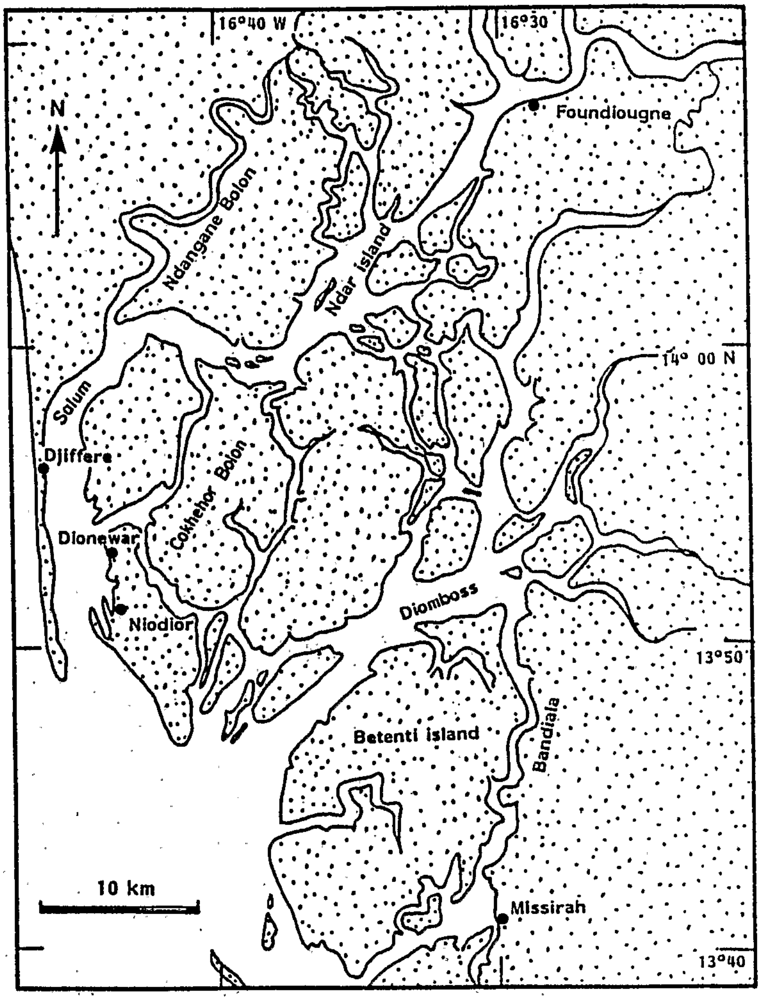

Fig. 2. The Salum delta. The three main distributaries, Salum, Diomboss and Bandiala, have their mouths opened to the sea. Between them, shallow interconnecting channels are named 'bolons'.

months every year. Therefore, as a whole, the estuarine waters are renewed only by the sea. The Salum opens into the Atlantic Ocean through three tributaries: the Salum itself, the Diomboss and the Bandiala (Fig. 2). The first two are channels several kilometres wide and their depth varies from a few metres to 20 m. The Bandiala is narrower and less deep. The three distributaries are connected by a dense network of small shallow channels, the so-called 'bolons'. A mangrove swamp stretches all over the delta. It is continuous in the south but becomes progressively discontinuous northwards in response to the change of climatic conditions characterized by the intensity of dust falls caused by increasing drought (Barusseau *et al.*, 1983).

An alluvial area of low topography, the Salum region is formed of mud, silt or recent sand deposits. The oldest formations are dated from the Nouakchottian transgressive phase (Elouard, 1967; Diop, 1978) when successive littoral spits were built in the former Salum Bay. They now form a set of sand barriers sometimes bearing kjokkenmöddings (human-made shell deposits). At lower levels the other morphological units are progressively arranged from the bare areas (tannes) and tidal flats to the channel bars. The average sedimentation rate has been assessed as 68 mm yr^{-1} (Faure, Viellefon & Diop, 1974).

The Salum delta distributaries are subjected to weak semi-diurnal tides (microtidal regime). Accordingly they provide excellent opportunities for field investigation of the purely tidal effects which occur in estuaries (Salomon & Allen, 1983).

METHODS

Stream flows in the three main arms of the Salum delta were studied from 1981 to 1984. Velocity and direction of currents were recorded using Braystoke and Aanderaa current meters. Measurements were taken at stations located in the middle of each channel (Fig. 3, Table 1). With the instantaneous recorder (Braystoke) 10 stations were examined; currents were registered every 15 min (surface and bottom). With the Aanderaa recorder, measurements at the surface were noted at one station every 2 min during 5·8 days. Water heights were measured at three points (two in the Salum, one in the Diomboss) during a 30 hr total observation time so as to assess the relative variation of water level during the tide.

Salinity variations in surface and bottom waters has been examined in the Salum and the Bandiala. In the field, measurements were made with a Bioblock refractometer calibrated in the laboratory with a conductivimeter at 25°C in comparison with standard seawater.

Sediment textures in the various geomorphological units were determined from short cores taken in the tannes, tidal flats, sand barriers and from grab samples in the channels. In addition, a morphological study of the banks and channel bars has been conducted. The water turbidity was measured in the Salum and also in the Casamance river where a *Landsat* imagery interpretation was performed in order to distinguish the various turbidity levels using the MSS channels 4 and 5.

WORKING OF SALUM ESTUARY

The hydrodynamic regime

The tide is the main agent of water movement in the distributaries. It is a semi-diurnal tide, very close to the M2 component whose period, based on 11 successive values taken at the Diomboss station 3, is 12h29. The tidal range varies from 1·1 m on spring tide to 0·5 m on neap tide. The first important characteristic is the respective duration of flood and ebb. The pattern observed is the opposite of that present in normal estuaries. Here the flood phase lasts longer than the ebb (Table 2). The average duration of 15 floods was 7h01 while for 18 ebb durations in the same conditions, it was only 5h25, a difference of about 30%.

In addition to this long lasting seawater penetration into the delta channels, current velocities are generally higher during the flood than on the ebb (Fig. 4). Generally the contrary is observed in estuaries, although noticeable exceptions exist (Dyer, 1973; Officer, 1976; Salomon & Allen, 1983). On the basis of all the data collected the maximum velocity occurred during the flood in 82% of the cases and on the ebb in 14% of the cases. The greatest flows were equally distributed between ebb and flood phases 4% of the time. This second factor enhances the seawater inflow.

Metre by metre measurements during the flood and ebb stages have shown that the flood is dominant over the whole water column. However, during the early part of the ebb the near bed waters may flow more rapidly than the surface waters (Fig. 5). The speed often increases upwards (10/12 profiles) and generally, this increasing trend follows a linear relation (1–8 $cm^{-1} m^{-1}$) in relation to the tide stage (the increasing rate is obviously higher when the surface velocity is higher). Accordingly, the ebb-flood velocity ratio is not far from being constant at each level, an important observation in order to simplify the assumptions relative to the assessment of ebb-flood discharge ratios.

Few measurements were made on transects. Nevertheless, it was possible to determine the direct influence of depth; slower currents were recorded near banks and channel bars where quick variations were observed due to the rapid change in morphology. Therefore the assumption may be made that there is a parabolic decrease of current speeds towards the channel margins, as observed in very wide channels (Lencastre, 1969).

The vertical oscillation of the water level is not synchronous with the current variations. The change in the current direction may occur slightly before or after slack water stage as shown elsewhere (Diara, 1983). In the Salum the duration of high water period is longer than that of low water on both records obtained (Figs 4 and 5). On average, the water level is above the mean level, defined as $H_{min} + 1/2(H_{max} - H_{min})$, for about 2/3 of the time. The tide heights are

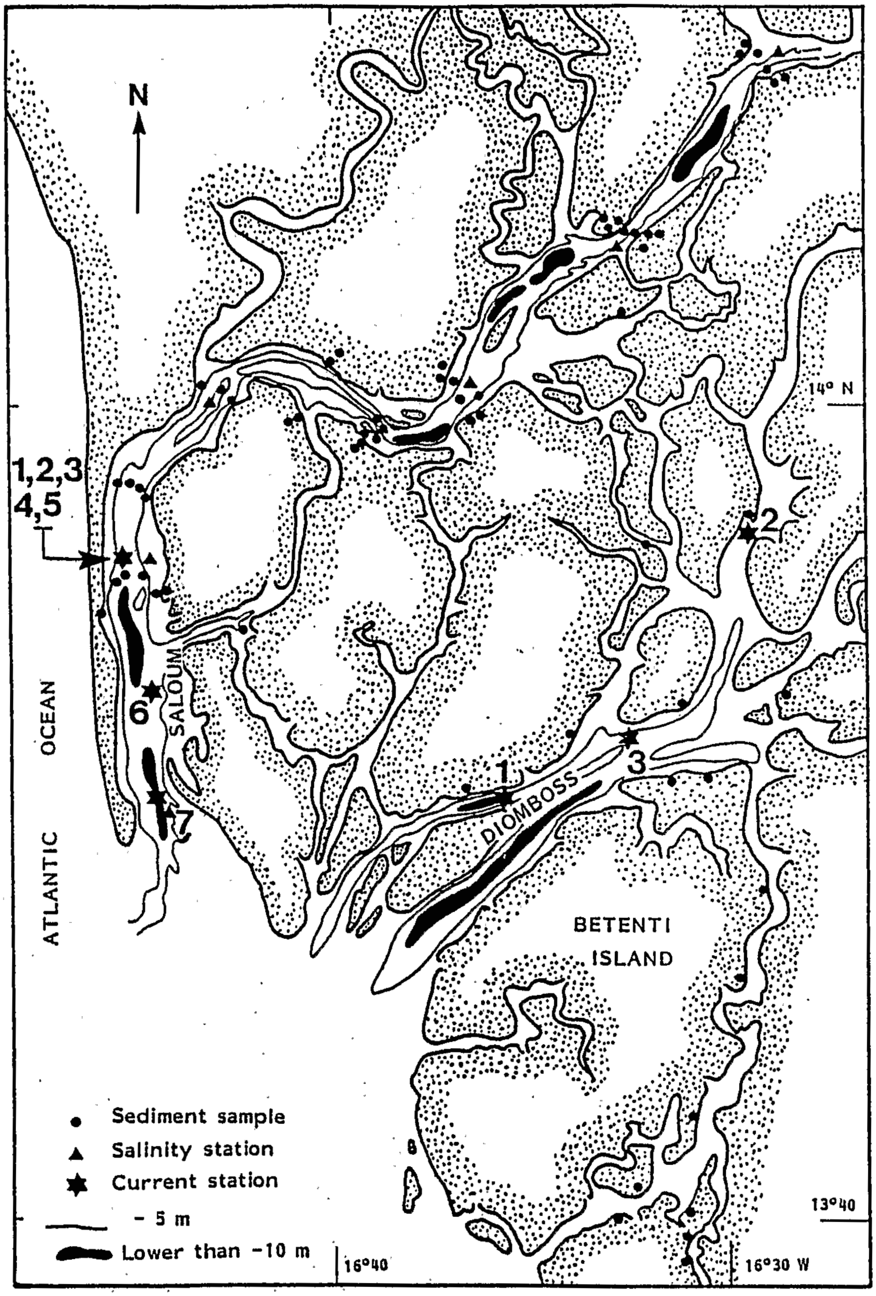

Fig. 3. Location map of measurement stations in the Salum delta.

seen not to link with flood and ebb current patterns of change. The rise of water level starts before flood direction currents are detected and continues into the ebb flow. Indeed, when the water level starts to rise as the tidal wave begins to move landwards, the water level inland is always higher than at the seaward margin. There is necessarily a time lag between the rise and the current reversal. At the end of the flood, a persisting rise after the outflow triggering is observed; water level inland is then lower than sea-

Table 1. General data about the current meter stations

Distributary	Location	Date	Type of current meter	Duration
Salum 1*	Djiffère	5 July 1981	Braystoke	4 h
„ 2	„	31 August 1981	„	10 h
„ 3	„	20 April 1982	„	12 h
Diomboss	Ile de Poutaké	1 May 1982	„	5 h
Salum 4	Djiffère	2 & 3 November 1982	„	26 h
„ 5	„	1 May 1983	„	10 h
Diomboss	Sangako	7 & 8 May 1983	„	13 h
Bandiala	Missirah	8 May 1983	„	9 h 45
Diomboss	Ile de Gouk	2–8 May 1983	Aanderaa	139 h 50
Salum 6	Dionewar	30 May 1983	Braystoke	12 h 45
„ 7	Niodior	10 June 1984	„	9 h 35

* Numbers refer to stations located on Fig. 3.

Table 2. Respective durations of flood and ebb in the Salum delta. From the 17 corresponding pairs of values, it may be quoted that floods is longer than ebb (only one pair shows an inverse relation)

Stations	Date	Duration of flood (S: surface; B: bottom)	Duration of ebb (S: surface; b: bottom)
Djiffère	31 August 1981	?	5 h 45 (S)
„	20 April 1982	7 h 00 (S)	5 h 00 (S)
„	2 & 3 November 1982	6 h 15 (S)	5 h 45 (S)
„	„	?	5 h 30 (S)
Diomboss	2–8 May 1983	6 h 45 (S)	5 h 15 (S)
„	„	7 h 30 (S)	5 h 20 (S)
„	„	5 h 55 (S)	5 h 45 (S)
„	„	8 h 00 (S)	5 h 10 (S)
„	„	6 h 40 (S)	5 h 10 (S)
„	„	8 h 10 (S)	5 h 20 (S)
„	„	6 h 30 (S)	5 h 25 (S)
„	„	7 h 45 (S)	5 h 40 (S)
„	„	7 h 00 (S)	5 h 00 (S)
„	„	7 h 30 (S)	5 h 30 (S)
„	„	7 h 00 (S)	5 h 00 (S)
„	7–8 May 1983	7 h 05 (S)	5 h 40 (S)
„	„	7 h 10 (B)	5 h 50 (B)
Bandiala	8 May 1983	?	6 h 00 (S)
„	„	?	5 h 40 (B)
Salum	30 May 1983	6 h 20 (S)	5 h 55 (S)
„	„	5 h 35 (B)	6 h 50 (B)

level. Consequently, the tidal inland has a height range smaller than in the open sea and the rising part of the cycle is longer. This can be explained by (1) the lack of surface gradients due to the low tidal range, (2) the resistance opposed to penetration of the tide into the mangrove, the tannes and the bolons, (3) the mechanical trapping of water during the outflow, and (4) the evapotranspiration and evaporation phenomena on the tidal flats and mangroves.

The tidal curve for 2 and 3 November 1982 at Djiffere is most peculiar as it has only a decreasing trend of the level during the night perhaps due to a strong effect of the factor (4).

It is possible to compute the flood and ebb discharge ratio from velocity distribution observed with the following assumptions:

- —the tidal wave is symmetrical and no discharge variation is due to the tide itself;
- —the vertical distribution of velocity is linear and the vertical velocity ratio for flood and ebb alternations does not change;
- —the transverse variations are negligible and proportional;
- —the wet surface does no change in a significant way.

In those conditions, velocity variations with time

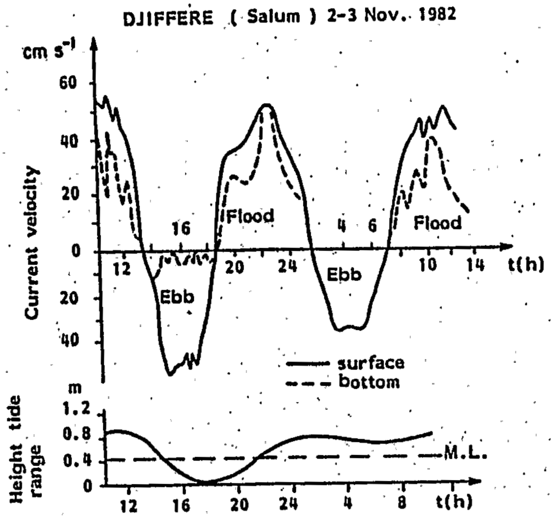

Fig. 4. Current velocities during 2.5 tide cycles. The flood is longer and faster than the ebb at the surface as well as at the bottom. Note also that the water level is longer above the mean level (M.L.) than below.

can be graphically integrated in order to compare the resulting values which are equivalent to distances (Simmons, 1966). The ratio of these values corresponds to the discharge ratio. Computation is made taking into account one given ebb and the preceding flood. Assessments were possible in 14 cases (Table 3) and clearly showed that Salum distributaries receive more water than flows back into the sea. Consequently, the alternating flow system has a resultant upstream.

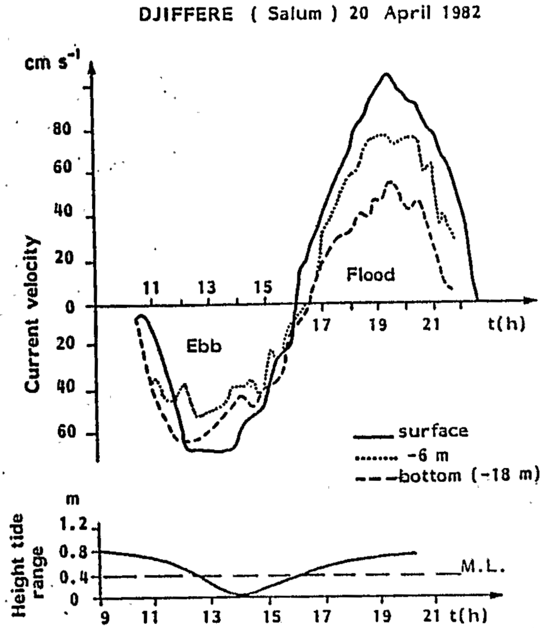

Fig. 5. Occurrence of a fast bottom layer during ebb. On the left lower part, the dashed line shows a current distribution which emphasizes the occurrence of a faster layer than on the flood (right upper part).

The hydrological and sedimentological regime

Measurements are only relative to the salinity (Fig. 6). Whatever the time of the year and the place, the estuarine salinity is always higher than the seawater. Even after the wet season, the salt content is never

Table 3. Discharge ratios of flood and ebb flows in Salum and Diomboss distributaries. The figures in columns 3 and 4 are obtained by determining the areas under the boundaries of current velocity curves with a polar planimeter. These figures are referred to arbitrary units but correspond to surfaces proportional to discharges either during flood or ebb

Distributary	Date	Tide inflow coefficient (Ci) (arbitrary units)	Tide outflow coefficient (Co) (arbitrary units)	Discharge ratio Co/Ci (%)
Salum	20 April 1982	3243	2572	79·3
Diomboss (Sangako)	7 & 8 May 1983	1857	1426	76·8
Diomboss (Ile de Gouk)	2–8 May 1983	2783	1867	67·5
	,,	4192	2212	52·8
	,,	2068	1867	90·2
	,,	3180	1833	57·6
	,,	2103	1218	57·0
	,,	3038	1696	55·8
	,,	2244	1182	52·7
	,,	3343	2143	64·1
	,,	2708	1419	52·4
	,,	3910	2527	64·6
	,,	2838	1859	65·6
Salum	30 May 1983	2895	2119	73·2

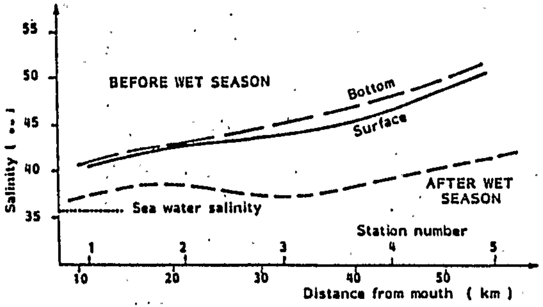

Fig. 6. Salinity distribution in the Salum River. Salinity is always higher than seawater even near the mouth (left part of the diagram).

lower than 35‰, but higher than 40‰ at a distance from the mouth. During the dry season, it progressively increases and values higher than 55‰ may be recorded in June at the upstream end of the deltaic area.

Vertical variation of salinity systematically shows a bottom layer whose values are slightly higher than in the waters above (Fig. 6). Then it is consistent with the hydrodynamic regime to assume the occurrence of a hypersaline water at the bottom flowing downstream. Indeed, repeated measurements at the end of the dry season (June 1984) on a vertical profile (Salum mouth) show the presence of a salt wedge (Fig. 7) with isohalines inclined seawards.

The various geomorphological units are characterized by differing sediment types.

In areas fully or partially exposed at low water, sand barriers are formed with medium sands in the north (median is nearly 230 μm; average of six values) and finer sands (*m* = 140 μm; eight values) in the south. This material is always coarser than the tanne and tidal flat deposits (*m* = 91 μm; 22 values). There is no grain-size difference between materials from these last two units. In both cases, the sediment is a coarse silt with a poor pelitic (<40 μm) fraction (5–20%) and little clay fraction.

In mineral assemblages quartz is very prominent; organic matter is generally absent but particulate organic matter contents up to 33·2% may be observed in some layers; traces of pyrite occur when particulate organic matter increases. In the clay material, kaolinite shows a slight predominance over smectite; numerous fragments of diatoms and sponge spicules testify to a rather rich content of amorphous silica. In tidal flats, the upper unconsolidated silt layer a few centimetres thick is superimposed on a mud layer with a pelitic content greater than 50%. This lithological change seems due to a drastic climatic modification of regional extension with a recent increase of aeolian silty dusts (Barusseau *et al.*, 1983).

In the channels, deposits of intermediate grain size have been measured. Bottom sediments in the channel axis give an average median of about 180 μm (17 values) while bars and banks present finer sediments (*m* = 125 μm; 22 values). Channel bars are sometimes submerged but can also constitute large islands with developed mangroves (îles du Diable, île de Ndar) while on the banks, wide alluvial deposits are present in the lower part of both the Salum and the Diomboss.

The sandy channel deposits are directly subjected to alternating tidal currents. So the prominent upstream flow which determines the residual currents causes a peculiar inverse orientation of sedimentary spits as off Niodior (Fig. 8) where the external spit is 3·1 km long and the internal one 2 km long. If such an orientation is not unusual in macrotidal estuaries (for

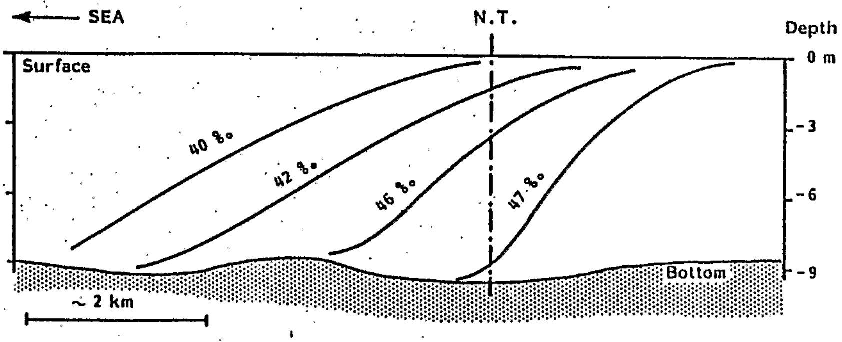

Fig. 7. Schematic longitudinal cross-section of the reverse salt wedge (Salum, June 1984). This sketch gives a rather qualitative representation of the super-saline wedge than a true quantitative one due to a few measurements on the Niodior transect (N.T.).

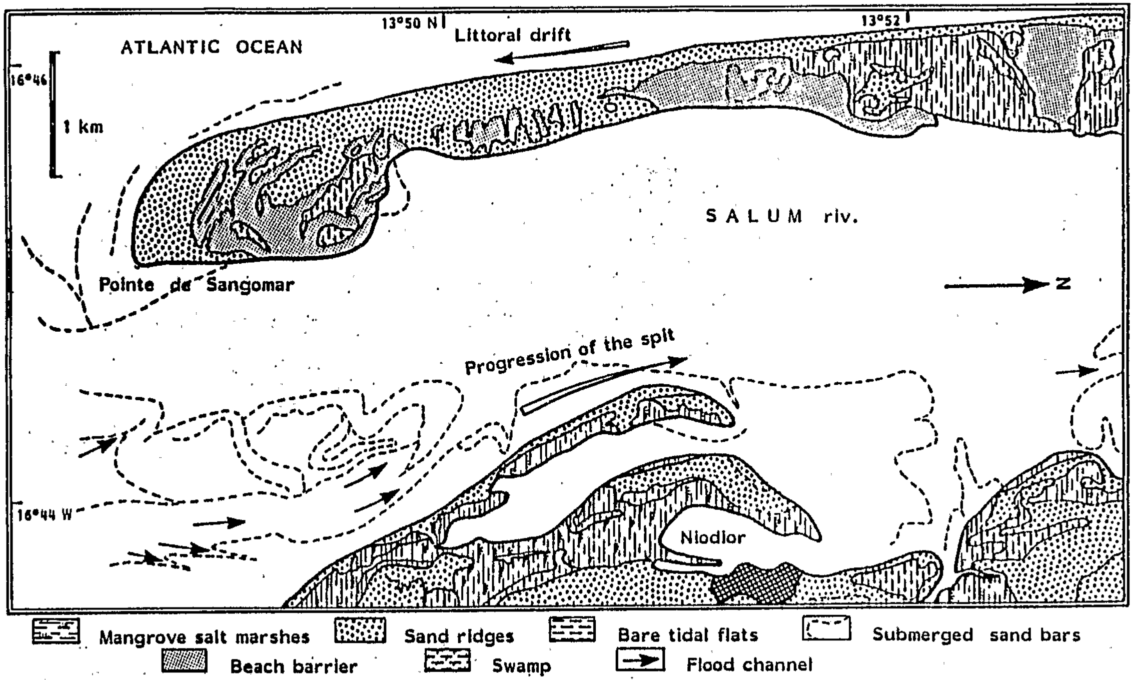

Fig. 8. Geomorphological sketch of the double upstream turned spits off Niodior and adjoining area.

instance, the well-known Pointe de la Coubre in the Gironde estuary) there is no theoretical reason for an occurrence in a microtidal one. Wave refraction may also be discarded because of the absence of oceanic waves with a northward propagation in the Salum (the most efficient waves originate from North Atlantic high pressure areas, i.e. from the north and north-west, but are here reduced by the sheltering effect of Cap-Vert Headland and the long Sangomar spit which protects the seaward part of the estuary). The development of islands (i.e. île de Ndar) also occurs on the island upstream end. About the same topic, there seems to be no ebb channel but rather some *flood channels* as that may be seen on SPOT simulation photographs (see for instance the detailed topography of submerged sand bars on Fig. 8).

The suspended material content increases with depth and also varies with location in the channel (Fig. 9). Loads at upstream stations are less than those downstream. This pattern is similar to that observed in the nearby Casamance River (Diop *et al.*, 1983) and Gambia River (Diop, 1981). Moreover, in these last two estuaries, *Landsat* imagery shows turbid plumes in an external position between clearer marine waters and clearer mid- and upper estuary waters (Fig. 10).

DISCUSSION AND CONCLUSIONS

An anomalous system of fluid dynamics in some tropical estuaries is clearly suggested by evidence of residual current and correlated simultaneous effects: i.e. hydrology, a seaward facing salt wedge; sedimentology with spits turned upstream, upstream progra-

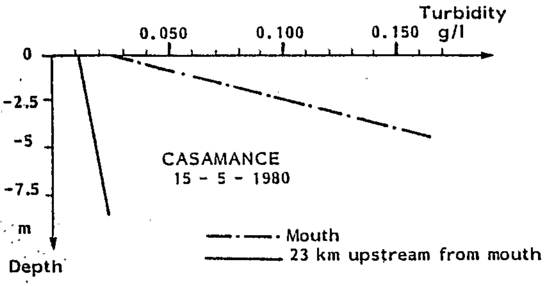

Fig. 9. Turbidity increasing in relation to depth.

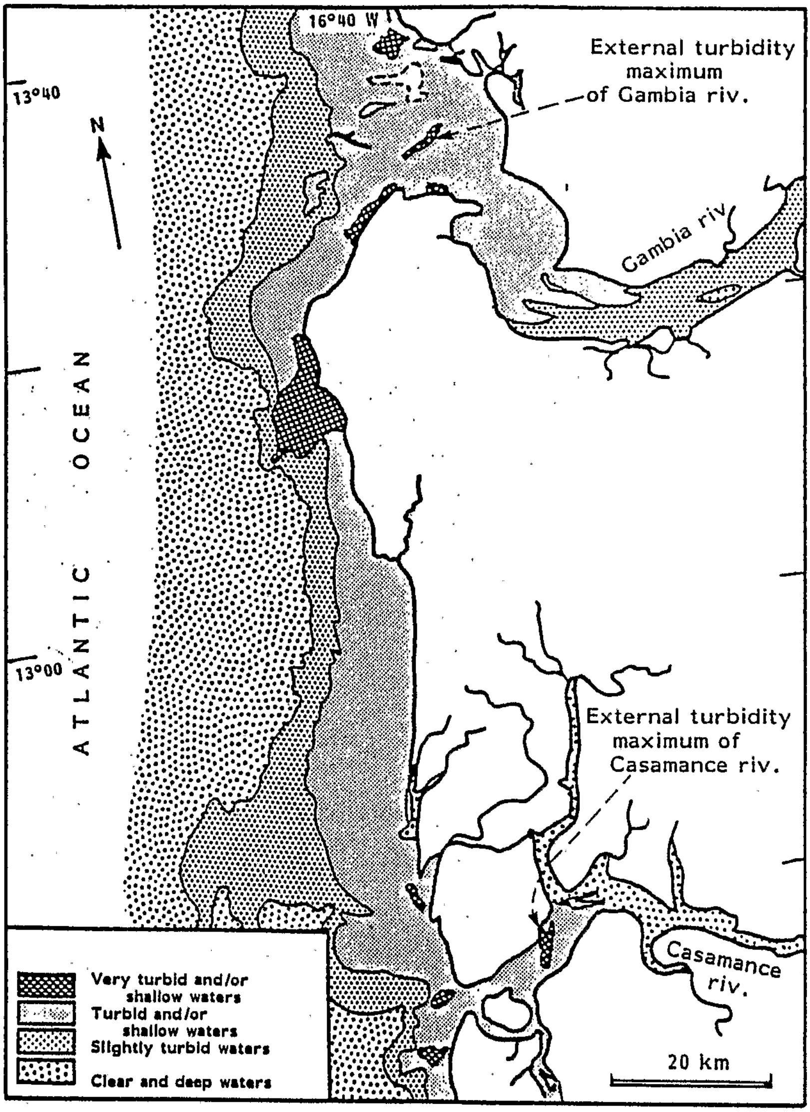

Fig. 10. Location of the turbidity maximum in the Gambia and Casamance estuaries. The turbidity maximum is not in an internal position as in normal estuaries but at the very mouth of the estuary. A coastal 'plume' is directly supplied from these turbidity maxima.

dation of islands and turbidity maximum in an external position.

The more obvious consequences are observed on topographic highs on flanks (Niodior upstream turned spits). Material involved is mainly transported as bedload (medium to fine sands). The sedimentary structure orientation cannot originate from wave refraction and the microtidal regime is unlikely to be a sufficient cause. Niodor double spit is also an evidence of duration of processes responsible for such accumulations; the internal spit bears several 'kjokkenmöddings' and presumably an Holocene (perhaps Nouakchottian) age may be inferred. In some periods like Miocene or the whole Mesozoic when wide intertropical zones extended to the most part of Earth, a large occurrence of such a pattern may be considered.

On the other hand if the reverse hypersaline wedge acts like that of normal estuaries (Pritchard, 1955;

Groen, 1967; Allen, 1973) by producing a turbidity maximum (Glangeaud, 1938; Bonnefille, 1977), then it could furnish a supplementary agent to transportation of suspended particles towards the sea. The hydrodynamic effects of this form of saline wedge may be substantial although as yet they remain unexplored.

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