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COMMUNICATION

Morphological and sedimentological changes in the Senegal River estuary after the construction of the Diama dam

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Abstract—The aim of this paper is to study the behaviour of a complex and unstable coastal system (the Senegal River delta) since the construction of the Diama dam. The Senegal River mouth is located on a sandy microtidal coast. The equilibrium of the coastline (the so-called "Langue de Barbarie" sand spit in particular) and the inner part of the river mouth is highly dependent on the longshore drift and the transported sandy material. The role of the Diama dam could therefore be very important according to the seasonal rainfall. For example, between 1986, after the Diama dam began to function, and 1990, the Senegal River mouth moved southwards by more than 2.8 km and is now located in its southernmost position. As a whole, the high accretion has helped strengthen the maritime segment of the "Langue de Barbarie" by a decreasing of the fluvial water discharge and the Senegal River mouth will be maintained for a while at the southern part of the delta.

Field measurements, including topography profiles, sounding transects and sedimentological analysis, Spot-imagery processing and comparisons of recent topographical maps have been used to evaluate the functioning and evolution of the Senegal distributary and coastal zone. © 1998 Elsevier Science Limited.

Résumé—A la suite de la construction du barrage de Diama sur le cours inférieur du fleuve Sénégal, la partie estuarienne de la vallée, la zone d'embouchure et la région côtière adjacente ont connu de rapides modifications. Dans la partie maritime, des études ont été réalisées en prenant en considération les changements morphologiques, mis en évidence par des suivis topométriques et bathymétriques et des comparaisons d'images satellitaires, ainsi que les variations granulométriques.

La situation initiale, en juin 1989, a montré une côte sableuse très dégradée. L'examen des paramètres morphologiques (pente moyenne de l'avant-côte et largeur de la plage) et des évolutions morphodynamiques (par comparaison des cartes topobathymétriques successives) indiquent que le littoral retrouve un bilan sédimentaire plus favorable dans les années qui suivent. Cependant, la partie nord du secteur, à environ 5 km de l'embouchure, accuse une tendance persistante à l'érosion que ne manifeste pas la zone sud ni la partie émergée du profil.

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Les changements texturaux montrent qu'à côté de variations saisonnières, la granulométrie des matériaux de la plage et de l'avant-côte manifeste des déséquilibres dont la dynamique est pluriannuelle.

Ces résultats semblent devoir être mis en relation avec la diminution du débit du fleuve Sénégal, le rétrécissement de la largeur de la passe d'entrée et son encombrement par des bancs sableux. © 1998 Elsevier Science Limited.

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INTRODUCTION

In November 1985, the Diama dam was built in the lower valley of the Senegal River, 100 km upstream from the mouth. The first purpose was to prevent the extension of the salt wedge which previously reached over 360 km upstream. A second objective was to retain the flood waters (from July to October) in order to improve the agricultural development of the lower and middle valley. This important change in the hydrological and hydrodynamical regime of the river was suspected to cause a major disturbance for the estuary zone.

The lower stretch of the Senegal River is diverted southward by a sand spit 30 km long, the "Langue de Barbarie" (Guilcher and Nicolas, 1954) which separates the terminal reach from the Atlantic Ocean (Fig. 1A). The spit was mainly built by sands originating from the north (Mauritania) and transported by a strong littoral drift (Barusseau, 1980).

The interaction between fluvial and marine induced sedimentary regimes is of primary importance for the evolution of the spit. Particularly, it induces temporary breachings which deeply modify the characteristics of the estuarine zone. The triggering mechanism takes place in the marine environment due to the conjunction of high sea level and strong waves, as described in the Saloum Delta (Barusseau *et al.*, 1995; Bâ *et al.*, 1995); fluvial action during flooding is also required to enlarge the breach. During the last century, Gac *et al.* (1981) counted several major marine and flood determined breaches, after which closure occurred rapidly. Generally, during the short period of breached beach barrier, the terminal mouth became narrower, due to the accumulation of sand shallows and banks. Sometimes, the southernmost part of the lower reach evolved as a lagoon, from a morphological point of view (Diop and Chevillotte, 1993).

Thus, the natural changes, in the pre-dam conditions, revealed the high sensitivity of the mouth and nearby coastal region to any change in the sedimentological and hydrological regime of the Senegal River, at a decennial to secular

scale. It was therefore important to study the influence of the dam construction on the morphological and sedimentological characteristics of this part of the valley and littoral zone.

HOLOCENE GEOMORPHOLOGICAL DEVELOPMENT OF THE "LANGUE DE BARBARIE"

Recent geomorphological history

The post-glacial rise of sea level is recorded since 12,000 BP in the Senegal Delta and from 8600 BP in the lower Senegal Valley (Monteillet, 1986). Increasing littoral drift due to the sea level rising at a rate of around 2.9 cm a⁻¹ contributed to the formation of prominent beach barriers around 7000 BP. The present sea level was achieved around 5500 BP and a vast lagoonal system was sheltered behind the barriers. The present sand spit (Langue de Barbarie) is more recent (Gac *et al.*, 1981). Former mouths were reported to the north of Saint-Louis on ancient maps. The mouth was close to the town during the 17th century and passed south of the town after 1850. From 1850 to 1900 the mouth extended 15-16 km southward and 7 breaches occurred. At the beginning of the 20th century, stabilisation of the dunes was attempted by planting trees (*filaios*). In 1981, the total length of the spit south of Saint-Louis was 21-22 km and 13 breaches had been reported between 1900 and this date. Only six of them were of significant duration and extension, during a 14-yr period corresponding to the alternation of strong and weak floods in connection with a high energy oceanographical regime according to the Saloum model. The maximum extension of the spit seems to be about 27 km, a length observed in 1959 (Gac *et al.*, 1981).

Southward of the Langue de Barbarie area, the coastline has shown an alternation of erosional and progradational periods. A long-term receding trend is suspected on a regional scale (Barusseau, 1985) but cannot be confirmed.

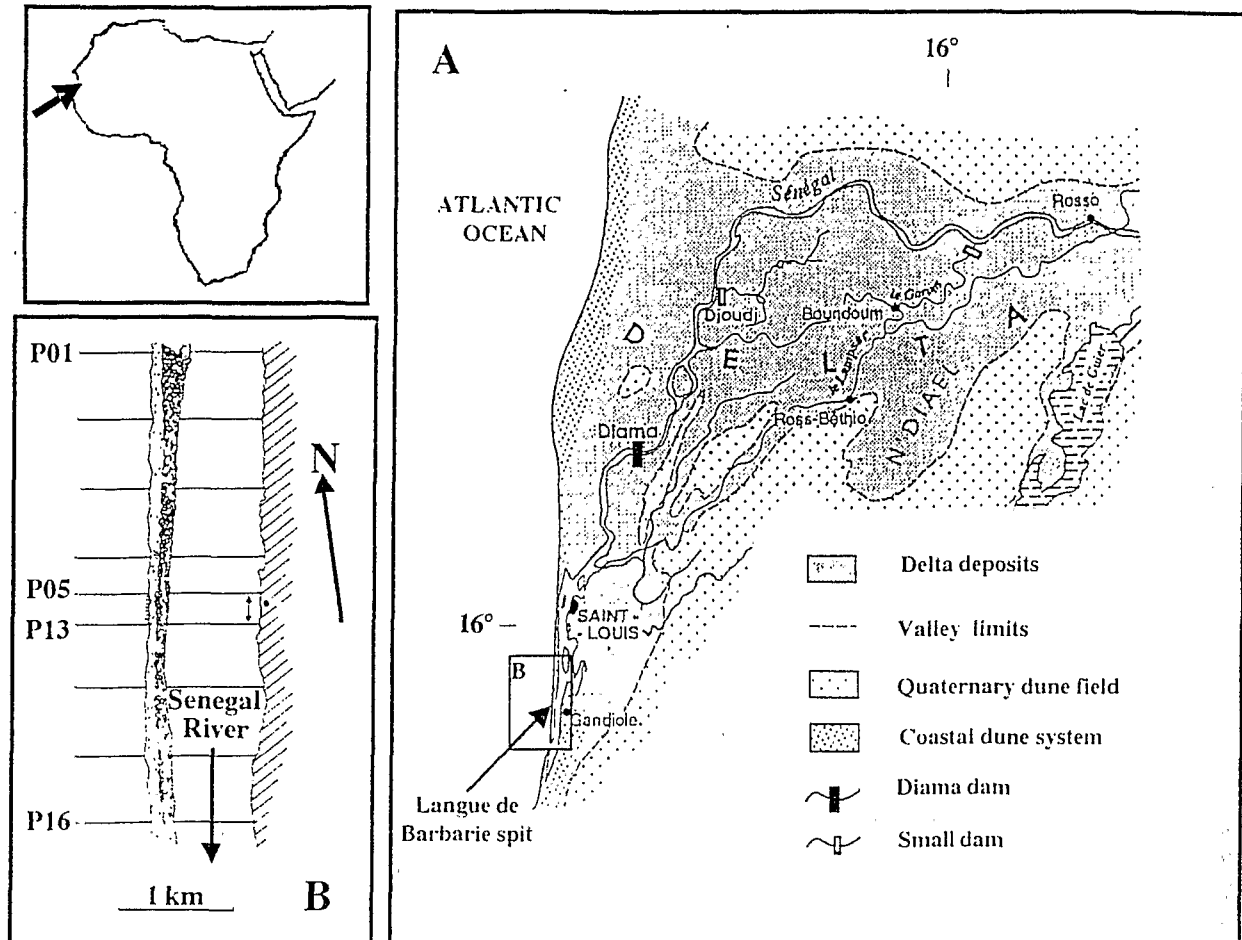


Figure 1. Location of the studied area. (A) General sketch. (B) Location of the profiles (P01 to P04: northern zone; P05 to P13: central close profiles 50 m apart; P14 to P16: southern zone).

Morphodynamical factors

Coastal sedimentary balance is largely controlled by oceanographical and meteorological factors. Tides are semi-diurnal on the Senegal coast, the tidal range is microtidal (1 m in spring tide and 0.5 m in neap tide). Tidal currents are only significant off Cap-Vert (40 cm s^{-1}); towards the north, they quickly weaken so that the residual currents are largely determined by the general circulation: the Canary current flowing southward and the opposite Guinea counter-current. Offshore Mboro, to the south of the study area, the SOGREAH (1981) measured, at a 9 m-depth, an average velocity of between 2 and 10 cm s^{-1} from December-January (faster) to April-May (weaker). Maximum velocities were between 17 and 32 cm s^{-1} and the current direction was parallel to the shore.

Prominent waves come from the northwest ($N320^\circ$ to 360°). During the monsoon time (summer), waves come from the southwest during a quarter of the time (NEDECO, 1973; Barousseau, 1980; SOGREAH, 1981), although,

according to a more recent study of wave data recorded by UTIS-ORSTOM/ISRA (Bâ *et al.*, 1995), these waves occurred only 16% of the time, northward to the Cap-Vert Peninsula. The significant height (H_s) rarely exceeds 3 m and maximum heights (1.5 times H_s) generally occur during October-November, coming from the north. According to NEDECO (1973), the wind action locally reinforces the wave height. From 2500 observations of the Deutscher Wettendienst, the most frequent wave heights are between 0.75 and 2.25 m. About 75% of all waves recorded had periods of between 2 and 16 seconds. Waves from the north are well represented in both the dry and the wet seasons. Waves from between $N180^\circ$ - 240° occur during the wet season only.

Longshore currents resulting from the wave action are generally directed southward. Associated rip-currents occur regularly, producing very rough bottom topography with 6 to 10 channels normal to the shore, 0.6 to 1.3 m deep and 3 to 5 m wide (no observation

Table 1. Fluctuations of the shoreline location (in metres) in relation to the situation of June 1990

Profile nb	1/10/89	1/6/90	1/10/90	1/6/91	1/11/91
P01	31	41	123	41	31
P05	41	51	72	72	-31
P06	00	20	41	82	51
P07	62	51	82	82	72
P08	72	41	72	51	62
P09	00	-10	00	0	-10
P10	-10	31	-10	0	41
P11	00	123	93	93	113
P12	-5	10	00	-10	-5
P15		41	20		51
P16		00	-31	-82	
mean width	21.2	39.9	46.2	36.5	41.7

The values in italics correspond to a shoreline recession on the profile at that time.

about the length). Mean longshore current velocity is about 0.30 m s^{-1} , close to the estimate of 0.2 to 0.5 m s^{-1} given by NEDECO (1973) according to the Eagleson formula.

Surficial hydrology is strongly affected by the wind stress, which causes the generation of compensating currents. Thus, north and northeast winds (trade-winds) move the surficial waters offshore creating a bottom flow towards the coast (NEDECO, 1973).

METHODS

A study has been carried out, to the north of the mouth, from 1989 to 1992. A set of 16 landmarks was set up and morphological profiles were measured twice a year from the top of the beach barrier to a depth of 10 m (Fig. 1B) and, similarly, on the other side of the beach barrier, in the Senegal Estuary. The profiles were 1 km apart in the northern and southern parts of the investigated coastline stretch (P01 to P04 and P14 to P16) and only 50 m apart in the central zone (P05 to P13). Morphological measurements were carried out with a Geodimeter 140[®], allowing an accuracy of $\pm 5.10^{-4}$ grade on the angles and ± 1 cm on the distance and elevation values. The Gandiole lighthouse was used as a reference for horizontal angle measurements. Sounding was performed with a Fuso-200[®] sounder at a maximum ± 15 cm accuracy and measurements were synchronised through VHF sets. The results were recorded through automatic 2D and 3D mapping. Comparisons between profiles were

made using depth measurements recorded in two successive surveys. The volume of sediment changes, by metre alongshore, was computed assuming a linear variation between two adjacent profiles.

On the profile tracks, sediments were recovered by scuba divers, before and after the wet season (July to September) according to the bathymetry. From June 1990 to November 1991, four sediment sets were collected for a grain size study aimed at defining the median (ϕ notation), sorting index (ϕ) σ_s , skewness index (ϕ) SK_s and kurtosis index (ϕ) K_G .

A remote sensing analysis was also carried out on two SPOT multispectral scenes for the region located between the Diama dam and the Senegal River mouth ($16^{\circ}05'N$ - $16^{\circ}25'W$): the first (O21-318, October 1st, 1986) a few months after the construction; and the second (O21-318, November 28th, 1990) 5 years after. The processing ("Planete"™ program) enabled analyses to be made using classification, false colour representations, filtration and comparison. In all cases, numerical evaluations in each channel were used without any correction of the atmospheric effects, always low in the northern part of Senegal.

RESULTS

Morphological observations

On the fluvial side of the beach barrier, slopes were regularised during the study period and maximum depths decreased by 1 m. Deposits were mainly observed on the left (eastern) bank,

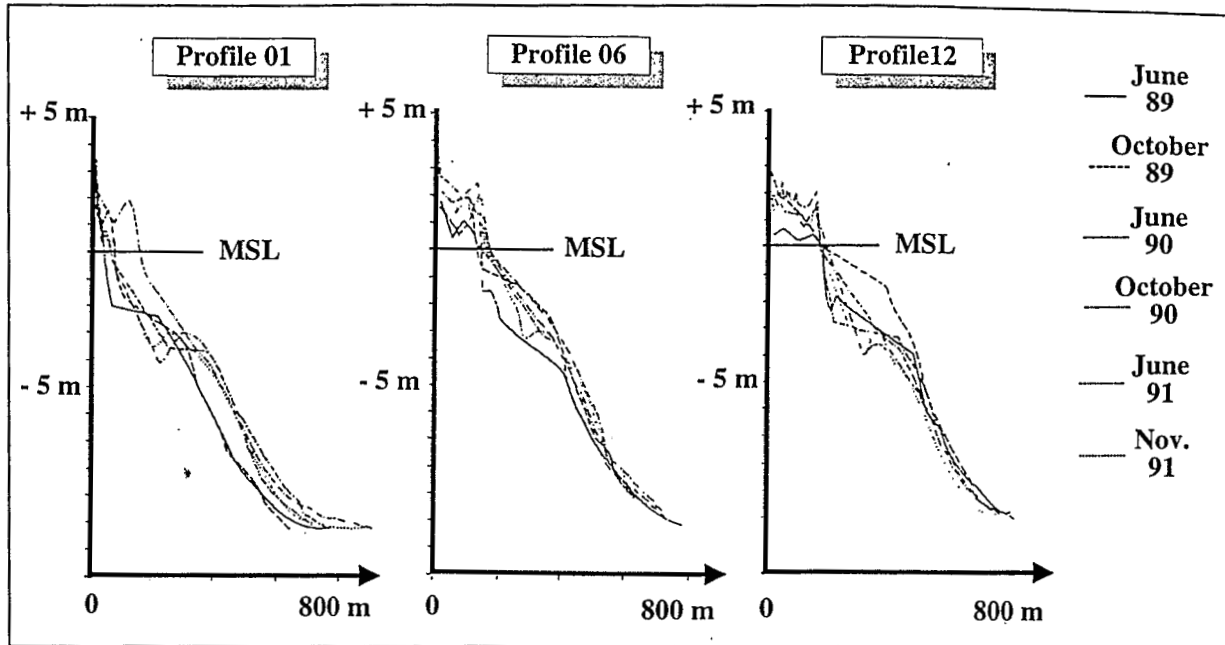


Figure 2. Variations of the aerial and submerged topography for 3 selected profiles.

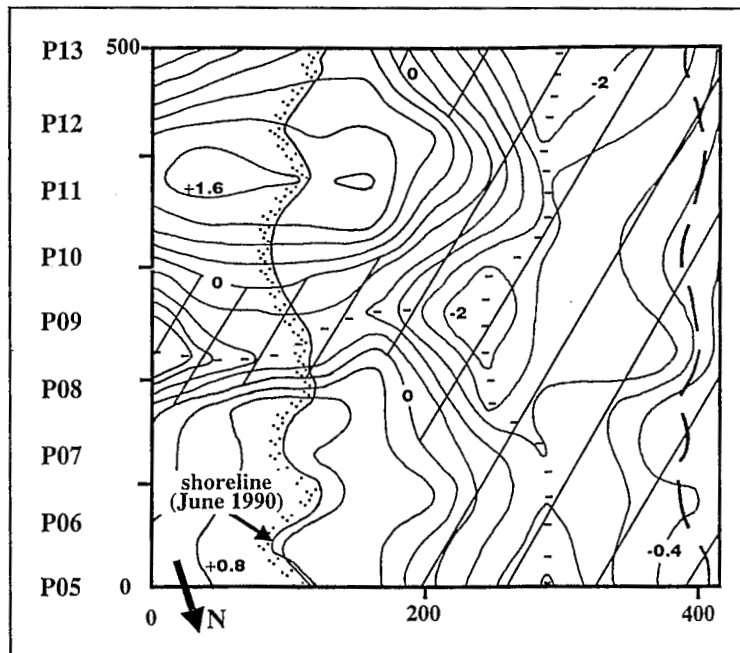


Figure 3. Changes in sediment thickness from the comparison of topometric and bathymetric measurements made in the close profile area on October 1989 and June 1990. The hatched area shows the aerial and submarine zones which displayed a negative sedimentary balance between October 1989 and June 1990. "-" corresponds to the lines of maximum erosion. The sketch shows the continuity of erosional and depositional patterns through the shoreline. The dashed line on the right side corresponds to the average position of the offshore bar crest or the location of the slope break. Main erosional and depositional changes occurred between this line and the upper beach.

Table 2. Grain-size parameters in relation to depth on June 1990, October 1990 and November 1991

Date	Profile nb	Depth (m)	P50	SIGMA	SK ₁	K _G
June 90	P01	0	1.75	0.38	-0.1	1.27
	P05	0	1.8	0.45	0.14	1.35
	P09	0	0.6	0.68	-0.37	1.2
	P12	0	1.65	0.44	0.09	0.82
	P16	0	1.75	0.49	-0.13	1.52
	P01	0.5	2.2	0.42	-0.05	0.79
	P09	0.5	2	0.26	0.06	0.82
	P12	0.5	1.75	0.45	0.13	0.76
	P16	0.5	1.1	0.87	-0.24	0.98
	P01	-1	0.25	1.22	-0.13	1.21
	P05	-3	1.95	0.6	0.13	1.54
	P09	-3	2.65	0.49	-0.13	1.64
	P12	-3	1	1.23	-0.23	1.26
	P05	-3.5	1.3	0.79	-0.13	1.37
	P01	-4	2.75	0.35	-0.01	1.43
	P05	-5	2.6	0.55	-0.15	1.64
	P12	-5	2.5	0.53	-0.09	1.26
	P01	-6	1.65	0.45	-0.05	1.43
	P09	-6	2.7	0.43	-0.1	1.39
	P01	-10	3.5	0.2	-0.12	4.51
P05	-10	3.1	0.47	-0.15	0.74	
P09	-10	3.5	0.26	-0.5	1.57	
P12	-10	3.5	0.22	0.05	4.51	
October 90	P01	0	1.85	0.41	0.13	0.79
	P05	0	2.25	0.55	-0.5	1.17
	P09	0	1.9	0.38	-0.5	0.6
	P12	0	1.75	0.42	0.07	0.79
	P16	0	2.6	0.34	0.06	1.51
	P01	0.5	2.2	0.35	-0.24	1.09
	P05	0.5	2.1	0.33	0.16	1.09
	P09	0.5	2.1	0.31	-0.07	1.23
	P12	0.5	2	0.33	0.39	0.82
	P16	0.5	2.15	0.38	-0.07	1.07
	P09	-4	1.85	0.92	-0.19	0.9
	P05	-5	2.5	0.79	-0.52	2.05

whereas the right bank was slightly eroded during floods between 1989 and 1991.

In the marine compartment, three sections may be normally distinguished in a profile perpendicular to the coast in the Langue de Barbarie area: the beach and beach barrier; the foreshore; and the nearshore. The first two are subjected to important morphological changes, whereas the nearshore is generally more weakly modified. The offshore limit of the foreshore zone is marked, at a 3-4.5 m depth, by a local decrease in the slope and sometimes by a

sedimentary bar, parallel to the shore and never more than 1 m high, which may be considered as an offshore bar.

There is a progressive change of the average foreshore slope alongshore. The slope is greater in the northern part of the study area (.017 to .019) than in the central (.014 to .016) and southernmost sections (.009 to .014).

Changes in the shoreline location were studied in relation to the position in June 1989 (Table 1), a period during which the coast underwent a maximum recession for most of the profiles.

Table 2. continued

Date	Profile nb	Depth (m)	P50	SIGMA	SK ₁	K _G
October 90	P09	-5	2.5	0.96	-0.35	1.9
	P12	-5	2.35	1.15	-0.48	1.29
	P16	-5	2.55	0.54	-0.38	1.84
	P05	-10	3.5	0.2	0.14	4.3
	P09	-10	3.25	0.28	0.5	0.59
	P12	-10	3.5	0.33	-0.83	1.23
	P16	-10	2.8	0.41	0.44	1.09
June 91	P01	0	0.15	1.72	-0.04	0.65
	P09	0	-0.5	2.48	-0.14	0.68
	P01	-3	2.75	0.5	-0.25	1.08
	P16	-3	1.45	0.99	-0.1	0.83
	P01	-6	3	0.29	-0.15	0.82
	P09	-6	2.9	0.31	-0.02	0.52
	P16	-6	3	0.36	-0.23	1.07
	P01	-10	3.4	0.28	-0.33	2.05
	P09	-10	3.5	0.15	0.05	1.5
	P16	-10	0.15	1.97	-0.21	0.76
November 91	P01	0	1.7	0.52	-0.23	4.26
	P05	0	1.5	0.73	-0.39	2.17
	P09	0	1.5	0.44	0.4	0.68
	P01	-3	1.95	0.74	-0.2	1.46
	P05	-3	2.25	0.38	-0.06	1.27
	P09	-3	2.4	0.7	-0.43	1.08
	P12	-3	2.5	0.51	-0.57	1.13
	P15	-3	2.2	0.5	-0.26	1.2
	P01	-5	2.25	0.34	0.07	1.13
	P05	-5	2.25	0.29	0.05	1.02
	P09	-5	2.1	0.36	-0.07	0.98
	P12	-5	2.1	0.42	0.09	0.91
	P15	-5	2.25	0.37	0.08	1.15
	P01	-10	2.8	0.35	0.7	1.72
	P05	-10	3.15	0.49	-0.23	1.59
	P09	-10	2.9	0.3	0.09	0.42
	P12	-10	2.75	0.34	0.42	0.68
P15	-10	2.7	0.54	-0.25	1.56	

From this state, the shoreline was prograding irregularly both in space (a majority of profiles were prograding but the beach width was becoming narrow in others) and time (the mean width varied from smaller values at the end of the dry season to larger ones at the end of the wet season). However, at the end of the period (2.5 years), the average total change was a progression of the shoreline for the whole section (41.7 m).

Fluctuations of the shoreline were accompanied by changes of the profile normal to the shore (Fig.

2). The beaches, at the beginning of the period, were narrow and generally low. The upper beach was steep in order to join the dune toe. Some profiles showed longitudinal furrows at a level lower than the coeval low tide level. The berm was about 2 m above the low tide level and the swash zone was about 30 m wide with a slope as great as 5-7%.

Due to generally multiple high breakers and the wide breaker zone, sounding was difficult or impossible between the shore and the offshore zone down to -2 m. The bottom line

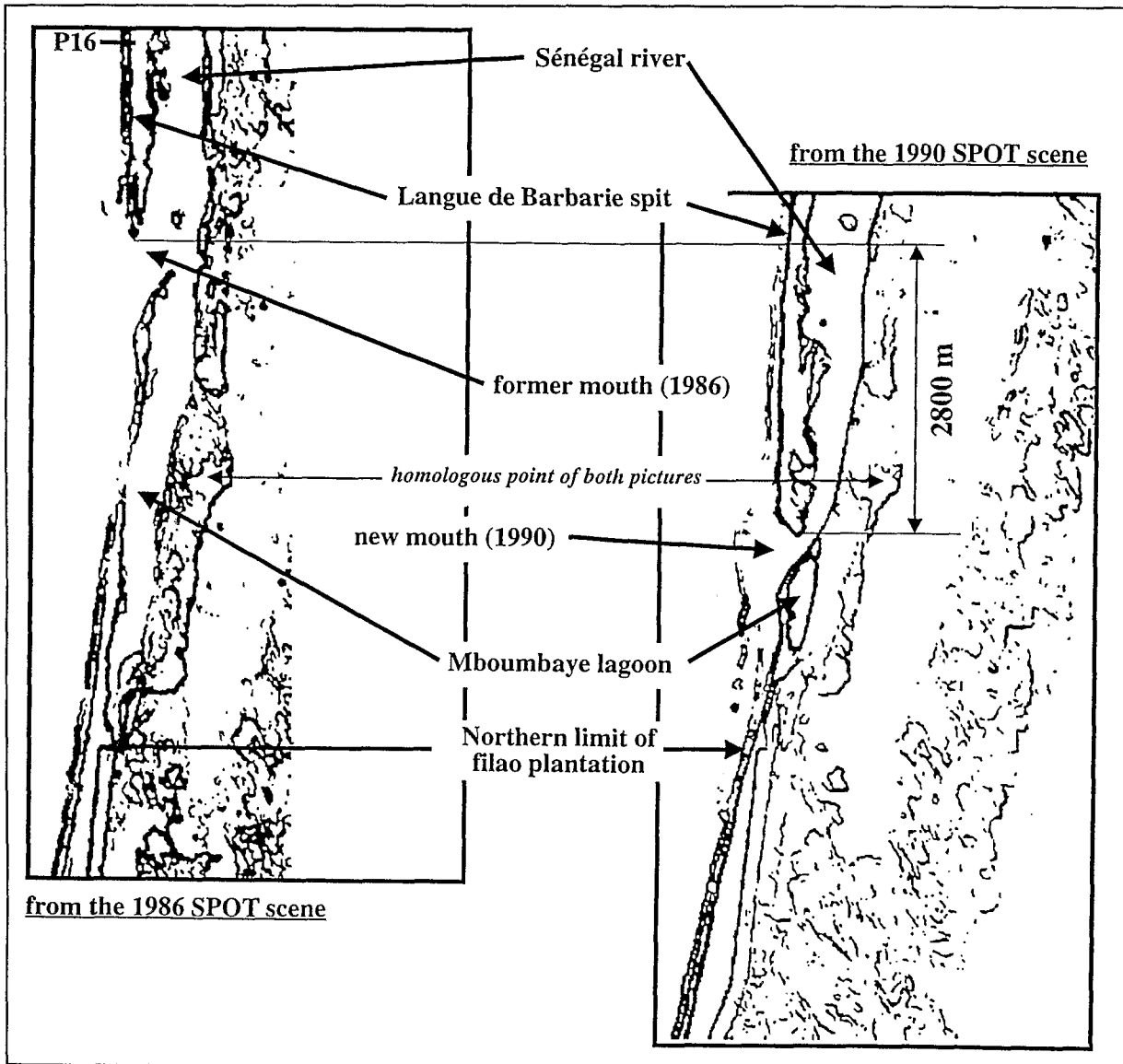


Figure 4. Variations of the mouth morphology between 1986 and 1990. The location of the displayed area is given in Fig. 1. Both sketches are arranged in order to locate homologous points at the same latitudinal position.

on the figure is consequently interpolated between the distal point measured on the beach profile and the proximal point measured on the marine profile.

Sometimes profiles showed a transitory offshore bar (20% of the cases) of low relief culminating at -3 m in the northern part and -4 m in the southern part. It was observed both in June 1990 and November 1991, in the dry and wet seasons, respectively. When the offshore bar did not occur, a slope change was located at the same position. This part of the profile was the most fluctuating one. Lower than -10 m, the depths were fairly constant during the 3-yr period of the study. In spite of the very simple form of the profiles, changes in time and

space were very frequent, with alternations between erosion and deposition stages.

The comparison between two consecutive topobathymetric surveys was carried out from the topometric and bathymetric data. For instance, in October 1989 and June 1990, exchanges occurred between the aerial part of the profile and the inner part of the shoreface (nearshore and foreshore), as displayed by the continuity of isolines of change rate through the shoreline (Fig. 3). They mainly led to an accumulation on the beach and a correlative erosion of sediments on the nearshore. In the aerial part of the close profile area (P05 to P13), the sedimentary budget between June 89 and November 1991 was positive (+1700 m³ per metre alongshore).

Sedimentological observations

Sediments in the estuarine reach of the fluvial valley exhibit no significant changes from those in the pre-dam period. The most important characteristics of the sediment are the identical grain size parameters in both the fluvial and marine environments, emphasising the dependance of the sedimentary influx on the littoral drift. In the estuary zone this dependance is increased during the post-dam period, registered by the microfaunal composition, which becomes richer in marine forams (Monteillet *et al.*, 1990).

The grain size analysis results for sediments from the marine reaches are presented in Table 2. The materials fine in an offshore direction and are characterised by the general relation:

$$Md_{\phi} = 0.1225d + 1.875 \quad (1)$$

where Md_{ϕ} = median in phi units; and d = depth in metres. However, the points are scattered at around -3 m where the temporary offshore bar or the point of slope change occurs. In the same areas, sorting decreases and, in most instances (37 out of 51), skewness shows that the coarse grain size half-distribution has better sorting than the fine one. In 43 cases out of 51, the distributions are leptokurtic with an excess of grains in both grain size tails compared to a normal distribution fitted to the central part of the grain size. Discrepancies are observed only on the lower beach and for sediments at -10 m.

By comparing the grain size structure changes (at -10 m, -5 m and 0 m), the temporal evolution of grain size at a given morphological level may be conceived as a slight and progressive deformation of the curve, modifying the frequency of each grain size interval. In some grain size categories the frequency increases, in others it decreases and, between these, the proportion of some grain diameters are unchanged. The balance between increased grain size intervals and diminished ones is generally not seasonally equilibrated but compensation occurs on a yearly or, more often, on a multi-yearly cycle.

The simpler case is exemplified at P09 (-10 m). Between June 1990 and November 1990 (wet season), the observed change is a decrease of the 62-100 μm fraction (maximum decrease at 80 μm) and an increase of the 100-250 μm fraction (maximum increase at 125 μm). The mobilised fraction is characterised by a Gaussian distribution centered on a 3.45 Φ (91.5 μm) modal value and $\sigma = 0.15 \Phi$ (Barusseau *et al.*, *in prep.*). The narrow dispersion of the extracted

sediment would mean a great selectivity of the eroding processes between the two samplings. During the next dry season (November 1990-June 1991), the disturbance was strictly compensated and the grain size changes at this site responded to the seasonal alternation of wave regime. More often, the disturbance was not equilibrated at the end of the first annual cycle. At P01 (0 m), and P09 (0 m, -5 m), the initial grain size was recovered only after the second wet season. In the northern part at the end of the studied period (at P01: -10 m; and P05: -5 m), the sediment had not yet recovered the fractions lost after the wet season of 1989.

Remote-sensing observations

Between 1986 and 1990 significant changes occurred in the mouth area south of the studied zone, as shown by morphological and sedimentological techniques (Fig. 4).

The 1990 scene shows mouth bars and shallows emerging at low tide, which partially closed the mouth (120 m *viz.* 360-400 m on the 1986 scene) and prevented a large development of the previously obvious flood plume.

The Langue de Barbarie spit greatly increased in length between 1986 and 1990 (2800 m) and its distal tip widened. Consequently, the former relict Mboumbaye lagoon was completely isolated from the fluvial and marine waters.

DISCUSSION AND CONCLUSION

As a tropical savannah river, the Senegal River contributes a terrigenous input, mainly as suspension load during floods (Probst, 1992; Mahé, 1993). This fluvial input is quantified at 0.9 to 1 $\times 10^6 \text{ t a}^{-1}$ (Ostenfel and Jonson, 1972). The suspensions are made of clay sized particles with an important very fine silt fraction (5-7 μm ; Gac and Kane, 1986a, b), but this suspended matter has no influence on the littoral sedimentary budget of the wave-dominated coast of the Senegal Delta. The coarser sediment load is less well studied as the bedload is difficult to assess. However, although the sand input played a significant role in the delta construction by feeding successive Holocene beach barriers (Monteillet, 1986), various observations in the modern environment show that the present sediment transport is less dependant on this fluvial contribution. The textural compositions of the sediments on both sides of the beach barrier indicate that the marine sand input, through littoral drift moving from north to south, is the main contribution to the spit construction.

This marine sand contribution is estimated, at this part of the West African coast, as between 0.5 and 1×10^6 t a⁻¹ (Pinson-Mouillot, 1980; Barusseau, 1980). In this respect, the post-dam situation is not strongly modified.

On the other hand, the hydrodynamic regime in the outer estuary region has been greatly changed, as demonstrated by the morphological reworking of the banks, probably due to the diminution of the cross-section and the mouth area. The fluvial influence has been greatly attenuated so that the major transformations resulted from the dominating action of the marine factors.

Consequently, the northern part of the sand spit shows a slight disequilibrium exhibited by the sub-aquatic parts of the profiles which are eroded, while the southern part of the spit evolves by high accretion extending the spit towards the south.

The time-integrated curves for each profile of the central part of the studied area give an average profile where depth is a function of distance (Quellenec, 1984). Two relations $y = ax^b$ may be described on each side away from the point of slope change.

i) shoreface: $y = 0.10$ to $0.15x^{0.50}$ to 0.65 ;

ii) nearshore: $y = 0.20x^{0.50}$ to 0.60 ,

where y = depth (in metres) and x = distance from the shoreline (in metres).

Parameters a and b are related in terms of erosion, equilibrium or depositional regime and, according to the reported values (Quellenec, 1984), the Senegalese coast northward of the river mouth tends to be undergoing erosion to the north as well as in the deeper parts of the shoreface, while accretion is prominent to the south.

Therefore, in spite of the short term nature of the data, it may be concluded that the forcing induced by the estuarine behaviour of the lower stretch of the Senegal River, down-current from the Diama dam, has greatly disturbed the mouth topography and coastline equilibrium. The marine factors have been reinforced, entailing the lengthening of the Langue de Barbarie beach barrier, the narrowing of the mouth and the accumulation of mouth bars. The morphological and sedimentological disturbances in the mouth region contributed to the generation of instabilities in the northern part of the studied area.

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