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Coastal Erosion, Processes and Rates: An Historical Study of the Gironde Coastline, Southwestern France

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ABSTRACT

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The macrotidal (2–5 m range) Gironde coast, situated to the south of the Gironde estuary, is dominated by NW swell. The prominent cape Pointe de la Négade separates two linear sections of this coastline, with different orientations and different dynamic settings: a northern section, dominated by a maximum resultant northerly longshore drift (400,000 m^3/yr); and the southern section, by a 630,000 m^3/yr southerly drift.

A synthesis of numerous studies allows erosion over (at least) the past 37 years to be estimated; for certain sections for the past 200 years. The average rate of erosion decreases on both sides of the Pointe de la Négade, where it reached its maximum between 1957–1994 (7.3 m/yr). The northern section, protected by dykes and sea defences between the estuary mouth at Pointe de Grave and Soulac, has been stabilised. Today, only the limited area of the Huttes is not protected and is subjected to erosion of 9.6 m/yr; it is a area of great concern. To the south, the average rate of erosion decreases rapidly—it reached 0.4 m/year in Montalivet—and then was relatively constant around 1 m/year as far as the Grand-Crohot. The extremity of the Cap-Ferret spit has been generally accreting to seawards; it has also extended to the south, for the past 200 years. Since 1970, the tip of the spit has undergone erosion.

Erosion of the Gironde coast results from a sedimentary budget in deficit by some 350,000 m^3/yr escaping northward (the difference between the northerly longshore drift (400,000 m^3/yr) and 50,000 m^3/yr retained in the system by the process of erosion/accretion of the Huttes beach and St Nicolas sandbank) and 630,000 m^3/yr transported toward the south. Aeolian loss appears minimal and offshore loss, due to relative sea-level rise, is estimated to be between 600,000 and 900,000 m^3/yr. The system receives no fluvial supply of sand and the primary source of sediment originates from coastal erosion, mobilised by longshore drift. Total sediment loss for the Gironde coast ranges between 1,580,000 and 1,880,000 m^3/yr; this explains the average erosion rate, of between 1 and 2 m/yr. Whilst the longshore transport is quite well known, the onshore-offshore movements, especially those caused by the present-day sea level rise and/or aeolian action, are still poorly understood and require further investigation.

ADDITIONAL INDEX WORDS: *Longshore drift, sedimentary budget, sea defences.*

INTRODUCTION

The understanding of the natural functioning of the coastal environment and of regional trends and processes in shoreline changes is necessary for coastal planning (LEATHERMAN, 1983; BYRNES *et al.,* 1991, 1995; CROWELL *et al.,* 1993; VILES and SPENCER, 1995; HOWA, 1997) and shoreline position prediction (DOUGLAS *et al.,* 1998).

About 20% of the world's coasts are sandy and 70% of these are undergoing erosion (SHEPARD and WANLESS, 1971; MORTON, 1979; BIRD, 1985). Causes of this phenomenon can be classified into two categories (MORTON, 1979; VILES and SPENCER, 1995; MCBRIDE and BYRNES, 1997): (1) natural causes related to sea-level rise, change in wave regime (increased storminess) and/or reduction in sediment supply, (2) anthropogenic causes, which may be direct (construction of sea defences, sand extraction, river damming) or indirect (resulting from climatic changes).

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Generally, beach erosion is the result of a negative sediment balance when there is a smaller quantity of sediment entering than leaving the coastal system (KOMAR, 1983; U.S. ARMY CORPS OF ENGINEERS, 1984.). However it is difficult to provide a completely accurate estimation of the total amount of sediment in transit.

Over the past 40 years many studies have been carried out around the world on historical shoreline movement (*e.g.* MORGAN and LARIMORE, 1957; EDELMAN, 1967; MORTON, 1979; LOTFY and FRIHY, 1993; OYEGUN, 1993; MCBRIDE and BYRNES, 1997; SUANEZ and PROVANSAL, 1998), but relatively few studies have been devoted to the establishement of the budget of littoral sands (CHAPMAN, 1981; HOWA, 1985, 1997). In France, few syntheses of this type have been undertaken, at a regional scale (BELLESSORT and MIGNOT, 1987; LORIN and VIGUIER, 1987; PASKOFF, 1993). However, the effectively linear Aquitaine coastline has a favourable situation and shape for this type of work (Figure 1); its erosion was evaluated systematically during the 1980s (LORIN *et al.,* 1979; LORIN and MIGNIOT, 1982, 1985; PÉNIN, 1980; HOWA, 1987).

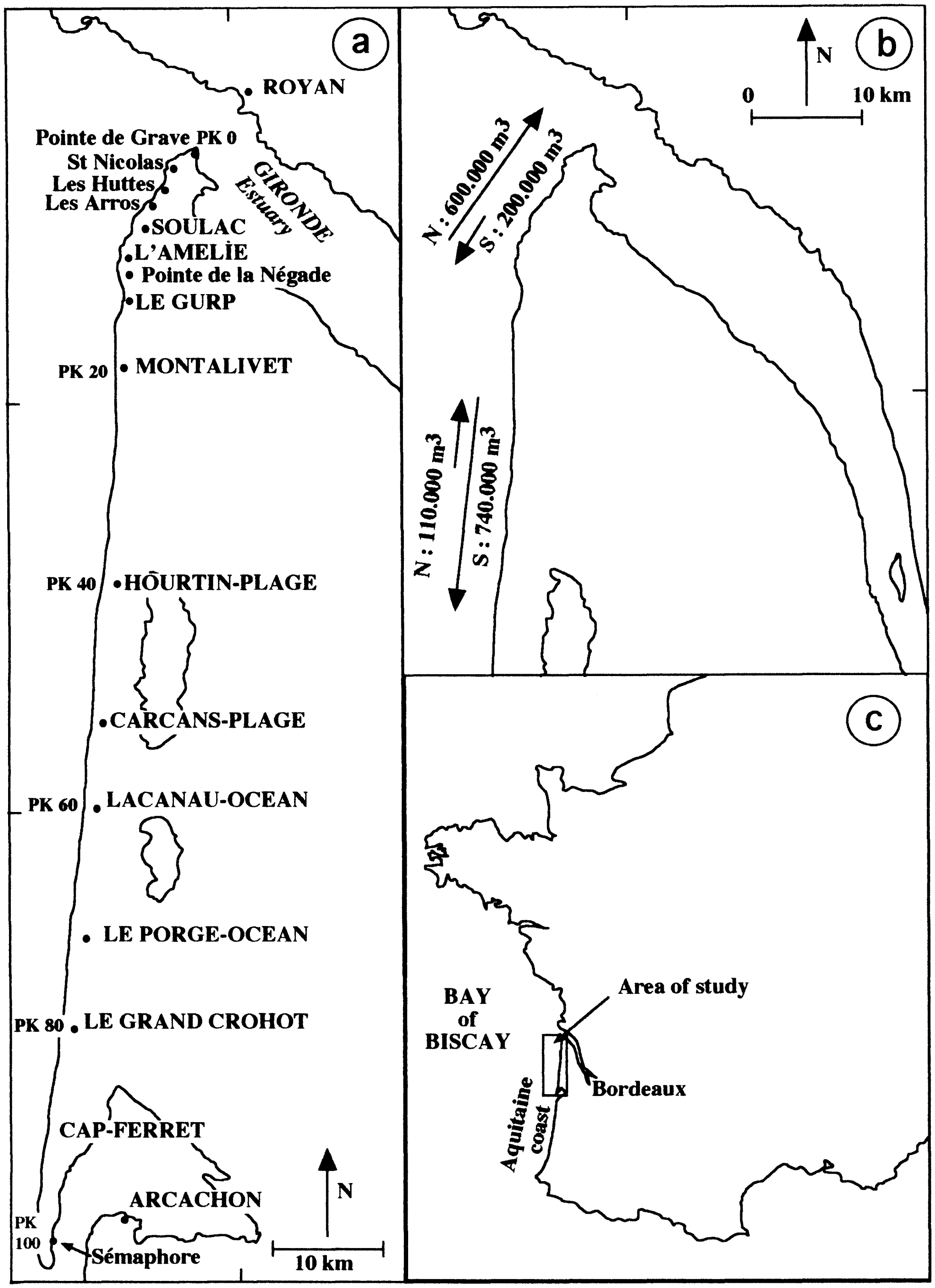

Figure 1. **1a**: The study area; **1b**: Annual longshore drift along the Gironde coast (after LORIN *et al.,* 1979); Note: PK is a kilometric system of reference, starting from the Pointe de Grave (PK 0); **1c**: Regional location of the study area.

None of the aforementioned studies have been totally comprehensive, in order to be able to propose a conceptual model of the sediment budget for the whole of the Gironde sector of this coast; this represents the northern part of the Aquitaine coast, a continuous sedimentary entity, between the mouth of the Gironde estuary and the inlet of the Arcachon lagoon (Figure 1). More than 10 years have elapsed since the last regional study and this contribution presents a new synthesis of the evolution of the Gironde coast, over the past two centuries.

Presently, sediment movements along the Gironde coast are considered to be the result of the combined action of (LORIN *et al.,* 1979): (1) longshore drift removing sediment and transporting it alongshore; (2) aeolian transport; (3) onshore-offshore exchange, between the shore and the nearshore zone; and connected with the slight increase of sea level.

The objectives of the contribution are:

(i) to provide an assessment of the factors affecting change and erosional processes and their intensity, along the northern part of the Aquitaine coast;

(ii) to compile the available data on shoreline movement;

(iii) to discuss the impact of sea defences protecting the coast and, especially, those protecting the coast to the south of the mouth of the estuary; and

(iv) to propose a conceptual model of the sedimentary balance which is the most influencial factor affecting coastal evolution (CARTER and WOODROFFE, 1994; MCBRIDE and BYRNES, 1997) and one of the essential tool for a successful management of the coast (BYRNE *et al.,* 1991).

STUDY AREA

Geographical Setting

Although the world's population is attracted by the coastal region, with more than half inhabiting the coastal area (VILES and SPENCER, 1995), the French Aquitaine coast is one of the Europe's less populated regions (348,000 people). However, as a tourist attraction there is an average increase of population of more than 150% during July and August: some of the smaller towns, such as Soulac-sur-Mer, can see their population multiplied by 10 (TARRICQ PH., Regional Commitee of Tourism, pers. comm.). The littoral zone is strewn with isolated bathing stations most often settled on the foredune; consequently, these stations are especially sensitive to changes in the shoreline position.

The Aquitaine coast is a 240 km long low coast, bordering the Bay of Biscay in southwestern France (Figure 1). Between the mouth of the Gironde estuary, in the north, and the mouth of the Adour river, in the south, this represents 5% (and the least protected part) of the total length of the French coastline. The coast is bordered inland by a forested complex of Holocene dune systems, isolating several coastal lakes (TASTET and PONTEE, 1998); this enhances the attraction of this region for tourism and recreation (MIGNIOT and LORIN, 1978). This long beach-dune sandy barrier is only interrupted by the inlet of the Arcachon lagoon and, towards the south, by the mouths of minor channels draining coastal lakes and know locally as "courants". Most of the coast is eroding at the present time.

The study area, which extends for 100 km, is entirely situated in the "Dèpartement de la Gironde", between the mouth of the Gironde estuary (Pointe de Grave) and the Cap-Ferret spit; this lies on the northern flank of the Arcachon lagoon (Figure 1a). This continuous sandy coast, bordered by a linear foredune which is maintained artificially by the Forestry Service (O.N.F.—Office National des Forêts), is formed by two linear sedimentary cells, of different orientations. Between the cape of Pointe de la Négade and the Pointe de Grave, the orientation of the coast is N 55°; between Pointe de la Négade and the Cap-Ferret spit, the coast is oriented approximately N-S (N 7°).

Sediment Supply

The major present day sediment sources for beach development are the riverine discharge and the up-drift shoreline erosion supplying the littoral drift (BIRD, 1969; MORTON, 1979).

The average annual discharge of water from the Gironde estuary, to the sea, is 990 m^3/s (NAGY BREITENSTEIN, 1993). Whereas the fluvial supply of sand to the coast is almost zero (LESUEUR *et al.,* 1996), an average of 1.5×10^6 t/yr of fine suspended sediment from the estuary is dicharged onto the adjacent continental shelf (CASTAING, 1981; NAGY BREITENSTEIN, 1993).

The tidal prism of the Arcachon inlet is, on average, 250×10^6 m^3 for a semi-diurnal tide (ORGERON, 1974; GASSIAT, 1989; BABIN, 1990). However, the amount of sediment which escapes to the adjacent marine areas from this lagoon is very limited since almost all the sand brought by rivers, is trapped in the inner bay-head delta (CUIGNON, 1984). Sand delivered to the lagoon mouth by longshore drift is partly trapped in the ebb tidal delta at its mouth (ARBOUILLE, 1987; MICHEL 1997); however, large quantities of sand bypass this feature, to continue there drift along the coastline.

Dynamic Setting

The dominant dynamic factors affecting the Aquitaine coast are the wind, oceanic swells, and the consecutive littoral drift, tidal action and the present day sea-level rise. They are outlined and discussed below.

Winds

The most frequent and the strongest local winds come from WSW and NNW. The extensive development of a coastal dune system represents the intensity of aeolian transport during the historical development of the coast. So, aeolian transport cannot be disregarded, and this has been given great prominence by many past workers (FROIDEFOND, 1985; FROIDEFONDm and PRUD'HOMME, 1991; PASKOFF, 1993; HOWA, 1997).

FROIDEFOND and PRUD'HOMME (1991) have estimated a landward aeolian flux of sand, of 15 to 30 $m^3/m/yr$, along the Gironde coast. These results are similar to those described by earlier authors (BRÉMONTIER, 1797; BUFFAULT, 1942; LAVAL, *in* BELLESORT and MIGNIOT, 1987; HANLÉ E. and HANLÉ J., *in* BELLESORT and MIGNIOT, 1987). If an average value of 20 $m^3/m/yr$ is used for the study area, the total landward transport of sand would be around 2 million m^3/yr.

Comparison of dune profiles, obtained between 1967 and 1979 along the Gironde coast (LORIN and VIGUIER, 1987), together with more recent field observations do not confirm such active dune development as proposed above. Contemporaneous landward aeolian transport is not effective in removing sand from areas of erosion of the coastline. However, these earlier estimates were not based upon the integration of statistical measurements of present-day morphological and dynamical relationship between beach and dune; rather they were approximations or local measurements in areas particularly exposed and vulnerable to wind action (FROIDEFOND and PRUD'HOMME, 1991). Consequently, these estimates relate more to a period before coastal dune fixation, when wind action was not hindered by the present-day vegetation; consequently, it would be inapropriate to include them in the present-day sediment budget of the Aquitaine coast.

Swell

Directions, Height and Periods. The swell waves of the Bay of Biscay are among the largest found on the French coast (VASSAL, 1980); they originate mostly from a W to NW direction. The WNW swells are the most frequent throught the year, whilst the SW directions occurs more often during autumn. The period of the swell waves is relatively long, at between 8 s and 16 s; it may reach 20 s (LORIN and VIGUIER, 1987), with an average of 12 s (PEDREROS *et al.,* 1996). The average significant swell wave height is 1.55 m (MICHEL and HOWA, 1994). During summer, from April to September, the maximum heights (H max) are lower than 2 m (75% of the time) and seldom exceed 6 m; however, the short period swell (less than 8 s) prevail for 50% of the time. During the winter storm season, from October to March, only 30% of the swell has an Hmax lower than 2 m, 35% range from to 2 to 4 m, and 9% exceed 6 m. Moreover, 52% of the swell has a period ranging from 12 to 15 s, with only 15% less than 8 s (LORIN and VIGUIER, 1987).

Sediment Movement. The currents generated by the swell are the main agents of sand transport, perpendicular and parallel to the coast. The total exchange of sediment perpendicular to the coast (onshore-offshore) has been calculated as 500,000 m^3/yr/km, based upon repeated topographic surveys (LORIN *et al.,* 1979). This movement is most important between the nearshore and foreshore zones and can be detected to water depths of 15 to 20 m. Swell, which approaches the coast obliquely, generates considerable movement of sediment parallel to the coast (KOMAR, 1983; DAVIS, 1985; BRUUN, 1995). In this region, the longshore drift (Figure 1b) has been calculated (MIGNIOT, 1977; BELLESORT and MIGNIOT, 1987; MICHEL, 1997) by the empirical formula of the L.C.H.F. (Laboratoire Central d'Hydraulique de France):

$$V = SH^2Tf(\alpha)t(Kg/c)$$

where V is the volume transported (in m^3), H is the wave amplitude h/10 (expressed in m) (h/10 is the average of the 1/10 highest waves), T the wave period (in seconds), $f(\alpha)$ a function of the angle of wave incidence at 15 m depth determined from a published Table (MIGNIOT, 1977), t is the duration of the wave action (in seconds), K is a coefficient which is a function of the grain size of the beach sand ($K = 1.8\ 10^{-6}\ D^{-1/2}$, D in mm), g is the accelaration due to gravity and c is the wave steepness.

This formula has often been verified for different areas (LORIN *et al.,* 1979; TASTET *et al.,* 1985; MICHEL, 1997).

Along the northern section, between the Pointe de Grave and the Pointe de la Négade, the longshore drift is mainly directed to the north and transports 600,000 m^3/yr of sand (Figure 1b). A reversal in longshore drift, induced by SW swell, occurs during parts of the year and has been estimated at 200,000 m^3/yr (BELLESORT and MIGNIOT, 1987). Thus, it appears that for this part of the coast, the net longshore drift is northerly at 400,000 m^3/yr (LORIN *et al.,* 1979; BELLESORT and MIGNIOT; 1987). This value, which has not been reassessed or re-examined (here or previously), has to be considered as a maximum.

Along the southern section, between the Pointe de la Négade to the Cap-Ferret spit, LORIN *et al* (1979) and BELLESORT and MIGNIOT (1987) have calculated a southerly annual longshore drift transport of 740,000 m^3 and a reverse northerly annual longshore drift transport of 110,000 m^3. Hence, for the section of the coast to the south of Pointe de la Négade, the net longshore drift is 630,000 m^3/yr. This latter value is in close agrement with a recent estimation of 680,000 m^3/yr southward, for the area to the south of Arcachon bay (MICHEL, 1997).

Tide

The tide is semi-diurnal in character and may reach 5 m in range during springs. Following the swell action, it is the second most important factor which influences coastal evolution. The tide controls the level of action of the swell, on the beach (BROWN *et al.,* 1991); it also generates strong currents in the mouths of the Gironde estuary and the Arcachon lagoon. These two features limit the continuous sedimentary body of the beach-dune barrier of the Gironde coast.

Tidal currents in the Gironde estuary have maximum velocities of 0.7 to 0.9 m/s, at 1.5 m from the bottom. Outside the estuary, velocities higher than 0.5 m/s have been measured in the nearshore, from Soulac to St Nicolas beach (HOWA, 1987). In the north pass of the tidal inlet of the Arcachon basin, flood- and ebb-tide currents may reach 1.25 m/s (THAURONT, 1994).

In addition to the astronomical tide, variations in water level occur in response to changes in atmospheric pressure and wind; these may reach 0.1 to 1 m depending on the seasons but usually occur during storms (LORIN and VIGUIER, 1987).

Sea-Level Rise

Over the last century, a rise in sea level has been observed locally and globally in several areas of the world. A recent study undertaken on tide gauge records at the mouth of the Gironde estuary (the northern limit of the Aquitaine coast) has shown a rise in the level of spring high tides of approximately 3 mm/yr, since 1913 (GUITARD, 1996); this has increased concern about coastal stability. The change in sea level can result in the appearance of gain or loss of sediment volume (U.S. ARMY CORPS OF ENGINEERS, 1984); consequently, a rise of 1mm/yr could lead to erosion along the Aquitaine coast, of 2 to 3 m^3/m/yr (BELLESSORT and MIGNIOT, 1987).

DATA AND METHODS

A compilation of all available published and unpublished documents, relating to the erosion and sedimentary dynamics of the Gironde coast, has permitted the establishment of a data base for the evolution of the shoreline over a period of

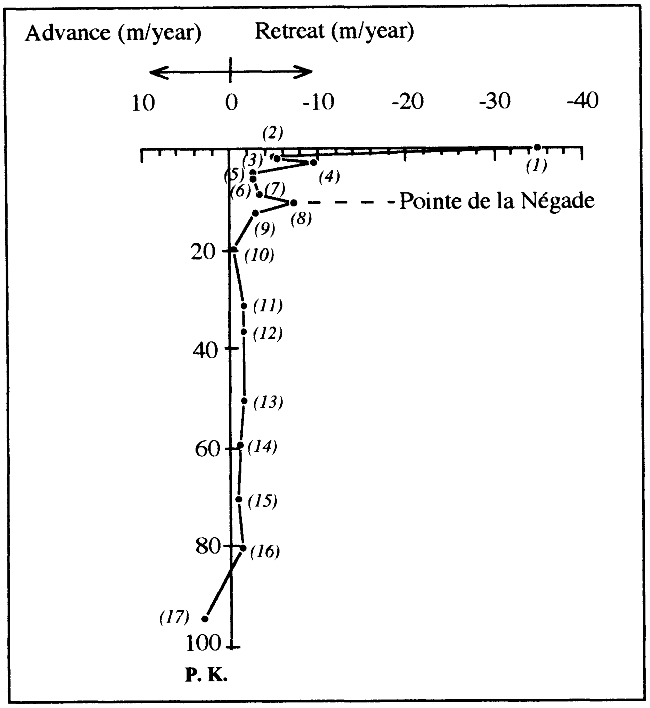

Figure 2. Temporal coastal changes (m/yr). (1): Pointe de Grave: stabilized by a sea defence in 1844; the erosion indicated corresponds to the period 1785–1844; (2): Pointe de Grave—St Nicolas: stabilized by a sea defence in 1959; the erosion indicated corresponds to the period 1785–1959; (3): Epi de St Nicolas–Huttes: retreat over 194 years; (4): Anse des Huttes: retreat over 206 years; (5): Arros: stabilized by a building in 1930; the erosion indicated corresponds to the period 1875–1930; (6): Soulac: retreat over 247 years; (7): l'Amélie: retreat over 104 years; (8): Pointe de la Négade: retreat over 37 years; (9): l'Anse du Gurp: retreat over 37 years; (10): Montalivet: retreat over 116 years; (11): Le Pin Sec: retreat over 119 years; (12): Hourtin: retreat over 165 years; (13): Carcans: retreat over 119 years; (14): Lacanau: retreat over 112 years; (15): Le Porge: retreat over 286 years; (16): Le Grand-Crohot: retreat over 288 years; (17): Cap-Ferret semaphore: shoreline movement over 214 years.

200 years (AUBIÉ, 1996). The available data, depending upon the area, corresponds to periods ranging from 37 to 288 years. From this data set, the rate of erosion has been calculated for 17 spatial sectors of the Gironde coast (Figure 2). For 16 of the sectors, the temporal coastal retreat and the southerly migration of the Cap-Ferret spit has been analysed (Figure 3). Although these data were obtained using a variety of (more or less accurate) methods ranging from old map comparisons to aerial photograph analyses, statistically they can be considered as satisfactory because the change in shoreline location is large in comparison to the error of measurement (CROWEL *et al.,* 1991).

In addition, the evolution of the shoreline over three recent succesive periods, 1967–1979, 1979–1985 and 1985–1994, has been studied (Figure 4). For the two first periods, the data used to establish coastal changes have been derived from direct field measurements. The 1967–1979 (Figure 4a) period was studied by comparison of dune and beach profiles surveyed by the Office National des Forêts (O.N.F., 1968; LORIN *et al.,* 1979). The study of changes taking place between 1979 and 1985 (Figure 4b) is based upon systematic surveys of shoreline change (LORIN and MIGNIOT, 1982, 1985).

Finally, for the 1985–1994 period (Figure 4c), changes have been assessed by comparing aerial photographs (scale: 1/5,000) taken by the O.N.F. at 27 locations *i.e.* approximately at 4 km intervals. Because the displacement of the crest of the foredune (or the top of the dune cliff) is the best indicator of erosion (PSUTY, 1988; PSUTY *et al.,* 1988), the difference between the present position of the dune top and that of World War II military buildings (blockhaus) built on the dune in 1942, have been measured. Where no military buildings were present, measurements were made to particular fixed reference points *i.e.* houses, churches, etc.. This methodology has been established as an approach to obtain data at selected points along a shoreline, when a map product is not required (LAETHERMAN, 1983; BYRNES *et al.,* 1991). On the other hand the 1/5,000 scale of the photographs has permitted a precision of less than 0.1 m/yr in the evaluation of the erosion rate (by comparison of two reconnaissances, separated by 10 years). This precision is in agreement with the most exacting standard defined by BYRNES et al. (1991).

RESULTS

Spatial Variations in Shoreline Change Rates

Except for the Pointe de Grave (Point 1, Figure 2), where the erosion was very intense before the stabilisation by a sea defence in 1844, and Cap-Ferret (Point 17, Figure 2), which is the only place in accretion, the average shoreline retreat rate fluctuate along the Gironde coast from 0.4 to 9.6 m/yr (Figure 2). The intensity of erosion shows clearly the difference in dynamics between the coast to the north and the south of the Pointe de la Négade, *i.e.* the point where the main change in the shoreline orientation occurs, separating the two different drift cells (Figure 1).

North of Pointe de la Négade

Since the last century the construction of sea defences to the north of Soulac (Figure 5) has restricted significantly the natural erosion. Indeed, the Pointe de Grave, which underwent a 35 m/yr retreat between 1785 and 1844 (Figure 3a), became stabilised by the Grave dyke in 1844. The sector between Pointe de Grave and Saint-Nicolas underwent erosion of 5.3 m/yr from 1785 to 1936 (LEVÊQUE, 1936). The zone between the extremity of the La Claire break-water (Figure 5) and Saint-Nicolas was recently stabilised (1959), this is in contrast to the erosion which took place from 1785 to 1959, of 5 m/yr (BUFFAULT, 1929; CASTAING and HOWA, 1985). Since 1964, the Saint-Nicolas beach has prograded considerably—Figure 3a- (HOWA, 1987; RUFINO DOS SANTOS and PINOT, 1990; PEDREROS, 1994).

On this coast, which has been well protected over the past 150 years, the slight embayment of the Anse des Huttes (Figure 1a and 5) is the only section not to have been managed; it experienced an average erosion of 9.6 m/yr between 1785 and 1991—Fig. 3a- (LEVEQUE, 1936; MESNAGE, 1982; HOWA 1985, 1987). The present-day erosion rate is 5 m/yr (1984–

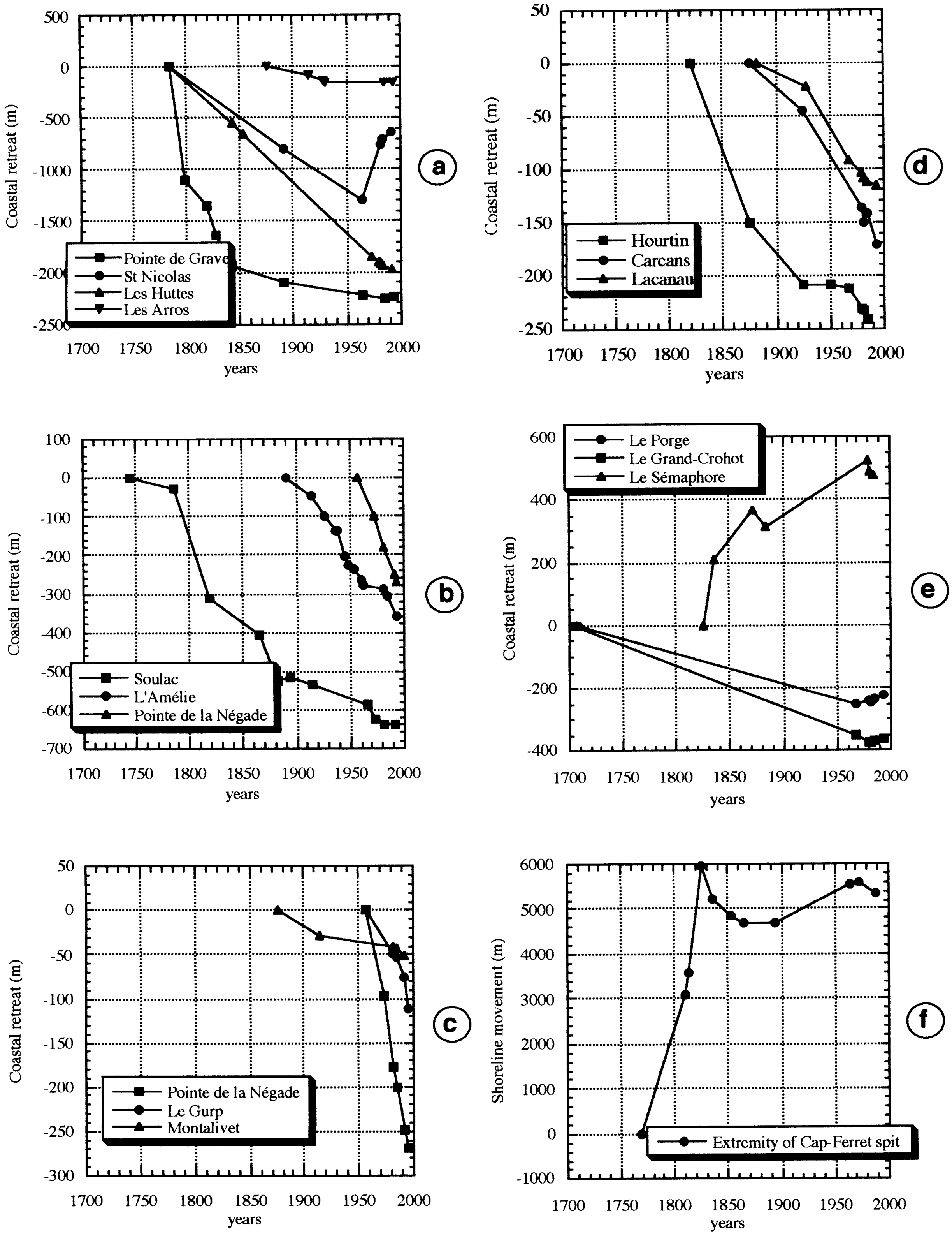

Figure 3. Shoreline changes along the Gironde coast, with the positions shown on Fig. 1a: (a) North of Soulac; (b) from Soulac to Pointe de la Négade; (c) (d) (e) South of Pointe de la Négade; and (f) north-south shifting of the extremity of Cap-Ferret spit.

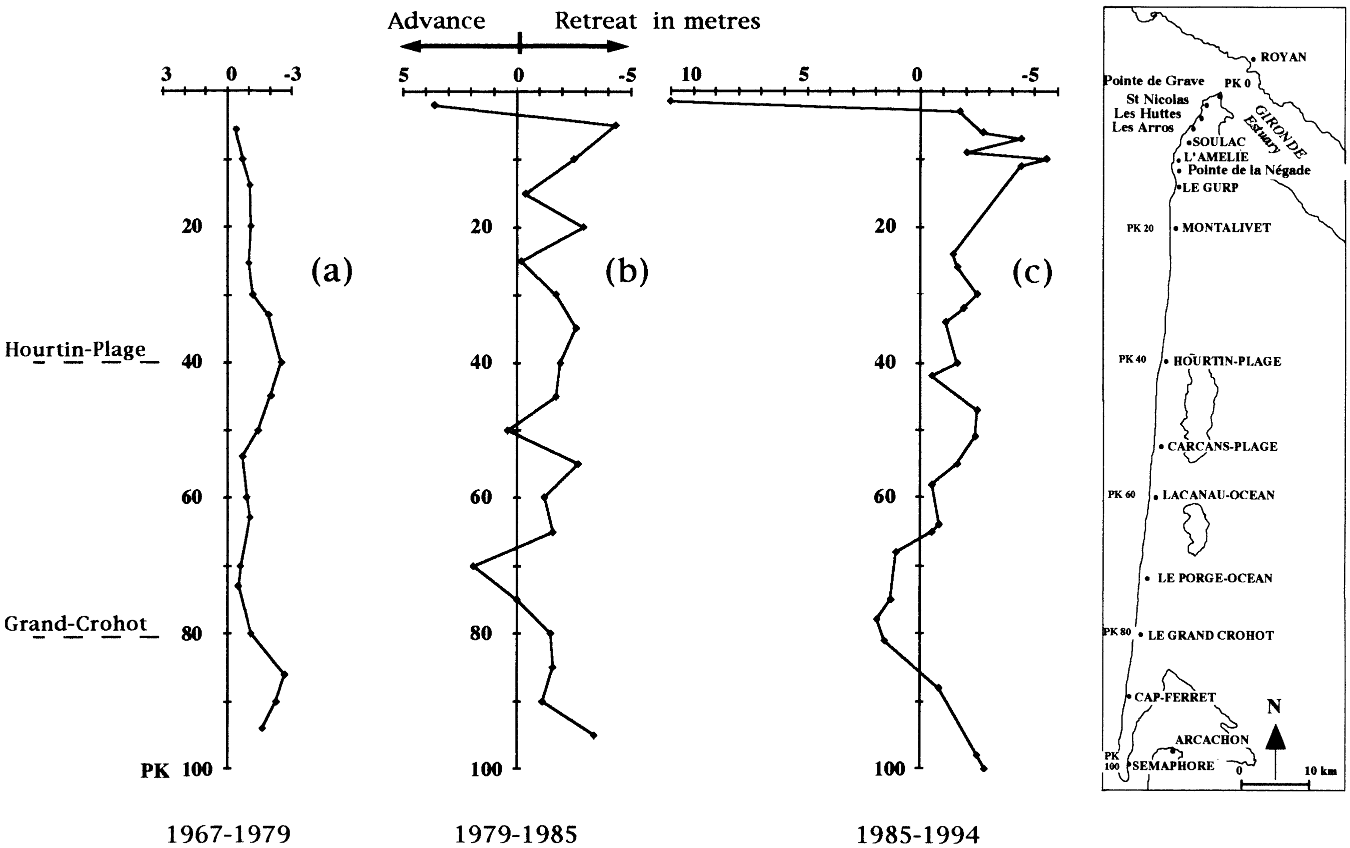

Figure 4. Shoreline changes between 1967 and 1994; (a) and (b): direct measure from the curve of LCHF (LORIN *et al.* 1979), (c): comparison of aerial photos from 1985 and 1994 (AUBIÉ, 1996).

1991). The longshore supply, fed by the erosion of the Huttes beach, partly supplies the down-drift Saint-Nicolas beach (HOWA, 1987; RUFINO DOS SANTOS and PINOT, 1990), where the weakness of incident swell appears to allow this important accumulation of sand (SOTTOLICHIO, 1994). However, the Anse des Huttes section will have to be protected soon, since a break could occur in the foredune; this would lead to the rupture of the sea defences and to a marine invasion of the reclaimed marshes, just behind the foredune (which is only 200 m wide at this location).

Southward, the Arros section has also been stabilised, since 1930 (Figure 3a); before this, it was experiencing an average erosion rate of 2.7 m/yr, since 1865 (BUFFAULT, 1930).

In front of the church of Soulac, the average erosion rate since the middle of the 18th century has been approximately 2.6 m/yr (Figure 3b). However this area experienced erosion of more than 9 m/yr around 1800. The more sensitive section is situated between Soulac and Pointe de la Négade where the erosion rate is again severe and irregular—Figure 2 and 3b- (L.C.H.F., 1982; So.Gr.E.A.H.-P.A.B., 1995a, 1995b). Erosion on the Amélie beach averaged 3.4 m/yr, over 100 years—Figure 3b- (LORIN *et al.,* 1979); however it was greater over short periods (*i.e.,* 8 m/yr between 1991 and 1994—PEDREROS, 1994; SOTTOLICHIO, 1994). A maximum of erosion rate took place at Pointe de la Négade, with an average of 7.3 m/yr (Fig. 3b and 3c), between 1957 and 1994 (HOWA, 1997). This high rate of erosion can be explained partially by the efficiency of the longshore drift. At Pointe de la Négade, the longshore drift diverges (Fig. 1b). This drift, which is not supplied by any external source, erodes sand from the coast and transports it to the north and to the south. This point of divergence, therefore, has undergone significant erosion. Frequently, lateral variations in erosion rate are caused by variations in the offshore morphology and/or wave height (DE MOOR, 1988; PYE and SMITH, 1988). The erosional pattern at this location is also linked to the morphological variations of the adjacent sea-floor. At Amélie, the shallow depth of the nearshore zone (DE RESSEGUIER and FROIDEFOND, 1978; FROIDEFOND *et al.* 1984). leads to swell converging on the coast and increasing in energy.

South of Pointe de la Négade

Between the cape of Pointe de la Négade and the Cap-Ferret spit, the shoreline change appears to be more regular than that of the area to the north (Figure 2).

The average erosion rate decreased from Pointe de la Négade, to Montalivet. The rate remained high in Le Gurp (Fig-

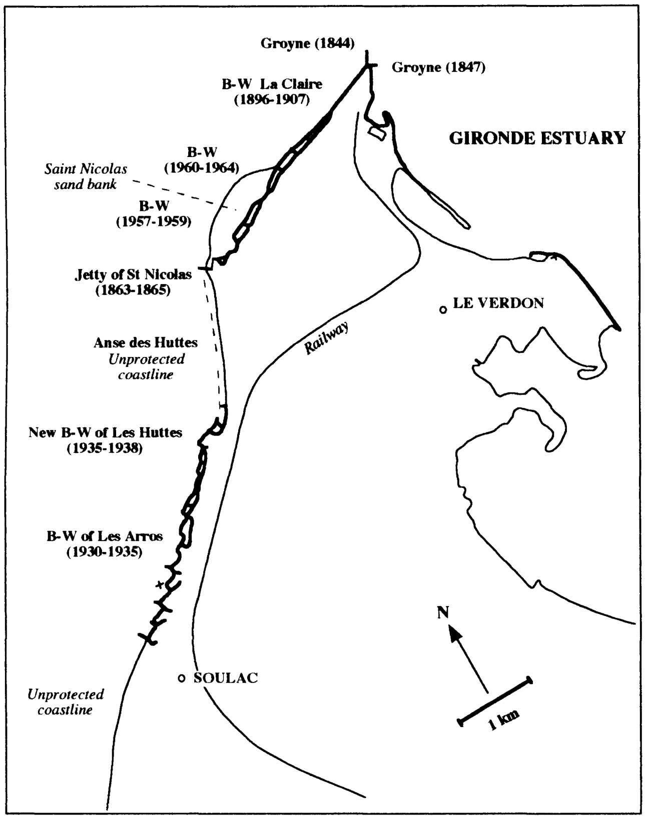

Figure 5. Sea defences between Pointe de Grave and Soulac (after Aubié, 1996). The protected parts of the coast are shown by a heavy line. Key: B-W = Breakwater.

ure 3c), 3 m/yr between 1957 and 1994 (Howa, 1997); it decreased to 0.4 m/yr, towards Montalivet (Buffault, 1929; Lorin *et al.,* 1979; Pedreros, 1994). The small retreat of the coast at Montalivet (Figure 3c) was probably due to the existence of clay units cropping out on the beach, together with the presence of rocks and shingle offshore; these help to reduce the swell strength (Lorin *et al.,* 1979).

The rate of erosion is almost constant between Montalivet and the Grand-Crohot (Figuers 2, 3d and 3e) ranging from 0.8 m/yr to 1.6 m/yr (Froidefond, 1985; Lorin *et al.,* 1979; Lorin and Migniot, 1982, 1985; Aubié, 1996).

Finally, the resultant pattern over more than two centuries at the site of the Cap-Ferret semaphore is of accretion, at a rate of 3.2 m/yr (Figure 3e). However, over the last 30 years this trend has reversed and has been one of erosion, at a rate of 2.6 m/yr (Gassiat, 1989). The recent erosional trend has also affected the head of the spit (Figure 3f) which, after extending for over two centuries, has been in retreat since the 1970's. Since the middle of the last century, the Cap-Ferret spit has oscillated around an equilibrium position, having undergone phases of erosion, progradation and stability: when the head of the spit extends, the oceanic face is eroded and *vice-versa.*

The evolution of the southern section of the Gironde coast appears to be linked to the longshore drift dynamics. Sediments eroded adjacent to, and immediately south of, Pointe de la Négade (where erosion is at its maximum) are transported southward along the coast. This sediment source supplies Cap-Ferret spit, whose extension is linked to the "hydraulic barrier" effect of the Arcachon lagoon inlet. A similar type of evolution has been described by Carter (1975, 1979) and Carter and Wilson (1990) for the Magilligan Point spit, in Ireland.

Temporal Variations in Shoreline Change (1967–1994)

With a view to know if there is a consistent temporal migration of the zones of erosion along the coast, the average rate of erosion over three periods of time, of between 6 and 12 years (1967–1979, 1979–1985 and 1985–1994) have been compared (Figure 4).

Between 1967 and 1979

The average rate of coastal erosion varied from 0.5 to 3 m/yr during this period (Figure 4a). The two main points of maximum erosion are: imediatly to the north and south of Hourtin (PK 40) and to the south of Grand-Crohot (PK 80). Also, two secondary points occured around Montalivet (PK 20) and to the south of Lacanau (PK 60). Between these maxima, minimum rates of erosion of 1 m/yr or less occured in Soulac, north of Lacanau, and north of Grand-Crohot. Because there is a distance of about 25 km between the points of maximum erosion, Lorin *et al.* (1979) have suggested the existence of "sediment trains", *i.e.* shoreface attached sandwave trains, moving along the Aquitaine coast.

Between 1979 and 1985

The average rate of erosion was more irregular than in the preceding period (Figure 4b). No regular zones of accretion or erosion occured as in the former. Maximum erosion rates were slower and the beaches of Saint-Nicolas, Carcans and Le Porge remained stable or accreted.

Between 1985 and 1994

Lateral variation in the erosion rate over this period (Figure 4c) is more consistent with the long term evolution (Figure 2), except for the Saint-Nicolas beach, where a remarkable rate of accretion has occurred. Four different dynamic zones can be defined:

(a) between the south of Soulac (PK 5) and L'Amélie (PK 12), where erosion was at its maximum,

(b) between Montalivet (PK 20) and Lacanau (PK 60), where the erosion rate was decreasing irregularly,

(c) between Le Porge (PK 70) and Grand-Crohot (PK 80), where the beaches have accreted,

(d) the Atlantic side of the Cap-Ferret spit (PK 90), which also underwent erosion, but at a slower rate than that between Soulac and Amélie.

The maximum erosion rates occured at the Pointe de la Négade (>5 m/yr) and at the site of the Cap-Ferret semaphore (2.8 m/yr). The minimum erosion occured to the south of Hourtin and at Lacanau, with rates of less than 1 m/yr.

This latter period, where the data come from the authors' measurements derived from aerial photographs, shows some similarity in behaviour to the average changes of the coastline over the entire period studied (Figure 2).

DISCUSSION AND CONCLUSIONS

Comparison between the three periods (Figure 4) leads to the conclusion that erosion in the Soulac-Amélie section has increased regularly during the last 30 years, from 1 m/yr for the 1967–1979 period to 5.5 m/yr for the 1985–1994 period. The Carcans section changed from a phase of limited stability, between 1979–1985 (with accretion of 0.2 m/yr), to a phase of erosion between 1985–1994 (at a rate of 2.5 m/yr). The Grand-Crohot section, which was erosional from 1967–1985, prograded subsequently at a rate of 1.6 m/yr during the 1985–1994 period.

The preceding comparison does not show any consistent shifts of the zones of maximum erosion (Figure 4). Hence, the existence of "sediment trains" (LORIN, 1980) does not appear to occur. Some sections of the coast change from a phase of erosion, to a phase of stability and *vice-versa*. Nonetheless, no simple pattern of time-dependent oscillations exists within the zones of erosion or accretion. Analysis of the rate of erosion, together with its temporal fluctuation along the coast, does not show any particular sequence. Variations in erosion rates appear irregular and, if a pattern occurs in this variation, it must exist on a much smaller scale than that used during this study. This type of shoreline rythm has been described, with a wavelength of 2.5 to 7 km, for the Texas coast (MORTON, 1979). In fact, the cyclic shifting character of "erosive megaprotuberance" (DE MOOR, 1988), which have been reported at a smaller scale of hundreds of metres elsewhere (DAVIDSON-ARNOTT, 1988; PSUTY *et al.,* 1988), are well known, but not totally understood, on the Aquitaine coast. Here they are called locally "coup de cuillère" (spoon shape).

IMPACT OF THE CONSTRUCTIONS OF SEA-DEFENCES

The Aquitaine coast is probably one of the least managed in France. However some of the coastal structures, which have been designed to slow down erosion along the Gironde coast, are leading to chain reactions and an increase in marine erosion and aeolian deflation at their extremities (*e.g.* PILKEY and THIELER, 1992). In addition, these processes lead to a reduction of the beach width immediately to seawards of the structures (HOWARD *et al.,* 1985; PASKOFF, 1985; KRAUS, 1988; GRANJA, 1995).

Between Pointe de Grave and Soulac, the construction of over 6 km of coastal structures was essential to protect the navigation channel in the Gironde estuary (Fig. 5). The structures have proved to be efficient and have prevented severe erosion of this particular section of coastline. Erosion was reduced drastically, once the first sea defences were erected (the groynes at Pointe de Grave, and the breakwater of La Claire (Fig. 3a)). The latter protect the coast and also trap sand transported by longshore drift; without them, the beaches would supply a submarine bank prograding on to the shipping channel to the south of the mouth of the Gironde.

Along the remainder of the Gironde coast, a few small-scale works have been carried out at the request of Local Authorities. At L'Amélie, a 270 m long revetement was built in March 1994 along a section of the coast where the erosion was on average over 3.5 m/yr. Even, during the first year, it became necessary to reinforce it after the winter; it was submerged in March 1997, during an equinoctal tide. Its construction has already brought consequences to the neighbouring areas and erosion is more severe at its extremities: likewise the lanward side of the revetement is also being excavated. In addition, the beach, which has become narrower as a direct result of the construction of the sea defences (VILES and SPENCER, 1995) is completely submerged, even at Mean High Water (MHW). This increase in beach face erosion, by removal of sand to the immediate offshore areas, is a consequence of the loss of the dynamic equilibrium between the beach and the foredune (MOREIRA, 1988).

At Lacanau, a 1.5 km alongshore revetement, and two perpendicular groynes were constructed between 1986 and 1995. These structures are causing serious damage at either end of the work, where the foredune, devoid of vegetation, is extending inland; at the same time, it is slowly engulfing houses. The impact of this revetement, where the average erosion is 1.1 m/yr, is less significant than at L'Amélie (where it exceeds 7 m/yr in storm periods). However, the beach is extremely narrow, or non-existent, at high tide.

A CONCEPTUAL MODEL OF THE SEDIMENTARY BALANCE

The Gironde coast is undergoing intense erosion due to the action of the oceanic swell. The action of the swell, which has one of the largest amplitudes of the Atlantic coast, is particulary efficient during episodic storms. The tide also contribute to the erosion, although to a lesser degree, except when the higher water levels coincide with storm periods.

Two contrasting dynamic areas are present on either side of Pointe de la Négade (Figure 6). To the north of this prominent coastal feature, the net longshore drift is northerly (at 400,000 m^3/yr); to the south, the net longshore drift is southerly (at 630,000 m^3/yr) (LORIN *et al.,* 1979). Together, these large-scale longshore movements of sediment, with the lack of any external source of supply, play an important role in developing/maintening patterns of coastal erosion.

The sediment budget of the Gironde coast is difficult to establish because many of the controlling factors are still unknown (Figure 6). Nonetheless, it is well established that there is an absence of any fluvial sand supply. The primary source of coastal sand is coastal erosion and subsequent alongshore transportation (HOWA, 1997), with possible additions from erosion of the nearshore adjacent sea floor.

Aeolian transport appears to have been overestimated by previous authors: the quoted figures corresponds to what probably occured before the fixation of the coastal dunes, by vegetation. Fieldwork proves that, at present, this aeolian transport is not sufficient to remove significant sand from the distinct areas of marine erosion. Furthermore, the development of new foredune ridges does not occur, indicating an equilibrium budget in the dune itself (PSUTY, 1988). So the

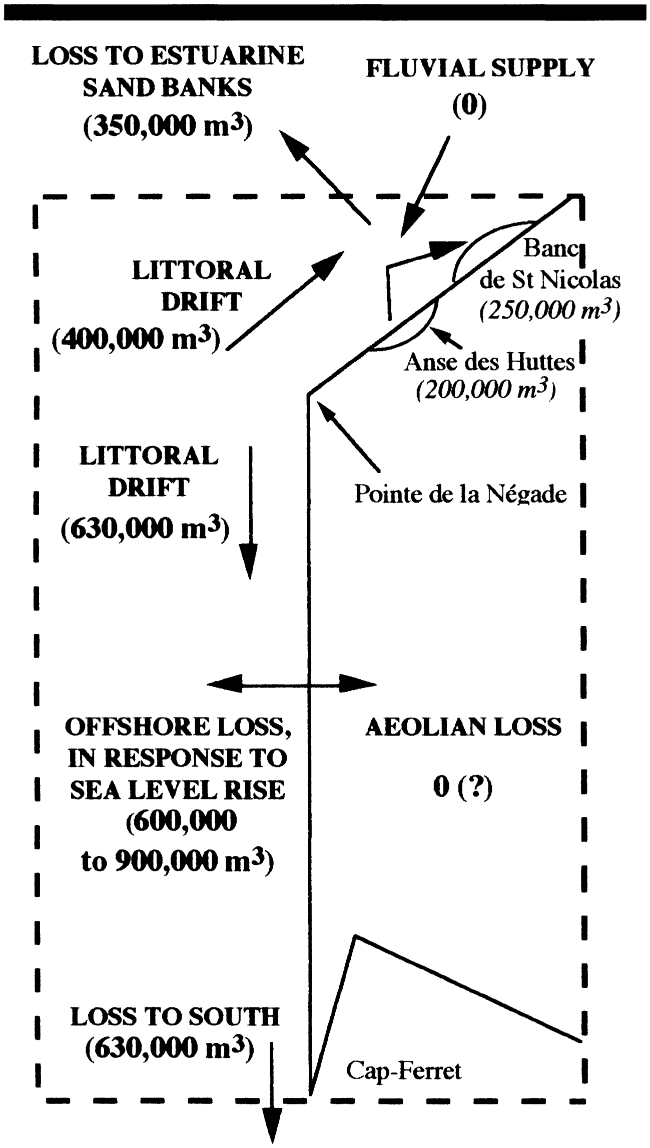

Figure 6. Schematic representation (inspired by Figure 3 in Howa (1997)), of the sediment budget on the Gironde coast. The longshore drift to the north of Pointe de la Négade is considered to supply the St Nicolas sandbank with 250,000 m3/year of sediment; of this, some 200,000 m3/year originate from erosion at Huttes (data from: LORIN *et al.*, 1979; Froidefond and Prud'homme, 1991; and Howa, 1997).

foredune seems to migrate in a landward "roll-over", retaining a more or less constant volume. Accordingly, the contribution to the erosion, by aeolian loss, is considered to be almost negligible.

The quantity of material removed from the coastal system, as the result of relative sea level rise (estimated at 1 mm/yr) has been calculated (BELLESSORT and MIGNIOT, 1987) to be 200,000 to 300,000 m^3/yr. This value needs now to be re-evaluated, as the relative sea level rise near the mouth of the Gironde is now considered to be around 3 mm/yr (GUITARD, 1996). So between 600,000 and 900,000 m^3/yr may be considered a reasonable estimate of sediment lost offshore.

Overall, the system shows a sediment deficit (Figure 6). There is indication of any sediment entering the system and, from the 400,000 m^3/yr transported northward by the littoral drift, 50,000 m^3 (the difference between the accretion of the Bank of St Nicolas (250,000 m^3/yr) and the erosion of the Anse des Huttes (200,000 m^3/yr)) are trapped within the system. Thus 350,000 m^3/yr of sand escapes to the south pass of the Gironde (HOWA, 1997).

To the south it has been demonstrated that the total flux of sediment carried by littoral drift can cross the Arcachon bay inlet (MICHEL, 1997); this takes place even if the transit is delayed by the necessary transfer, from one bank to another, in the ebb-tidal delta. This delay has encouraged the extension of the Cap-Ferret spit during the last millenium. Hence, it can be estimated that 630,000 m^3/yr of sand are lost (to the south) at the end of the Cap-Ferret spit.

Therefore at least between 1,580,000 m^3/yr and 1,880,000 m^3/yr are removed from the shoreline from the Pointe de Grave to the Cap-Ferret spit. So the average loss of sand from the Gironde coast is approximates at between 15 m^3/m/yr and 20 m^3/m/yr. These values are in agreement with a mean erosion rate of between 1 and 2 m/yr, calculated using the volumetric to areal conversion factor proposed by the U.S. ARMY CORPS OF ENGINEERS (1984); this is comparable to the actual landward displacement of the shoreline.

However, this proposed sedimentary budget for the Gironde coast needs some further investigation. Too many parameters have been only estimated approximatly. Likewise, present studies of sediment exchange between the beach and dune, as well as secular variations of sealevel, should help to evaluate accurately and quantify the sediment budget of this part of the Aquitaine coast. In addition, a careful study of wave propagation in the offshore zone is necessary, for a better understanding of the spatial and temporal variation in the rates of erosion. Lastly, shoreline mapping, using the new technologies in computer cartography and/or geographic information system -GIS- (BYRNES *et al.*, 1995; MCBRIDE and BYRNES, 1997) should be a next step in the establishement of a more precise approach for coastal management.

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