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Shoreline management and its implications for coastal processes in the eastern part of the Rhône delta

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Abstract. The coastal fringe of the eastern part of the Rhône delta is a large area where activities related to ecological and economical interests have increased since the beginning of the century, including the salt industry of the *Compagnie des Salins du Midi et des Salines de l'Est*, the industrial complex of *Fos-sur-Mer*, tourism managed by the local authorities of *Port-Saint-Louis* and *Arles*, and dune restoration of the La Gracieuse spit undertaken by the *Port Autonome de Marseille*. The vulnerability of the area for changes brought about by these activities is linked to the extent of several coastal changes, whereas these changes are related to the physical functioning of the coastal fringe, such as coastal processes, but also to external components such as relative sea-level rise, subsidence, reduction of sediment input, human impact, etc.

For many decades, coastline 'protection' in the eastern part of the Rhône delta has been undertaken to withstand erosional processes that offset beaches and retreat of the littoral. The use of different engineering structures illustrates the heterogeneity and differences in age of the various management policies. At the eastern side of the Rhône, the *Port Autonome de Marseille*, dealing with management, has opted for soft engineering structures using fences for dune restoration on the La Gracieuse spit. At the western side of the mouth, the *Compagnie des Salins du Midi et des Salines de l'Est* has been using hard engineering structures to combat erosion (rocks, groins, tetrapods, etc.).

A brief assessment of the management efficiency is presented, including an analysis of the data collected concerning the survey of the zones where the structures were built. Their varying efficiency shows the important role played by the sediment supply to the littoral (solid river discharge) and the coastal hydro-sedimentary processes. In the eastern part of the Rhône river the success of the dune restoration is mainly due to the important sediment supply transported in this area by eastern drift currents. At the western part of the mouth, the decrease of sediment supply linked to erosional processes in the shallow off-shore beach has made the structures more vulnerable, and therefore, the activities of the salt industry. For this last threatened zone, three management scenarios are discussed by taking into account economical, physical and ecological parameters.

Keywords: Beach nourishment; Erosion; Hydro-sedimentary process; Sediment supply.

Abbreviations : CEPREL = Centre d'Etudes pour la Protection du Littoral (Montpellier, France); SOGREAH = Société Grenobloise d'Applications Hydrauliques (Grenoble, France); CSMSE = Compagnie des Salins du Midi et des Salines de l'Est.

Introduction

The maintenance of the emerged zones in delta areas is mainly related to four components (e.g. Capobianco et al. 1998; Palanques & Guillén 1998):
1. Eustatism (SLR), which is very often increased by subsidence in the delta area – inducing relative sea-level rise;
2. Sediment supply (solid river discharge). The solid river discharge is influenced by different parameters such as the recent climatic change (end of the Little Ice Age) and/or the decrease of the agriculture in the drainage basin and/or the river management (dams, dikes, etc.);
3. A component defined by coastal processes which control sediment transport along the coast; this component refers to forcing agents such as waves, currents, winds;
4. A component related to shoreline management; the use of coastal defence to combat erosion is generally linked to a lack of sediment supply in the zones where they are built, therefore knowledge of erosion/accretion patterns is indispensable to define effective and efficient 'protection' methods (Granja & Soares de Carvalho 1995; Komar & McDougal 1988).

In the Rhône delta, relative sea-level rise based on tide gauge records has been estimated at 2 mm/yr from which 1mm/yr is related to subsidence (Suanez & Provansal 1996; Suanez et al. 1997). The downward movement, mainly found along the coastal fringe, might be explained by the magnitude of the sedimentary mass in the submerged zone since the embankment of the Rhône during the 19th century.

The sediment supply to the coast mainly occurs during flooding events; for the Rhône river 80 % of the solid river discharge input is related to liquid discharge >3000m ^{3}/s (Pont & Bardin 1996). Previous studies (Pichard 1995) have shown that the River Rhône is characterized by an important decrease of flood frequency since the end of the Little Ice Age. For the recent period, two parameters need to be considered: (1) the decline of agriculture inducing the return of vegetation in the drainage basin; (2) river management (dams, dikes, gravel extraction, etc.).

Nevertheless, up to now it is very difficult to relate the reduction of the solid river discharge either to recent climatic changes, or to human impacts. For the suspended sediment a recent estimate is 6Mt/yr (Pont & Bardin 1996; Pont 1997): it was estimated to be as much as 22 Mt/yr in the middle of the 19th century (Surell 1847 *in* Corre 1992). This reduction has certainly affected the bed-load sediment transport which contributes to the supply of the littoral, but its estimation is still not accurate. A first assessment obtained by using empirical methods, gives the wide range of 50000m ^{3}/yr to 4M m^3/yr for one major flood (Suanez 1997).

In this paper the last two components: shoreline management and coastal processes, will be emphasized. Relative sea-level rise and sediment input will be used as forcing agents. After a brief history of the policy and the shoreline management methods, the results of coastal monitoring will be discussed: firstly an assessment of coastal 'protection' efficiency or inefficiency will be considered; secondly coastal processes will be analysed by looking at the global nearshore circulation and the long-shore sediment transport. In the Discussion section at the end of the paper, future perspectives concerning ideas for possible management in the forthcoming years will be proposed for the zones at greatest risk.

Study area

The study area is located in the eastern part of the Rhône Delta and consists of a 30 km long sandy coast extending from the Gracieuse spit in the east to the Beauduc spit in the west (Fig. 1). This area is affected by important industrial activities: on the eastern part of the Rhône river the industrial complex of Fos-sur-Mer has been established since the beginning of the 1960s; on the western part (littoral of Faraman) a salt industry (*Compagnie des Salins du Midi et des Salines de l'Est*) was installed in 1856. This area corresponds to the youngest part of the Rhône delta. Its construction may be divided into three stages: the first period is related to the Rhône of Bras de Fer which was active during the Little Ice Age (from 1587 to 1711). At that time the mouth of the Rhône was located further to the west (in the Grau de la Dent area). The high hydro-sedimentary activity of the river during this period has contributed to the construction of a cuspate sub-delta that still plays an important role in the actual coastal processes. The second stage concerns the shift of the Rhône river to the east. In 1711, very extensive flooding redirected the Rhône into its present-day course inducing the erosion of the deltaic lobe and therefore the building of the Beauduc spit. The last period is concerned with the changes of the actual mouth of the Rhône river. Because of human management, this area has evolved from three branches existing at the end of the 18th century to only one branch, oriented first towards the east, during the 19th century (Grau de Pégoulier), and later, by the end of the 19th century, towards the south (Grau the Roustan). One of the effects of this development has been an inherited sedimentary context characterized by the fossil sub-delta located on each side of the Rhône (Fig. 1): the sub-delta of Bras de Fer in the west and that of Pégoulier in the east. Today they may be seen as sedimentary stocks which play an important role in the coastal processes.

Coastal management

Mainly two sectors are involved: the littoral of Faraman located in front of the salt industry and La Gracieuse spit on the eastern part of the Rhône river. The policy and the choice of coastal management are different for both sites: on the western side of the Rhône, for many decades the *Compagnie des Salins du Midi et des Salines de l'Est* has been usinghard engineering structures to combat erosion (groins, blocks of rocks, tetrapods, gravels, etc.). On the east, the *Port Autonome de Marseille* has opted for soft engineering structures (dune fences) in order to preserve the natural landscape.

The erosion of the littoral of Faraman is a historic phenomenon. The old beacon of Faraman was built in 1830, 420 m inland from the shoreline, and it was destroyed in 1906 by marine erosion. The retreat of the coast during this period was important (5.5 m/yr). The first coastal protection policy in this area started early in the 1930s. It was materialized by the construction of five wooden groins on the western side of Grau de la Dent between 1930 and 1940, but they were rapidly destroyed by erosion. A second programme took place in 1941 and 1942 when six groins composed of rocks were built between Grau de la Dent and the eastern part

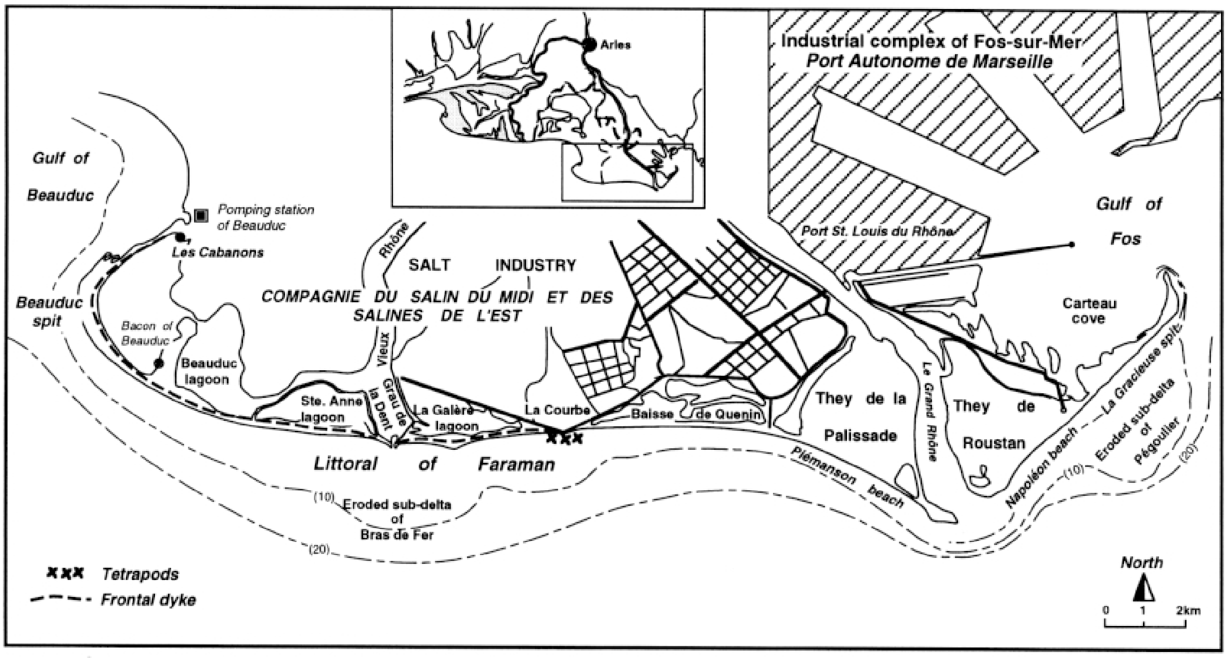

Fig. 1. The study area.

of La Courbe (Fig. 2). In 1975 these hard structures were destroyed by erosion except for the groin of Vieux Phare.

In the beginning of the 1970s the frequent submersion of the lagoons by marine water intrusion during storm surges became a real problem for the salt company, due to the increase of salinity in the lagoon and disturbance of the hydrological circulation. Therefore, in 1972 a frontal dike was built 200m behind the shoreline between the eastern part of La Courbe and Les Cabanons in the Beauduc spit (Fig. 3). In the La Courbe area where the beach has completely disappeared

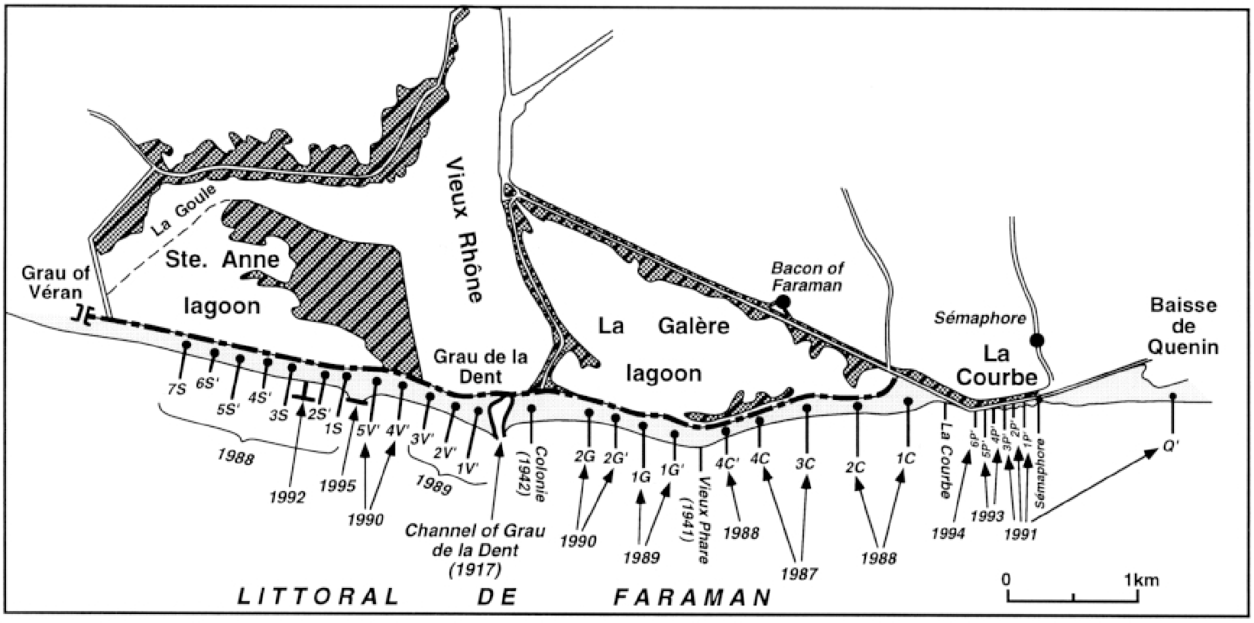

Fig. 2. Location of shoreline management activities during the 1980s and 1990s (groynes) at the littoral of Faraman (Source: Anon. 1996). Concerning the notation of groynes, the figure corresponds to the number of the groyne for each sector, the character corresponds to the location (for instance: S or S' = Ste. Anne lagoon, V or V' = Vieux Rhône).

Fig. 3. Frontal dike and groynes established on the littoral of Faraman (la Galère lagoon area).

because of erosion, the frontal dike has been reinforced using tetrapods (Fig. 4). The dunes were degraded, as were many parts of the coastal fringe (Augustinus et al. 1990). In the zones where the foredune was seriously eroded, such as La Baisse de Quenin, dunes were stabilized by the use of rocks or geotextile. Today the foredune of the littoral of Faraman may be seen as an 'artificial dike' (Caillaud et al. 1990). In September 1987 the coastal policy of the salt company changed: according to the decree of the local authorities, the littoral of Faraman became the property of the company for a period of thirty years, permitting the building of new coastal defence structures. From 1987 to 1995, 29 rock groins were installed between La Baisse de Quenin and Ste Anne lagoon (Fig. 2).

The management of the coast on the eastern side of the Rhône river (essentially the Gracieuse spit), is directly related to the industrial activities established in the gulf of Fos (Fig. 1). La Gracieuse spit represents a natural barrier against East and E-SE storm waves for the Gulf of Fos. This characteristic played an important role in choosing Fos-sur-Mer as the site for the establishment of the industrial complex during the 1960s. Therefore, the maintenance of the La Gracieuse spit was crucial.

Fig. 4. The use of tetrapods to stabilize the shoreline in La Courbe area.

For many decades, the impact of natural dynamics (storms) and human pressure (tourism) induced the destruction of the foredune. In 1984, a first assessment was requested by the *Port Autonome de Marseille* (Anon. 1984). The study showed that the spit was characterized by large low zones (breaches) allowing the overwash of marine water during storm surges (Fig. 5). In 1988, a programme for dune management was developed and undertaken by the *Port Autonome de Marseille*. An artificial foredune of 3 m height was built over 3.5 km and fences were used to trap the aeolian sand transport (Fig. 6). The sand was collected behind the spit (Carteau cove) in order to avoid the narrowing of the beach close to the infrastructure (Anon. 1988; Longe 1990).

A first assessment of the efficiency of shoreline management

A survey of the managed zones has been carried out in different ways:

- A first assessment was performed by analysing shoreline changes using aerial photographs dating from 1944 to 1995 (Suanez & Provansal 1998; Suanez & Simon 1997). The results show a significant change concerning the shoreline evolution for the beginning of the 1990s: on both sides of the Rhône river the retreat of the coast has mainly been stopped (Fig. 7). This recent development is directly related to the impact of the shoreline management.
- According to a second method, coastal changes at a smaller scale were monitored: (1) on the western side of the Rhône; since 1988 the salt company has made annual measurements of the beach width checking 113 profiles spread over the whole littoral of Faraman (Anon. 1989, 1992); (2) on the eastern side, the survey of the dune on the Gracieuse spit is undertaken by the *Port Autonome de Marseille* using beach profiles; in addition, for this latter area, field measurements undertaken by ourselves since 1994 are also used.

The measurements carried out by the salt industry show different developments according to the sectors. In La Courbe and La Galère lagoon areas, the erosion has been stopped. From 1988 to 1996 the shoreline has prograded between the groins of Sémaphore and 6P'; on the western part of the La Courbe area the same trend is observed. On the western part of Grau de la Dent, the groins do not work very efficiently; except for the area between the groins 1V' and 4V', the whole coast has eroded since 1988. The building of a wave-breaker in this zone in 1995 has halted the retreat of the littoral, although essentially on a small area. Nevertheless, the supply of the littoral of Faraman contained within the engineering infrastructures, derives from the erosion of the near-shore zone (Blanc & Poydenot 1993). The study of the bathymetric data recorded between 1988 and 1995 showed that a large part of the sub-aquatic beach between the Beauduc lagoon and the Piémanson beach has been eroded. 74% of the total surface corresponding to a the shallow zone (from 0 to – 6 m deep) was characterized by a sediment deficit, from which 39% was subjected to important erosion processes (– 0.57 m/yr); 26% of the total surface was considered to be stable or in accretion, from which 15% showed a positive sediment budget (+0.25 to +0.5 m/yr).

The measurements obtained since 1988 on the artificial foredune of the La Gracieuse spit show effective management (Moulis et al. 1993; Moulis 1995; Bruzzi & Provansal 1997; Suanez 1997). In this case the survey corresponds to beach profile measurements from the back of the dune to the near-shore zone (–1.5m depth). From these data two types of information have been extracted: the shoreline changes and the total surface variations (Fig. 8a and 8b).

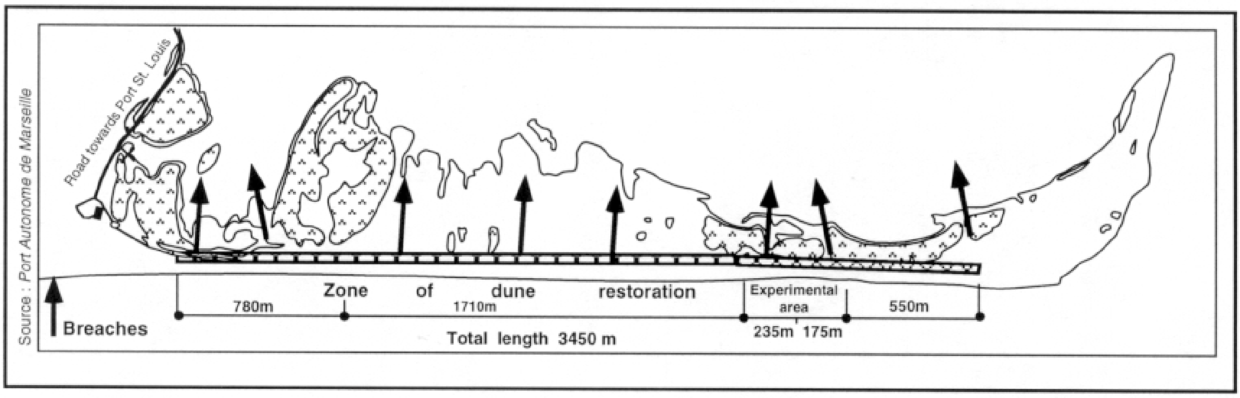

Fig. 5. Dune management on the La Gracieuse spit.

The beach profile of the central part of the La Gracieuse spit drawn up by the Centre d'Etudes pour la Protection du Littoral (Montpellier) shows that the total surface has strongly increased from 1988 to 1995 (Fig. 8a); the global volume gained during this period reached more than 100%. This evolution is marked by two stages: (1) from 1988 to 1990 the gain has been particularly important and rapid; the compartments at the base of the construction were completely filled up, raising the back beach which then allowed the filling of the higher compartments; (2) from that time onwards the total surface increased slower than before to become stable (1993-1994): nevertheless the impact of seasonal variations is well defined. Since 1994 this evolution has been confirmed by our measurements on three different sectors of the spit (Fig. 8b): for all the profiles the evolution is consistent. In fact, since 1992 the foredune has been completely stabilized inducing a progradation of the shoreline in some areas while an important vegetation cover mainly consisting of *Ammophila arenaria* and *Tamarix canariensis* has colonized the northern face of the artificial foredune.

The data obtained on the shoreline changes show an evolution strongly influenced by seasonal fluctuations (Fig. 8a and 8b). The retreat of the coastline is linked to stormy periods (autumn and spring) but it does not necessarily influence the global sediment budget. This global evolution is also related to nearshore sedimentation processes particularly important on the tip of the spit. In this sector, the bathymetric profile has prograded by ca. 150 m between 1963 and 1995 and the accretion is still active down to 16 m depth (Suanez 1997).

Fig. 6. Artificial foredune of the La Gracieuse spit – programme of dune restoration undertaken between 1988 and 1993 by the Port Autonome de Marseille (location map of photographs).

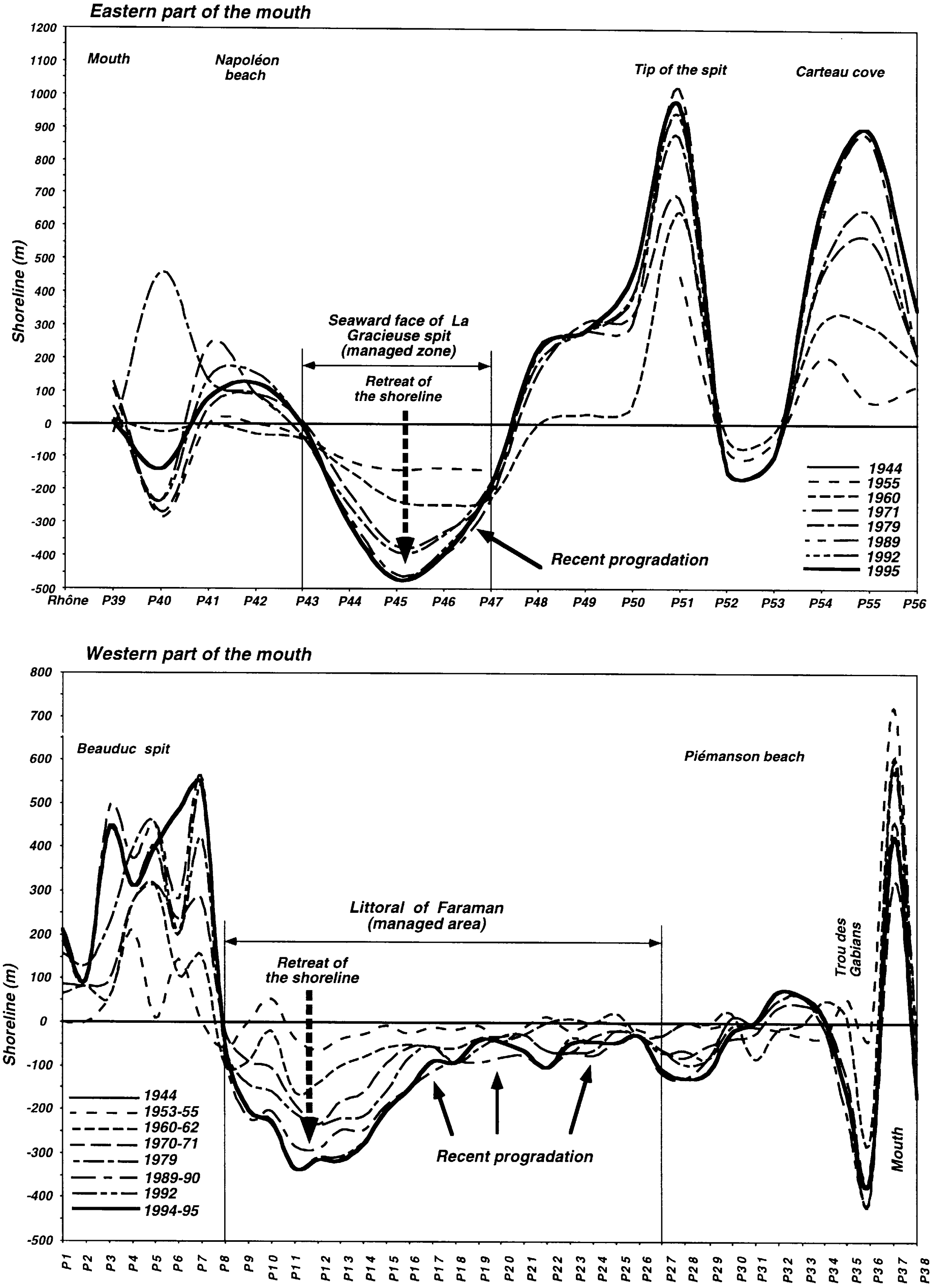

Fig. 7. Shoreline evolution for the last 50 years.

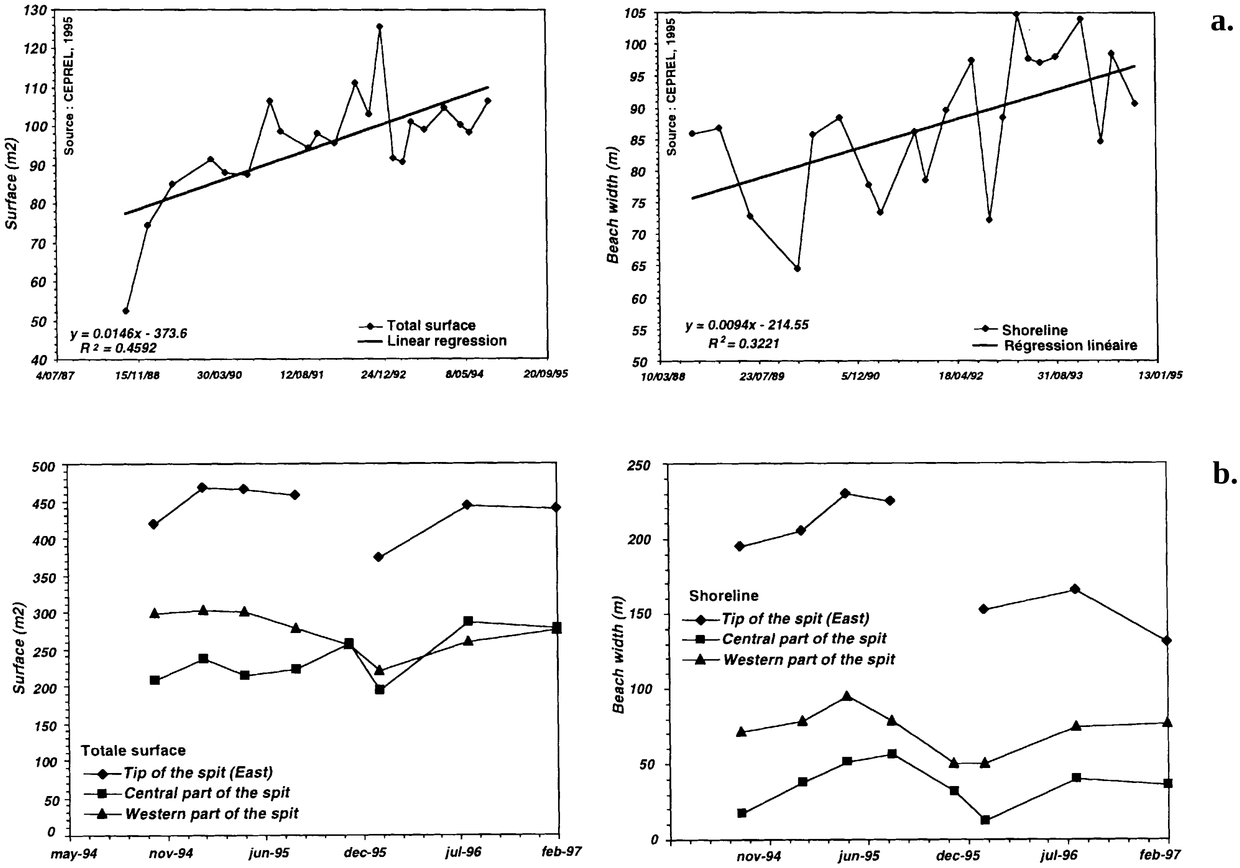

Fig. 8.a. Measurements on the central part of the spit (Centre d'Etudes pour la Protection du Littoral, Montpellier). **b.** Measurements on the whole spit (western, central and eastern part of the spit).

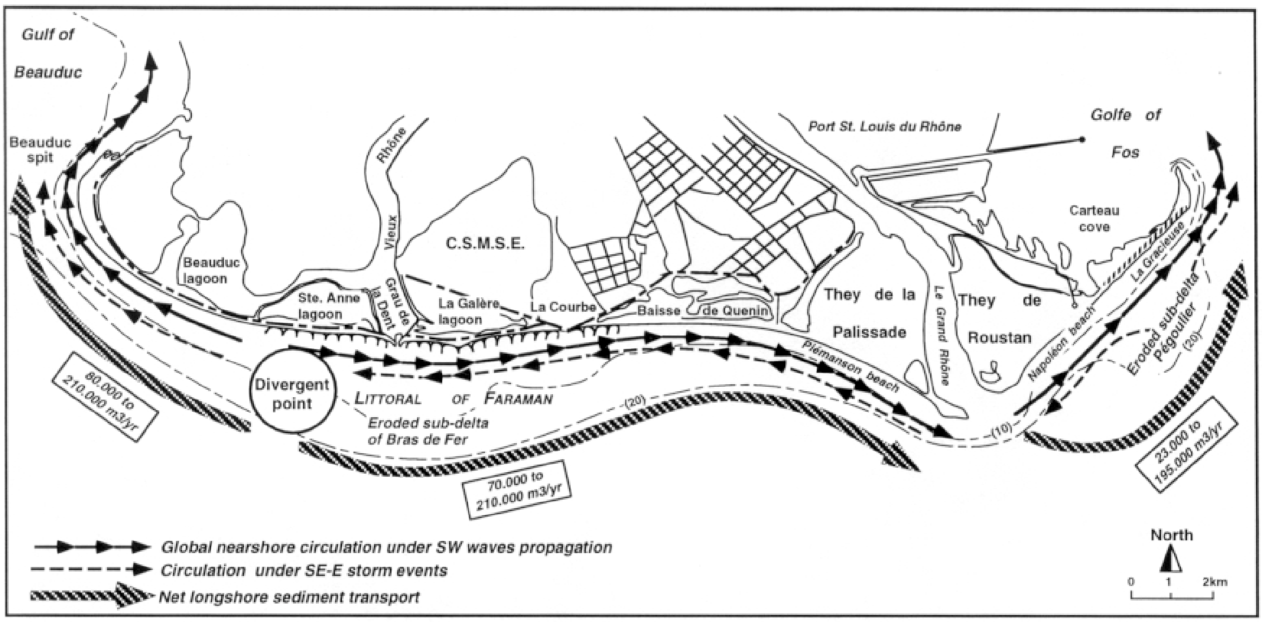

Fig. 9. Near-shore circulation and long-shore sediment transport rates.

Coastal processes

The assessment of shoreline management and its efficiency requires a better understanding of the coastal processes. Nowadays, the data obtained in this field allows us to analyse the coastal sediment dynamics and their long term evolution (Suanez 1997; Bruzzi & Provansal 1996).

The coastal processes are related to the main forcing agents which control sediment transportation along the coast. In our case, the most important process is related to the drift currents induced by waves. In the Rhône delta a general near-shore circulation flowing from west to the east is recognized (Fig. 9). This is due to waves from the SW which are the most frequent. This circulation affects the coastal fringe from Grau de la Dent to the La Gracieuse spit. A point of divergence – due to the wave refraction on the fossil sub-delta of Bras de Fer– is observed in the western part of the littoral (Ste Anne lagoon). It generates a drift current flowing in this case, from the east to the west towards the Beauduc spit. Nevertheless, a second general near-shore circulation flows from east to west under an east-southeast wave regime (Fig. 9). This circulation is related to storm events; therefore, in this case the long-shore sediment transport is reduced to a short period (episodic events of some hours to some days).

This global near-shore circulation pattern controls the removal of different sediment sources along the coast. In the western part of the Rhône, the supply from the coast (Piémanson beach and Beauduc spit) is mainly achieved by the erosion of the fossil sub-delta of Bras de Fer; on the eastern part, the supply is linked to the actual river discharge (active source) and the erosion of the fossil sub-delta of Pégoulier. The sediment budget has been calculated by converting shoreline changes to subaerial deltaic area changes; volume changes are obtained assuming realistic closure depths which can vary along the coast due to the existing morphology. The long-shore sediment transport rates have been calculated using a box model (Jimenez & Sanchez-Arcilla 1993). The values obtained on both sides of the Rhône for the last 50 years show greater values on the western part: 150 000 to 420 000 m^3/yr, than on the eastern part: 23000 to 195000 m^3/yr (Suanez 1997; Suanez & Simon 1997).

Discussion

The difference in efficiency of the artificial structures established in the Rhône delta on either side of the mouth of the river Rhône highlights the important role of the coastal sediment supply. The success of the dune restoration programme on the La Gracieuse spit is mainly due to the continual renewing of the sediment supply linked to solid river discharge of the Rhône. Medium term (5-10 yr) to longer term (25 yr) periods might be proposed to define the time scale efficiency of this management if we consider that sediment supply in this area is sufficient enough (1) to offset the impacts of predicted Sea-Level-Rise (Suanez & Provansal 1996); (2) to restore the loss of sediment due to erosion during short term episodic events such as storms (Bruzzi & Provansal 1997). On the western part of the mouth, except in some areas, the hard structures (groins) allowed the apparent stabilization of the coastal sector zones where they were built; however, a substantial enlargement of the beach is derived from the erosion of the sub-aquatic beach. This process induces the problem of groin stability and poses the question of their real efficiency to stop an apparently irreversible mechanism. In this case, short term period (1-5 yr) is proposed to define the time scale efficiency of this management. This is obvious from the fact that, every year, more than 50% of groins are damaged during storm events, and therefore, have to be restored constantly.

In addition, in this area the coastal defences (frontal dyke and groins) have eliminated sediment exchanges between the fringe (front of the coastal defence) and the deltaic plain (behind the coastal defence) inducing a notable height difference between these two sites (Fig. 10). This development carries the risk that should the sea level exceed the construction height limit, or should the construction collapse, then the area behind which is dependent on the protective qualities of the structures would be subject to severe flooding.

Following this last development, three scenarios for management may be put forward:

1. In the first scenario, the salt industry should not maintain the lagoons located close to the actual shoreline by destroying the frontal structures and therefore allowing the submersion of this area. A new shoreline would migrate inland inducing the reshaping of the general coastal fringe profile. Due to the actual linearity of the coastline, which would be reinforced by such a development, the erosion processes would be strongly reduced. Nevertheless, the decrease of the risk due to the migration inland of the frontal defence will be effective on the short to medium term (less than 10 yr). We can assume that the erosional processes related to important rip current circulation in this area (Blanc & Poydenot 1993; Blanc 1996), will rapidly take place again.

2. The second scenario would include the use of artificial nourishment of beaches. This stabilization

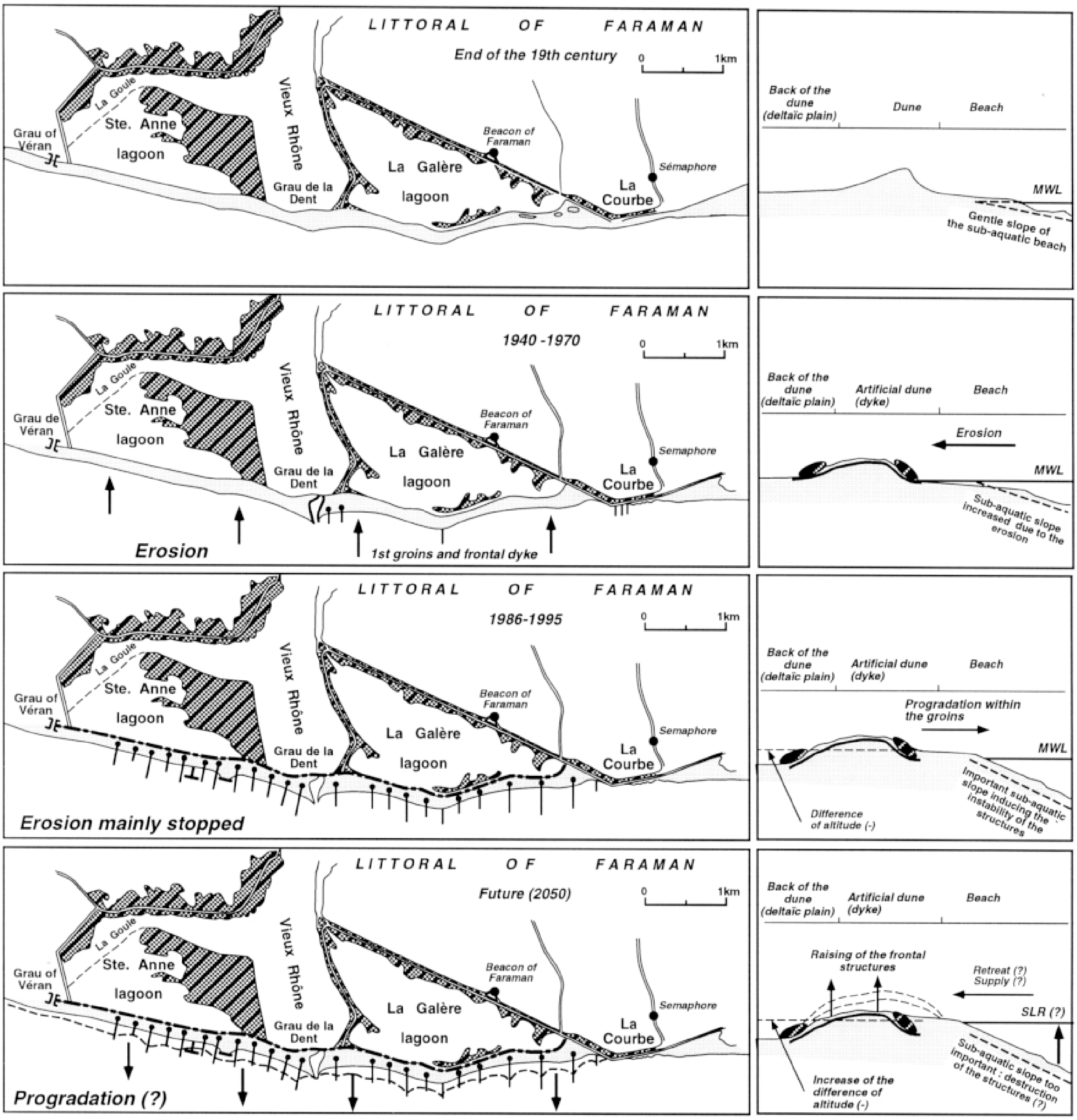

Fig. 10. Development of the littoral zone of Faraman in the Rhône delta from ca. 1900 until recent times and a prospect for the next 50 years.

method, as was used particularly along the Dutch coast (Verhagen 1992; Hillen & Roelse 1995), has already been proposed by Paskoff (1991); this 'artificial' sediment supply may correspond to a 'new life' for the whole sector. Nevertheless, this scenario will be effective on the short term (1-5 yr). Erosional processes, particularly active in this area, will induce an immediate loss of this substantial sediment supply. Furthermore, two problems exist:

a. The first problem is to find sedimentary stocks not too far away from the area and corresponding to the sedimentological characteristics of the autochthonous sand. If we consider the global delta system, we can assume that the amount of sand collected somewhere in the delta will be a loss of sediment for this area, inducing a disfunctioning of the coastal processes.

b. The second problem is formed by the high costs related to this stabilization method.

3. In the third scenario the main problem, corresponding to a lack of sediment, would be solved. It would consist of the digging of an artificial channel following the former course of the Rhône of the Bras de Fer. In this way it will be possible to redistribute a part of the solid river discharge of the Rhône to the littoral of Faraman (this project does not seem unrealistic if we consider that the mouth of the Rhône was characterized by three branches until the 19th century). Again two problems may be considered in relation to the scenario:

a. The first problem concerns the water circulation pattern in the salt industry area. Nowadays the marine water used for salt production is pumped in the gulf of Beauduc (Fig.1) and channelled by gravity or via pumping through the lagoons into the salt compartments located in the eastern part of the complex. The establishment of an artificial channel across this water circulation pattern would necessitate some new management structures in order to continue the transfer of marine water from the west to the east. Therefore the problem would be in the financing of such costly investments linked to this kind of management.

b. The second problem is concerned with the global delta sediment budget. We can assume that the redistribution of a part of the solid river discharge in the western part of the Rhône will affect the sediment supply in the eastern part of the mouth, especially on the La Gracieuse spit. In this way, such a scenario will induce erosional processes in this area.

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