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Sand Barrier Behavior Under Man-Induced Inlet Relocation.

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ABSTRACT

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Sand barriers are dynamic constructions with a natural environmental trend that can be altered by human activities. Along this paper we present a case of study where sand mining activities have brought about the change of inlet position. The work is focused on the evolution and influence over sediment budget of the tidal inlet developed at Rodas Sand Barrier, at the Northwest of Spain Atlantic Coast. Decadal evolution, using aerial photograph analysis, was carried out to understand the effect of human activities and to relate actual situation to the past. A two years record of sand barrier profiles and volumetric changes was carried out in order to describe seasonal behavior. Results show dune destruction and beach progradation at the northern sector of the sand barrier, where a tidal inlet is developed nowadays, and light dune and beach retreat at southern sector, where another inlet was developed around fifties. Accumulation could not be related to erosion since these processes were not registered simultaneously. In this sense, we have suggeted that cross-shore component is the principal factor of sediment transport. Due to this sand barrier behavior only northern sector is fed when the ephemeral inlet is established, but southern sector has not an active supply of sediment.

ADDITIONAL INDEX WORDS: *Beach, foredune, Cíes Islands, erosion, ephemeral inlet, onshore and longshore transport.*

INTRODUCTION

Sand barriers are dynamic constructions that run parallel to the shore and are back by a bay, lagoon, marsh, or tidal flat. Sand barriers change according to waves, water currents and wind regime that built them. Waves and currents transport sediment off, during storm conditions, as well as onto the barrier, during fair weather conditions. This cyclic sediment redistribution can be accelerated during very large storms, which carry sand eroded from the beach barrier onto the landward side as overwash. The storm overwash, combined with a gradually rising sea level promotes an additional sediment transport onto the back barrier and finally the filling of the lagoon. This natural trend of a sedimentary complex can be interrupted or accelerated by human activities like construction of infrastructures or sand mining (BIRD, 1996; NORSTROM, 2000; BORGES *et al.*, 2002 or VILA *et al.*, 2002).

This work deals with the study of an example of this truncated evolution due to human activities: sand mining and artificial constructions, the case of Rodas Sand Barrier. These activities have promoted changes over the inlet position, storm waves energy reduction into the lagoon, as well as an important increase in the rate of overwash processes, and consequently a quick lagoon filling process (COSTAS *et al.*, 2002).

The study is developed at seasonal scale in order to determine the influence of inlet evolution into the sedimentary budget along the beach, as well as to describe inlet closure, open and migration processes. A decadal evolution review was introduced to compare past and present situations. This comparison helped us to understand the response of the sand barrier to the human activities.

STUDY AREA

Rodas Sand Barrier is located at the Cíes Islands Archipelago, which is between 42º 15' and 42º 11' North and 8º 53' and 8º 55'West, at the mouth of the Ría de Vigo, NW of Spain. Winds in the study zone show seasonal behavior (ALEJO, 1994). Western-northwestern winds are predominant during summer (March to September), while southern direction is the predominant during winter (October to March). These general regimes are interrupted by southwesterly winds associated with storm developments. The local tide is mesotidal, with a mean tidal range of 3 m. The area is affected by a modal wave distribution, showing a seasonal behavior as for wave energy distribution. Significant wave height mode is concentrated around 1.5 and 2.5 m with an associated peak period of 14 s, during winter, and 1.5 m and 10 s during summer (MINISTERIO DE FOMENTO). The swell conditions at this coastal zone approach from NNW. Sea conditions approach mainly from N direction (ROM, 1991). In spite of this general characterization we have to point out the importance of the damage caused by SW storm waves.

Rodas Sand Barrier is a natural 1-km long barrier bounded by two rocky outcropes or headland resulting in a headland

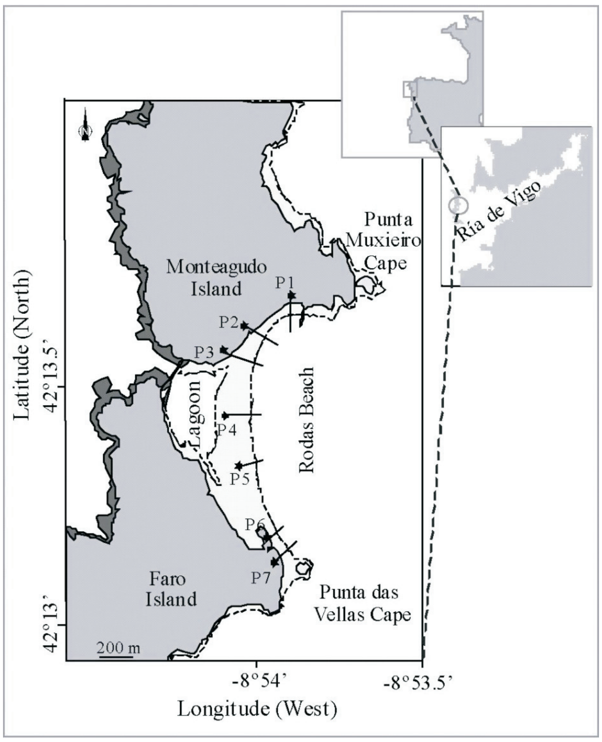

Figure 1. Ría de Vigo location and detailed study area showing beach profiles sites.

embayed beach (Figure 1). The sedimentary complex was developed at the eastern slope of the islands since it is sheltered from the energetic wave attack coming from the open ocean. Waves approaching from NNW come in the Ría de Vigo through the northern mouth of the Ría. Rodas is sheltered from these waves due to the shadow effect caused by Punta Muxieiro Cape (Figure 1). These waves reach at right angles to the beach as a result of wave diffraction and refraction processes. On the other hand, waves approaching from SW come in the Ría through the southern mouth and reach the beach obliquely. Rodas is a low energy beach, in response to this shelter zone feature. The modal wave height is around 0.5 m and the maximum height observed was around 1 m (COSTAS, 2002).

The sand barrier acts as a natural link between two of the three islands that make up the archipelago, and encloses a shallow and salt lagoon from the Ría de Vigo waters. The lagoon is connected with the open ocean through the two margins, western and eastern one. The western connection consists of a restricted channel between the two islands. It is permanently opened, flowing water into the lagoon according to the tidal cycle. At the eastern slope there is a sporadic connection with the Ría de Vigo, which consists of a tidal inlet that cuts through the barrier to connect the lagoon to the ocean. It is developed when storm waves and spring tides occur simultaneously, during winter. It is quickly restored with gentler waves (COSTAS *et al*., 2002). The inlet development is nowadays across the northern sector of the sand barrier (COSTAS *et al.*, 2002).

METHODS

The influence of inlet cycle on the sedimentary budget with regard to the inlet position was evaluated using aerial photographs analysis for the period between 1956 and 1989, in order to describe the decadal behavior.

This one was combined with a two years record of sand barrier profiles evolution and volumetric changes in order to describe the seasonal behavior. Beach profiles were performed approximately bi-monthly. Measures were carried out from December 2000 to January 2003 with a total of nine profile surveys.

The profile data yield cross-sectional profiles and volumetric time-series plots, which show morphological and volumetric changes that occurred at Rodas Beach. Profiles were measured at seven fixed sites along the sand barrier using standard profiling techniques during spring tides (Figure 1). The profiles location was chosen according to morphological visual characteristics. The profiles started at a fixed point at the seawall or foredune (Figure 1). Each of these points was related to Local Hydrographic Zero Datum.

Table 1. *Mean profile slope and net volumetric changes calculated for nine surveys.*

PROFILE	*MEAN SLOPE (tg B)*	*NET VOL. CHANGE (m^3)*
1	*0.093*	*2008.48*
2	*0.107*	*3075.73*
3	*0.115*	*738.08*
4	*0.145*	*511.86*
5	*0.108*	*-8088.00*
6	*0.127*	*-3485.29*
7	*0.117*	*-909.09*

Profile 1 was placed at the north of the sand barrier. Profiles 2 and 3 registered the inlet evolution since they were situated at inlet sector. A sidewalk backs both sectors zones of the sand barrier. The other profiles (4, 5, 6 and 7) were placed at the sand barrier sector where the foredune is developed. COSTAS *et al.* (2002) defined four sectors along the sand barrier according to the morphology and volumetric changes registered along the profiles. Present paper is focused at the first and second sectors, which were related to the tidal inlet evolution.

Three additional surveys during January, March and June 2003 were carried out in order to monitor the inlet evolution with detailed topographic changes.

Hydrodynamic conditions observed along the study period have shown an obvious seasonal trend. In spite of this general trend, there were differences between the three surveyed winters. Winter from 2000 to 2001 was the most rigorous, during this time severe storms were registered from November 2000 to March 2001. On the other hand, winter from 2001 to 2002 showed fair conditions, only storm conditions were registered during January 2002. The last winter surveyed showed intermediate conditions.

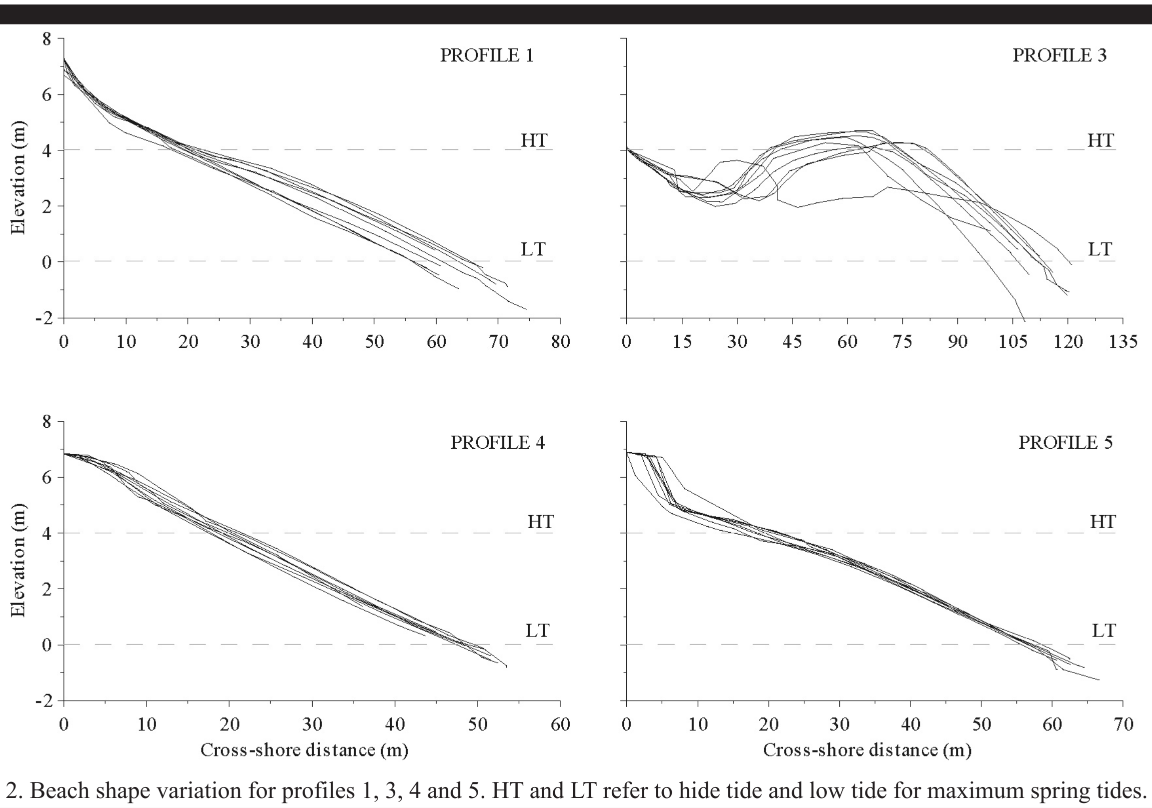

Figure 2. Beach shape variation for profiles 1, 3, 4 and 5. HT and LT refer to hide tide and low tide for maximum spring tides.

HISTORICAL REVIEW

Studies about historical evolution of the Rodas Sand Barrier were introduced by COSTAS *et al.* (2002). At that work, the authors defined four zones along the sand barrier, and calculated area variations for two periods: (from 1956 to 1972, and from 1972 to 1989) according to the aerial photograph interpretation. First zone was defined as Punta Muxieiro Dune Complex, second was Rodas Foredune, third was Punta das Vellas Dune Complex, and the last one was the Lagoon. The zones showed a gradually area decrease, due to erosion at Muxieiro Dune and Vellas Dune. Authors also detected a decrease at the lagoon surface due to infill processes. On the other hand, they observed a discontinuous trend at Rodas Foredune. During the first period, was registered a decrease in area related to destruction of this one by overwash processes, while during the second one the area registered an increase resulted from the overwash deposits previously generated.

They identified an active inlet at the southern sector during the first period studied (1956-1972), which changed to the northern sector during the second one (1972-1989). COSTAS *et al.*, 2000 attributed the inlet replacement to human activities developed during fifties and sixties, such as sand mining activities, dike construction and reinforcement, at the western margin of the lagoon. These changes were attributed to those activities as a response to the destabilization promoted by them.

Medium term or decadal evolution studies pointed out the possible development of a secondary inlet in 1956. This one could be located at the northern sector where is developed the inlet nowadays. It could be seen through the aerial photograph analysis as a cut in the foredune, which extended from the Punta Muxieiro Cape to Rodas foredune, obstructing the communication between both foredunes. The presence of this secondary inlet could be a response to the concentration of wave energy registered at this area when storms waves approached from South. The extension of this secondary inlet was smaller than the actual. Southern one was more important during that period according to the aerial photographs. Both inlets, southern and northern one, shared the same tidal prism. The morphology of this inlet shows a frequency of open and closure processes smaller than the inlet located at the southern sector. In this sense, we associate these processes to extreme storm events. Nowadays, northern inlet shows a size increase since this inlet has captured the total tidal prism. We point out the presence at this sector of a house at the backside of the foredune, which can be seen in 1972 postcards. This construction was destructed down during an extreme storm (oral communication) before 1994.

SEASONAL BEHAVIOR

All profiles surveyed along the sand barrier have shown similar morphological features with low variability during the study period. The beach was studied following the four sectors identified by COSTAS *et al.* (2002).

Sector 1, defined by profile 1 (Figure 2), has not shown important morphological changes. A marine sidewalk, backing this sector, obstructs the natural sediment transport to Punta Muxieiro Foredune by the southerly winds during winter. On other hand, we have registered an atypical profile evolution since the volumetric changes were inversely related with the profile slope changes: during profile accretion the slope decayed whereas during profile erosion the slope increased (R^2= 0.71). Similar responses were reported by NORSTROM (2000) or VILA, *et al.* (2002) at zones following a sea wall construction, which increase the shore reflectance. The volumetric net change of this profile shows net accretion at this sector (Table 1). The profile registered an important sediment accumulation in March 2001 and in January 2003 surveys and erosion for January 2002. Accretion surveys were registered when inlet open and closure processes were prolonged along winter, as we will describe at following section. Erosion survey coincides with the lower energy winter.

Sector 2 was defined by profiles 2 and 3. This sector showed important morphological changes during the study period (Figure 2). The bench mark of these profiles was situated at the walk path, at the edge of the sand barrier, behind the dune. This dune was eroded during the first winter, as we registered during December 2000 survey. This erosion was induced by the inlet breaching processes. After that, dune area was occupied by the ephemeral inlet during severe winters, and by a berm under fair winter and summer conditions. As a consequence, we registered an increase in the beach sector width of these profiles around 20 m. Volumetric changes calculated resulted independent of slope trends, at profiles 2 and 3. The most important volumetric change along the beach was registered at this sector. This value corresponds to accretion on profile 2. We associate this fact to the concentration of energy, which turns this zone into a dynamic sector. This fact allows a quick response and restoration to the situation before the inlet breaching (Figure 3). Despite these important changes, this sector showed a minor accretion trend (Table 1).

Sector 3, defined by profile 4 (Figure 2), showed a stationary behavior. This profile did not record morphological changes. The sector registered the steepest slope and the narrowest backshore alongshore the beach. Profile 4 showed an uniform shape from the foredune crest, or incipient foredune, to a little plunge step (around 30 cm). The sector did not show significant net changes, it seems that changes during study period were balanced (Table 1).

Finally, sector 4 was characterized by profiles 5, 6 and 7 (Figure 2). The bench mark of these profiles were located at the established and well vegetated foredune. Foredune evolution is related to a recession trend following the model for established foredune explained by HESP (1988). Sector showed an erosive trend (Table 1).

Above, we have described sand barrier conditions, so we could say that the sand barrier is eroding at the southern sector, stable at center and accreting at northern one, despite dune destruction at this area. Although this preliminary sediment budget, we can not affirm that the erosion at southern sector is related to the northern accretion due to limitations of budget calculations. Beach and shoreface volumes are difficult to quantify because much of the dynamic profile is subaqueous and rarely this zone is measured by repeated beach surveys. Then, subaerial beach changes represent only a small fraction of the total volumetric changes across the beach and shoreface. Other problem affirming that, is the initial situation for these calculus, since northern zone was been eroding by the inlet. On other hand, erosion at southern sector rarely coincides with accretion at the northern one. Initial survey registered a major erosion at northern sector against the stable situation registered at the other one, whereas at second survey, the erosion was widespread along the beach. In this sense we could attribute sediment transport to cross-shore component.

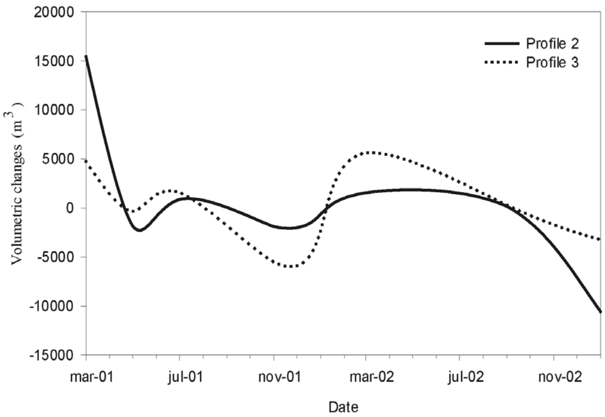

Figure 3. Volumetric changes along the surveyed period for profiles 2 and 3 located at inlet area.

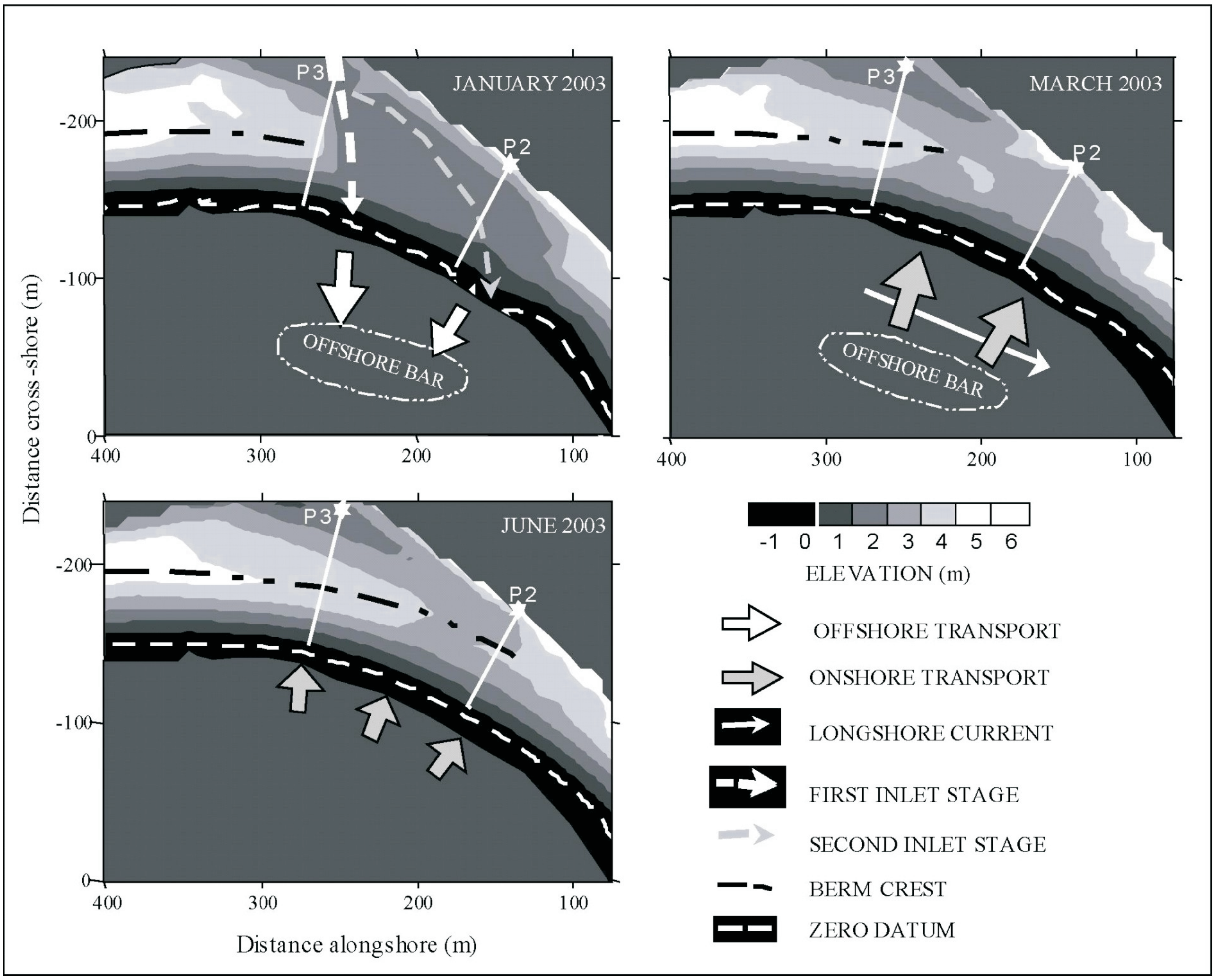

Figure 4. Sand barrier evolution at inlet development area from January 2003 to June 2003.

Inlet Behavior

Under first stormy conditions and spring tides in winter, sea level into the lagoon rises and promotes sand erosion from the beach. The eroded sand is transported off shore, resulting in sand accumulation at the breaker zone. This first opening or stage of the inlet in a winter is developed at right angles to the shoreline with an amplitude around 36 m (Figure 4). At this moment, profile 3 is the only one profile affected by this erosion since its position is closer to the lagoon than profile 2. When storms settle down, swell waves dominate and tide range falls, the eroded sand is transported onshore blocking the inlet. This closure mechanism can be around three days long. If during this winter comes another severe storm, waves will erode this vulnerable sector leading to reopen the inlet. At that time, the inlet migrates to the North and its amplitude increases around 100 m, taking up the space occupied by the anterior dune.

Inlet migration is controlled by the interaction between the onshore transport, which is the main component of sediment transport along this beach, and a weak longshore current due to the oblique incidence of waves. The inlet is closed again when storm activity declines. On the other hand, if storms activity continues during that winter, the inlet position will be close to profile 1. Onshore transport and longshore current towards the North, as a minor transport component, will build up a berm, in a similar way to a spit, from profile 3 to profile 2. Berm accretion and growth continues closing the inlet, when weather clears up with the beginning of the summer conditions (Figure 4).

Similar mechanisms of inlet closure were described by others authors under similar conditions, embayed beaches with small rates of longshore sediment transport and micro- or mesotidal environments where tidal prism would be small (FITZGERALD, 1988; HAYES, 1991; TREOLAR, *et al.,* 1993 and COOPER, 1994). RANASINGHE, *et al.* (1999) have developed a morphodynamic model to simulate the seasonal closure of tidal inlets. Their model has shown that when longshore sediment transport rates are low, such under low energy wave conditions and/or embayed beaches, with many seasonally open tidal inlets, cross-shore processes control the behavior of the tidal inlet.

This evolution was registered during the first surveyed winter and it implicated sediment transport to the profile 1. This accretion was pointed out above when we described the evolution of sector 1 resulted from this transport.

Figure 3 resumes the volumetric changes into the sector 2 or inlet sector, it shows the important variability that take place at this sector. The graph also shows that volumetric changes at profile 2 were held up with regard to changes at profile 3. It was due to the migration processes of the inlet from profile 3 to profile 2 during winter.

CONCLUSIONS

The intensive sand mining developed at Rodas Sand Barrier appears to have been the principal cause of the establishment of an only inlet at the northern sector of the sand barrier, the permanent southern inlet closure, and the erosive regime at southern one.

Cross-shore is the principal component of sediment transport alongshore the beach, in particular, at inlet location, where a larger sediment mobility or volumetric changes occurred. In spite of this mayor component, longshore currents have some bearing on morphological results.

That principal sediment transport pattern promotes the supply of sediment to the northern sector of the beach during inlet opening. When southern inlet was active (before seventies), it could keep the sediment supply to this zone, consequently this one would have prevented from actual erosion.

Actual inlet position is related to a previous secondary inlet, which worked as a sporadic opening related to the storm waves energy concentration that affects this zone.

Despite the accretion registered at sector 2, this one is retreating; dune was completely eroded by inlet breaching processes, and beach extends towards the previous dune zone.

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