

# Historical Evolution and Morphological Analysis of "El Puntal" Spit, Santander (Spain)

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## ABSTRACT

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The historical evolution of 'El Puntal' Spit in Santander, Spain, is herein presented. Field measurements of tides, currents and bathymetric profiles, carried out to design a new navigation channel for the harbor of Santander, are used to explain the morphodynamics of the tidal channel and the spit. The Empirical Orthogonal Function (EOF) method is applied to analyze the longshore changes of the spit caused by storm and tide activities. Results of the EOF analysis show that the spit can be divided into a tide dominated section and a storm dominated section. The intertidal shoreface slope of these sections shows a distinct pattern of behavior under storm conditions: while the tidal sections accretes, the storm sections erode; during wave calm periods the opposite occurs. Dredging activity in the navigation channel (tide section) during the last fifty years has led to an overall non-equilibrium of the spit.

**ADDITIONAL INDEX WORDS:** *Beaches, matrices, navigation, tides, sediment transport.*

## HISTORICAL EVOLUTION OF 'EL PUNTAL' SPIT

The harbor of Santander is located on the Cantabrian Coast of Spain, Gulf of Biscay, within the Bay of Santander, Figure 1. The navigation channel which connects the open sea and the bay has a W-E orientation and is bounded northward by the Magdalena Peninsula and Southward by El Puntal Spit, a sandy spit which protrudes well inside the bay. In this section we review the morphological evolution of the spit in the last two hundred years due to ocean dynamics, mainly wind waves and tidal currents, and to human action.

Figure 2 shows the harbor entrance in 1730. At that time, Santander was a small town which spread around the Cathedral. The bay had a tidal prism approximately 60% larger than the present value and the channel was slightly different from today.

The main channel features at that time were (1) a NE-SW orientation, (2) a great depth and (3) a steep slope at the spit side. Outside the

bay, an offshore shoal emerged. This shoal was called *Las Quebrantas* which means 'breaking zone.' Under wave action, sediment was transported from this shoal to the beach.

The main consequence of the development of the shoal was the separation of the spit dynamic into two regions: Somo-Loredo Beach, which had a predominant east longshore transport and the Puntal Beach which had a west longshore transport. The sediment was carried to the bay and drifted into the channel where ebb tidal currents brought it back to the shoal.

During the 19th and the first half of the 20th Century, the city of Santander grew remarkably, as did its harbor. The land needed for this expansion was obtained from the bay by reclaiming its western part (see Figure 3) resulting in the subsequent decrease of the tidal prism. Figure 3 shows the entrance channel in 1875. Notice the difference in size of the offshore shoal compared with Figure 2 and also the curvature of the spit end.

The situation in 1960 is shown in Figure 4. At that time the Location Project was almost completed. Since then, intensive dredging activity, mainly in the offshore shoal *Las Que-*

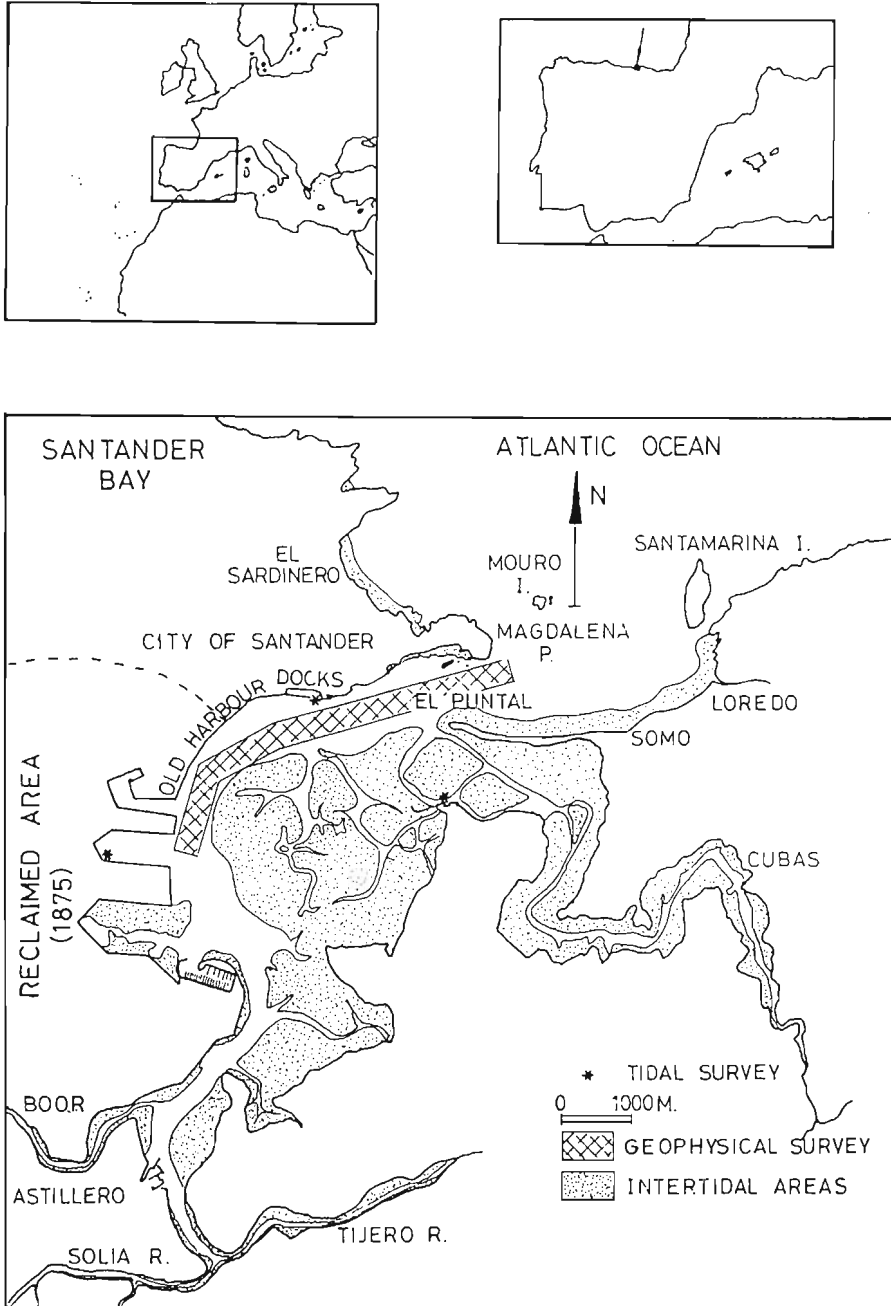


Figure 1. Study area.

brantas and in the spit end, has been carried out in order to maintain a navigable channel (see Figure 2).

Comparing the figures from 1960 and 1875,

the following points can be noted: (1) A loss of sand of about  $2 \times 10^6 \text{ m}^3$  along the spit between its end and Las Quebrantas; (2) a retreat of the low tide bathymetric of roughly 100 m; (3) an

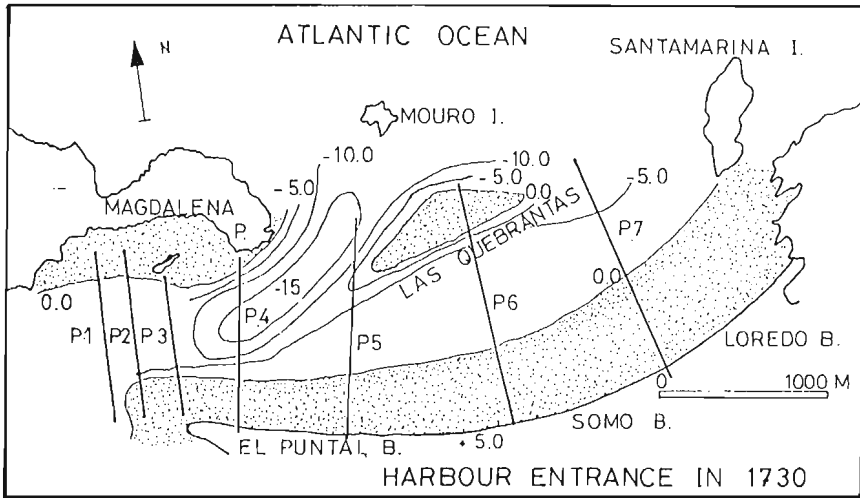


Figure 2. Harbor entrance in 1730.

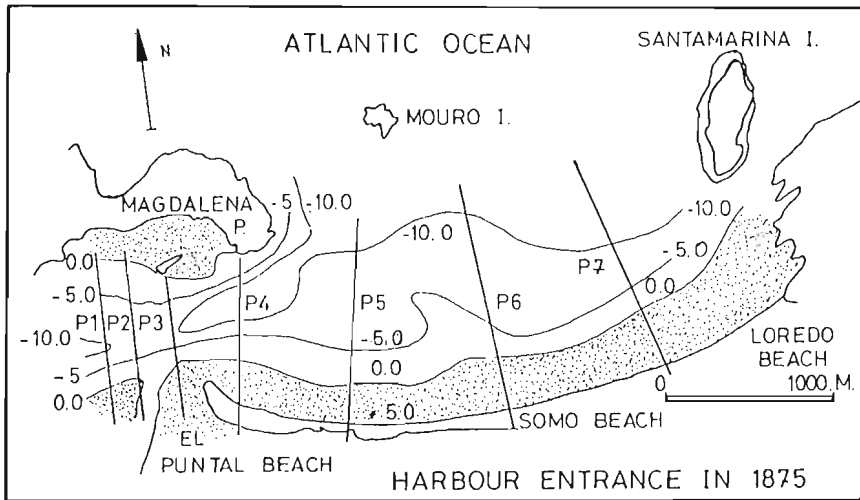


Figure 3. Harbor entrance in 1875.

increase in the steepness of the channel slopes; (4) the increased depth of the channel, achieving in some points 15 meters under low tide level; (5) a slight variation in the channel orientation towards the east; and (6) the discharge point of the Cubas River was moved to inside the Bay.

Finally, Figure 5 shows the situation in 1985.

As can be observed, all the alterations described above continue to happen and some of them more noticeably. In particular, the Quebrantas shoal has almost disappeared, the Loredo region has retreated about 200 meters and some rocks in the submerged as well as in the aerial beach profile are now visible. An evaluation of the sand lost in the system during

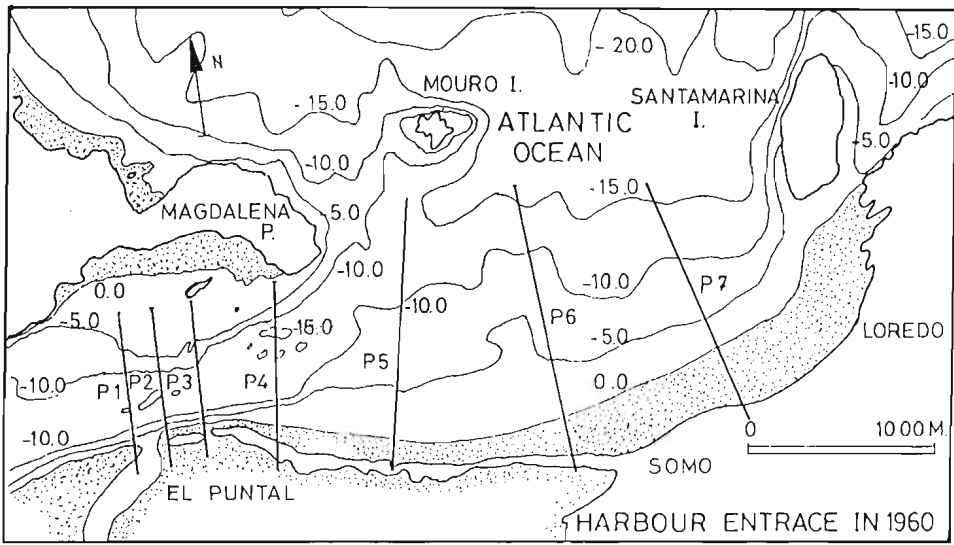


Figure 4. Harbor entrance in 1960.

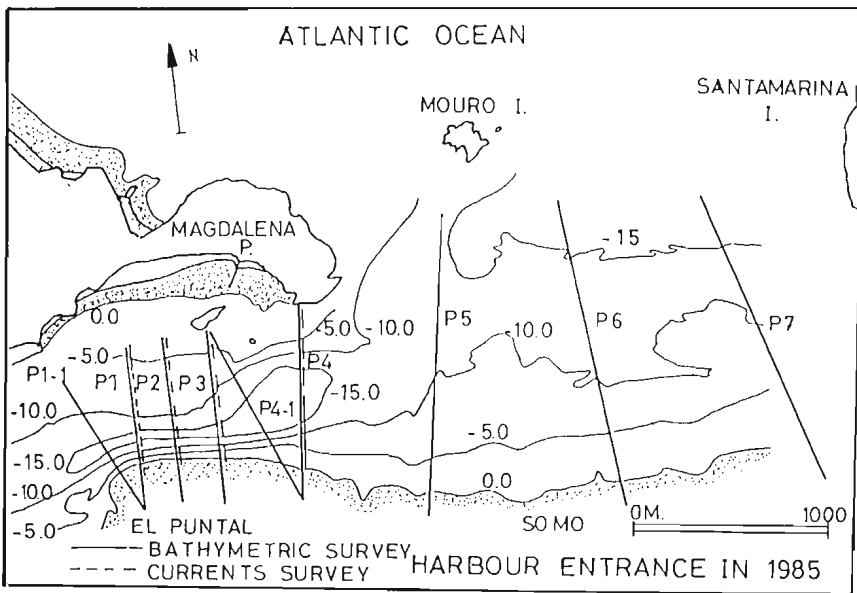


Figure 5. Harbor entrance in 1985.

the last 25 years might be as large as  $6 \times 10^6$  m<sup>3</sup>.

Now, after more than 25 years of intensive dredging and strong alterations of the equilibrium conditions of the spit-navigation channel system, the navigation conditions at the entrance are far from satisfactory. Furthermore, present conditions are not compatible with today's harbor traffic and its future development. Consequently, the Harbor Authority decided to study the morphodynamic conditions of the navigation system in order to seek a solution which satisfies the navigation requirements, minimizes the dredging costs and takes into account the role of El Puntal Spit as a branch that is used as a recreation area.

### PHYSICAL ENVIRONMENT AND FIELD MEASUREMENT

The north coast of Spain consists of a series of pocket beaches and small inlets separated by pronounced rocky headlands. Santander Bay is one of the largest inlets on the Cantabrian Coast and is located about 200 km west of the French border. The bay provides a natural shelter from the waves of the Gulf of Biscay which arrive from NNW and have an annual average significant height of 1 m with winter storm waves of 4 m. Wave propagation to the average is modified by the Magdalena Península which produces wave diffraction and reflexion. Most of this wave energy is finally dissipated along the spit. Inside the bay waves are predominantly from the SW and, because of their local generation, they are short and small waves.

The mean tidal range in Santander Bay is 3 meters; the spring tidal range is 5 meters and the tides are semidiurnal. The actual tidal prism is about  $87 \times 10^6$  m<sup>3</sup> and the maximum discharge around 5500 m<sup>3</sup>/sc.

Four rivers discharge into the Bay: Cubas, Boo, Tijero and Solía. Their average discharge does not reach 15 m<sup>3</sup>/sc, although under flood conditions the discharge may be as large as 400 m<sup>3</sup>/sc mainly from the Cubas River.

The mean grain size is  $D = 0.3$  mm, however a very significant longshore grain distribution exists, so that at the end of the spit the mean grain size is  $D = 0.45$  mm and at Loredo Beach is  $D = 0.25$  mm. The source of this sand is mainly fluvial (60%) but the biological source (35%) is also noticeable.

Field measurements of water level around the bay, currents, bathymetric beach profiles of the spit and geophysical profiles along the navigation channel were recorded during one year. Figures 1 and 5 show the areas of monitoring. In order to avoid human influence upon the field data, dredging activity was suspended during the period of measurement.

Water level was recorded at three locations within the bay (Figure 1) using pressure gauges. Currents were recorded in four channel sections (Figure 5) ten times per tidal cycle. An ACDP (Acoustic Doppler Current Profiler) mounted on a boat was used. Bathymetric profiles were surveyed eleven times from December 1987 to January 1989, at the locations shown in Figure 5. The exposed beach was measured using standard surveying techniques and the offshore portion was measured using sounding and triangulation.

### TOPOGRAPHIC AND BATHYMETRIC VARIATION ANALYSIS

The data set for this study, therefore, consists of one year of monthly onshore-offshore profile surveys. These profiles include not only beach profiles (P5, P6, P7) but channel profiles as well (P1, P2, P3, P4). Alongshore spacing of the profiles was approximately 100 m for channel profiles and 500 m for beach profiles. Each profile was surveyed from mean high water (MHW) on the intertidal beach seaward to a depth of approximately 15 m. The landward part of each profile was surveyed to a depth of approximately 1 m from a series of bench marks established in the dune areas. In this way, the seaward part of the land profile overlapped with the shoreward part of the offshore profile. Channel profiles crossed the entrance from side to side.

These data were arranged in the form of a matrix  $h(x,y,t)$ , where  $x = 46$  (number of on-offshore points),  $y = 9$  (number of transects) and  $t = 11$  (number of surveys). The transect spacing and location was designed to allow for the space variability of waves and tidal currents. Transects P1-1, P2, P3 are in a current-dominated area, transects P5, P6, P7 are in a wave-dominated area, whereas P4-1, P4 are in a transition area.

## Cross-Shore Variations

Beach profiles P5, P6, P7 showed typical seasonal changes during the survey, (see Figure 6.) These variations occurred mainly within the tidal range in transects P5 and P6. Furthermore, the development of one or more storm bars (between 0, -5) can be observed. No significant variation below the - 10 m depth contour was detected. Transect P7 showed a 'perched beach' profile which leant against the rocks which have emerged in the last decade. These rocks were located 800 m away from the shore and in 6 to 10 m water depth.

Channel profiles P1, P2, P3 showed not only seasonal changes but an annual trend, see Figure 7. Transect P1-1 (see Figure 5) showed that the Spit lengthened Westward more than 30 m in one year. Transect P4, located in the transition area, recovered its initial situation as a beach profile.

## Eigenfunction Analysis

Previous studies of beach changes and other phenomena have been conducted using the Empirical Orthogonal Function (EOF) method (LORENTZ, 1959 WINANT *et al.*, 1975; DAVIS, 1976; AUBREY, 1978; DICK and DALRYMPLE, 1984; ZARILLO and LIU, 1988; MEDINA *et al.*, 1990). The method is an efficient way to describe beach profile changes, both spatial and temporal. This method can be used to expand the data in the form:

$$h(x, y_0, t) = h(x, t) = \sum_n a_n e_n(x) c_n(t) \quad (1)$$

where  $h(x, t)$  are the beach profile data,  $c_n(t)$  represent the temporal eigenfunctions,  $e_n(x)$  represent the spatial eigenfunctions and  $a_n$  represent the normalizing factors, see AUBREY (1978).

Obviously, the method can be applied not only to cross-shore profiles  $h(x, y_0, t)$  but to longshore profiles  $h(x_0, y, t)$ , to bathymetric maps  $h(x, y, t_0)$  and to any multi-dimensional set of data.

## Longshore variations

The different dynamics that govern the wave-dominated area and the current-dominated

area and their different time scales, give different profile morphologies and time delays along the spit. This can be easily observed applying the EOF method to any longshore characteristic, for instance the intertidal slope or a longshore profile. The longshore variation of the intertidal mean slope can be represented by  $X(y, t)$ , where  $y$  = number of transects,  $t$  = number of surveys and  $X(y, t)$  = horizontal distance between high water level (+ 5.0) and low water level (+ 0.0). The smaller the value of  $X$ , the steeper the slope is.

The first eigenfunction, corresponding to the largest eigenvalue, represents a mean slope along the spit, Figure 8. This eigenfunction accounts for about 99.9% of the variance, that is the mean square value of the data. Notice the longshore variation of the mean intertidal slope, that reaches 1/40 in the wave dominated section and 1/10 in the current dominated section.

The second largest eigenfunction accounts for the 0.07% of the variance, or about 70% of the variance with the mean slope function removed. The second temporal eigenfunction, Figure 9, identifies seasonal variations through the surveyed data. The second spatial eigenfunction, Figure 10, identifies the location and the magnitude of these seasonal changes. Notice the different sign of the spatial eigenfunction of the profiles P1, P2, P3, P4 and the profiles P5, P6, P7 stating that when the slope increases in the wave dominated area, it decreases in the current dominated area.

This result can be further explained if we look for the evolution of the longshore profiles + 5.0, + 2.5 and + 0.0. The first eigenfunction, Figure 11, represents a mean situation of the profiles during the survey. The longshore variation of the intertidal slope can be observed as presented above. The second temporal eigenfunction, Figure 12, shows the same trend in all the profiles but a delay between each of them. The second spatial eigenfunction, Figure 13, shows that the different behavior between wave/current sections occurs only in P1 for profile + 5, P1, P2, P3 for profile + 2.5, and in P1, P2, P3, P4 for profile + 0.0.

## Temporal Longshore Variation:

(Figure 12)

The shape of the curves for the three contour

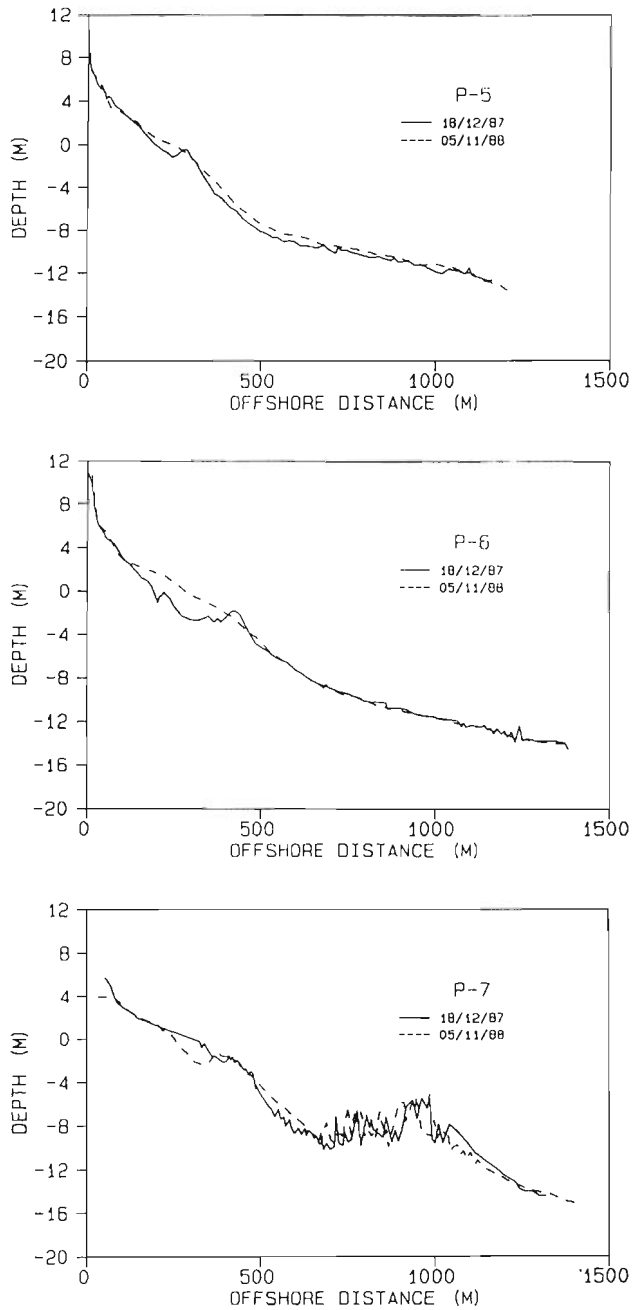


Figure 6. Channel profiles.

lines is worthy of comment. They are slightly phase lagged. This lag indicates the recovery time delay of the 0, + 2.5 and + 5 beach con-

tour. Notice that the 0.0 contour reaches its maximum deviation about 2 months earlier than the + 5.0 contour. It is also worth noting

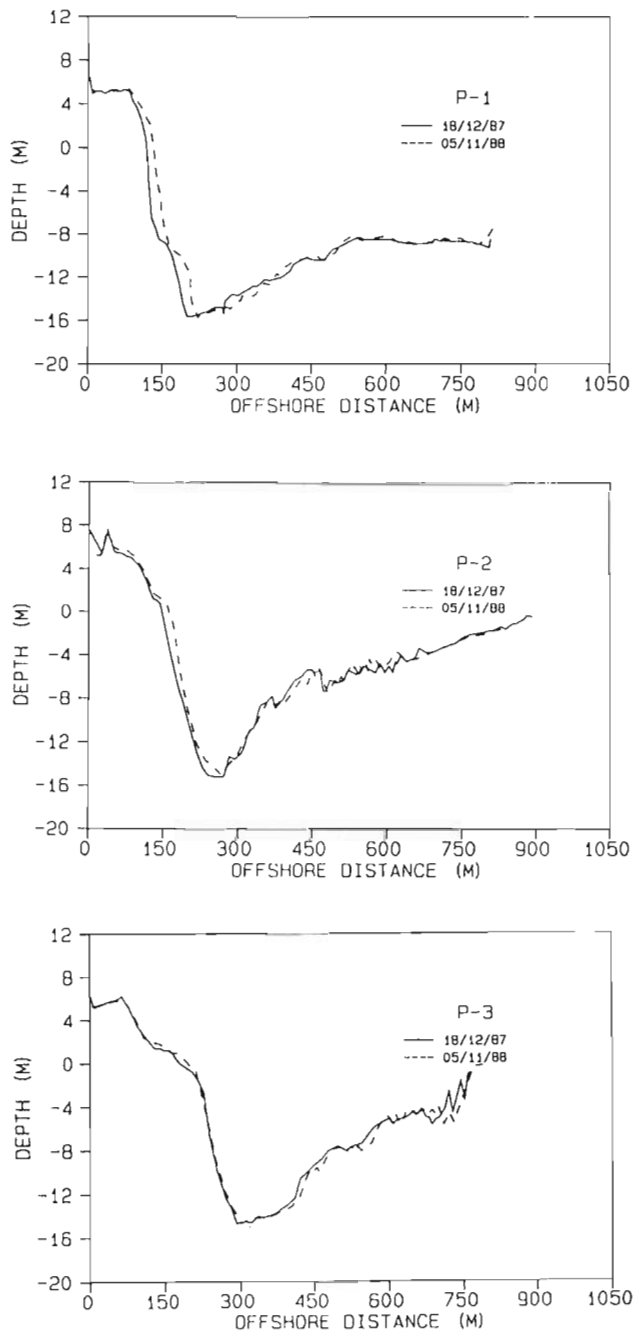


Figure 7. Beach profiles.



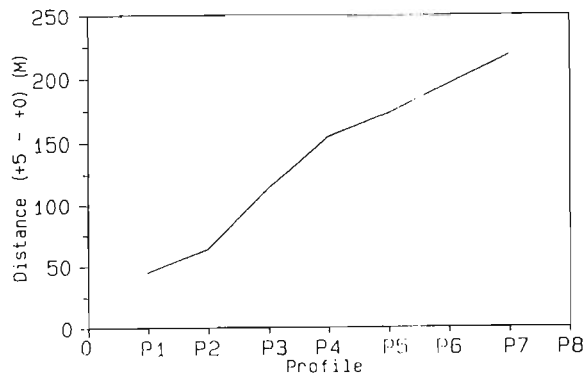


Figure 8. First spatial eigenfunction for longshore intertidal slope.

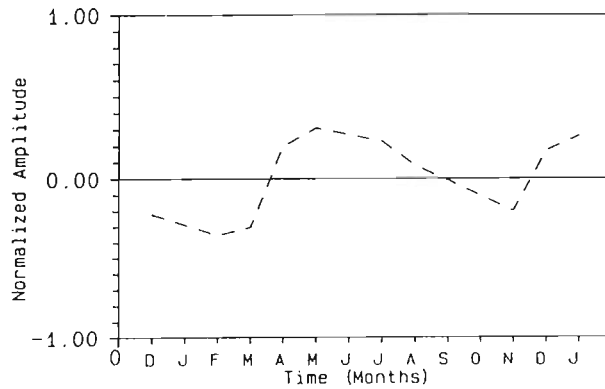


Figure 9. Second temporal eigenfunction for longshore intertidal slope.

that the shape of curve is asymmetric, in the sense that it takes longer for the beach to recover (about 8 months) than to erode (about 2 months).

**Spatial Longshore Variation: (Figure 13)**

The variation of the 2.5 and 5.0 contour lines is much smaller in absolute value than the 0.0 contour. Further, the opposed behavior of the wave dominated area (P6 and P5) and the current dominated area (P1 to P4) is important. When P5 and P6 recover, P1, P2, P3 and P4 retreat, and vice versa. As will be seen later, this morphological pattern reflects the overall sediment transport along the spit (beach and channel). This behavior may also be observed in

Figure 10, when the longshore evolution of the beach slope is drawn.

**MORPHODYNAMICS OF THE SPIT:  
DISCUSSION**

The morphology of the inlet shown in Figure 2 are similar as those described by BRUUN (1978); a lateral sedimentary structure and a large offshore shoal. Under wave action, sand moves from the shoal to the beach and from there drifts alongshore to the east and to the west. Once sand reaches the spit end it falls down into the channel. There the sand moves upstream and downstream under current action as a rolling carpet. Finally, most of the material returns to the shoal where the cycle starts

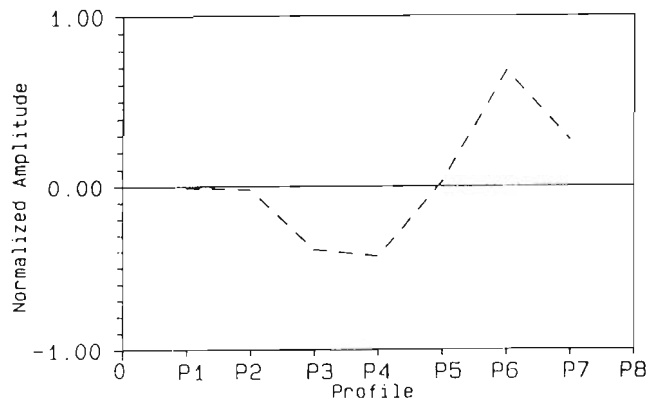


Figure 10. Second spatial eigenfunction for longshore intertidal slope.

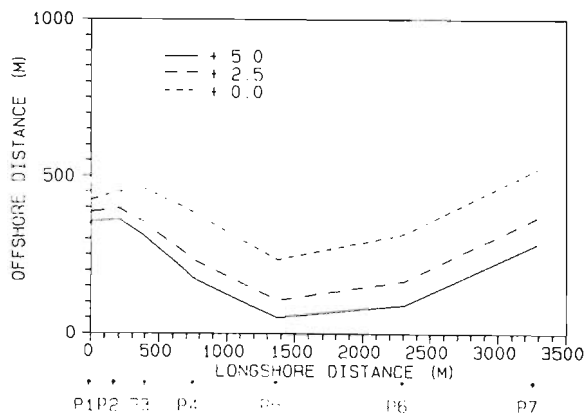


Figure 11. First spatial eigenfunction for longshore profiles.

again. However the cycle is not a continuous sediment transport process, because of the time lag between the sediment transport capability of waves and tides.

Figure 3 shows the entrance after one intensive land reclamation project which reduced the tidal prism by roughly 40% (CENDRERO *et al.*, 1981). Consequently the onshore and longshore currents induced by the wave action predominate over the tide current action, the shoal advances to the beach and the spit end turns towards the inside of the channel.

Due to the increasing size of ships in the last few decades, a situation was reached in which

dredging of the spit end became necessary. Figures 4 and 5 show the evolution of the spit under this dredging.

The main feature is the cancellation of the spit curvature which means that the longshore sediment transport goes farther inside the bay. The spit growth displaces the River Cubas discharge point inwards. An increase ratio of 10 m/year is the average value estimated for the last 80 years. Note that during these 80 years over  $6 \times 10^6 \text{ m}^3$  of sand was dredged. However, during the study no dredging was done and the spit grew 30 meters in the year.

The present situation is as follows:

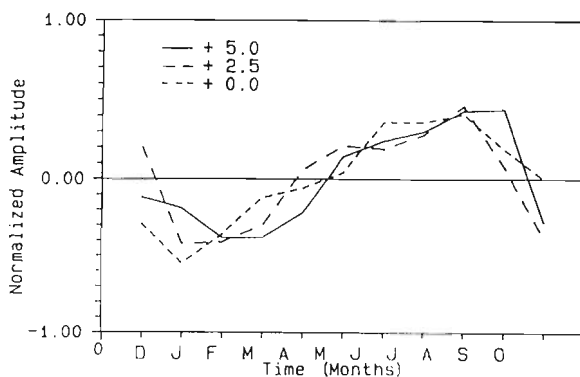


Figure 12. Second temporal eigenfunction for longshore profiles.

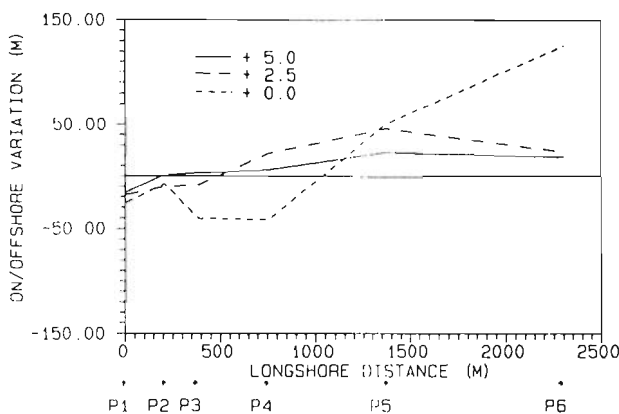


Figure 13. Second spatial eigenfunction for longshore profiles.

(1) The beach profile survey shows that rock appears in profile P7.

(2) Dunes have been cut by successive storms, thinning their aerial structure.

(3) The time lag between longshore transport and ebb current sand transport provokes temporal sedimentation of sand in the navigation channel.

(4) The Harbor Authority needs to dredge around the spit end.

The methodology followed in this study serves to discover the mean equilibrium condition of the entrance to Santander Harbor and its deviations. The mean spit shape is compatible with the navigation requirements. How-

ever, during a certain period of time, usually around 8 months, the deviation of the spit from its mean position reduces the navigation channel locally. To avoid these situations it was recommended to the Harbor Authority that they dredge small amounts of sand from the spit end and discharge it close to the beach in the large area called Quebrantas, helping to speed up the natural process of current action.

#### ACKNOWLEDGEMENTS

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## □ RÉSUMÉ □

Présente l'évolution historique de la flèche El Puntal à Santander (Espagne). Pour l'élaboration d'un nouveau chenal de navigation au port de Santander, on a exécuté des mesures in situ des marées, des courants et des profils bathymétriques. Ils ont permis d'expliquer la morphodynamique du chenal de marée et de la flèche. Une fonction orthogonale empirique a servi à analyser les modifications causées par les tempêtes et l'action de la marée le long de la flèche. Les résultats de cette méthode montrent que la flèche peut être divisée en deux sections, l'une dominée par la marée, l'autre par les tempêtes. Les petnes de l'estran océanique de ces sections se comportent différemment en conditions de tempête: les sections dominées par la marée sont en accrétion, celles qui le sont par la tempête s'érodent. Au cours des périodes de calmes, c'est l'inverse qui se produit. Les dragages du chenal de navigation (section dominée par la marée) effectués dans les 5 dernières années ont conduit à un déséquilibre global de la flèche. *Catherine Bousquet-Bressolier, Géomorphologie EPHE, Montrouge, France.*

## □ ZUSAMMENFASSUNG □

In dieser Arbeit wird die historische Entwicklung des Hakens "El Puntal" in Santander (Spanien) vorgestellt. Feldmessungen der Gezeiten, Strömungen und Tiefenprofile, die während der Anlage eines Zufahrtskanals für den Hafen von Santander gewonnen wurden, werden zur Erklärung der Morphodynamik des Gezeitenkanals und des Hakens herangezogen. Die Methode empirischer Orthogonalfunktionen (EOF) wurde angewendet, um die Veränderungen des Hakens durch Sturm und Gezeiten in seiner Längsabtragung festzustellen. Die Ergebnisse der EOF-Analyse zeigen, daß der Haken in eine gezeitendominierte und eine sturmdominierte Abteilung getrennt werden kann. Der Strand im Gezeitenbereich in diesen beiden Anschnitten weist ganz spezifische Verhalten unter Sturmbedingungen auf: während die Gezeitensektion Akkumulationen zeigt, wird die Sturmsektion erodiert. In Phasen mit ruhigem Wellenregime tritt genau das Gegenteil auf. Baggeraktivitäten im Gezeitenabschnitt des Navigationskanals haben dazu geführt, daß in den letzten 50 Jahren am gesamten Haken keine Gleichgewichtsverhältnisse mehr auftreten.—*Dieter Kelleat, Essen, F.R.G.*

## □ RESUMEN □

En este trabajo se presenta la evolución histórica de la flacha de "El Puntal," en Santander (España). Para explicar la morfodinámica del canal de marea y de la flacha se ha utilizado las medidas de campo de mareas, corrientes y perfiles batimétricos realizados para el diseño de un nuevo canal de navegación para el Puerto de Santander. Se ha aplicado el método de las Funciones Ortogonales Empíricas (EOF) para analizar los cambios longitudinales del Puntal debidos al efecto combinado de los temporales