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# Influence of Beach Morphodynamics in the Deep Burial of Fuel in Beaches

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**ABSTRACT**

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O Rostro beach was one of the most seriously affected beaches during the *Prestige* oil spill along the "Costa d'a Morte" in Galicia, Spain, in November 2002. More than 10,000 tons of residual material were removed from the beach, with a significant quantity of the oil buried in the sandy sedimentary column of the beach. Under sporadic wave conditions throughout the years, this situation made the clean-up activities very difficult. Among the reasons why a significant quantity of oil was buried in the beach are the following: first, the arrival of large quantities of oil to the beach; second, an elevated number of high wave energy storms with atypical sequence in direction; and third, the particular morphodynamic features in O Rostro Beach, which is an intermediate bayed beach with a stable middle-scale transversal bar-horn system that, interacting with the local dynamics, has a high capacity to bury oil in sand matrix (2 to 3 m deep). The information collected in the 3-year exhaustive monitoring plan (spring 2003 to summer 2006) in O Rostro Beach has provided better knowledge and comprehension of the processes involved in the interaction of the oil spill dynamics with the beach morphodynamics. Based on these field data, the zones with deeply buried oil were located; also, it was evidenced that 4 years after the oil spill, the buried oil degraded rapidly. A conceptual evolution model of the oil leaked to the beach is proposed, with the aim of explaining how and where the oil initially arrived, where it was buried in the sandy core, and how the oil has evolved physically and mixed with sand throughout the last several years. Based on the conceptual evolution model of the oiled substance, the morphodynamic characterization of the beach, and the field data collected, the clean-up activities have been optimized and significantly improved in O Rostro Beach.

**ADDITIONAL INDEX WORDS:** *Prestige catastrophe, fuel spill, oil burial, oil shoreline monitoring, beach morphodynamics, coastal evolution, cuspate features, O Rostro Beach.*

## INTRODUCTION

As a result of the sinking of the *Prestige* tanker on November 19, 2002, a number of beaches along the "Costa d'a Morte" in Galicia (Northwestern Spanish coast) were severely affected by the massive oil spill. Among the beaches most affected by the disaster were those situated between the capes of Touriñán and Fisterra, with O Rostro Beach being the most seriously affected during the spill (see Figure 1). During the catastrophe and subsequently throughout the summer, autumn, and winter of 2003, a significant amount of beached oil was removed from the beach by the collaboration of thousands of volunteers and mechanical methods (see Figure 2). However, cleaning activities have continued for the last several years because of the sporadic appearance of more reduced quantities of fuel along the beach. The arrival of large quantities of oil to the beach, combined with the exposed location of O Rostro Beach to the high energy waves in the Costa d'a Morte, and the morphodynamic characteristics of this intermediate barred beach with the consequent variability of the beach profile and planform (Wright and Short, 1984) caused the oil to become partly buried. This buried oil gradually reappeared and was dragged toward the coast, where a permanent cleaning service was required to remove it. More than 10,000 tons of residual material were removed from the berm and intertidal zone in O Rostro Beach from the winter 2002 to the summer 2006.

The mobility of the grains of sand on a beach is extremely important in the evolution of an oil spill, as the spill will be subjected to these same forces. Therefore, an oil spill that has reached the foreshore area of a beach can, if it is not cleaned soon enough and the wave conditions change, end up on the dunes or even buried under several meters of sand, making its retrieval impossible. This same movement of the sand makes it possible for the oil, buried weeks, months, or even years earlier, to return to the surface. The uncovering of the spill also has a long-term negative effect on two of the main functions of the beach: to be part of highly valuable ecosystems and to serve as an area for public use.

Although sand systems in beaches are not among the most

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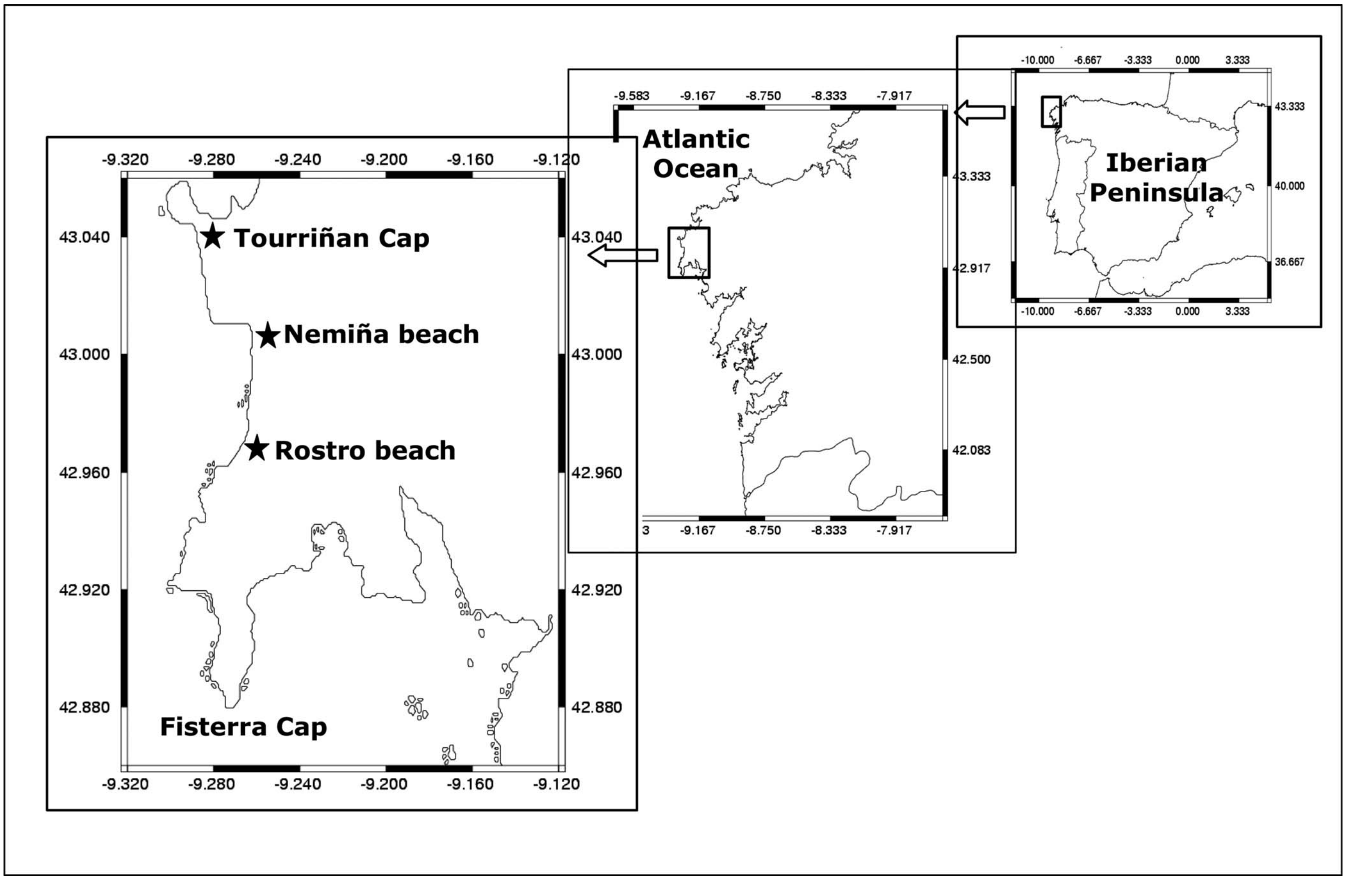


Figure 1. Location of the study area. O Rostro Beach in the "Costa d'a Morte" Fisterra (Galicia, Spain).

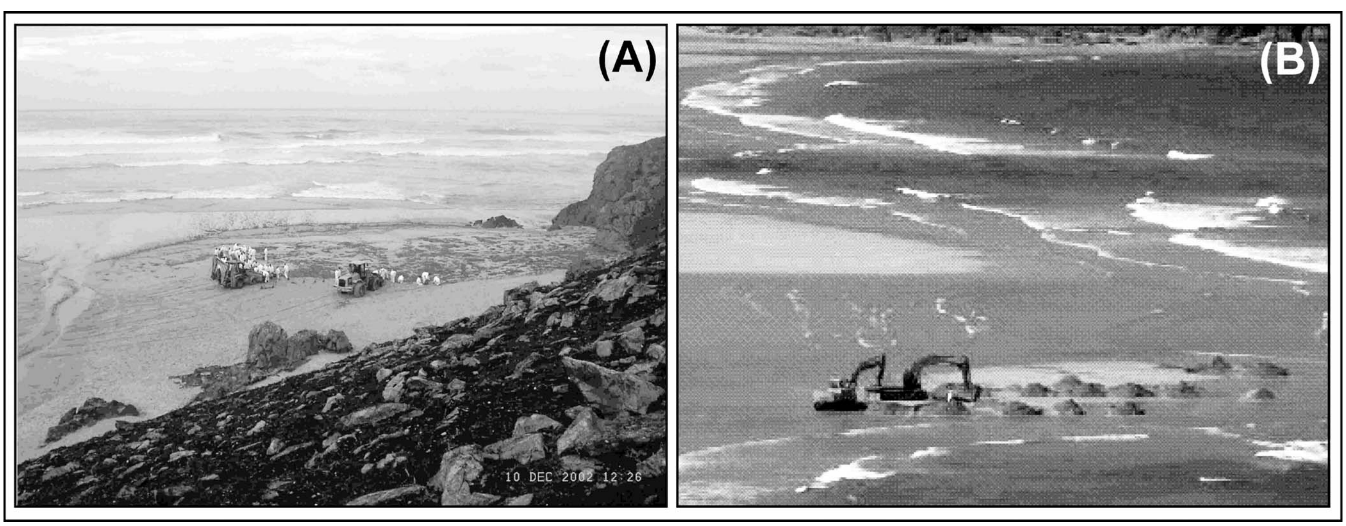


Figure 2. Oil clean-up campaigns in O Rostro Beach. (a) Volunteers working in the winter 2002. (b) Mechanical extractions in the spring 2003.

productive ecosystems, they set boundaries for other extremely valuable ecosystems such as dunes, rocky reefs, and estuaries, all of which usually border beaches that can be affected by a spill. From the public use perspective, and setting aside the rational reasons for choosing beaches as leisure areas, one must acknowledge that tourism is an economic factor for many of the Spanish coastal areas and an oil spill can cause significant economic losses.

The aforementioned issues highlight the importance of removing the spill immediately, therefore avoiding its burial and the prolonged negative effects on the economy and the environment. However, it is not always possible to remove the spill as soon as one would like: the inaccessibility of some of the beaches, the arrival of a spill at night, or the material limitations when a spill of catastrophic dimensions occurs cause the oil to remain for some time on the beach, subject to the whims of the waves and the movement of the grains of sand on a beach. However, not all beaches behave the same. Some are more active than others, experience more profile and planform mobility, and are therefore more likely to bury the spill. Depending on the type of oil spill and the beach characteristics—that is, the type of sand, its features, rocks and contours that define it, and the wave characteristics—it is possible to estimate whether the spill will end up on the dunes, in the foreshore area, or buried under the exterior bars.

Hence, in order to minimize the environmental impact of future oil spills on beaches and to optimize cleaning activities extended several years throughout time, such as the case of O Rostro Beach, a better knowledge of the processes involved is required. To understand where the fuel is located when it arrives on the beach and how the oil evolution is throughout time (cross-shore and long-shore oil transport on the beach, possible burial locations. and physical and chemical transformation), it is required to know the following: (1) the beach morphodynamics; (2) the morphodynamic state of the beach during the arrival of the oil, which means characterizing the morphology and dynamics throughout the event; (3) the modal state of the beach and its morphodynamic variability through time; and (4) the beach limits (lateral and the cross-shore underwater toe), which confine the circulatory system and the oil transport on the beach.

In the case of O Rostro Beach, a 3-year exhaustive monitoring plan and morphodynamic studies on the beach were developed (CEPRECO, 2006; González and Medina, 2006; Ministerio Medio Ambiente, 2005). The monitoring plan was carried out under the Directorate General of Coasts, Environmental Commission for the Prestige Disaster (Spanish Ministry of the Environment), and the Centre for the Prevention and Fight Against Maritime and Littoral Pollution (CEPRECO, Ministry of the Presidency), lasting from the spring 2003 to the summer 2006. The monitoring plan included a continuous program throughout time and some specific field campaigns. In general terms it consisted of weekly and daily morphological (plan and profile) inspections of the beach berm and intertidal zone; local topographies (beach dunes, berm, and intertidal zone) and bathymetries (water depths $<$10 m); inspections of deep and shallow buried oil by mechanical mediums cross- and long-shore on the beach berm and intertidal zone; sea bottom dive inspections by cross-shore transects from deep water to surf zone ($h \sim 22$ m to 3 m), including collection of sand-oil sea bottom samples; and granulometric and geochemical study based on the collection of more than 15 cores extracted from the intertidal zone with maximal depth of 2.38 m in different beach zones and time periods. This study permitted the establishment of an oil evolution model in the sedimentary column in the intertidal beach zone (Bernabeu *et al.,* 2006). In general, the information collected in the exhaustive monitoring plan carried out in O Rostro Beach provided a better knowledge and comprehension of the processes involved in the interaction of oil spill dynamics with beach morphodynamics.

The purpose of this article is to describe and analyze the interaction of the morphodynamics in O Rostro Beach with the transport of oil and its evolution since the oil spill to some years later. Once this interaction is established, a conceptual evolution model of the oil leaked to O Rostro Beach is proposed, with the aim of explaining how and where the oil was buried once it was beached and its evolution throughout the following years. The proposed model is supported by the data collected in the monitoring plan.

The article is organized as follows: the first section is a description of the physical environment (morphology and marine dynamics); next, a description of the collected data in the monitoring plan is presented; subsequently, a morphodynamic model of O Rostro Beach is described, taking into account the different process scales (short-, middle-, and long-term scales); and finally, an oil transport and conceptual evolution model of O Rostro Beach is proposed.

## STUDY AREA

In this section a morphological and marine dynamic description of O Rostro Beach is presented.

### Morphology of O Rostro Beach

The Fisterra beach system is located on the Western Galician coastline (Figure 1). The coast in this zone is characterized by cliffy areas, with a north-south alignment where O Rostro Beach is situated. The global bathymetry shows a large coastal platform (Figure 3a) around 11,000 m wide reaching to the water depth contour–100 m in front of the Nemiña and O Rostro Beaches and reducing to the south. This platform is characterized by the presence of large rocky shoals, which generate a very irregular bathymetry, with large sandy rhythmic features and shoals (see areas circled in Figures 3a and 3b). These, as we will see, significantly affect the propagation of the waves, conditioning the dynamics and morphology of the beach areas.

O Rostro Beach is 2000 m long and 50 m wide and is a bayed beach laterally confined at its extremities (see Figure 4). With a SSW-NNE alignment, the beach is very exposed to dominant and most frequent waves in the area (sector NE-E). The planform of the beach (see Figure 4, a beach situation in summer 2004), shows a coastline with four shoreline cusp horns, which are not periodically spaced and do not propagate alongshore. Aerial photographs (1945, 1957, 1973, 1990, and 2004) and the monitoring data collected between

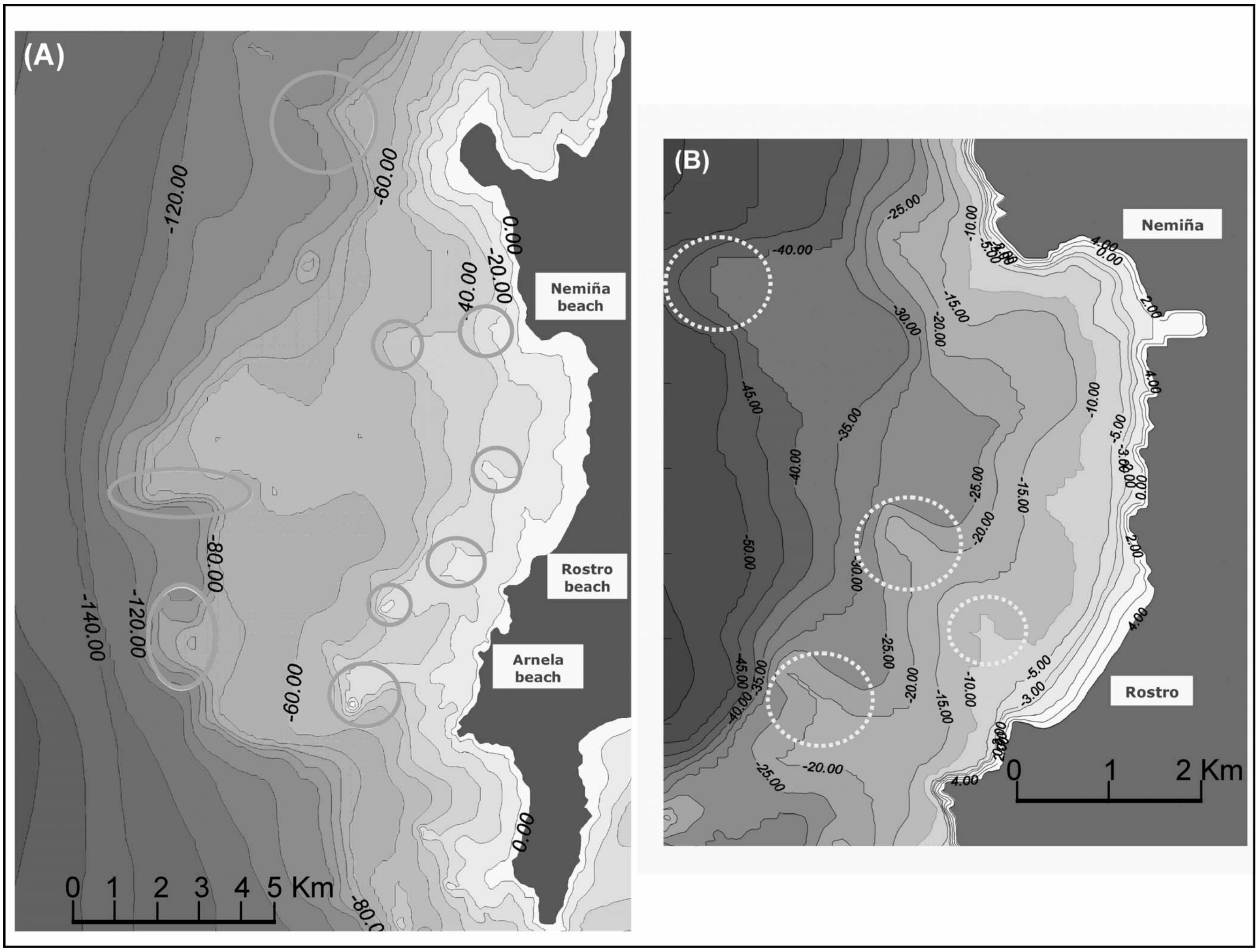


Figure 3. Bathymetry in the Fisterra Coast. (a) Global bathymetry in the zone. (b) Local bathymetry.

2002 and 2006 show that changes in the position of the horns are negligible, although their cross-shore length and width may vary in time. These have been kept over the years through summer and winter seasons, whereas during the winter they have a greater surface area. With regard to the cross-shore profile, the beach has a large dune area broken only by the mouths of two small streams: one in the north between cusps 3 and 4 and another in the south between cusp 1 and the rocky area. In its submerged profile, the beach has a series of transverse and longitudinal sand bars, typical of intermediate beaches (Wright and Short, 1984). The transverse bars are situated opposite the horns and cause the waves to break, even where they are less energetic (see the location of these bars in Figure 4).

It should be highlighted that in the flank to the north of the beach, next to the rocky area, the bar is practically longitudinal in proximity to the coastline (see Figure 4). The submerged area to the south of the beach, close to the hulk of a buried wreck, has a rocky bed with little presence of sand (see Figure 4). As will be seen below, the interaction between all of these morphological features of the beach, along with the local wave dynamics, conditions the system of currents and, as such, the movement of oil on the beach.

The beach is composed of sand with a median size of $D_{50}$ $\sim$ 0.34 mm in the north, $D_{50} \sim 0.49$ mm in the central section where the biggest horn (2) is located, and $D_{50} \sim 0.46$ mm in the south, with a beach mean sediment size of $D_{50} \sim 0.41$ mm. Sediment data were obtained in a field campaign in May 2006 (see CEPRECO, 2006).

## Marine Dynamic of O Rostro Beach

The stability and morphodynamic evolution of O Rostro Beach and also the movement of oil on the beach are mainly governed by the action of the wave climate and wave-induced current system. In this section the climate wave and current system are described in detail.

### Wave Climate

There are no long-term wave measurements available locally in O Rostro Beach. However, there are two directional

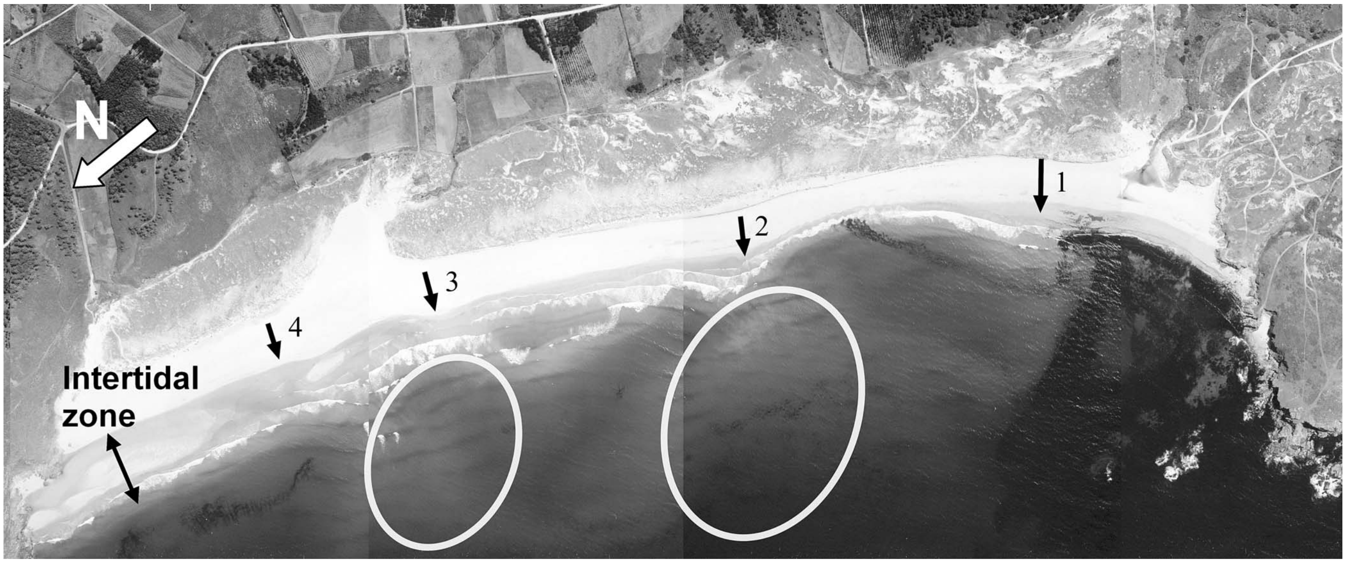


Figure 4. Photograph of O Rostro Beach. Location of the permanent beach horns.

buoys: Villano, north of the study area, and Sillerio, south of the study area, offshore in the Fisterra area. Hence, in order to obtain directional high-resolution temporal wave series near O Rostro Beach throughout the oil spill and the subsequent years, wave generation model (hindcast) results based on meteorological wind statistics and maps calibrated with satellite images and wave buoys have been applied in combination with local propagation models.

Deep-water wave data $(H_s, T_p, \theta)_\infty$ were obtained from the oceanographic database of the Spanish authority of harbors Puertos del Estado (www.puertos.es), specifically from the Wave ANAlysis (WANA) data set (time series 1996–2007), which provides the time series of wave and wind parameters obtained by numerical modeling. Wave fields are generated by means of the Wave Model (WAM), which is driven by wind fields. The WAM (WAMDI Group, 1988) is a third-generation wave model that solves the energy balance equation explicitly for the two-dimensional surface wave spectrum without making any presumptions on the shape of the wave spectrum. The WAM grid has a resolution of 0.25 degrees (30 km) in the Atlantic. The grid point WANA-1042072 (43.00° N, 9.50° W) was used (approximately 15 km offshore just in front of O Rostro Beach). Two directional buoy measurements, Villano (43.49° N, 9.21° W) located in a water depth of 386 m and Sillerio (42.12° N, 9.40° W) located in a water depth of 323 m, and satellite altimeter data (Topex-Poseidon Mission) were used in this work for calibration and verification of hindcast model results. Spatial and temporal optimization methods were applied to obtain continued data series, which are available from the period of September 1, 2002, to June 30, 2006, with a 3-hour time interval.

Figure 5 shows the wave directional distribution and the mean regimen for the significant wave height for the offshore WANA data calibrated in deep water. The dominant and prevailing waves in the area can be seen coming from the fourth quadrant and fundamentally in the sector NW to WNW, with a probability of occurrence of 45% for NW, 23% for W, and 5% for SW, with a mean significant wave height and peak period of $H_{sm} = 2$ m and $T_p = 10$ s and a typical annual storm condition with significant wave height exceeded 12 hours in a year and peak period ($H_{s12} = 8$ m and $T_p = 16$ s). These wave conditions show the high wave energy in the area.

The evolution of the significant wave height and mean directions of the waves throughout the study period is presented in Figures 6a and 6b. The WANA data, taken every 3 hours, are shown in a continuous red line and the mean daily data in dots. As can be seen from these figures, from the date of the initial spill (the accident happened on November 13, 2002, and the tanker sank 6 days later), between November 2002 and April 2003 there were a large number of big storms, mainly from the NW, as on November 22, 2002, with significant wave height $H_s = 7.5$ m and peak period $T_p = 15.5$ s, and on January 23, 2003, with $H_s = 8.1$ m and $T_p = 16$ s. Particularly relevant were those storms from the WNW on December 27, 2002, with $H_s = 6.0$ m and $T_p = 13.5$ s and on January 18, 2003, with $H_s = 7.0$ m and $T_p = 14$ s. The storms from SW-WSW play an important role in the stability of the beach, as will be discussed later, and from November 14 to January 31, four storms from these directions with an average duration of 6 days occurred. It should be highlighted that between October 2002 to December 2003, 17 storm events occurred with 4.5 m $< H_s <$ 9.2 m, including four events with $H_s >$ 7.5 m. Nevertheless, during the next 2 years (2004 to 2006), 20 storms with 4.5 m $< H_s <$ 6.9 m occurred, with five storms coming from the WSW-SW with 4.3 m $< H_s <$ 5.1 m. Until the summer of 2006 no high wave energy fluxes of similar significance to that of the winter of the tragedy had been experienced, also a few events from the SW-WSW have occurred in the last few years. In the "Conceptual Evolution Model of the Oiled Substance on the Beach" section, we will

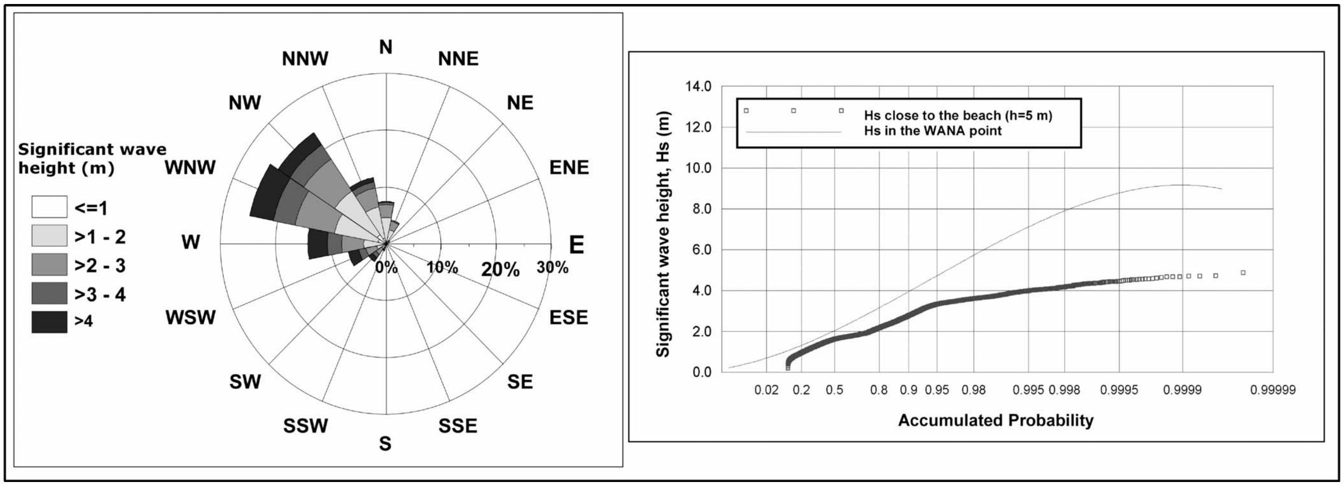


Figure 5. Directional wave height distribution in the calibrated WANA point and mean significant wave height regimen.

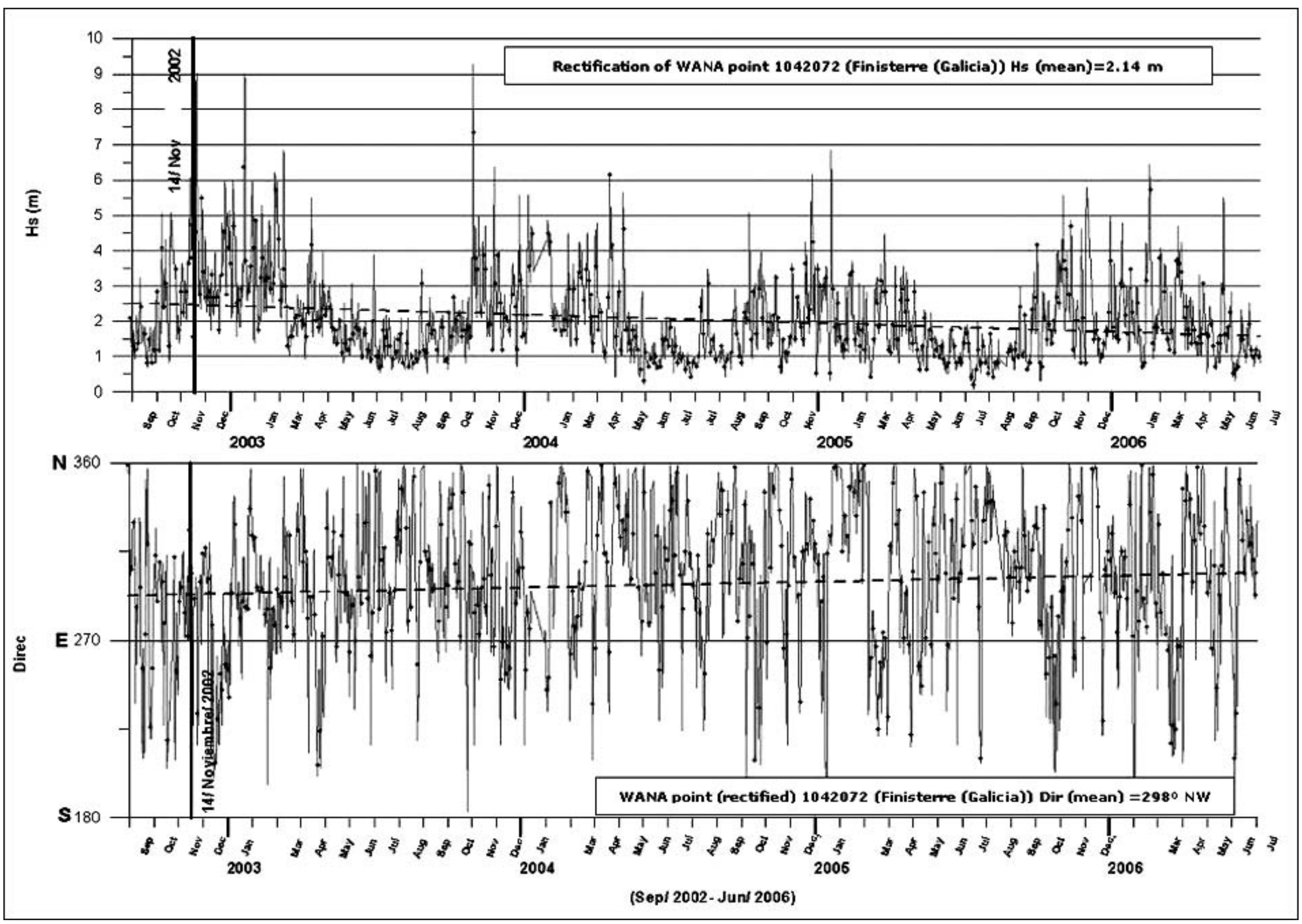


Figure 6. Wave climate evolution offshore (Calibrated WANA point). (a) Significant wave height time series. (b) Wave directional time series (3-hour data in solid line and mean daily data in dots).

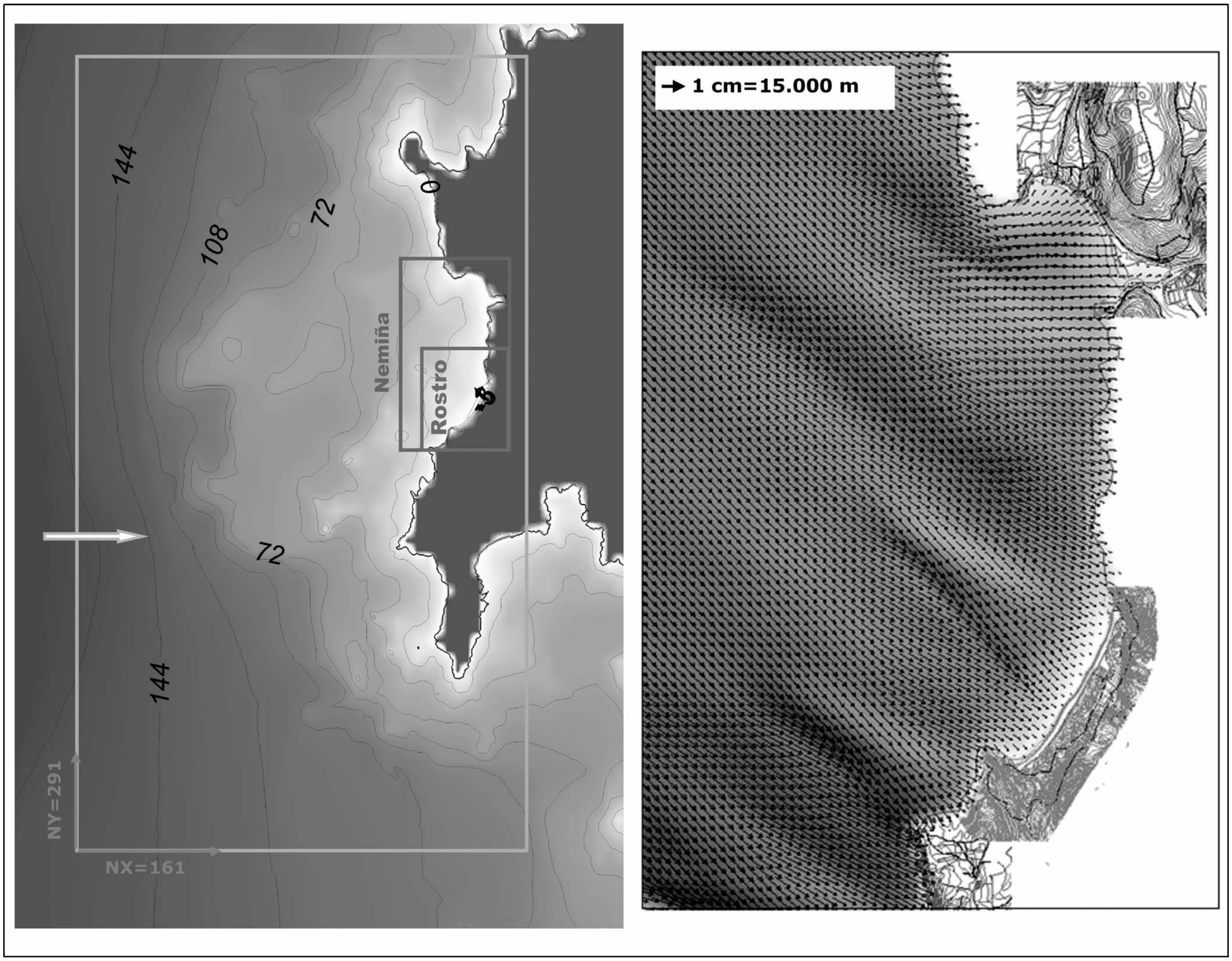


Figure 7. Wave propagation storm condition (with Oluca-SP Model). (a) Propagation grids. (b) Wave storm condition ($H_s$ = 6 m, $T_p$ = *16 s, Dir: NW*).

consider the details of the sequence of these storms and how they affected the beaches in terms of oil transportation.

A wave propagation study was carried out to propagate the wave series from the WANA point to O Rostro Beach. Discrete bathymetric and coastal boundary data were recomposed using local bathymetries from the field campaigns combined with bathymetry from the nautical charts of the Instituto Hidrográfico de la Marina (chart numbers 926, 927, and 9271). The Oluca-SP wave spectral model (GIOC, 2003), which is part of the Coastal Modeling System, or SMC (González *et al.,* 2007), was used to propagate waves from the WANA point to the coastline. Oluca-SP is a weakly nonlinear combined refraction and diffraction model, which is based on the parabolic approximation solution to the mild-slope equation (Kirby *et al.,* 1992, 1994). Based on 250 wave cases obtained as a combination of different waves in deep waters ($H_s$, $T_p$, and $\theta)_\infty$ and tidal level conditions (tides in the area are semidiurnal with a mean tidal range of 3 m and mean spring tidal range of 5 m), and using the spectral propagation model Oluca-SP, several transfer interpolation functions were obtained for different points along O Rostro Beach. Thus, the 4-year offshore wave data with a 3-hour time interval were transferred to the beach. The propagation grids used and an example case of wave storm conditions from the NW ($H_{so}$ = 6 m, peak period $T_p$ = 16 s) are shown in Figure 7; the spatial grid resolutions were $\Delta x$ (= 200 m) for the exterior grid and $\Delta x$ (= 20 m) for the local grid near the coast. Details of the wave propagation of the representative storm conditions in O Rostro Beach ($H_s$ = 4 m, $T_p$ = 14 s, level = mean high tide) for NW, W, and SW directions are also shown in Figure 8. Figures 7b and 8 show a wave concentration generated for the offshore bathymetry for waves coming from NW (the dominant and more frequent waves) toward the middle of the beach, where the waves break on the large central bar, in front of the cusp horn. Also, some wave height variation alongshore with slight concentrations in the other horns and

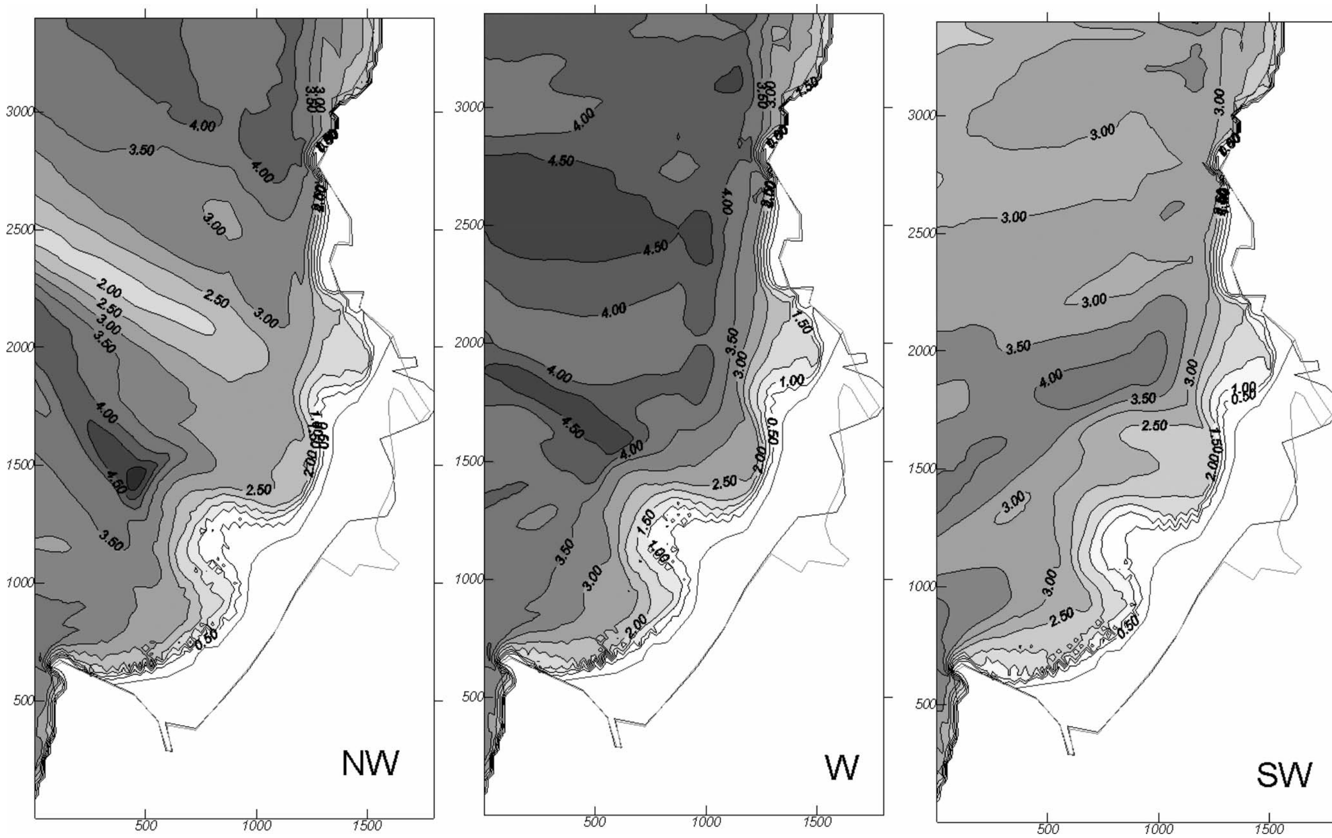


Figure 8. Representative wave storm conditions in O Rostro Beach ($H_s$ = 4 m, $T_p$ = 16 s, for Dir: NW, W, and SW).

concentrations on the north and south extremes of the beach is shown. This behavior for the NW waves is also the same under moderated wave energy flux intensities (mean conditions) but with reduced wave height gradients alongshore. Figure 8 shows how the waves from different directions concentrate in the cusp horn, changing the direction and impact in accordance with the exterior wave direction. This is a determining factor, as we shall see below, because it increased alongshore displacements of the horn-bars under certain wave storm conditions in the zone. This wave storm behavior for the different directions is quite similar for mean wave conditions (reduced wave height and periods), but with less intensity.

### Circulatory System on the Beach

The COPLA-SP depth-averaged current model (GIOC, 2003a, 2003b), which is also part of the SMC (González *et al.,* 2007), was applied to obtain the wave-induced currents in the surf zone. The COPLA-SP solves the vertically integrated equations of conservation of mass and momentum in two horizontal dimensions, and it is forced with the wave gradient of radiation stresses obtained from the Oluca-SP wave propagation model.

Under the most frequent storm conditions from the NW, O Rostro Beach presents two circulatory systems: an area confined between the lateral cliffs, the shoreline, and the water depth contour −5.0 m, and another area offshore, between the water depth contours −5.0 m and −15.0 m. The offshore current system (see Figure 9) is a longitudinal current, starting at the cliff to the north of Nemiña Beach and ending at the cliff to the south of O Rostro Beach. More precisely, it is in an area where there is a type of underwater deposition zone of sand surrounded by rocky elements at a water depth around −10.0 m. It should be noted that under extreme wave conditions Nemiña Beach and O Rostro Beach share the same underwater cross-profile. Nevertheless, the points where the current is practically stopped are potential areas of oil accumulation, as will be seen below. These exterior currents disappear under normal or mean wave conditions.

With regard to the local current system in the beach area, Figure 10 shows the current systems associated with three typical storm wave conditions ($H_s$ = 4 m, $T_p$ = 16 s, level = mean high tide, from NW, W, and SW). In Figure 10 (NW), there is a current that comes from the north along the cliffs and stops in the beach area. In this area, the joining of the circulation cell coming from the horn and the current from the north generates a kind of vortex area or current stopping point, which facilitates the accumulation of sand or oil in this zone. In a similar way, at the south cliff, the waves in the area generate a current that goes along the length of the cliff

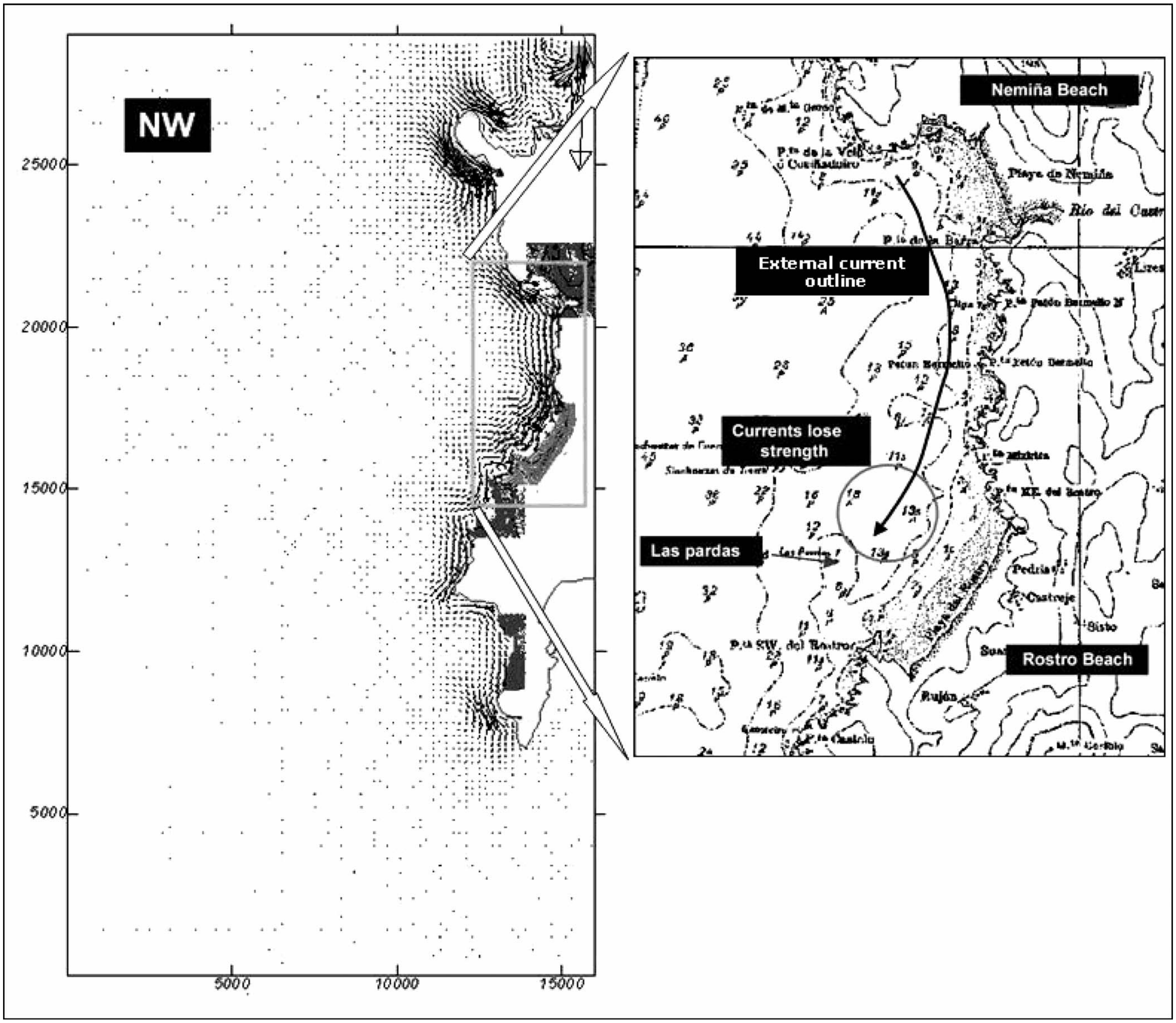


Figure 9. Offshore circulatory system in O Rostro Beach. The circle represents the zone where the offshore currents coming from the north significantly lose strength.

and ends in the middle of the biggest cuspate arc. As expected in the transversal bar-horn systems, wave surge piling up on the transversal bar-horn is divided in two diverging streams toward the adjoining embayments, where the stream loses strength when both side flows converge. As a consequence of this, a rip current seaward is generated through the center of the embayment until this stream loses intensity (water depth $h \sim 4$–5 m under wave storm conditions, $h \sim 1$–2 m under mean wave conditions). Under storm conditions, the set-down on the transversal bar is very important because of the wave height concentration in this zone, becoming an important set-down gradient generated in this water depth, finally resulting in a longshore current toward the transversal bar until the loop over the bar is closed once again. This circulation system under wave storm conditions, as will be discussed below, transports sediment and reinforces the submerged topography of the transversal bar-horn (horn enlargement). This pattern is also repeated under mean wave conditions, with the difference being that the reduced wave height causes the size of the circulation cell to be smaller, not even closing the loop, finishing in the submerged profile in front of the embayment arc ($h \sim 1$–2 m). This wave condition and the associated circulatory system reinforce the submerged bar and profile in the embayment zone, with sediment coming from the transversal bar-horn system, generating a shoreline retreat landward in the horn area.

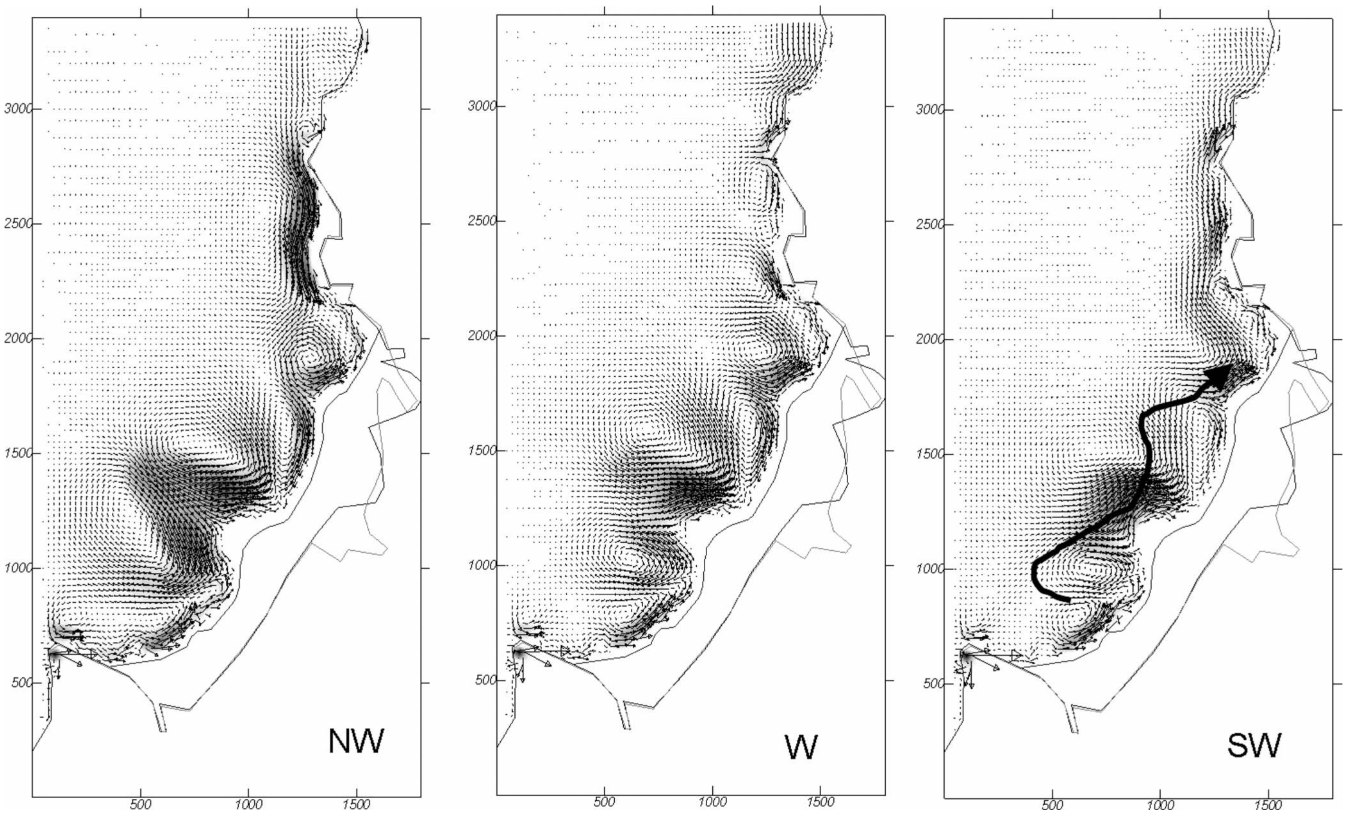


Figure 10. Representative wave-induced circulation system in O Rostro Beach ($H_s$ = 4 m, $T_p$ = 16 s, for Dir: NW, W, and SW).

The circulatory system in a cuspate shoreline for waves approaching the beach normally and where wave breaking occurs evenly alongshore in a straight line has been described by Bagnold (1940). For Bagnold's scheme, if storms last long enough, the tendency is to erode horns and transport material toward the embayment zones, in this case the equilibrium bathymetry is an alongshore uniform coastline. This circulatory scheme, in contrast to Bagnold's model, reinforces and enhances the transversal bar-horn system; the existence of the wave concentrations generated by the offshore bathymetry generate important longshore variations of breaking wave height for the dominant waves in the area (winter and summer), resulting in the circulation system described above, which is supported by the numerical simulations.

Regarding the other wave directions from W to SW, the general current pattern is similar for both mean and storm conditions. The difference lies in the fact that the currents in the cusp horn areas are more intense on the north side and less intense on the south side, which is why they tend to be displaced, behavior that has been evidenced in the field. This means that under changing wave storm conditions (different offshore directions), and taking into account the high wave energy of the storms in the area (with $H_{s12}$ = 8 m as the year return period storm), the movement of these transversal bars and horns implies an important movement of sediment and, as such, of oil on the beach. In some cases this means that oil was buried if it was exposed or uncovered if it was buried. Finally, waves originating from the south generate a net current to the north (see image on right in Figure 10), which tends to accumulate material in the north, eroding the south and part of the beach bar-cusps.

## FIELD DATA COLLECTED IN THE MONITORING PLAN

Because of the uncertainty about the location and volume of the buried oil in the beach, a 3-year monitoring plan was carried out from spring 2003 to summer 2006. It consisted of specific field campaigns (initial oil location and collection on the beach, geochemical oil-sediment analysis, visual underwater inspections, deep inspections of buried oil, and topo-bathymetric data) and some continued observations in the intertidal zone of the beach (inspections in plan and profile and other morphological features).

### Initial Oil Location and Collection on the Beach

Between November 2002 and March 2003, more than 4000 metric tonnes of oil were initially removed by volunteers and traditional cleaning techniques when the oil arrived in the intertidal zone of O Rostro Beach. Initially, when the fuel reached the beach it was deposited in extensive layers accumulated in the intertidal zone, with important accumulations above the high tide mark in the horn areas. However, because of the large dimensions of the beach, the high wave energy and strong induced currents in the surf zone, and the limitations to access underwater zones exposed to the action of the breaking waves, a large quantity of fuel was buried in the sand core of the beach. Over the years, the buried oil gradually reappeared as iridescences or tar-balls under specific storm wave conditions, principally with storms coming from the SW to WSW. This oil was dragged toward the coast principally in the embayment zones, where a permanent cleaning service was required to remove it. More than 5800 tons were removed in 2003 and 100 tons in 2004. Some part of this oil was removed by local excavations along the beach after the impact of some storms that uncovered buried oil layers in the sand core.

### Geochemical Oil-Sediment Analysis

A geochemical and granulometric study has been developed. Two fieldworks were carried out in January 2004 and June 2006. In the first fieldwork, nine cores were extracted from three cross-sections located approximately in the area of the horns 1, 2, and 4 (see Figure 4). In the second fieldwork, six cores were extracted in horns 1 and 2. Three cores were taken from each of these sections perpendicular to the coastline: from the low intertidal zone, from the mid-intertidal zone, and from the upper intertidal zone near the high tide level. Details about the fieldworks and the methodology applied to process the cores can be consulted in Bernabeu *et al.* (2006). This study has enabled the establishment of an oil evolution model in the sedimentary column up to a depth of 2.38 m (maximum depth of extractions, where oil has been found). This model establishes the hydrodynamic processes implicated (fundamentally, wave energy flux and variation of the groundwater level) and joined with the pressure induced by the weight of the column of sand and water, constituting an important mechanical degradation of the oil; in fact, it is more effective than the biodegradation and chemical degradation on the beach sediment, accelerating the natural disappearance of the contamination. Four different types of oil were identified in the soil column in 2004: tar-balls (cm), particles (mm), oil coatings on sediment grains, and oil emulsion. Nevertheless, the fieldwork in 2006 showed only small particles in the cores of the center of the beach (biggest horn), with only oil coatings and emulsions in the south of the beach. However, within the proposed model, and from the existing data, it is not possible to determine the time scale of these processes. Regarding the sediment granulometric characteristics, the mean grain sizes were presented previously.

### Visual Underwater Inspections

With the purpose of quantifying the oil deposited on the offshore sea bottom, two field programs based on divers visual inspections were carried out in May 2004 and May 2006. In the first field program, 12 transects equally spaced in the beach zone (~100 m) were carried out, starting in water depths of about 22 m (offshore the circle in Figure 9) and ending at the surf zone with water depths around 5 m. In these transects only small particles of fuel (~1 to 3 cm) were visualized rolling over the sea bed offshore, without mixing with the sand, in water depths between 10 m and 15 m (around the area with the circle in Figure 9). Regarding the second field program, only three transects were examined, starting in water depths of 18 m and ending in water depths of 4 m. In this case the floating fuel found in 2004 had practically disappeared, with some isolated groups of particles moving over the sea bottom in the same zone.

### Deep Inspections of Buried Oil

Two field campaigns were conducted to detect deep buried oil in the beach sand core in O Rostro Beach and to evaluate the evolution of this throughout time. The first was 2 years after the oil spill in August 2004, and the second campaign was 2 years later in May 2006.

In the first campaign, 228 deep excavations using mechanical means were conducted (hydraulic excavators and backhoe loaders). Most excavations were developed in the intertidal zone of the beach and some of these on the transversal bars in front of the horns in low spring tide. The 2–3-m-deep excavations were uniformly spaced along the beach with separations approximately ~20 m to 30 m (see Figure 11). Thick layers of fuel mixed with sand (10 to 50 cm wide) were found mainly in the sides of the transversal bar-salient systems, buried between 1 m and 2.5 m deep. Tar-balls of several centimeters were found in the intertidal zone of the embayments principally in the low tide terrace, which were buried at depths of less than 1 m. Finally, tar-balls were found in the rip-current channels (1 m to 2 m water depths above the spring low tide level). Although the campaign was carried out in the summer, the wave and current conditions did not permit the excavators to work in deeper water depths.

A map of the areas containing buried oil in summer 2004 was depicted based on the 228 excavations carried out in summer 2004, the cores extracted in January 2004, the sea bottom inspections performed in May 2003, and the routine cleaning activities. Figure 12 shows these areas shaded with dots. It is remarkable that the greatest quantity of buried fuel was encountered in the (B) and (C) central areas, where the largest horn is located. Finally, no significant buried oil was found at the north of the beach (area [E] shaded with lines).

The second campaign (May 2006) was conducted to observe the evolution of the buried oil found in 2004. Hence, the field work was focused in the identified zones A, B, and C (Figure 12). More than 50 excavations, between 2 m and 3 m deep, were carried out, including large areas and shallow excavations in the low tide terraces located in the embayment zones (length = 5 m, width = 2 m, depth ~1 m). In Figure 13, the zones identified in 2004 are represented by the polygon (area shaded with squares); the triangles represent the zones where still buried tar-balls of some centimeters were found in 2006. Nevertheless, in the triangle the large layers of oil detected in 2004 disappeared, and the volumes of oil were substantially reduced. As well as in 2006, the triangles with more buried oil were those located in the largest horn. In the embayment zones a few oil fragments were found, which is in agreement with the geochemical oil-sediment analysis, where the oil degradation accelerates the natural disappearance of the contamination. In broad terms, the selected zones


Figure 11. Field campaign in O Rostro Beach (spring 2004). Beach excavations (2–3 m deep).

do not present a significant quantity of oil compared with the situation in 2004.

Finally, in this campaign some topo-bathymetric profiles along the beach were obtained. Furthermore, 12 sand samples were collected to study granulometric characteristics (see location in circles, Figure 13), whereas the mean grain sizes were presented previously.

## Daily Inspections in the Intertidal Zone

From September 2003 to September 2004, daily observations in the intertidal zone of the beach were carried out. They consisted of images taken from fixed geo-referenced points on the hill behind the beach. These images permitted the daily observation of qualitative variations on the beach in plan and profile and other morphological features in the intertidal zone, such as the cross-shore and long-shore variations of the horns and movement of the transversal bars. Based on these images, it was documented that the horns advanced seaward in the winter season and suffered a retreat landward in the summer season, without a net displacement in any direction. These aspects were specially observed in horns 2 and 3 (Figure 4). Regarding the embayment arcs, small variations were evidenced in the winter and summer, with a small retreat in the winter and recuperation in the summer. This behavior had also been evidenced with the historical aerial images.

On the other hand, throughout the monitoring year, a follow-up of the oil that gradually reappeared and was transported toward the intertidal zone was carried out. A typological characterization of this fuel, together with a representation of the dispersion of the oil along the beach was represented daily on a geo-referenced ortophoto (1 : 5000). It is noted that the most important quantities of fuel that reappeared on the beach were associated with storms coming from the SW to WSW. As an example, some iridescences were observed in the northern half of the beach after a 6-day storm from the WSW with $H_s$ = 5.6 m and $T_p$ = 14 s in January 10, 2004.

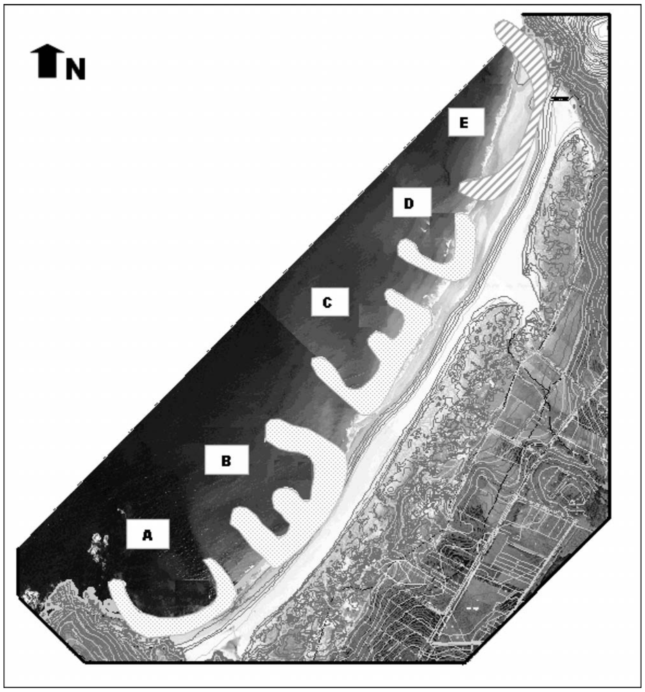


Figure 12. Areas containing buried oil in O Rostro Beach in 2004. Based on deep excavations carried out in the 2004 campaign and the sea bottom inspections in 2003. No significant buried oil was found at the north (areas shaded with lines).

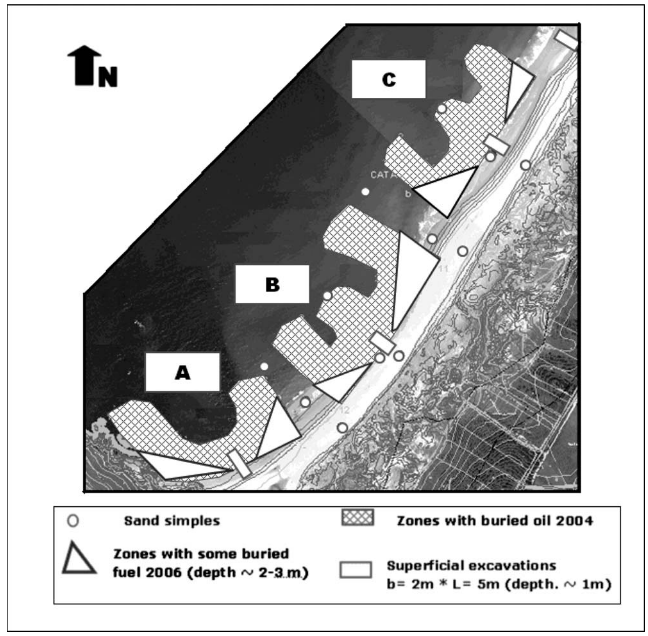


Figure 13. Areas containing buried oil in O Rostro Beach in 2006. Polygon with numbers in the vertices are the zones identified with buried oil in 2004. Triangles represent zones where tar-balls of several centimeters were found in 2006. Overall, the other areas do not present a significant quantity of oil compared with 2004.

## MORPHODYNAMIC MODEL OF THE BEACH

In order to understand the evolution of the oil on the beach, it is essential to focus on the interaction between the dynamics and the morphology. The oil is transported by the wave-current dynamics in the same way as the sediment that shapes the beach. As such, to understand its accumulation on the intertidal zone or its burial together with the sand requires knowing and understanding the processes of the system. Below we describe the morphodynamic behavior of the beach in accordance with three process scales: long-term (dynamic equilibrium: years-to-decades), short-term (storm conditions: hours-to-days), and medium-term (seasonal: winter-summer).

### Long-Term Scale

No relevant changes have been noted regarding the position of the coastline in a decadal scale. This can be confirmed based on historical aerial photos from 1945, 1957, 1973, 1990, and 2004, along with the daily inspections in the intertidal zone from September 2003 to September 2004. Both sources show that the beach is stable and does not have a net loss or gain of sand. Hence, in terms of the beach sediment budget, it can be assumed that O Rostro Beach is a physiographic unit in equilibrium.

Concerning the cross-shore profile of the beach, it should be kept in mind that this may vary alot depending on the situation along the length of the beach, whether this is on the horn and transversal bar or over the trough of the beach. From the detailed topo-bathymetry obtained in May 2006 (CEPRECO, 2006), an adjustment of the equilibrium profile of Dean (1991) was made in the cross-shore profiles located in the beach embayments. A mean shape parameter of $A$ (= 0.14 m$^{1/3}$) was obtained, which is equivalent to a mean sediment size of $D_{50}$ (= 0.42 mm), very close to the actual mean $D_{50}$ (= 0.41 mm) measured from sand samples of the beach (samples also taken in May 2006). This indicates that, in general, the mean slope of the beach profile corresponds to the slope of an equilibrium profile. The profiles in front of the horns, and on the transversal bars, tend to have a lower mean slope and a higher elevation on the bar compared with the profiles of the embayment. As will be seen in the medium-term analysis, these profiles undergo modifications between winter and summer. The seaward limit of the profiles in the field corresponds pretty well with the depth of closure by Hallermeier (1981) with $h^*$ ($\sim$12 m) and the limit of the exterior current system under the annual storm condition, as is shown by the numerical simulations.

The overall planform of the beach is oriented normal to the mean energy flux of the local waves 290° $\sim$ NW (298° in deep waters WANA point). Thus, in general terms, we can say the planform of O Rostro Beach is in an equilibrium position (González and Medina, 2001).

Superposed to this equilibrium planform are some transversal bar-horn features described previously. Different authors have studied these kinds of cuspate features. Since the first observations by Munk (1949) and Tucker (1950), these morphological patterns have often been related to infragravity waves, principally to edge waves, which generate periodically spaced cusps (Bowen and Inman, 1971; Guza and Inman, 1975). Other mechanisms that have been mentioned in the literature are the existence of eddies and long-period standing waves (Wilson, 1972). Based on field observations, some authors propose the theory that irregular bathymetry always controls the water circulatory system, such as the case of Sonu (1972). On the other hand, authors such as Noda (1974) affirm that there is no explanation for bathymetry generation if the circulatory system is not assumed to be responsible for it. Based on this last idea, Deigaard *et al.* (1999) explain the existence of rhythmic formations by coupling between small perturbations on water motions with a reference uniform bathymetry. Furthermore, various authors have explained the presence of large- and short-scale features by high-angle wave instability, as in the case of the North Carolina coast (Ashton, Murray, and Arnault, 2001) and sand waves along the Dutch coastline (Falqués, 2006) for large-scale features and the Puntal Spit, Santander, Spain (Falqués *et al.,* 2007; Medellín *et al.,* 2008) as a case of middle-scale coastline cusps. Ortega, Losada, and Baquerizo (2003) have explained the development and stability of large-scale horns in Carchuna Beach (Spain), mainly as a consequence of the refraction of different wind wave storm conditions. In a similar way, in O Rostro Beach the wave climate and the offshore submerged bathymetry generate and maintain middle-scale transversal bar-horn systems along the beach. These cuspate features induce a particular circulation system, as well as a particular sediment and oil transport on the beach. Hence, to understand how oil evolution has been on the beach, it is important to understand the morphodynamics of these features.

As a consequence of the high wave energy in the area with dominant and more frequent waves coming from the NW, the refraction of these (mean and extreme wave conditions) on submerged offshore rocky shallows, and the confined characteristic of the beach between two lateral cliffs, a stable large transversal bar-horn system is generated on the central part of the beach. Other smaller bar-horn features are present on the beach as a consequence of wave refraction induced by local bathymetry. The interaction of these bar-horn systems with the lateral confining boundaries generates significant alongshore variations in the wave height at breaking, which results in a particular circulation cell pattern under extreme and mean wave conditions, as presented in the Marine Dynamic of O Rostro Beach section of this article. These conditions guarantee the stability of these bar-horn systems, with no significant changes in their position, although their cross-shore length and width may vary in time in accordance with the wave climate. These morphological changes can be better appreciated in the short- and medium-term scales, as observed in the field campaigns, an aspect which shall be discussed next.

## Short-Term Scale

Under the dominant wave storm conditions in the area (NW), the general circulatory cell system can be summarized,

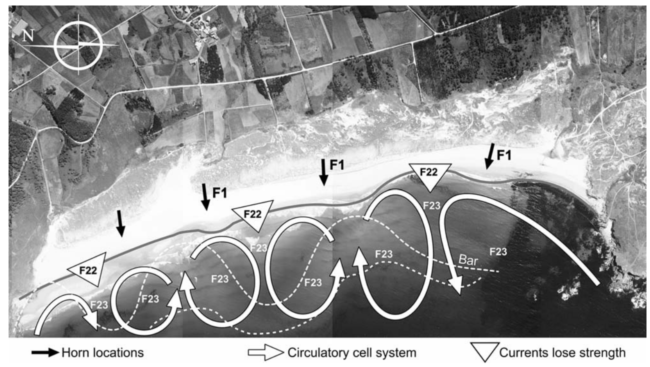


Figure 14. Scheme for the circulatory system under the dominant storm waves in the area (short-term scale). Based on the numerical simulations (COPLA-SP Model) and scheme of the distribution of the fuel in O Rostro Beach. Conceptual evolution model of oiled substance.

based on the numerical simulations and field observations (2003–2004), as the one depicted in Figure 14. This circulation system transports sediment to the submerged topography of the transversal bar-horns. Through this mechanism the beach is protected from the assault of the waves in the areas of concentration. When the beach is hit by these dominant storms, the bar increases in volume, the horn advances seaward, and the embayment of the coastline retreats. The greatest amount of sand contributed to the bar-horn system is derived mainly from the underwater profile including the longshore bar in front of the embayment, also with a contribution from the shoreline and intertidal zone. Nevertheless, this last zone has not evidenced important changes in the field observations.

The position, size, and shape of the bars and horns depend on the wave energy flux, the offshore wave direction, and the storm duration. Storms coming from the W to SW, although less frequent, have a sufficient energy level to displace and change these elements. Figure 15 shows a scheme of the alongshore displacement of the bar-horn systems caused by a change in the direction of the waves from the NW to storms coming from the W to SW. In this diagram it should be highlighted that as the bar-horn system is displaced toward the north, a large movement of sand toward this area is initiated, which leads to a significant change in depth to the order of some (2 to 3 m) in profile. The same figure illustrates a diagram of the profile before (solid line) and after (detached line) the direction change. This alongshore displacement has been observed visually in the field with magnitudes on the order of 30 m to 50 m.

An accumulation in the north side of bar-horns causes similar erosion to the south side. It is important to note that these changes are relevant when trying to find the oil, because a change in the wave direction of the storms actually happened during the event. This means that there are areas in the sides of the bar-horn systems where the oil was buried 2 or 3 m below the surface, as evidenced by the deep excavations and cores collected in the field campaign in 2004, which are represented in the marked zones in Figure 12. This

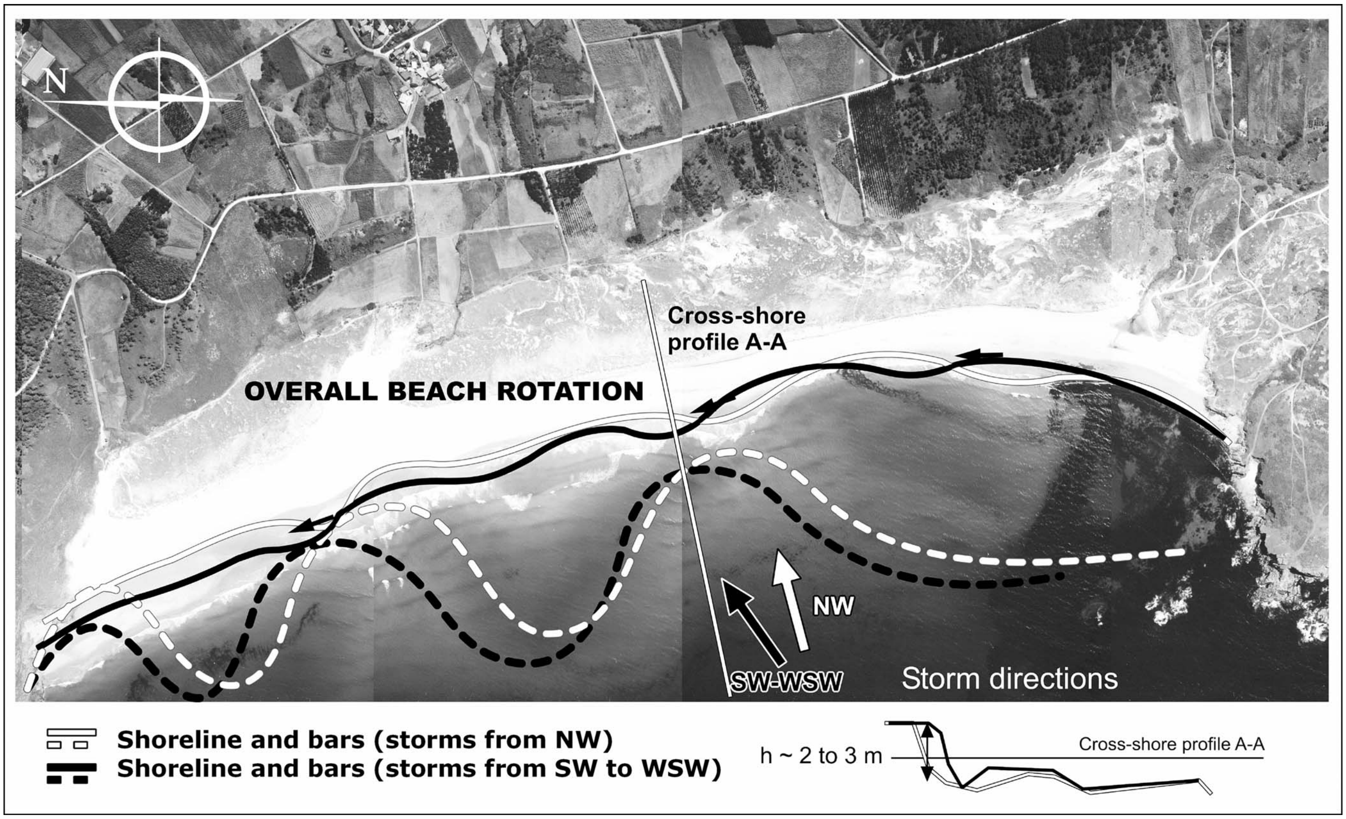


Figure 15. Scheme of the alongshore bar-horn migration due to changes in the direction of the wave storms (NW to E or SW), short-term process. Scheme based on field observations.

oil may become exposed in the future, as has happened through some extreme events and mean wave conditions from SW-WSW in the past several years. With regard to the storms from the SW-WSW with long durations (5 to 7 days), it should be mentioned that, as well as generating displacements in the bar-horn systems, a net current toward the north is created, with the effect that sediment tends to accumulate in this area with sediment from the south and the bar-horn systems. Under dominant and prevalent conditions, this material returns to its original location.

Finally, it is noted that bar-horn system 2 (Figure 4), presents the largest dimensions and mobility compared with the other bar-horns in the beach. This means that this element has the highest capacity to bury oil, as the fieldwork in 2004 verified.

### Medium-Term Scale

Winter-summer cycle also plays an important role on the oil burial. As the small wave energy conditions commence (mean wave conditions of summer), the beach dynamic and morphology pattern changes. The alongshore wave height gradients reduce, wherewith the alongshore mean sea level variations also decrease (set-up and set-down gradients), causing the size of the circulation cells to be smaller, whereas the return currents in the embayment zones diminish or disappear, not closing the loops on the transversal bars. As a consequence, Stokes currents start to displace the transversal and longitudinal bars slowly toward the coast. The transversal bars and horns start to lose material toward the embayment area, where a small part permits a slight shoreline advance in the cusp arc, while most of the material is deposited in the channel and the underwater profile. A scheme with the shoreline and submerged bars in winter and summer conditions is proposed in Figure 16 (the winter condition being in detached lines and the summer condition in solid lines). This sketch is based on field observations in the period 2003–2004 (intertidal zone) and the morphodynamic model of Wright and Short (1984). The field observations and historical aerial photos have verified the way in which the horn areas notably evolve in summer, whereas the embayment area remains almost unchanged. This aspect is of great importance in explaining the behavior of the oil, because in the summer part of the oil buried in the horn during the storm conditions may pass to the embayment intertidal areas (solid ellipsoids in Figure 16). At the same time, oil buried in the submerged bars in the embayment zones may move up the cross-shore profile of the beach. On the other hand, in the winter the embayment area becomes uncovered, allowing the outcrop of buried oil.

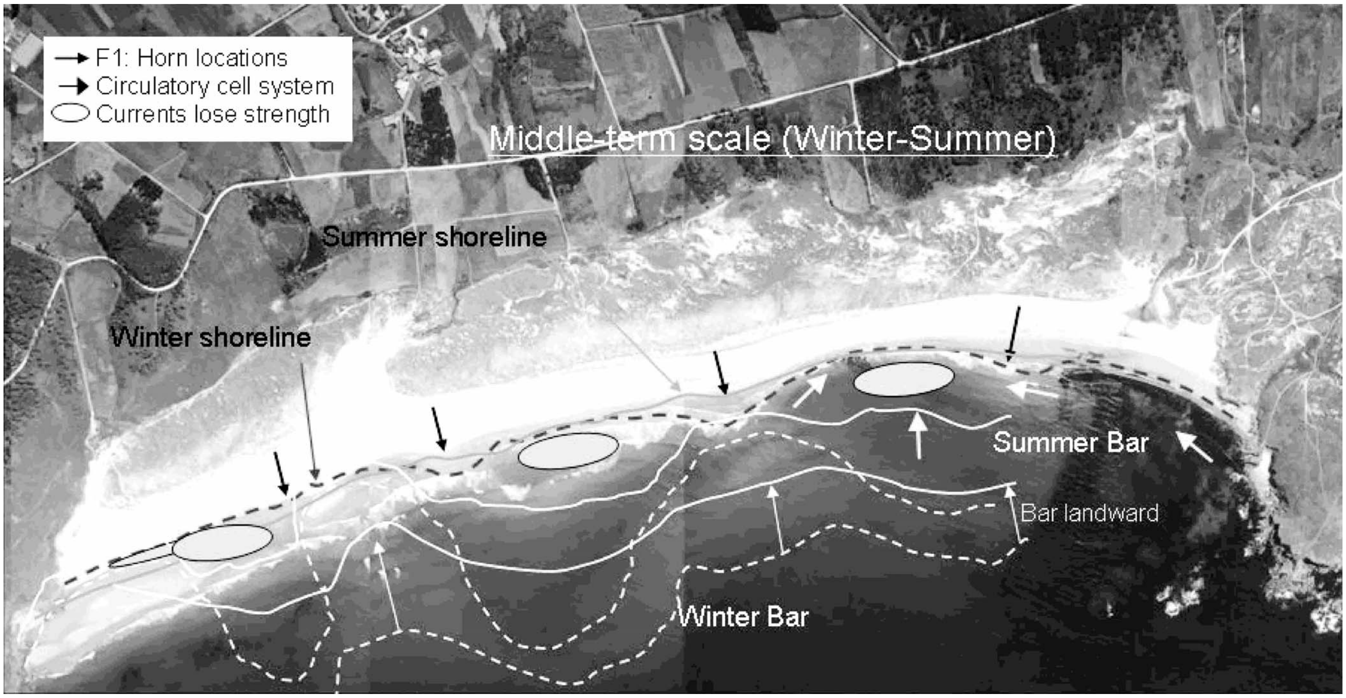


Figure 16. Scheme of the winter-summer evolution of the beach (middle-term scale). Migration of bars landward and bar-horn size reduction under low wave energy conditions. Schema based in field observations (the winter condition being in detached lines and the summer condition in solid lines).

**Morphodynamic State Distribution**

One way to determine the morphological variability of a beach is by means of the temporal variability of the morphodynamic states of the beach. Figure 17 shows the mean distribution of the morphodynamic states of O Rostro Beach between 2002 and 2006. These have been obtained by applying the Wright and Short Model (1984), which is based on the nondimensionl fall velocity $\Omega$ ($= H_s/w_s \cdot T_p$) proposed by Dean (1973). This parameter has been obtained using the calibrated WANA wave series propagated to the breaking zone of the beach (a daily average and alongshore significant wave height $H_s$ and peak period $T_p$ were used) and the median grain size $D_{50}$ ($=$ 0.41 mm) to obtain the grain fall velocity ($w_s$). In order to take into account the memory of the system and the lag of the beach response regarding instantaneous local dynamics, an averaged nondimensional fall parameter has been applied, $\Omega_{ave}$ (Wright, Short, and Grean, 1985), which, for a given day, takes into account the morphological states in the previous days. The $\Omega_{ave}$ parameter has been calibrated using weekly visual observations in the field of the morphology of the beach (2003 to 2004). As shown in Figure 17, the modal beach state of O Rostro Beach corresponds with the Rhythmic Bar and Beach (RBB). However, the beach exhibits a great temporal distribution of morphodynamic states, from Transversal Bar and Rip (TBR) to Longshore Bar and Trough (LBT), which means that the beach has an important capacity of movement, as well as a capacity to bury oil.

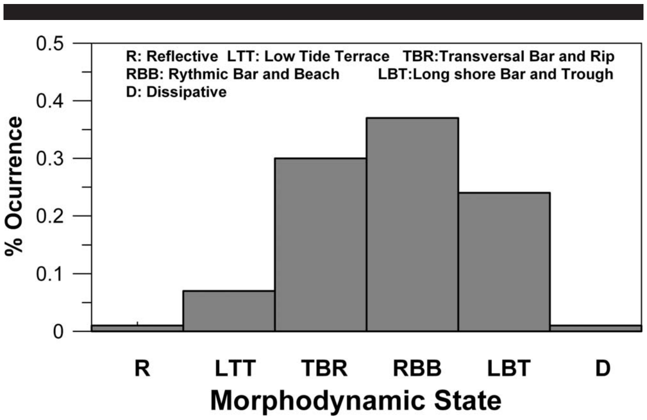


Figure 17. Morphodynamic state distribution in O Rostro Beach (wave time series from September 2002 to July 2006); model validated and calibrated with visual observations.

## INITIAL TRANSPORT AND EVOLUTION MODEL OF THE OILED SUBSTANCE

In this section a classification of the oil transported to the beach, according to its physical evolution induced principally by the movement, will be carried out. Afterwards, a conceptual evolution model of the oil spill on a beach is described, considering first its movement and initial locality and second its evolution throughout time. The proposed oil evolution model is based on the beach morphodynamic model described previously and its interaction with the oil. This model attempts to explain the field observations.

## Oil Characterization in Accordance with Physical Evolution and Movement

It is a well-known fact that when an oil spill is mixed with the salt water from the ocean and this mixture is agitated by waves and coastal currents, the result is a changing emulsified substance. The changes occur not only to its chemical properties but also to some of its physical properties, such as density. These changes in density are very important as they influence the movement of the substance, especially if we consider that in beach areas, the oil gets mixed with sand. The movement and location of this new mixture will now be subject to its new physical properties, mainly presenting a much higher density.

Based on the field observations of the dynamics of the spill on O Rostro Beach, two different types of oils are studied. The first type is a floating oil spill, very similar to the oil that first reaches the beach or that which, over a period of time, can still be found on a beach creating iridescences. This type of slick will be hereafter referred to as F1; its density, $\rho_f$, is lower than that of the seawater, $\rho_w$ ($\rho_f < \rho_w$).

The second kind of spill is heavier than seawater ($\rho_f > \rho_w$). This spill has been transformed due to different physical-chemical processes throughout its life before reaching the beach. Once it is there and has been mixed with sand, its characteristics are modified. Hereafter, this fuel will be referred to as F2. The F2-type fuel can be subdivided into three categories: the first type is lighter than beach sand, with a fall velocity, $\omega_f$, lower than the sand settling velocity $\omega_s$ ($\omega_f < \omega_s$). This fuel, called F21, is characterized by being deposited on the sea bottom, moving like very fine sand but not mixing with it. The second type, F22, has a very similar settling velocity to that of sand ($\omega_f \sim \omega_s$) and is characterized by being mixed with the sand (tar-balls). Its movement is similar to that of medium or coarse sand transported as suspended-load or bed-load. The F22 oil moves within the tidal area and is often covered by very thin layers of sand. The last type of oil is heavier than sand with a higher settling velocity ($\omega_f > \omega_s$). This oil, hereafter referred to as F23, is a mass or matrix of sand-oil, and its movement is similar to coarse gravel. It is very difficult to transport and is mainly found buried in large quantities under thick layers of sand in the submerged part of the beach, bars, and underwater cross-shore profiles.

## Conceptual Evolution Model of the Oiled Substance on the Beach

### Initial Oil Distribution on the Beach

The initial location of the oil on the beach and its future evolution are conditioned by the initial morphodynamic state. If a beach is, according to Wright and Short (1984) classification, in a reflective state and the oil arrives with a storm, the amount of wave energy flux is high and, therefore, so is the movement of the sand on the beach and the oil. Initially this floating oil will have the characteristics of F1 oil. It will be found on the high tide line, where it will transform into the F22-type because of the agitation and the mixture with the sand induced by the breaking waves in the surf zone. The dune erosion process, along with the transportation of the F22 oil, will most likely bury part of it in the offshore bar, turning part of the F22 into F23. Afterward, over a series of months, the more superficial parts of the oil will disperse with time due to the erosion of the bar. A very different situation occurs if the beach is, according to Wright and Short (1984) classification, in a dissipative state and the fuel arrives with a low wave energy flux and currents. In this case, most of the fuel will accumulate close to the shoreline and, as there is less energy, there will be less movement of both the beach and the oil, making it less likely to be buried. Part of the oil can be found as F1 on the high tide line, transforming itself with time into F22-type oil. Another part of the oil will tend to sink to the submerged beach as F21. In this second case, the extraction of the oil is much easier compared to the previous case (initial reflective beach), where the extraction process is much more complex and will have to be done over a longer period of time.

In the case of beaches with intermediate morphodynamic states, the processes are much more complex because of the morphology (bars, cusps, rip channels, *etc.*) and the circulatory system that generates great movement on the beach. Next, based on the O Rostro morphodynamic model and the field observations, a description of where the oil was located initially and a conceptual evolution model of the oil in the beach are proposed.

Initially, the oil arrived in O Rostro Beach transported by the offshore currents coming from the north, which are associated with the dominant and more frequent wave conditions (Figure 9). Just offshore the beach (water depths −10 to −15), there is an area (see circle in Figure 9) where these littoral currents coming from the north significantly lose strength. This zone was highly susceptible to capturing part of the floating type F1 oil. Later, this oil was transformed into type F21, precipitating itself in small balls of between 1 and 3 cm in diameter over the sea bottom, without mixing with the sand. This oil location was observed by divers taking underwater samples in 2003. The oil that was beached, however, was brought by the currents along the length of the cliffs at either end of the beach and by the huge oil slick (F1) along the full length of the beach.

As seen above, the planform of O Rostro Beach has been in dynamic equilibrium in the last few decades, orientated perpendicular to the mean flow of energy (290° ~ NW). From the time of the accident of the *Prestige* tanker (November 13–14, 2002), to the time the first oil was beached on the Fisterra coast, the prevailing direction of the most energetic waves was from the NW (see Figure 6). Hence, the dominant morphodynamic state at that time was expected to be an intermediate beach with a system of rhythmic transversal bars with horns. From the massive amount of oil beached November 22, 2002, until around January 12, 2003, the prevailing direction of the waves was between SW and W, with an unusual continued period of some 15 days of waves from the SW to WSW (December 15–30). This dynamic brought a global counterclockwise rotation to the beach, along with its bars and horns, with an accumulation of sand to the north and a recession at the south end of the beach. Under these circumstances, the oil that settled in the north of the beach was

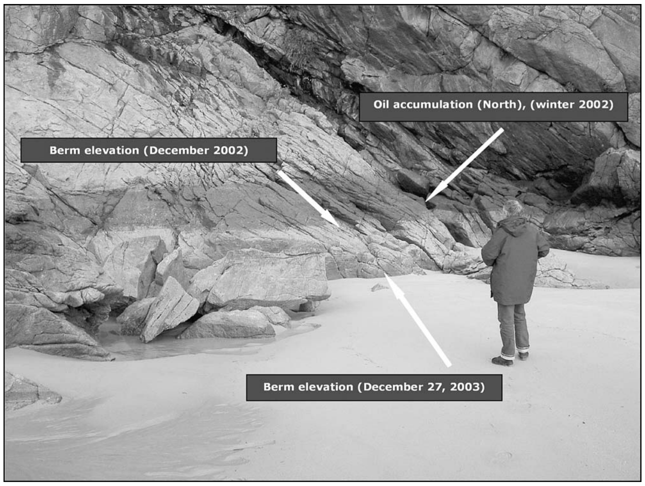


Figure 18. Berm elevation near the north cliff in O Rostro Beach (November 2003). The location of the beach berm when the fuel arrived 1 year ago and the width of the oil layer accumulated in this zone are noted.

deposited on sand not normally in the area, whereas oil that settled in the south did so in an area normally covered by sand. In the middle areas, where the bar-horn systems are found, a similar situation occurred.

Over the following months, the prevailing wave direction, in mean and extreme wave conditions, returned to being ostensibly the same as the mean energy flow (from NW), with the beach swinging back to its equilibrium position. This started the burial of oil toward the middle and south of the beach and outcrop toward the north. There is a great deal of evidence supporting this behavior of the beach, which has been identified throughout its monitoring. It is remarkable that on December 27, 2003, the berm elevation near the north cliff of the beach had a lower level than previously seen in the winter of 2002. This is confirmed by the fact that the rocks of the cliff in this area were marked with oil accumulation associated with a higher beach (see Figure 18). The berm elevation in this zone has never (until 2006) acquired the same position as that in the winter of 2002. This special condition with a high wave energy flux from the SW during continued long periods of time has not occurred in the last several years, as previously shown.

The movement of oil (type F1) in the areas of the bar-horns was located on the high tide mark and also in some higher elevations in the horn areas where the run-up action is most important (see Figure 14). On the other hand, the tar-balls F22-type oil was located by the longshore currents in the intertidal area of the embayments, some of which was then displaced to the underwater profile channel located between the embayment and the bars, like type F23 oil. The high tide swash zones located in the horns and the intertidal zones in the embayment arcs have been the areas where initially the cleaning activities were more intensive.

The high dynamic intensity on the transversal and longitudinal bars (breaking waves, induced currents, and sediment transport) have a great influence in these zones. For this reason, gravel, shells, and other heavy elements are located on the bars. Hence, the only type of oil capable of staying on the bars was type F23. The tendency of this heavier oil is to bury itself inside the bar through the dynamic winter-summer action, reaching hard-to-access depths.

## Long-Term Oil Distribution on the Beach

The initial F1 fuel located on the sand transported from the south was mechanically and manually removed in the first few months; throughout the years, when the sand returned to the south, the limited buried F22 oil was transported with the sand. The oil that over time stays in the north is F1-type and is observable as iridescence from the center or south of the beach.

As evidenced in field observations some years after the oil spill, the buried oil is exposed under high wave energy flux events (storm conditions). Under the conditions of typical strong storms from the NW, oil buried in the embayment area (low tide terrace) might be exposed because of the coastline retreat of this zone. Therefore, F22 buried oil from the submerged profile and bars in the embayment could be transported to the intertidal embayment arc having previously passed over the transversal bar and horn. Under the influence of nontypical strong storms from the SW to W, combined with a long duration, the beach is able to free some of the oil buried in the southern area (A in Figure 12) and in the middle areas (B and C in Figure 12). The greater part of the oil will be type F1 (iridescences), although type F22 oil might also appear in the embayment areas. A few cases of this situation have been verified on some occasions through monitoring. Finally, regarding the F21-type oil located offshore the coast in the exterior deposition zone of sand ($h \sim 10$–15 m), the only situation in which these small balls may ascend to the beach profile would be under very prolonged summer wave conditions of little energy, an improbable situation on this coast. The sea bottom inspections carried out in 2006 show that these F21 particles almost disappeared from this area. Among the different possible hypotheses are a mechanical, chemical, and biological degradation process at these water depths or wave storms stronger than those that occurred during the oil spill from the NW, which allow (1) the mixing of fuel with sand, turning it into F22-type oil, ending in the sand matrix after a long period of time or (2) strong currents that transport these small particles downcoast. Because in the last several years there have been no storms stronger than those occurring during the period of the oil spill, the first hypothesis is the most probable.

Over the years, a great quantity of oil has been extracted mechanically from the intertidal areas, principally from the low tide terrace. However, as discussed previously, some oil still remains buried in the sand matrix, and part of it has been liberated. Based on the conceptual evolution model of the oil, the morphodynamic characterization of the beach, and the knowledge acquired from the data collected in the monitoring plan, the clean-up activities have been optimized and significantly improved. On one hand, it is possible to identify which wave climates could loosen buried oil and to estimate with a high probability where this oil would be located. Combined with wave climate forecast, this has permitted the organization of operational clean-up activities in advance under specific storm conditions. On the other hand, based on evidence that after 4 years the buried oil degraded rapidly, it was decided not to extract deeply buried fuel in order to prevent an even greater impact on the beach. Nevertheless, future storms with similar incidents to those occurring during the "*Prestige*" tragedy could free oil that is deeply buried. As it is not clear what environmental impact this weathered material could have, it is recommended that it be removed by the clean-up teams.

## CONCLUSIONS

(1) O Rostro Beach was one of the most seriously affected beaches during the *Prestige* oil spill along the "Costa d'a Morte" in Galicia. More than 10,000 tons of residual material has been removed from the berm and intertidal zone. Between November 2002 and March 2003 more than 4000 tons of oil was initially removed by volunteers using traditional cleaning techniques. Additionally, more than 5800 tons were removed in 2003 and 100 tons in 2004. An important quantity of oil was buried in the sandy sedimentary column of the beach, which was dug up along the beach under sporadic wave conditions over the years.

(2) The arrival of large quantities of oil to the beach, combined with an initial exceptional sequence of high wave energy storm conditions, and a morphodynamic intermediate beach with a high capacity of movement were the reasons for a significant quantity of oil being buried in the beach. The beach initially received a sequence of many high energy waves ($H_s > 7$ m) with long storm durations (6 to 10 days), waves coming from the dominant direction condition (NW) and the less frequent directions (SW to WSW), and an uncommon directional sequence throughout time (NW to SW and finally to NW). On the other hand, O Rostro Beach is a bayed beach laterally confined at its extremes, exposed to the dominant and more frequent waves in the zone. It has middle-scale transversal bar-horn systems along the beach, generated and maintained by the wave climate in the area and the offshore submerged rocky bathymetry. These stable cusped features over time do not present a significant change in the position of the horns, although their cross-shore length and width may vary in time forced by the local waves, leading to a high capacity of movement as well as in a deep oil burial (2–3 m deep).

(3) The information collected in the 3-year exhaustive monitoring plan (spring 2003 to summer 2006) in O Rostro Beach has provided better knowledge and comprehension of the process involved in the interaction of the oil spill dynamics with the beach morphodynamics. Based on these field data, the zones with deep oil burial were located, and it was also found that 4 years after the oil spill the buried oil had degraded rapidly. This statement is based on specific field campaigns (initial oil location and collection on the beach, geochemical oil-sediment analysis, visual underwater inspections, deep inspections of buried oil, and topo-bathymetric data) and some continued observations in the intertidal zone of the beach (inspections in plan and profile and other morphological features).

(4) In order to understand the interaction processes between the morphodynamics of a beach like O Rostro Beach with oil arriving on its shore, it was necessary to characterize the marine dynamics and its interaction with the beach morphology system in accordance with three process scales: long-term (dynamic equilibrium: years-to-decades), short-term (storm conditions: hours-to-days), and medium-term (seasonal: winter-summer). Furthermore, it was required to know: (1) the morphodynamic state of the beach during the arrival of the oil, which means characterizing the morphology and dynamics throughout the event; (2) the modal state of the beach and its morphodynamic variability through time after the oil spill; and (3) the beach limits (lateral and the cross-shore underwater toe), which confine the circulatory system and the oil transport on the beach. The morphodynamic characterization of O Rostro Beach has permitted the establishment of a conceptual evolution model of the oil.

(5) A conceptual evolution model of the oil leaked to O Rostro Beach is proposed, with the aim of explaining how and where the oil initially arrived, where it was buried in the sandy column of the beach, and how the oil has evolved physically and mixed with sand over the last few years. The proposed model is supported by the data collected in the monitoring plan and the morphodynamic characterization of the beach.

(6) Based on the conceptual evolution model of the oil, the morphodynamic characterization of the beach, and the knowledge acquired from the data collected in the monitoring plan, the clean-up activities have been optimized and significantly improved. It is possible to identify which wave climates could expose buried oil and to estimate with a high probability where this oil would be located. Combined with wave climate forecast, it has permitted the organization of operational clean-up activities in advance, under specific storm conditions.

(7) Finally, based on evidence that after 4 years the buried oil had degraded rapidly, a decision was made not to extract deeply buried fuel in the underwater zones in order to prevent causing a greater impact on the beach. However, future storms with similar incidents to those occurring during the "*Prestige*" tragedy could free oil that is deeply buried. As it is not clear what environmental impact this weathered material could have, it is recommended that it be removed by the clean-up teams.

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