IMPACT OF RIVER REGULATION ON THE SUBMERGED MORPHOLOGY OF A MEDITERRANEAN DELTAIC SYSTEM: EVALUATING COASTAL ENGINEERING TOOLS

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Although the influence of both natural and human-induced changes on the evolution of worldwide deltas have been widely addressed, few studies have analyzed the variations of the submerged morphology due to river regulations by dams. In this work, we analyze the changes in the submerged morphology of a Mediterranean deltaic system after the regulation of its main fluvial inflow. We use high-resolution bathymetric measurements and globally used coastal engineering models and tools to characterize the cross-shore and alongshore variations of the nearshore bathymetry of the delta. The applicability and limitations of these tools are discussed, identifying their major weaknesses for their application in this type of environments.

Keywords: deltaic systems; coastal engineering tools; longshore sediment transport; wave model

INTRODUCTION

Deltaic systems are strongly vulnerable to variations on their submerged morphology, as they allocate numerous activities and have important ecological, economic, and social importance. Indeed, in recent centuries, anthropogenic activities and natural changes significantly altered coastal processes and changed the morphology of deltaic environments [Coleman and Wright, 1975, Orton and Reading, 1993], including river damming and (relative) sea-level rise, which are probably the most severe causes of the retreat of worldwide deltas [Syvitski et al., 2009].

The influence of both natural and human-induced changes on the evolution of worldwide deltas have been widely addressed, with numerous studies focused on changes on the evolution of Mediterranean deltas, such as the Ebro [Jimenez and Sánchez-Arcilla, 1993], Po [Simeoni and Corbau, 2009], Nile [El Banna and Frihy, 2009], Rhône [Sabatier et al., 2006, 2009], Adra [Jabaloy-Sánchez et al., 2010] and Guadalfeo [Bergillos et al., 2016a]. However, few studies have analyzed the variations of the submerged morphology due to river regulations by dams. The main objective of this work is to analyze the changes in the submerged morphology of the Guadalfeo deltaic system after the regulation of its main fluvial inflow. We used high-resolution bathymetric measurements and globally used coastal engineering models and tools to characterize the cross-shore and alongshore variations of the nearshore bathymetry of the delta. The applicability and limitations of these tools are discussed, identifying their major weaknesses for their application in this type of environments.

STUDY SITE

The Guadalfeo deltaic system (Fig. 1) is located on the southern coast of the Iberian Peninsula facing the Mediterranean Sea. The Guadalfeo River is fed by one of the most high-energy drainage systems along the Spanish Mediterranean coast and provides the major contribution of sediments to the nearby beaches. The topographic gradients lead to large contributions of a wide range of sediment sizes. Consequently, the particle size distribution on the coast around the mouth of Guadalfeo River is particularly complex, with varying proportions of sand and gravel [Bergillos et al., 2016a]. Moreover, bathymetric evidences confirm that the continental shelf is narrow, with an average length shorter than 5 km. According to data from SIMAR point 2042079 (see Fig. 1, Puertos del Estado, Spanish Ministry of Public Works), the storm wave climate is distinctly bimodal with the prevailing wave directions west-southwest (extra-tropical cyclones) and east-southeast (Mediterranean storms). Peak significant wave heights during typical and extreme storm events exceed 2.1 m and 3.1 m, respectively. Under South Atlantic storm conditions, swell waves generated in the Gulf of Cadiz propagate through the Strait of Gibraltar. These swell waves impinge the coast simultaneously with the local wind waves, but with slightly different angles [Ortega-Sánchez et al., 2008]. The astronomical tidal range is ∼ 0.6 m (microtidal conditions), whereas typical storm surge levels can exceed 0.5 m [Bergillos et al., 2016b].

In 2004, the construction of the Rules dam was completed 19 km upstream of the Guadalfeo River mouth, regulating 85% of the basin runoff [Losada et al., 2011]. The river damming modified the natural

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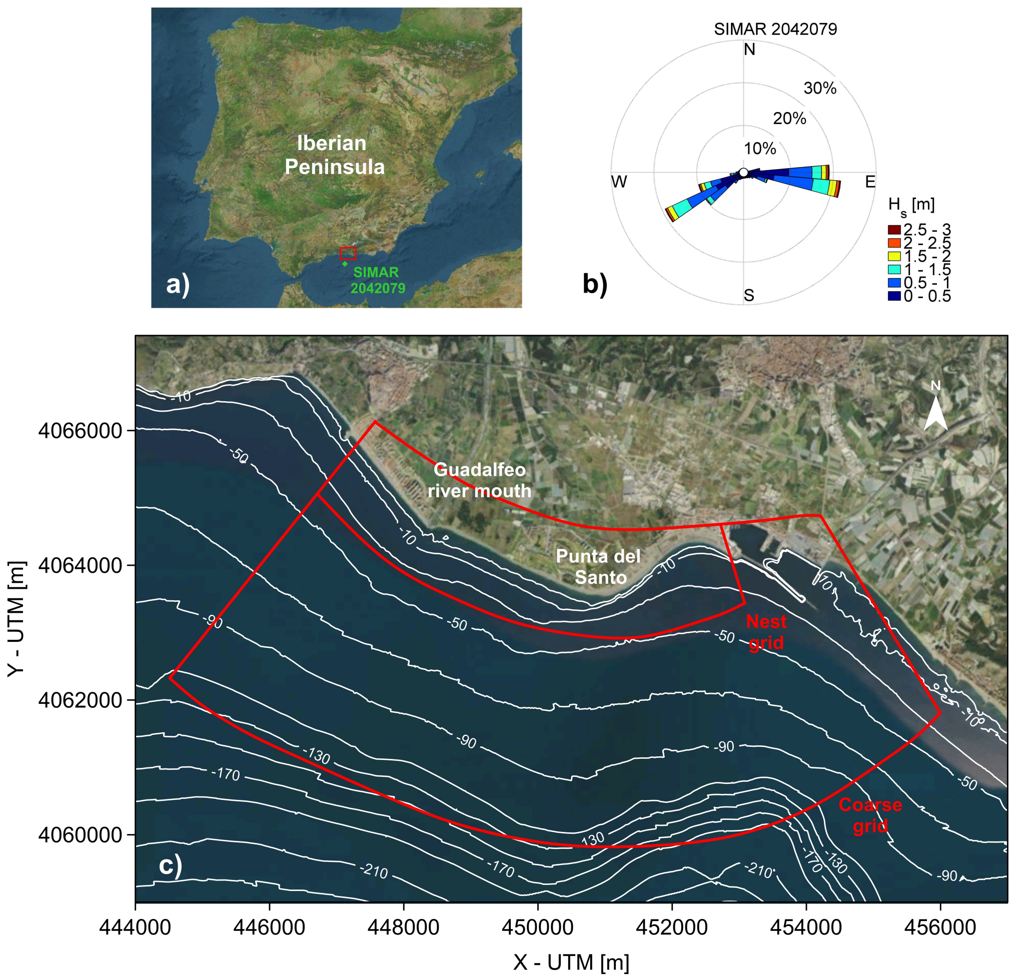

Figure 1: **Study site: a) General situation of the deltaic system within the Iberian Peninsula and location of the SIMAR point where wave data are obtained; b) wave rose based on the SIMAR point data; and c) Guadalfeo deltaic system. Red polygons indicate the numerical grids defined for the SWAN model.**

flow regime and altered the behavior of the system downstream of the dam. In particular, the reduction in sediment supply to the coast due to river regulation has been greater than $74,000$ m^3/y since 2004 compared to the volume that would have reached the coast under natural conditions [Bergillos et al., 2016c], contrasting with the accumulation of sediment as delta deposits in the reservoir upstream [Millares et al., 2014]. As a consequence, the deltaic coast, whose dynamics has been historically governed by the sediment supply of the river during intense events [Jabaloy-Sánchez et al., 2014], currently presents coastline retreat and severe erosion problems [Bergillos et al., 2016a].

MATERIALS AND METHODS

Our analysis is based on the available and collected bathymetric data and sediment samples of the delta between 1999 and 2014. We use different coastal engineering tools to characterize and analyze the variations in the sediment volume around the mouth. In particular, waves were propagated using a calibrated and validated numerical wave propagation model (SWAN) and temporal variations in the longshore sediment transport (LST hereinafter) were obtained [López-Ruiz et al., 2014]. These variations were used to characterize the changes in the plan view of the delta.

Bathymetric data

High-resolution multibeam bathymetric surveys were carried out covering the entire deltaic coast in September 1999, October 2004, September 2008 and December 2014 by the Provincial Coastal Service

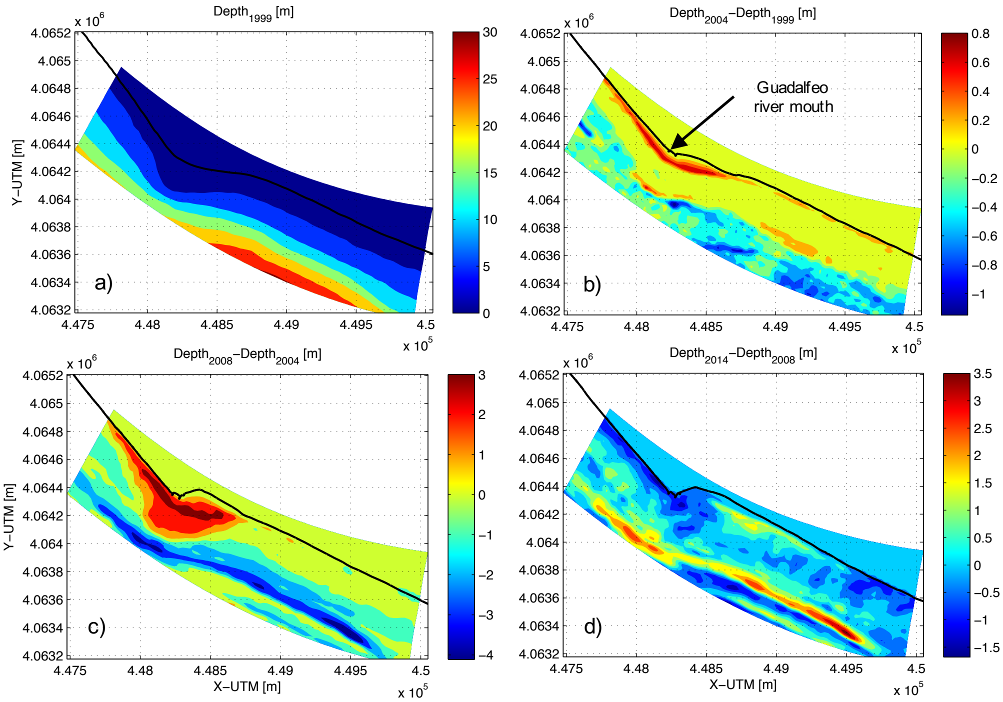

Figure 2: Water depths around the river mouth according to bathymetric measurements: a) 1999; b) to d) differences between 2004 and 1999, 2008 and 2004 and 2014 and 2008, respectively.

of Granada, the University of Granada, the Spanish Ministry of Environment and Rural and Marine, and the Andalusian Institute for Earth System Research, respectively (Fig. 2). The data were acquired using Differential Global Positioning System (DGPS) navigation referring to the WGS-84 ellipsoid. Accurate navigation and real-time pitch, roll and heave were corrected. The multibeam data were also corrected for the sound velocity. These morphological data were used to address the influence of delta retreat and the resulting changes in the submerged morphology (mainly induced by river damming) on the nearshore wave propagation and the LST patterns. The methods employed to analyze these two topics are described in the following sections.

Wave propagation

The SWAN model was designed to simulate random, short-crested waves in coastal regions (Lesser et al., 2004; Dan et al., 2011). The main processes included in the model are refraction due to bottom and current variations; shoaling, blocking, and reflections due to opposing currents; transmission/blockage through/by obstacles; wind effects; whitecapping; depth-induced wave breaking; bottom friction; and non-linear wave-wave interactions.

Although refraction is the dominant propagation process [Magne et al., 2007], to accurately model the surface gravity waves propagating over the complex inner shelf bathymetry, combined refraction and reflection models are required. To this end, Gorrell et al. [2011] demonstrated that, although the SWAN assumptions include small bottom slopes, the alongshore variations of the nearshore wave field caused by refraction over steep shelfs, as those in the study site, are predicted satisfactorily.

In this work, the model domain consists of two different grids, shown in Fig. 1. The first is a coarse curvilinear 82x82-cell grid covering the entire deltaic region, with cell sizes that decrease with decreasing depth from 88x60 to 48x35 m. The second is a nested grid covering the beach with 144 and 82 cells in the alongshore and cross-shore directions, respectively, and cell sizes of about 25x14 m. For the spectral resolution of the frequency space, 37 logarithmically-distributed frequencies ranging from 0.03 to 1 Hz were used; for the directional space, 72 directions covering 360° in increments of 5° were defined.

The model was calibrated through comparison with field data collected from 20 December 2014 to 30 January 2015 by means of two ADCPs, resulting in coefficients of determination (R^2) higher than 0.86, providing confidence in the applied wave propagation model. For further details on the model calibration the reader is referred to Bergillos et al. [2016a].

To address the changes in the wave patterns due to variations of the submerged morphology at the study site, frequently occurring sea states (Table 1), under both low energy and storm conditions, and for both easterly and westerly waves, were propagated from deep water to the nearshore using the WAVE module of the Delft3D model [Lesser et al., 2004, Lesser, 2009]. This module is based on the SWAN model [Holthuijsen et al., 1993, Booij et al., 1999], which was described above.

	Low energy		Storm	
	East	West	East	West
H_0 (m)	0.4	0.4	3.2	3.2
T_p (s)	4.5	4.5	8.4	8.4
θ (°)	112	245	112	245

Table 1: Sea states propagated to analyze the effect of the morphology changes on wave propagation and LST.

Longshore sediment transport

Mixed sand and gravel beaches in the westerly coasts of the Mediterranean Sea are usually characterized by curvilinear shorelines, as those in the vicinity of the Guadalfeo delta. As demonstrated by López-Ruiz et al. [2012a] and López-Ruiz et al. [2012b], these geometries induce important alongshore gradients in two main variables related to shoreline morphodynamics, i.e., the wave angle in the surf zone and the wave energy content, that in turn promote the presence of important alongshore variations in both grain size [McLaren and Bowles, 1985] and beach slope [Dean and Dalrymple, 2002].

Evidences in nature can be found for both processes. As described in Ortega-Sánchez et al. [2017], the presence of a curvilinear coast induces alongshore gradients in both the surf zone width (and hence in wave energy) and nearshore wave angle that limits the applicability of the most widely used LST formulations, such as the CERC [U.S.A.C.E., 1984] or the Kamphuis [1991] expressions. The former was obtained considering uniform stretches of coast in the longshore direction, without variations in the beach and sediment characteristics, whereas the latter was obtained empirically for sandy beaches with sediment sizes different from those of mixed sand and gravel beaches. Moreover, the Kamphuis [1991] expression over-predicts the LST rates on coarse-grained beaches [Reeve et al., 2012].

Considering all these limitations, a significant effort was carried out to obtain an alternative LST approach in recent years [López-Ruiz et al., 2012a,b, 2014]. In this work, the energetic approach proposed by López-Ruiz et al. [2014] is applied. This expression uses a framework specifically defined for curvilinear coasts, considering alongshore variations of the shoreline and wave angles, and also gradients in the wave energy characterized by the surf zone width. Moreover, it was obtained without the use of hypothesis of uniform nor regular beach characteristics in the alongshore direction. As well as the others energetic approaches, the expression accounts for the potential LST that can be transported given specific wave energy conditions. This potential LST fits the actual LST rate if there is enough sediment of the characteristic grain size to be mobilized. Furthermore, there is another source of uncertainty related with grain sizes, since the use of a characteristic D_{50} implies that the sediment is considered as uniform for a specific beach profile, although it can vary alongshore.

The LST approach proposed by López-Ruiz et al. [2014] was applied using the wave breaking data obtained with SWAN. In order to characterize the variations in the LST patterns due to changes in the nearshore bathymetry of the delta, the LST expression was applied for the sea states defined in Table 1 for each bathymetric dataset. Furthermore, to analyze the influence of the LST rates and the variations in the submerged geometry of the delta, the LST was computed for every 3-hour sea state registered between the dates in which the bathymetric samples were obtained. The wave propagation of this amount of sea states would require a significant computational effort, so downscaling techniques were applied to reduce the number of wave simulations. The reader is referred to Bergillos et al. [2016a] for further details on the downscaling technique employed.

RESULTS AND DISCUSSION

Wave patterns over the submerged delta

Results from SWAN model show that the behaviour of the nearshore waves over the deltaic coast changed significantly during the period between 1999 and 2014. Fig. 3 depicts these variations between

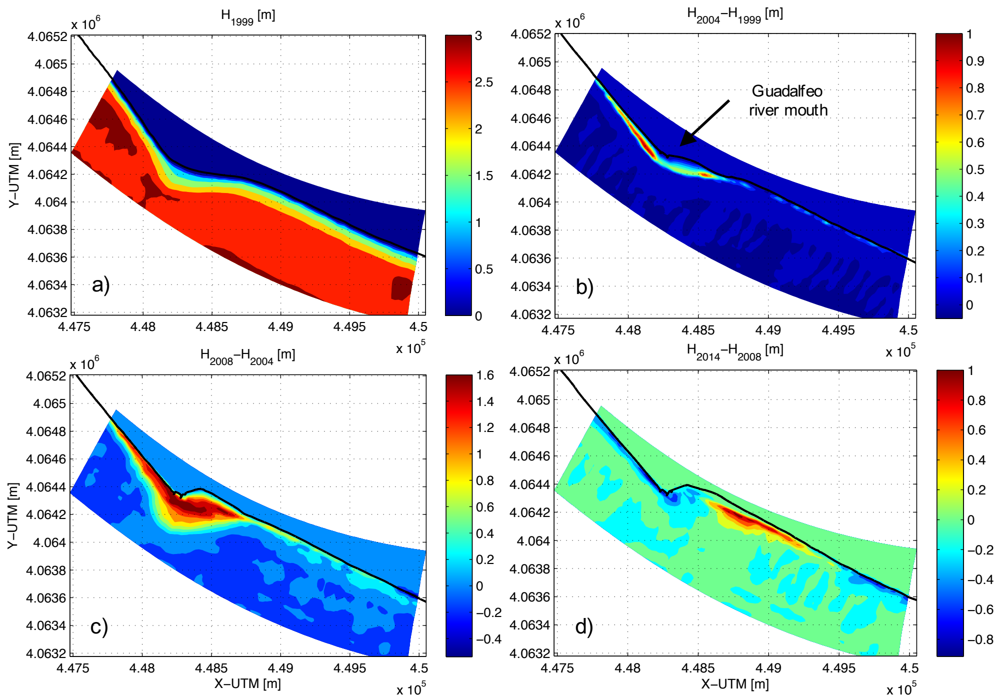

Figure 3: Wave height obtained for westerly storm conditions: a) Results for 1999 bathymetry; b) to d) differences between 2004 - 1999, 2008 - 2004 and 2014 - 2008, respectively. Black solid lines indicate shoreline position for each bathymetric sample.

each consecutive bathymetric sample for the storm conditions defined for westerly waves (Table 1). For the 1999 bathymetry, wave energy is concentrated around the river mouth due to the effect of the curvilinear bathymetry, as explained by López-Ruiz et al. [2014]. For the following bathymetric sample (Fig. 3b), a significant increase in wave height is observed in the vicinity of the river mouth. Although these variations are also due to changes in intermediate and nearshore water depths, the majority of the variations are explained simply because there was a significant shoreline retreat. This implied the inundation of areas that were initially dry, limiting the results of the analysis if only the wave height values are compared.

Hence, to understand the evolution of the delta mouth dynamics in terms of nearshore wave propagation patterns, the spatial and temporal variations in the breaking wave height (H_b) were analyzed under low energy and storm conditions (Table 1), instead of comparing the complete matrix of wave height obtained. Figure 4 depicts the alongshore distribution of H_b for the four available bathymetries (1999, 2004, 2008, and 2014) under both westerly and easterly waves.

Under low energy conditions, the H_b values, and their alongshore variation, are similar for the four bathymetries under both westerly and easterly waves (Fig. 4a and c); however, significant differences are observed for typical storm conditions (Fig. 4b and d). Under westerly storm waves, it is observed how the delta retreat between 2004 and 2008, and the resulting reduction in wave refraction, induced significantly larger values of H_b at the eastern flank of the mouth. The maximum difference represents an increase of almost 10% (difference in H_b of 0.22 m).

Under easterly storm conditions (Fig. 4d), higher H_b values are observed in 1999 and 2004 at the eastern flank of the mouth, probably due to the advanced seaward coastline position in 1999 at this location (Fig. 2a). However, the delta retreat during the period 2004-2008 led to greater values of H_b at the western flank of the mouth, with differences up to 21% and 0.25 m. During the 2008-2014 period, changes in the wave breaking conditions were significantly less than during the period 2004-2008 (increases of 2% and 10% in H_b for westerly and easterly storm conditions, respectively). As discussed later, this is attributed to the lower erosion rates between 2008 and 2014 at this location and the ensuing more stable nearshore morphology in terms of wave propagation.

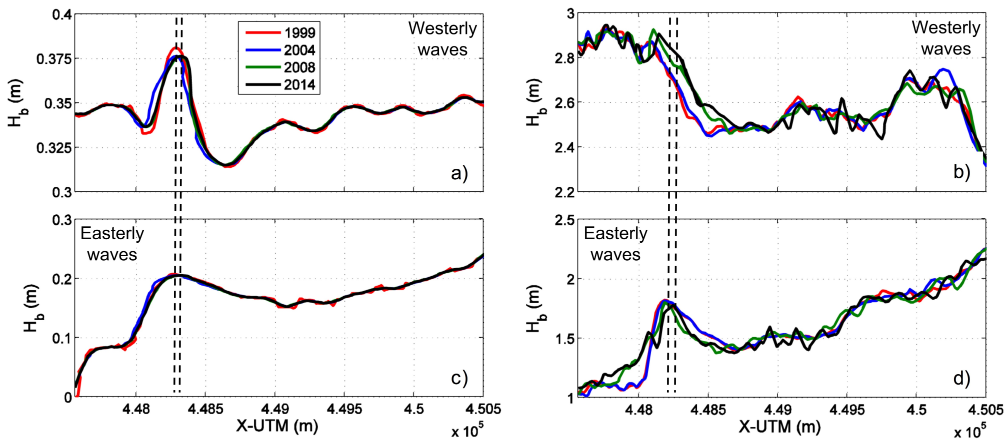

Figure 4: Wave height at breaking (H_b) obtained for the bathymetric samples under mild (panels a and c) and storm (panels b and d) conditions. Dashed black lines indicate the position of the Guadalfeo River mouth.

LST patterns and nearshore morphology of the delta

The LST expression derived by López-Ruiz et al. [2014] was also applied to the Guadalfeo deltaic system. In this case, the expression was applied with two different types of wave conditions: (1) a synthetic dataset of conditions to describe the LST behavior along the deltaic coast for low energy and storm conditions and (2) the complete wave time series between 1999 and 2014, considering different water depths for the intervals between the dates in which bathymetric data were available (1999, 2004, 2008 and 2014). The influence of both the volumetric changes and shoreline evolution of the delta were analyzed in detail with these time series.

In the case of the synthetic dataset, the deep-water wave angle and the spectral peak period shown in Table 1 were used for both low energy and storm conditions. The shoreline angle and beach slope distributions were obtained from the bathymetric data of 1999, 2004, 2008 and 2014. The surf zone width was obtained from the results of the SWAN model, obtaining the breaking point for 250 beach profiles equally distributed along the shoreline and defined as shore-normal.

Fig. 5 depicts the LST rates obtained for low energy and storm conditions (Table 1). As a general spatial trend, the gradients in LST are important mainly at the Guadalfeo River mouth. It is also observed that greater values for LST are obtained under westerly waves, for both low energy and storm conditions. Regarding the low energy conditions, under westerly waves (Fig. 5a), the gradients in LST at the Guadalfeo River mouth are of minor importance for all bathymetries except for 2004, just after the entry into operation of the dam. In this case, gradients are more than 5 times greater than those for the other bathymetries. Under easterly waves (Fig. 5c), the trend is very similar, with the only difference being that LST at the east side of the river mouth is more irregular than under westerly waves.

For storm conditions (Fig. 5b and d), LST patterns are different from those for low energy conditions. Significant differences are also observed between westerly and easterly wave conditions. Under westerly storms, the LST gradients are significantly larger than those obtained under easterly storms, particularly for the 2008 and 2014 bathymetries. However, under easterly storms, the behavior is clearly different: although for 1999 the LST gradients were important, they increased by a factor of two in 2004. These gradients vanished almost completely for 2008 and 2014, with the shoreline much more in equilibrium for such conditions. This indicates that the delta has acquired a shape that minimizes LST gradients for all wave conditions except for westerly storms, which are the most energetic.

The complete time series of wave conditions between 1999 and 2014 were obtained using downscaling techniques, as explained in detail in Bergillos et al. [2016a]. With the complete LST series, their probabilistic distributions along the delta as well as those for the alongshore gradients of the LST ($\partial Q/\partial s$, being s the longshore coordinate) were obtained. The results are shown in Fig. 6, where the probability distribution functions (pdfs) of LST rates and gradients are depicted for each period, depending on the location along the shoreline. The limits of the probability values were adjusted to appreciate the distribution of LST and

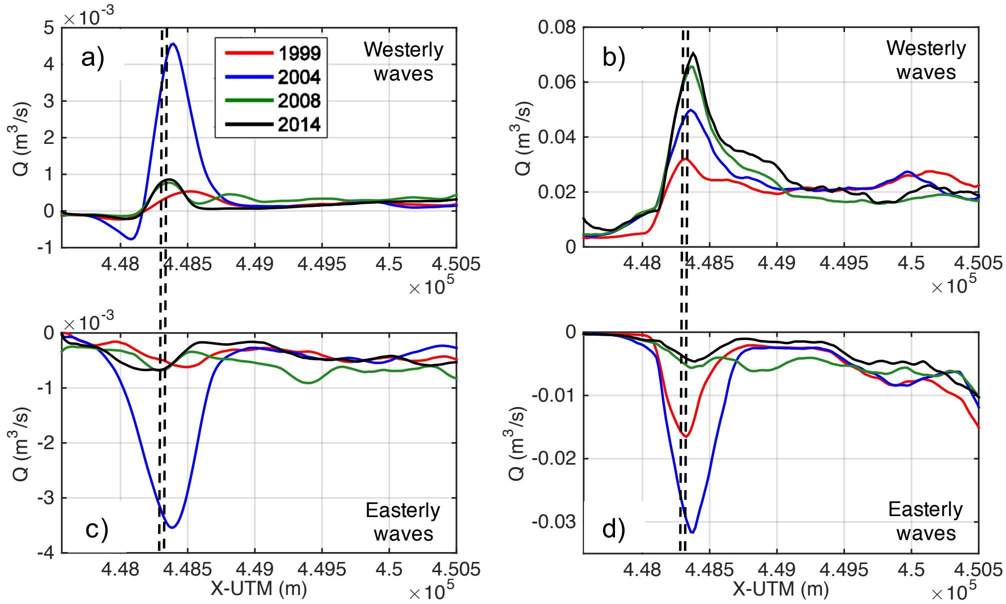

Figure 5: **LST rates (Q) obtained for the bathymetric samples under mild (panels a and c) and storm (panels b and d) conditions. Positive values of Q indicate a drift toward the East. Dashed black lines indicate the position of the Guadalfeo River mouth.**

its gradients associated to low probabilities (pdf < 0.035).

As a general trend for the period 1999-2014, higher values of LST for both drift directions were clearly more likely in the vicinity of the river mouth. However, some differences in the pdfs are observed between the periods. During the period 1999-2004 (Fig. 6a and b), LST values with probabilities over 0.035 (red colors) barely present significant alongshore gradients. On the contrary, LST with probabilities around 0.01 presented significant alongshore gradients and values of $Q \simeq 0.02$ m^3/s for westerly drifts close to the river mouth. Hence, LST related with westerly waves ($Q > 0$, westerly drift) was more frequent and intense than for easterly waves.

For the period 2004-2008 (Fig. 6c and d), higher values of LST and the associated alongshore gradients in the vicinity of the river mouth were clearly more frequent than for the period 1999-2004. Although during this epoch LST with absolute values over 0.02 m^3/s were more likely for westerly drifts, implying that significant alongshore gradients in LST were more frequent for westerly waves, the symmetry of the deep red colors in the river mouth indicates that the majority of the LST values around the river mouth were concentrated in $Q \in (-0.015, 0.015)$ m^3/s. This implies that easterly waves were more important in this epoch, from a morphodynamic point of view, than in previous one. For the last period (2008-2014), the LST distribution is again very asymmetric with an important dominance of westerly drifts. However, in this case the highest LST rates ($Q > 0.03$ m^3/s) were much more likely than in the previous epochs, with pdf > 0.01.

Volumetric changes induced by LST and delta evolution

Fig. 7 shows the average LST rates and the volumetric differences based on the gradient in the LST for the three periods considered. Since the LST formulation accounts for sediment transport in the breaking zone, the changes in sediment volume refer to changes in the shallower nearshore zone. The LST volume gradients, which are based on the potential littoral drift rates (Fig. 7a), predict erosion of the western flank of the delta and accretion of the eastern flank (Fig. 7b). However, higher eroded volumes were measured on the eastern flank during the three periods (Fig. 2) and this is explained because LST volumes patterns were not realized because of the trapping of eastward moving sediment by the river jetties (when they extend into the sea). This occurred over most of the study period (Fig. 8), thereby reducing erosion on the western flank and causing erosion rather than accretion on the eastern flank. This highlights the importance of the river jetties in reversing the morphodynamic behavior expected for an unmodified beach.

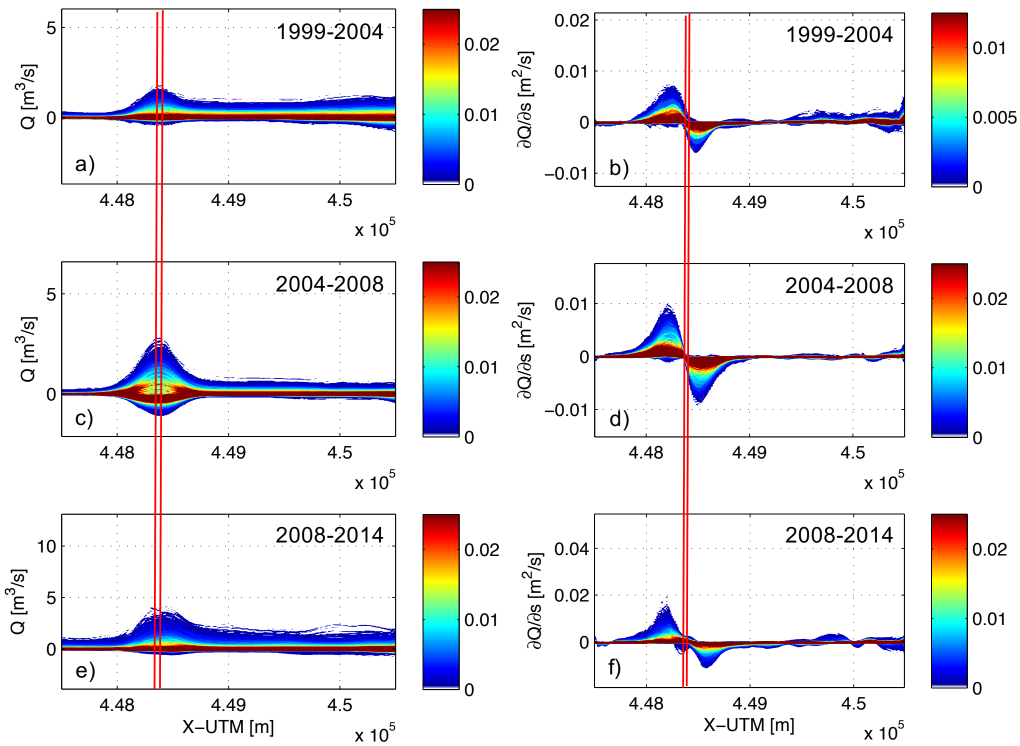

Figure 6: Probability distribution functions (pdfs) for the LST (first column) and its gradient (second column) during the intervals between bathymetric surveys. Colors correspond to the probability of values of LST and LST gradient (vertical axes) in its alongshore locations (horizontal axes). Positive values of Q indicate a drift toward the East. Solid red lines indicate the position of the Guadalfeo River mouth.

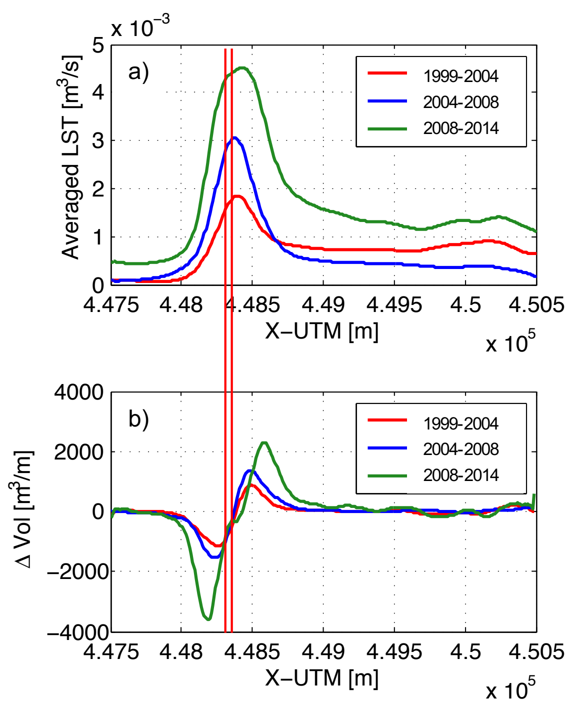

Figure 7: Averaged LST rates (panel a) and alongshore evolution of LST volumetric changes in the nearshore (panel b) for the time intervals analyzed. Solid red lines indicate the position of the Guadalfeo River mouth.

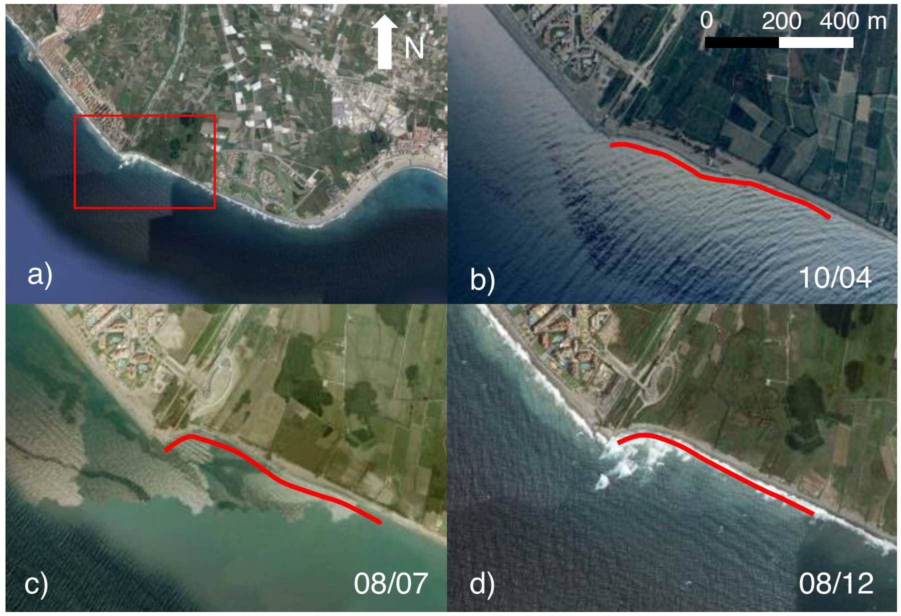

Figure 8: **Aerial images of the Guadalfeo River mouth taken in 1999 (a), 2002 (b), 2004 (c), 2006 (d), 2007 (e), 2008 (f), 2010 (g) and 2013 (h). The identified shorelines are highlighted in colors. (Source: Bergillos et al. [2016a]. Reproduced with permission of Elsevier).**

The total sediment volume losses along the stretch of beach in study (Fig. 1) induced by LST were approximately 90,000; 12,000 and 120,000 m^3 for the three periods considered, respectively (Fig. 9). These modeled values are similar (differences lower than 35%) than the measured volumetric changes between the shoreline and the maximum breaking depth for each epoch (~ -70,000; -18,000 and -175,000 m^3, respectively) and indicate that LST is the main contributor to coastal changes. The uncertainty associated with both measurements and modeling, particularly the lack of available multibeam bathymetries at a larger temporal resolution, should be considered to understand the obtained differences.

The negative sediment balance in the studied stretch of beach contrasts with the accumulation of sediments and the advance seaward of the coastline in the eastern section of the study site (Fig. 1), detailed in Bergillos et al. [2015]. This is mainly due to the greater LST rates under westerly waves (Fig. 5) and the resulting dominance of westerly drift (Fig. 7b). The total mobilized sediment volumes modeled for each time interval (Fig. 9) are also consistent with the nearshore volumetric changes observed (Fig. 2).

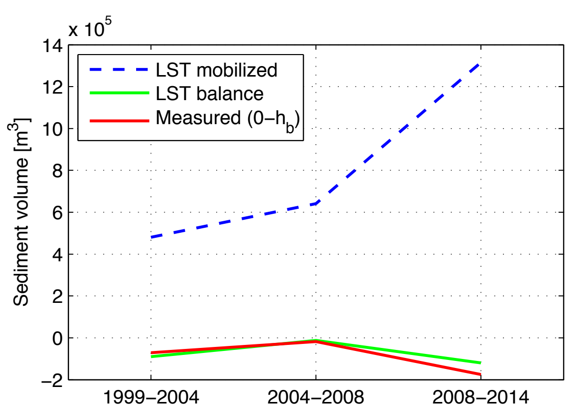

Figure 9: **Sediment volumes (in m^3): total mobilized by LST (dashed blue), balance of LST (solid green), and measured between the shoreline and the maximum breaking depth h_b (solid red).**

CONCLUSIONS AND FINAL REMARKS

This work analyzes in detail the changes in the submerged morphology of a Mediterranean deltaic system after the regulation of its main fluvial inflow. The study is focused on the Guadalfeo deltaic system (southern Spain), where the river inflow was altered in 2004 with the construction of the Rules dam 19 km upstream of the mouth. Evidences of how this dam has modified the behavior of the delta, generating coastline retreat, and changes in the sediment volume around the mouth are evident after the analysis of the bathymetric data. In particular, regarding the plan view of the delta, the LST variability along the coast was significantly modified by the Rules' Reservoir construction, generating significant changes in the shoreline geometry. These changes were more evident just after the entry into operation of the reservoir, whereas in recent years these gradients have decreased. Natural evidences taken from Google Earth imagery are in agreement with these results.

Coastal engineering techniques were applied to assess these changes in the nearshore bathymetry, including numerical wave propagation with SWAN model, downscaling techniques to obtain long LST time series, a new LST approach specifically developed for curvilinear and nonuniform beaches, and a statistical study of the LST and its gradients between bathymetric surveys. Based on the obtained results, the following conclusions were drawn:

1. LST on the coast was significantly modified by the combined effect of changes in the nearshore bathymetry and wave directionality. The modification of the alongshore gradients of the LST was more evident just after the entry into operation of the reservoir (2004), contributing to the changes of the submerged morphology. These changes were the main responsible of increasing the probabilities of high values of LST and its alongshore gradients. These LST gradients have decreased during recent years except for western storms around the river mouth. The modification in LST patterns may not be attributable only to changes in the wave conditions nor human interventions, but to a combined effect of both. Furthermore, volumetric changes obtained from the LST gradients are able to explain quantitatively the majority of the volumetric changes calculated with the bathymetric data. Hence, LST was the main driver of the nearshore changes in the delta. Qualitatively, the trends of LST and the erosion/accretion patterns indicate that jetties at the river mouth, which are sticked out most of the time, play a key role on the shoreline evolution of the delta.

2. The methodology applied resulted in an accurate analysis, since the sediment balance obtained through the LST rates is in good agreement with the measured morphological changes. This indicates that every coastal engineering tool applied in the process was accurate, even when the characteristic of the beach prevent the use of traditional tools: (1) the wave propagation model was calibrated obtaining good correlations even when the study site is very demanding with the assumptions used in the development of the SWAN model; (2) the LST approach applied obtained accurate LST rates; and (3) the combination of the downscaling techniques and the statistical treatment of the LST results derived in an efficient and easy-to-interpret analysis of a significant amount of information.

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