Coastal Research Library 41

Carlos Coelho
Caroline Hallin
Francisco Sancho
Paulo A. Silva *Editors*

Coastal Dynamics 2025

Volume 1

OPEN ACCESS

Springer

Coastal Research Library 41

Series Editors

The aim of the Coastal Research Library (CRL) is to disseminate accurate information to both the public and research specialists around the world on all aspects of coastal issues in an effort to maintain or improve the quality of our planet's shoreline resources. By covering the entire field of coastal research [e.g., geology, biology, ecology, geomorphology, physical geography, climate change, coastal evolution and shoreline change, littoral oceanography, hydrodynamics and AI modeling, sea-level change, beaches and dunes, coastal hydraulics, erosion, waves, flooding, environmental (resource) management (law), policy and planning, coastal and marine engineering, GIS and remote sensing, socio-economic topics, coastal hazards and extreme storms, anthropogenic change, etc.], the scope of the CRL is broad with a unique cross-disciplinary nature that encompasses all subjects relevant to natural and engineered environments (freshwater, brackish, or marine) and the protection/management of their resources in the vicinity of coastlines around the world. This book series offers current cutting-edge coastal research from the world's leading scientists and is relevant to professionals, academics, and stakeholders, as well as the general public.

The CRL tends to focus on topics linked to complex multidisciplinary problems and contentious issues that surround the coastal environment and occur within the coastal zone. Welcome additions to the series can include: Contributed Volumes, Handbooks, Monographs, Proceedings, Professional Books, Textbooks, and others.

We invite you to submit your new proposals to CRL Series Editor: Chris Makowski, Ph.D. Email: cmakowski@cerf-jcr.com

Carlos Coelho · Caroline Hallin ·
Francisco Sancho · Paulo A. Silva
Editors

Coastal Dynamics 2025

Volume 1

Springer

Editors
Carlos Coelho
Civil Engineering Department
University of Aveiro
Aveiro, Portugal

Caroline Hallin
Water Resources Engineering
Lund University
Lund, Sweden

Francisco Sancho
Hydraulics and Environment Department
National Laboratory for Civil Engineering
Lisbon, Portugal

Paulo A. Silva
Physics Department
University of Aveiro
Aveiro, Portugal

ISSN 2211-0577 ISSN 2211-0585 (electronic)
Coastal Research Library
ISBN 978-3-032-15472-9 ISBN 978-3-032-15473-6 (eBook)
https://doi.org/10.1007/978-3-032-15473-6

This work was supported by the Coastal Dynamics 2025 conference.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Unravelling the Response of the Guadiana Ebb-Tidal Delta to Extreme Wave Events

Carlos Rubio[1(✉)], Erwan Garel[2], Carmen Zarzuelo[1], and Alejandro López-Ruiz[1]

[1] Departamento de Ingeniería Aeroespacial y Mecánica de Fluidos, Universidad de Sevilla, Seville, Spain
crubio1@us.es

[2] Centre for Marine and Environmental Research - CIMA, Universidade do Algarve, Faro, Portugal

Abstract. This study investigates the morphodynamic response of the Guadiana ebb-tidal delta to extreme wave storms using a process-based numerical model. Field data including wave climate, wind and bathymetry were integrated into the Delft3D model, calibrated and validated with hydrodynamic data collected at the lower estuary in 2013, 2015 and 2023 and bathymetric maps of the ebb delta from 2016 and 2017. The analysis focuses on the impact of Storm Emma (February-March 2018), characterised maximum wave height up to 7.1 m. Results show that Emma induced a significant shift in sediment dynamics, causing retreat and erosion of the updrift shoal complex (with a net sediment volume loss of 2.40%), sediment transfer to the downdrift complex (that gained sediment volume of 0.32%), and channel rotation.. These changes contrast with the seaward growth of the shoal under mild conditions observed during non-extreme conditions, as between 2016 and 2017. The results highlight the importance that large extreme wave events can have on the morphodynamic evolution of ebb tidal deltas.

Keywords: numerical model · ebb tidal delta · Emma storm · morphology

1 Introduction

Ebb-tidal deltas are among the most dynamic coastal areas in the world. Understanding their morphodynamics under various forcing conditions, such as wind waves, tidal flows or littoral drift, has become increasingly important for effective management. This need arises from growing pressures exerted by climate change and human interventions, such as development of navigation channels, which have significantly threatened their environmental quality in recent decades. This study aims to characterise the morphodynamic response of the Guadiana ebb-tidal delta (GETD) to extreme wave storms using a process-based numerical model. The results are crucial for understanding how changes in the frequency and intensity of these extreme events may affect its morphodynamic evolution in the coming decades.

The GETD is a mixed-energy, tide-dominated delta on the southern border between Spain and Portugal. In the region, tides are semidiurnal with a mean tidal range of 2 m.

C. Coelho et al. (Eds.): CD 2025, CRL 41, pp. 758–764, 2026.
https://doi.org/10.1007/978-3-032-15473-6_115

The offshore wave climate is dominated by W–SW waves (71% of occurrences) and SE sea waves (23% of occurrences) of moderate energy, with yearly averaged significant wave height of 1 m and peak period of 8.2 s [1]. The littoral sand transport in the area is eastward, feeding the delta by an average of 100 Mm^3/year, with little contribution from the Guadiana River.

The delta (Fig. 1) typically consists of a main inlet channel and outer ebb shoal featuring subparallel lobed swash bars, flanked by shallower areas affected by waves. The updrift area consists of a narrow and straight lateral bar, while the downdrift area consists of a broad complex, which is the remnant of the historic delta (before the jetty was built), which widespread erosion nourishes adjacent beaches [2].

Storm Emma made landfall in the southwest of the Iberian Peninsula on 28 February 2018 and lasted about 4 days during a spring tide period. Propagating in a WNW direction, the storm reached a maximum wave height of 7.1 m, with a mean wave height of 4.1 m, causing beach erosion and damage to several coastal infrastructures along the coastline of the Gulf of Cádiz.

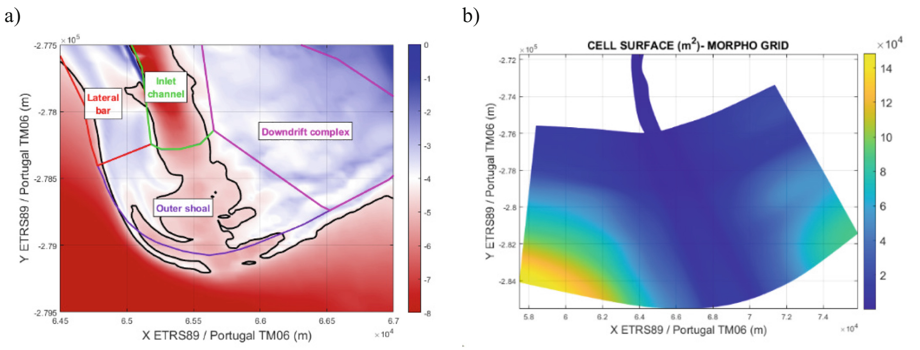

Fig. 1. (a) Initial bathymetric grid (2016). The figure shows areas of motion transfer according to [3]: updrift lateral bar, outer shoal, inlet channel and downdrift complex. (b) Cell surface (m^2) of the morphological grid.

2 Methods

2.1 Field Data

Wave observations recorded every three hours were retrieved from the Faro buoy (IH - Instituto Hidrográfico de Portugal), located at 50 km west of the study site. Gaps in the hourly time-series were replaced by hindcasts extracted nearby from the SIMAR (point 1049047) numerical model (Spanish National Port Authority). Significant wave heights from the model (Hs*) were corrected using the correlation Eq. (1) obtained through comparison with available buoy observations (Hs) for the period 1958–2024:

$$H_s^* = 0.987 \cdot H_s + 0.468 \tag{1}$$

Hourly wind data were obtained from the SIMAR model. The daily average Guadiana River discharge was obtained from a hydrographic station (Pulo do Lobo) near the estuary head [4]. Both data for 2016–2018.

Hydrodynamic observations included water level and depth averaged velocities collected at the lower estuary (i.e., 4 km upstream from the mouth) in 2013, 2015 and 2023 at 15 min intervals with an Acoustic Doppler Current Profiler (ADCP). Bathymetric data were collected (in RTK mode) in June 2016 and 2017 using a single beam echo sounder along parallel transect of 50 m intervals. The water depths were tide-corrected and referenced to the mean sea level (MSL) in ETRS89, Portugal TM06 coordinate system (Fig. 1a).

2.2 Numerical Model

The Delft3D model was implemented at the study site to simulate the morphodynamics of the GETD, using both the hydrodynamic (Flow) and wave propagation (Wave) modules. The simulations were carried out in two dimensions, solving the depth-averaged flow. The van Rijn [1993] equations were used to calculate the suspended and bedload sediment transport due to waves and currents.

The grid of the model covered the ebb-tidal delta and lower estuary stretch lying from the mouth to 7 km upstream (Fig. 1b). A non-uniform grid with minimum grid size of 20 $\times$ 20 m was used [6] over the ebb delta. The boundary conditions were: (1) the fourteen main tidal constituents for the offshore boundary, (2) Neumann conditions for the lateral cross-shore boundaries, and (3) depth averaged velocities at the upstream boundary. These velocities were obtained from prior hydrodynamic simulations carried out on a different grid covering the complete estuary (from the head at Mértola to 10 km offshore) that included the Guadiana River discharge.

The numerical model was calibrated and validated for hydrodynamics and calibrated morphodynamics.

For the former, water level and depth-averaged velocity data from 2015 [5] and 2023 were used (Fig. 2). The validation was performed using data from a period of high river discharge in 2013, which peaked at 2,331 m^3/s.

The results of the hydrodynamic validation for the depth averaged velocity along the estuary channel are excellent. The results were observed for the period 01 March 2013 to 01 May 2013 with a root mean square error of 0.28 m/s, a correlation coefficient of 0.93 and a skill score of 0.91 for the northward velocity and 0.07 m/s, 0.93 and 0.89 for the eastward velocity.

For the morphodynamic calibration, bathymetric maps of the GETD from 2016 and 2017 were used, simulating the period between the two field surveys and comparing predicted and observed bed levels. This period was characterized by a wave climate with mean wave energy consistent with the historical data and no major storms occurred. The BSS (Brier Skill Score) index [6] was used to quantify the agreement between observations and model results, complemented by the adjustment of the mean-squared error skill score [7].

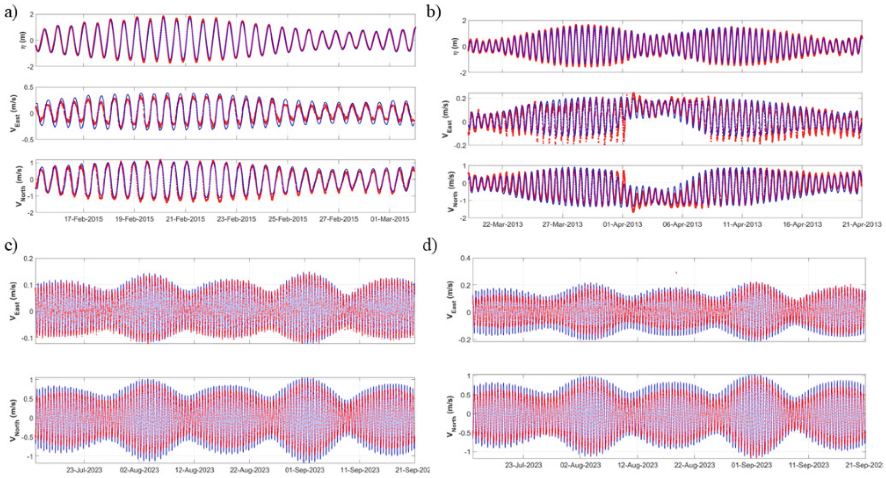

Fig. 2. Hydrodynamic model calibration and validation results. ADCP field data (blue) and DELFT3D model data (red) are compared with water level η (m), north velocity, and east velocity. (a) Model calibration (Feb 15, 2015 - Mar 02, 2015). (b) Strong river discharge event (Mar 01, 2013 - May 01, 2013). (c, d) Model Jul 14, 2023 - Sep 15, 2023.

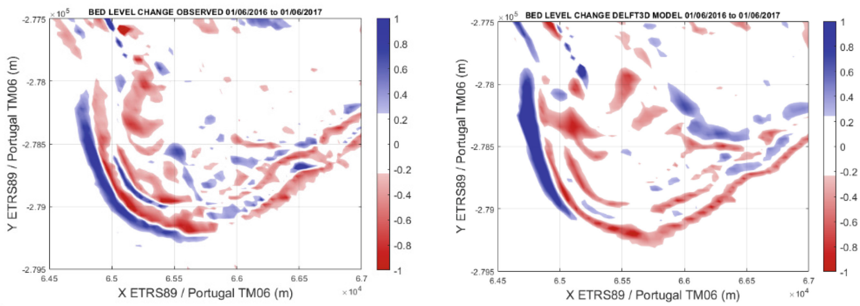

Fig. 3. Difference in bottom depth (in meters) between 2017 and 2016 from observations (left) and simulations (right). The color indicates changes in bed elevation > 0.2 m Negative values indicate erosion (red), while positive results indicate sedimentation (blue).

For the morphodynamic calibration, a BSS of 0.59 (good) was obtained for the GETD (Fig. 3). If only grid cells with bed level changes > 0.5 m are considered, the BSS result is 0.84 (excellent, according to the Sutherland scale). Furthermore, the erosion and deposition patterns observed during 2016–2017 period are qualitatively well captured (Fig. 3), although the erosion processes are slightly underestimated.

3 Results

The morphodynamic behaviour observed between 2016 and 2017 corresponds to a typical year with non-extreme energy conditions [3]. Broadly, it is characterized by a seaward growth of the outer shoal and landward retreat of the downdrift complex. In contrast, run between June 2017 and June 2018 show that the Emma storm produced a markedly different pattern of erosion and sedimentation (Fig. 4). During the storm, the updrift flank of the delta retreated, and sediment was transferred to the downdrift complex that extended offshore (Fig. 4). There was also a noticeable shift (up to 30 m) and clockwise rotation of the channel of about 6º (dashed lines Fig. 4).

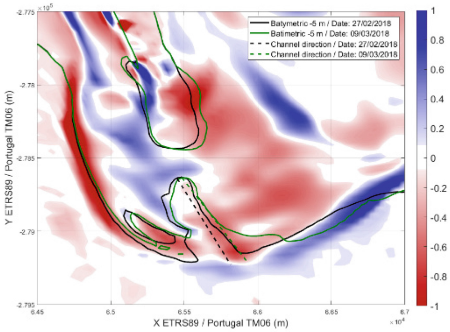

Fig. 4. Result of the Delft3D model. Bed level change between June 2017 and June 2018, showing the influence of Emma Storm. Erosion in red and sedimentation in blue. The continuous lines represent the -5m depth contours. The black lines correspond pre-Emma (27/02/2018) while the green lines represent, after the Emma Storm (09/03/2018). The dashed lines indicate the navigation channel direction for both years.

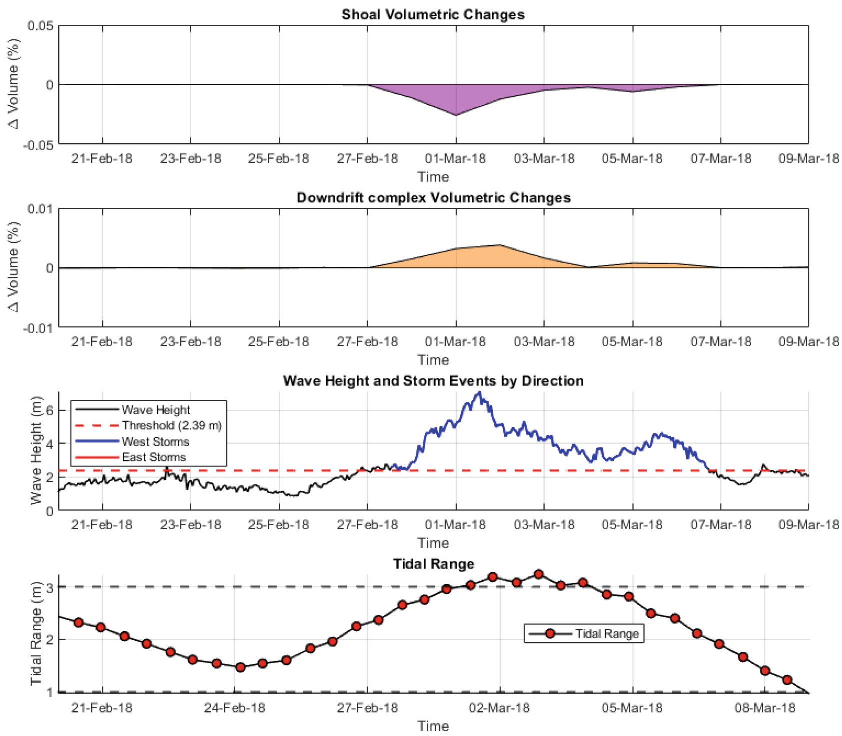

Fig. 5. From top to bottom: (1) Volumetric change in the shoal complex, (2) Volumetric change in the downdrift complex, (3) Significant wave height, (4) The tidal range.

Average daily volume changes in the GETD analysis areas (shoal and downdrift complex) were calculated, showing that the largest volume changes (increase/decrease) occurred during the Emma storm (Fig. 5). The simulation revealed a total net sediment volume loss of 2.40% in the updrift area (Fig. 5a) during Storm Emma (February-March 2018), offset by an increase of 0.32% in the downdrift complex (orange area, Fig. 5). These quantitative results are consistent with the qualitative trends observed in Fig. 4. In addition, the data show that sediment transport is significantly correlated with storm events. Figure 5 clearly shows that volume changes coincide with both storm events and periods when tidal conditions deviate from the average range (more than 3m above the average maximum range).

4 Conclusions

This study analyses the impact of the Emma storm on the mophodynamics of the GETD. Numerical model results show that Emma caused large areas of erosion and deposition in the delta, with patterns that contrast with those observed under mild wave energy conditions. Overall, the storm induced a clockwise rotation of the entire delta (with retreat of the west flank and accretion of the eastern flank), including the navigation channel, associated to significant changes in sediment volume across the main features of the delta.

These findings have critical implications for the effective management of the delta, its navigational channel and adjacent beaches, particularly in the context of increasing intensity and frequency of extreme wave events driven by climate change. Furthermore, this study highlights the value of numerical modelling as a robust tool for understanding and predicting the complex dynamics of the GETD.

Acknowledgements. This work was supported by the Spanish Ministry of Economy and Competitiveness, Project PID2021-125895O/AEI/https://doi.org/10.13039/501100011033/FEDER, UE (RESILIENCE).

References

1. Costas S et al (2018) Surficial sediment texture database for SW Iberia Atlantic Margin. Earth Syst Sci 10(2):1185–1195
2. Garel E, Sousa C, Ferreira Ó, Morales JA (2014) Decadal morphological response of an ebb-tidal delta and down-drift beach to artificial breaching and inlet stabilisation. Geomorphology 216:13–25
3. Garel E, López-Ruiz A, Ferreira Ó (2019) A method to estimate the longshore sediment transport at ebb-tidal deltas based on their volumetric growth: application to the Guadiana (Spain–Portugal border). Earth Surface Process Landforms **44**(13)
4. López-Ruiz A, Garel E, Ferreira Ó (2020) The effects of high river discharges on the morphodynamics of the guadiana ebb-tidal delta. J Coastal Res 95(sp1):558–562
5. Garel E, Sousa C, Ferreira Ó (2015) Sand bypass and updrift beach evolution after jetty construction at an ebb-tidal delta. Estuarine Coast Shelf Sci **167**(A):4–13
6. Sutherland J, Peet A, Soulsby R (2004) Evaluating the performance of morphological models. Coast Eng 51:917–939
7. Bosbomm J, Reniers AJHM, Luijendijk A (2014) On the perception of morphodynamic model skill. Coast Eng 94:112–125