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Coastal flooding thresholds and morphological evolution of a Mediterranean spit-barrier

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Abstract:
Many river mouths presenting a seasonal variation of flow suffer of periodically (semi-) closure of their channels by the development of sand spits. Due to their low elevations, they are subject to different levels of coastal flooding during storm events. This is the case of the microtidal mouth of the Têt (Canet en Roussillon, Occitanie) which has a persistent sandy spit in its northern part. In order to study the impact of marine energy events on the morphology of this spit, high-frequency hydrodynamic measurements, video and topographic surveys by UAV were set up on a monthly basis and before and after each potentially morphogenic event. The analysis of twelve marine storms showed a linear relationship between the significant wave height and the mode of overtopping over the spit, ranging from a few localised overtopping to complete coastal flooding for several hours. Four morphogenic response thresholds were identified, allowing us to predict the behaviour of this sandy spit as a function of coastal flooding hazards. On the other hand, it seems that the pre-existing morphology of the spit, in particular the altitude of its crest, modulates the extent of the overtopping, although there does not seem to be any systematic control.

Keywords:
Coastal flooding, Coastal hydrodynamics, Storm, UAV, Video monitoring.

1. Introduction

In a context of climate change and sea level rise, the coastline and the people living there are at increased risk of flooding and damage from the wave overtopping, particularly during storm events. River mouths are especially vulnerable to coastal flooding because of their low elevations and densely populated cities (EDMONDS *et al.*, 2020). Many mouths, with low or variable fluvial discharge during the year, are subject to a seasonal (semi) closure of their channel due to the development of a sand or gravel spit. The spit develops itself when the wave-driven longshore sediment transport exceeds the ability of the river flow to remove sediment from the channel

(MCSWEENEY *et al.*, 2018; RANASINGHE & PATTIARATCHI, 2003). During marine storm events, spits are natural coastal defenses acting as protective barriers, but because of their low elevation, they are easily overtopped. Depending on the initial morphology and wave characteristics, various morphological responses can be observed: from the narrowing of the spit by swash processes to major evolution such as spit breaching. If all these processes were widely described, the definition of morphological/hydrodynamics threshold is a still challenging question when one wants to anticipate coastal flooding during storms. In this study, we aim to analyze the behavior of a Mediterranean sandy spit during several storm events to determine coastal flooding thresholds (hydrodynamic vs. inherited morphology) and better document morphological evolution during these events.

2. Regional settings

The Têt is a small mountainous river (about 100 km) that drains a catchment basin extending over 1 400 Km^2 and flows in the SW of the Gulf of Lions, along the Mediterranean coast (France) (figure 1).

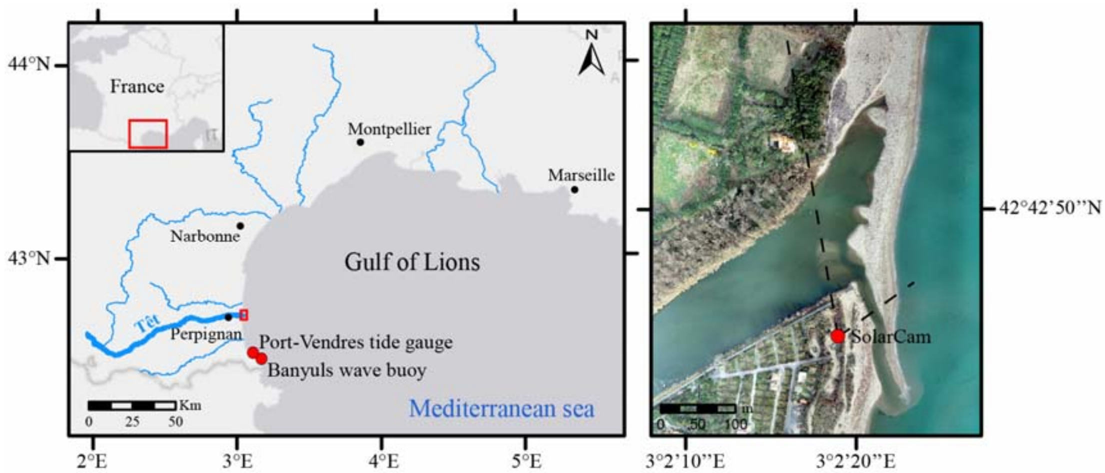

Figure 1. Location of the study site and positioning plan of the instruments.

The field site is a microtidal (< 0.30 m at mean spring tides) and wave-dominated environment (ALEMAN, 2013). Mean offshore significant wave heights (Hs) are generally low (Hs < 0.3 m for 75% of the time and Hs < 1.5 m for 94%), but can exceed more than 4 m during each winter storm (BALOUIN *et al.*, 2020), and more than 7 m during the most energetic events. With an average width of 150 m, the mouth of the river is often disturbed by the presence of one or two sand spits which can reduce its opening (about 20 m) and modify the alongshore location of its outlet over nearly 1 km, that can result in its partial closure (BALOUIN *et al.*, 2020). These spits are narrow (20 m), with a low elevation (1-2 m above mean sea level), inducing a vulnerability about flooding processes during marine storms. Their development is caused by the effect of prevailing SE waves (northward migration) or during onshore wind events (Tramontane) which generates short NE waves (southward migration) during low flow periods. This behavior matches with the definition of Intermittently Open/Closed Estuaries (IOCESs) (MCSWEENEY *et al.*, 2018).

3. Materials and methods

3.1 Hydrodynamic data

Offshore wave conditions were recorded at the south of the study area at the Banyuls buoy moored at a depth of 50 m by the CANDHIS network (CEREMA / DREAL Occitanie). An analysis of Hs between November 2020 and November 2021 identified a series of 11 storms (for Hs > 2 m). An extreme event in January 2020, Storm Gloria, was also included in this study. Set-up and run-up were calculated using the formula of STOCKDON *et al.*, (2006). The sea water level was recorded at the tide gauge of Port-Vendres by the REFMAR network (*https://data.shom.fr/*). Even if major floods play a decisive role in the spits breaching (MESLARD *et al.*, 2022), the period studied only presented 2 flood events (> 100 $m^3 s^{-1}$) whose limited water discharge did not allow the generation of breaches (BALOUIN *et al.*, 2020).

3.2 Morphologic data

Topographic monitoring of the mouth at a monthly frequency and before/after each potentially morphogenic event was carried out using a UAV Phantom 4 RTK®. Ground Control Points were measured using a centimetric DGPS-RTK, in order to improve the calibration of the Digital Surface Model generated by photogrammetry under Pix4Dmapper®. The altitude and position of the crest of the northern spit were then extracted and cross-shore transects were carried out. In addition, a video monitoring by the low-cost SolarCam® system (https://www.solarcam.fr/) allowed the continuous monitoring of flooding periods. The images were rectified (transposed into an orthonormal coordinate system) and georeferenced using ground control points previously measured with a DGPS Trimble® R6 using Matlab® tools developed for coastal monitoring (VALENTINI & BALOUIN, 2020).

4. Results and discussion

4.1. Selected storm events

The one-year survey allows to identify 11 storms with Hs during the apex up to 2 m. The storm Gloria (January 2020) is also included on the data base. The main hydrodynamic characteristics of each event are summarised in table 1. The topographic monitoring of storms 1 and 2 being too far from the events, only the visual observation of overtopping and the presence of breaches were considered.

Table 1. Main hydrodynamic characteristics during the apex of each selected storms.

Name	***Start – End Dates***	***Hs (m)***	***Tp (s)***	***Direction (°)***
Storm 1	*01/19/2020 08:00 - 01/23/2020 18:30*	*6.1*	*11.4*	*91.1*
Storm 2	*11/07/2020 12:00 - 11/07/2020 13:00*	*2.1*	*7.1*	*162*
Storm 3	*11/19/2020 23:30 - 11/20/2020 16:00*	*2.1*	*6.3*	*165*
Storm 4	*11/26/2020 10:00 - 11/26/2020 11:00*	*2*	*6.3*	*96*
Storm 5	*11/27/2020 16:30 - 11/29/2020 04:30*	*3.9*	*9.1*	*105*
Storm 6	*01/09/2021 12:00 – 01/10/2021 15:30*	*3.1*	*10*	*82*
Storm 7	*02/06/2021 01:30 – 02/06/2021 22:30*	*2.8*	*9.1*	*83*
Storm 8	*02/14/2021 09:30 – 02/14/2021 17:00*	*2.3*	*6.7*	*110*
Storm 9	*02/21/2021 13:00 – 02/23/2021 08:30*	*5.1*	*10*	*104*
Storm 10	*05/09/2021 17:00 – 05/10/2021 00:30*	*2.5*	*7.7*	*113*
Storm 11	*11/10/2021 18:00 – 11/11/2021 15:30*	*3.1*	*8.3*	*114*
Storm 12	*11/23/2021 18:00 – 11/24/2021 18:30*	*2.7*	*8.3*	*81*

4.2 Morphological impact of storm events

Figures 2 and 3 showed a similar morphological evolution of the North Spit to the different types of overtopping observed. During the less energetic storms (storm 3 and 4), the absence of overtopping did not lead to any morphological evolution of the crest (morphologic impact level 0). However, a gain of sediment on the top of the beach face by swash deposits can be observed. A localized elevation and slight offshore migration of the crest can be observed on the lowest areas of the spit (morphologic impact level 1, storm 2, 8 and 10). These mechanisms can also be observed at the scale of the entire spit when the overtopping was generalised (morphologic impact level 2, storms 6, 7 and 11). In this case, the rise of the crest as well as the weak offshore migration takes place along the entire length of the spit. During the overtopping process, the infiltration of the uprush reaching the crest diminishes the intensity of the backwash and the crest is therefore accreted. The higher energy levels lead to large overwash causing a strong landward migration of the crest, reaching 10 m (morphologic impact level 3, storms 5, 9 and 12). The altitude evolution of the crest was then very variable illustrating the complex sediment transport during these energetic events. For example, during the storm 5, the landward movement of the spit occurred with no vertical variations except in the southern part where the river channel is filled. Storm 9 showed accretion zones in the north and south areas whereas the center part is an erosion. Storm 12 showed an accretion in the north and erosion in the south. Finally, when the overflow results in the total coastal flooding of the spit (morphologic impact level 4, storm 1), an erosion of the beach face and the crest occurred, and an initiation of a breach take place.

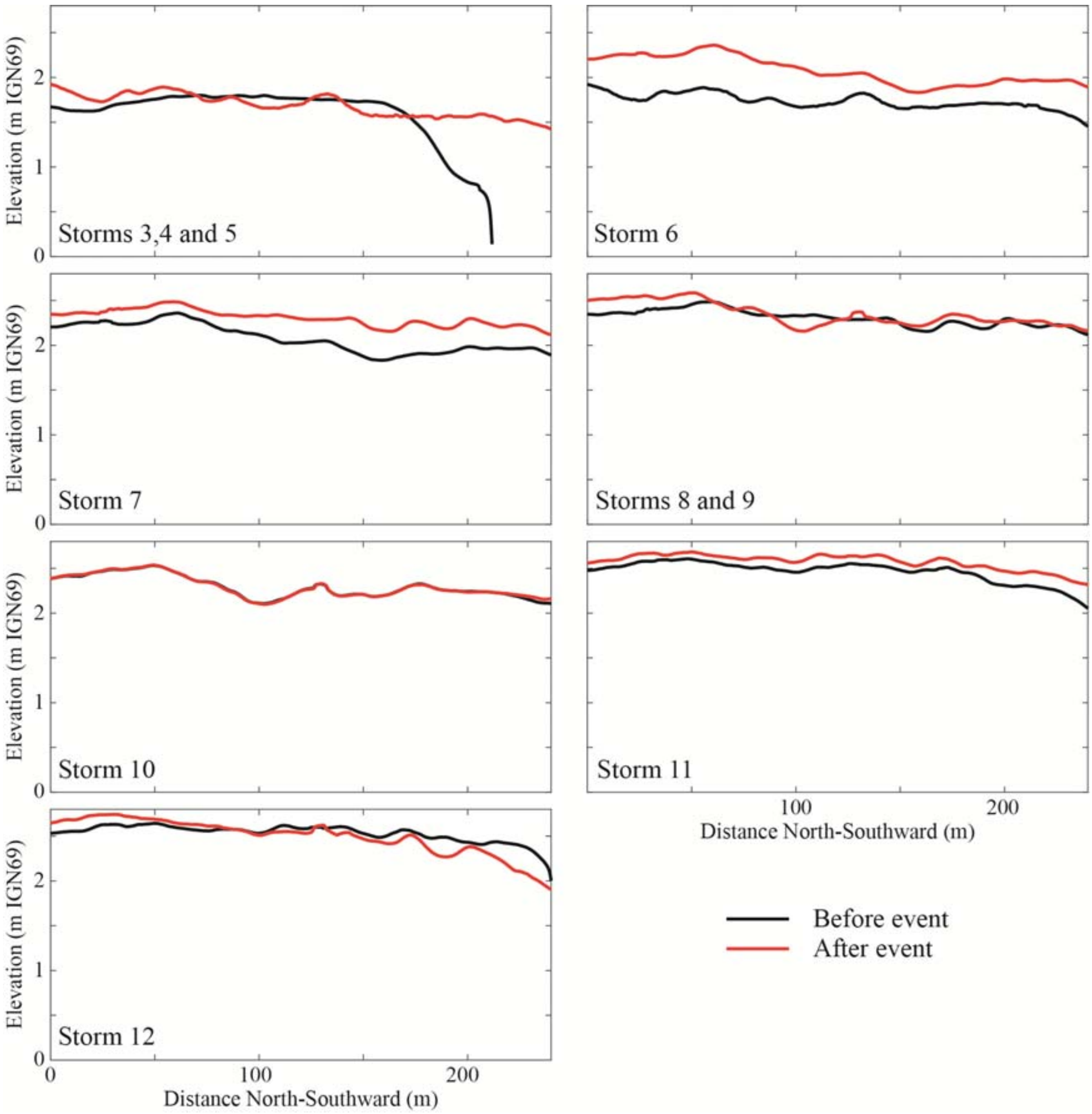

Figure 2. Evolution of the northern spit crest's altitude along a longshore (north-south) transect during each storm event.

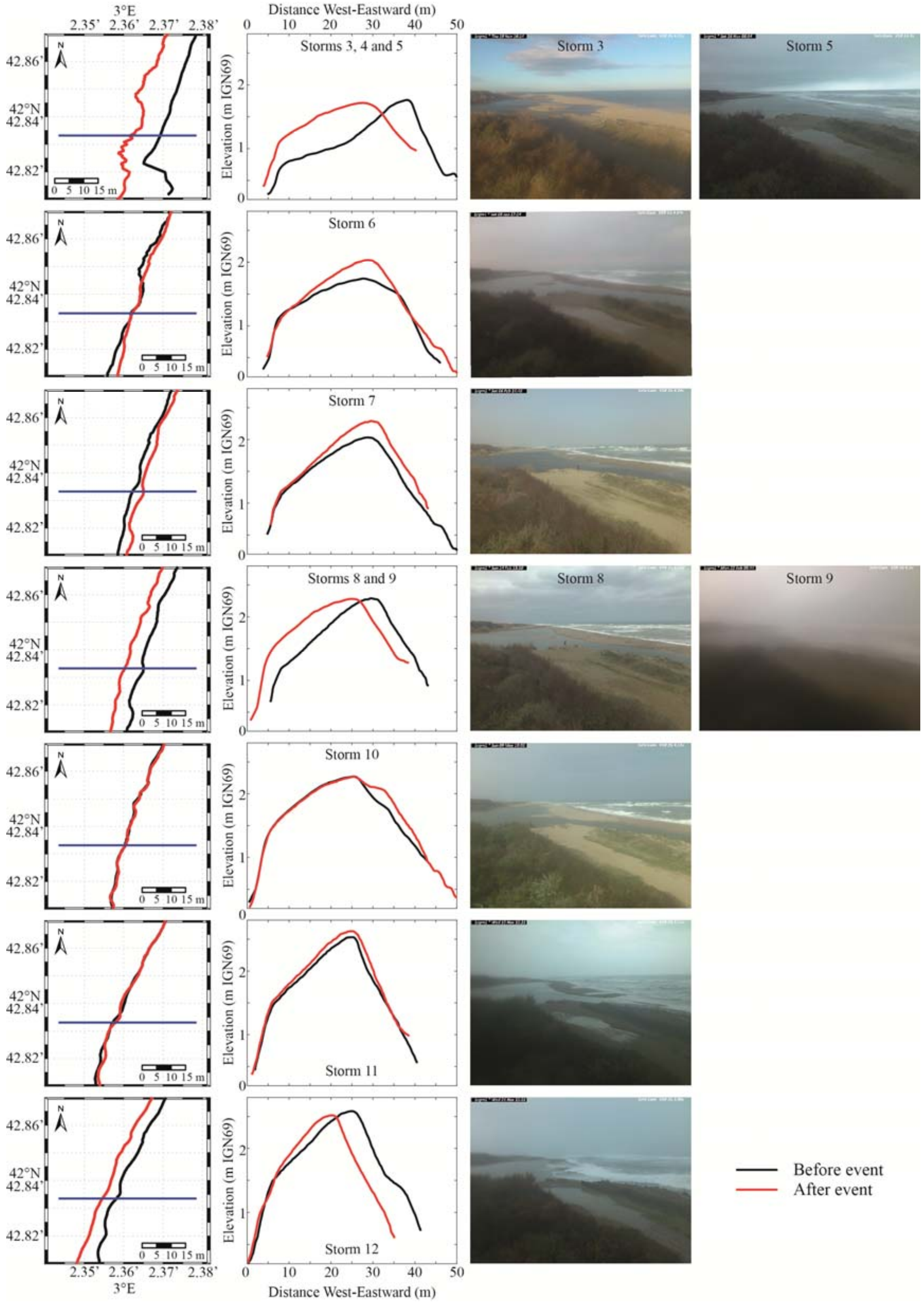

Figure 3. Evolution of the northern spit crest's position, cross-shore transect and photography of SolarCam® during storm events. Blue line represents the location of the cross-shore transect.

4.2 Coastal flooding thresholds

Various hydrodynamic and morphological parameters were compared with the previously defined morphologic impact levels. The analysis clearly demonstrated the relationship between the Hs or maximum elevation reached by the set-up and run-up, with the degree of impact (figure 4). Other indicators associated with Hs like period and wave power showed a fairly good relationship with the degree of impact. Sea level elevation and direction of waves do not provide any information except the fact that oblique waves are more dissipated by refraction and do not generate major impacts. The pre-storm maximum altitude of the overtopping area did not show any clear trends. For this last parameter, this may be due to the low amplitude of the crest elevation in the database (1.4 to 2.6 m). Thus, for a certain wave height, a greater altitude of the crest could be submerged, which the correlation does not reflect. These results indicate that offshore wave parameters are the more appropriate to explain spit overtopping and coastal flooding. Similar work on the Mediterranean coast at the Lido de Sète by GERVAIS *et al.*, (2012), also highlighted the importance of Hs in the resulting morphological impacts. Our results indicate the following Hs thresholds: for Hs < 2.5m there was no overtopping. Spit flooding remained localised or even moderate over the whole spit for Hs ranging from 2.5 to 3.5 m. It became important when the Hs reached 3.5 and became intensive for Hs > 6 m.

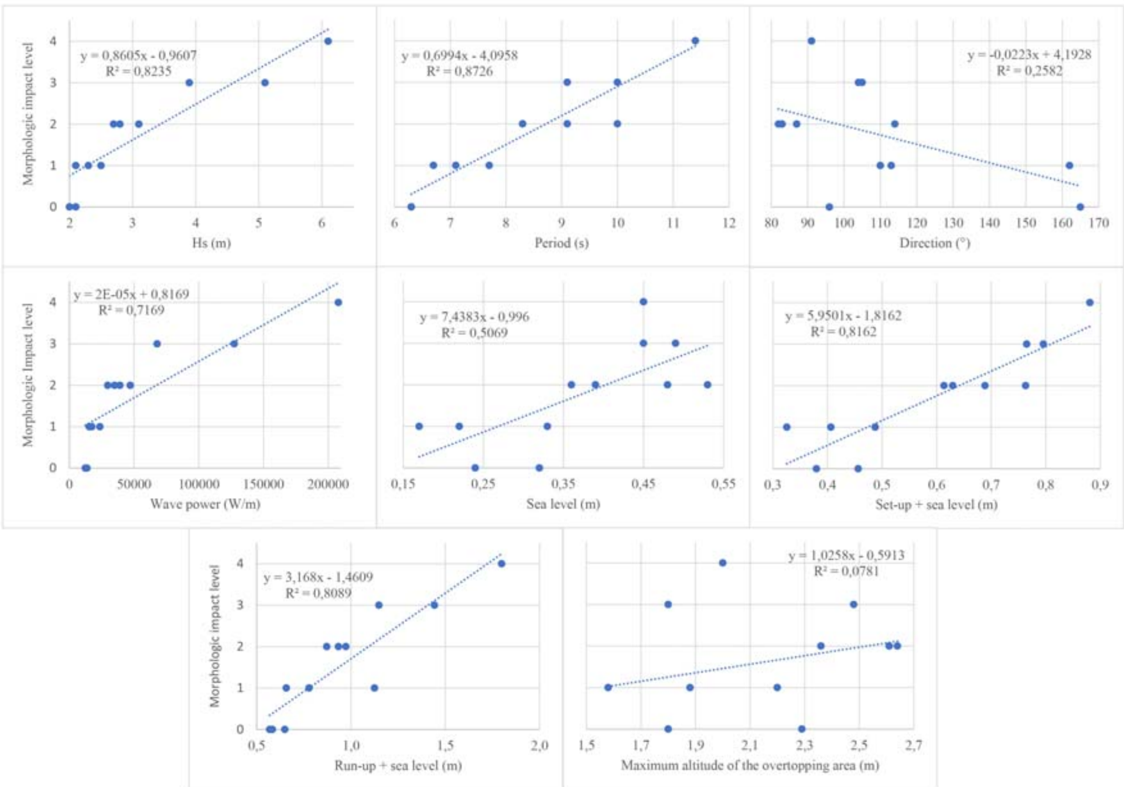

Figure 4. Relationship between the morphologic impact level and various storm intensity indicators and the maximum altitude of the overtopping area.

5. Conclusions

The analysis of twelve marine storms shows a linear relationship between the offshore Hs and the mode of overtopping of the spit, ranging from a few localized points overtopping to complete coastal flooding for several hours. Other indicators like period and wave power and show a fairly good relationship with the degree of overtopping and can therefore be considered to a lesser extent on the coastal flooding thresholds. In this study, we propose a storm impact scale defined by four levels of impact, ranging from the elevation and localised offshore migration of the crest to the destruction of the spit. Thus, morphological response thresholds can be identified with: a) no change for moderate wave conditions (Hs < 2.5 m), b) elevation gain and localised offshore migration, or generalized to the whole crest for stronger conditions (2.5 < Hs < 3 m), c) more important evolutions leading to a strong generalized landward migration for the most important storms (3.5 < Hs < 5.5 m) and d) breach generation for extreme storms (Hs > 6 m). Our storm impact scale applied on a sandy spit completed the gravel dominated barrier model of ORFORD & CARTER (1982) or of SUANEZ *et al.*, (2018), which is adapted for spit barriers where longshore drifting also controls morphodynamic processes. The pre-existing morphology of the spit, in particular the altitude of the crest, modulates the extent of the overtopping, although there seems to be no systematic control. Even if site-specific, these results provide a first storm impact scale allowing to anticipate coastal flooding processes. Further comparison with other Mediterranean sites will help to refine the storm impact indicators needed for coastal management purposes.

Acknowledgements

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