XVII[èmes] Journées Nationales Génie Côtier – Génie Civil
Chatou, 2022
DOI:10.5150/jngcgc.2022.098 *© Editions Paralia CFL*
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Role of storm-induced erosion on the vulnerability of the Occitanie coastal area to marine flooding phenomena

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Abstract:
Coastal flooding hazard at the Occitanie region is of crucial importance nowadays. Stormy events on sandy coastal environments, often weakened by chronic sediment deficits, can generate strong erosion, which could potentially accentuate the phenomena of flooding and the damage to facilities and infrastructures. This work deals with the evaluation of the vulnerability of these coastal systems at the regional scale and the use of a modelling approach on two pilot-sites in order to characterise the effects of storm erosion on marine inundation. Firstly, an analysis on the vulnerability of the coastal beach-dune systems in the Occitanie region has been conducted. Regional maps of the distribution of global and partial vulnerability show that, at a regional scale, 35% of the coastlines have a high global vulnerability. Secondly, a modelling approach using the Xbeach morphodynamic model (surfbeat mode) has been applied at two selected vulnerable sites: Canet-en-Roussillon and Frontignan-plage. After a calibration on existing historical storm events, the model is used to simulate a fictitious storm event with a 50-year return period (on wave heights) by assessing the effects of integrating the morphodynamics on the flooding phenomena. Results evidence the strong effect on coastal erosion during storms on the marine flooding phenomena (7 to 8 times higher for the Canet simulation), and the importance of taking erosion into account in coastal flooding anticipation and management.

Keywords:
Coastal engineering, Sediments transport, Coastal monitoring, Dune ecosystems.

1. Introduction

During storms, beaches, dunes and back-dune areas change under the action of intense meteo-oceanographic processes. These processes, waves, wind, rain, tide and atmospheric pressure act directly and/or indirectly, in combination or not, on the morphology of the coastal dunes by influencing the sediment transport.
SALLENGER (2000) proposes a Storm Impact Scale for barrier beaches. This scale has the advantage of considering both water level and dune morphology. It highlights the fact that the same storm will not have the same erosive impact and potentially the same level

of flooding depending on the type of pre-existing dune state. The detailed description of all the parameters controlling the impacts of storm waves on beaches and dune systems is beyond the scope of this study and the reader is referred to the studies by MASSELINK & VAN HETEREN (2014), DESMAZES *et al.* (2014), for more comprehensive and detailed overviews.

The first step of the study is to assess the vulnerability of coastal dune-beach systems along the Occitan coastline by adopting a multidisciplinary methodology. A simple and reproducible indicator is developed, which could support the management of the coastal zone. Different variables are exploited to better investigate their influence on the environment, based on an adaptation developed in the bibliography on the Spanish oceanic coast (DVI by GARCÍA-MORA *et al.,* 2001) and Italian Mediterranean area (MDVI by CICCARELLI *et al*., 2017).

Accurate assessment of the magnitude, location and extent of the effects of coastal physical mechanisms (including sediment transport) is becoming an essential element of risk management, and in this sense, the use of models describing physical processes to predict storm-induced morphodynamic changes under historical or projected scenarios is very important. The vulnerability indicator at regional scale is a quantitatively simple and straightforward strategy for defining the priority for more local numerical investigation.

So, in the second part of this study, a numerical approach is carried out on two pilot sites using the morphodynamic model XBeach (ROELVINK *et al*., 2009), in surfbeat mode, to model morphological evolutions and the resulting flooding. The XBeach model is a powerful tool in solving the physical processes dominating the behaviour of beach/dune systems during storm events.

2. Data and method

2.1 Vulnerability of dune-beach systems

A vulnerability assessment with a classification procedure is studied. Four groups of variables are investigated: geomorphological conditions of the dune-beach system (GCD), vegetation condition (VC), anthropogenic effect (AE) and marine influence (MI). The analyses are made at the spatial scale of the dune-beach systems pre-identified in the study from EID-MEDITERRANEE (2015), i.e. 81 sectors in total: 6 in the Gard, 39 in the Hérault, 16 in the Aude and 20 in the Pyrénées-Orientales regions. The boundaries between sectors identified correspond either to a geomorphological break (mouth, port, cape) or to a change of environment, i.e. the sudden passage from a natural environment to an artificial environment, or vice versa or from a degraded dune to a restored one. In our study, 17 variables, including both quantitative and qualitative parameters, were considered for a vulnerability classification procedure, 8 variables for GCD, 4 for VC and AE, respectively and 1 only summary variable for MI (see Table 1). Each selected variable was associated with a sliding scale ranging from 0 (no vulnerability) to 3 (very

high vulnerability), as illustrated in Table 1. The different variables have not been weighted to avoid subjectivity.
In the system of variables representing GCD, the min and max width of the beach-dune system at the elevation of +2.4m NGF (MIN-2.4MC, MAX-2.4MC), the min and max elevation of dune crest (CRETE-MIN, CRETE-MAX), the min and max width of the emerged beach (PLAGE-MIN, PLAGE-MAX), the number of breeches normalized on the sector length, N-BRECHES and the annual erosion rate (m/yr) over a 30-year period (EVO-TDC) are included. Among the variable's representative of VC, the ecological conservation status (CSERV-ECOL), the presence of embryo dune (D-EMBRY), fore dune (D-VIVE) and fixed dune (D-FIXEE) are used. The variables chosen to represent the vulnerability of the barrier beach resulting related to AE include the numbers of accesses to the beach on the littoral sector, either of an artificial (ACCES-PRIV) or semi-natural nature (ACCES-PUB), which have a structuring role on the dune and the number of structures at the beach and at sea (OCC-SOL-MAJ and OUV-STAT). In order to condense the information related to the marine influence on the overall vulnerability, maximum value of the runup associated to a 50-year return period storm is used (*Nmax-Run50)*. This calculation derived from study of BALOUIN & BELON (2012) using Lidar surveys Litto3D as topography and using the DSAS (Digital Shoreline Analysis System).

Tableau 1. Variables considered in the classification procedure of the vulnerability of dune-beach systems. Vulnerability classes for each variable range from 0 (no vulnerability) to 3 (very high vulnerability).

Variables		***Vulnérabilité classes***			
	1. GCD	***0***	***1***	***2***	***3***
1	*MIN-2.4MC*	*>26*	*<26*	*<14*	*<5.4*
2	*MAX-2.4MC*	*>128*	*<128*	*<47*	*<14.0*
3	*CRETE-MIN*	*>4*	*<4*	*>2*	*<1*
4	*CRETE-MAX*	*>6*	*<6*	*>4*	*<2*
5	*PLAGE-MIN*	*>74*	*<74*	*>31*	*<10*
6	*PLAGE-MAX*	*>256*	*<256*	*>92*	*<29*
7	*N-BRECHES*	*<2*	*>=1*	*>3*	*>6*
8	*EVO-TDC*	*>0*	*<0*	*<-0.5*	*<-1*
	2. VC	***0***	***1***	***2***	***3***
1	*CSERV-ECOL*	*Good*	*Medium*	*Weak*	*None/ Bad*
2	*D-EMBRY*	*Absence*	*-*		*Presence*
3	*D-VIVE*	*Absence*	*-*	*-*	*Presence*
4	*D-FIXEE*	*Absence*	*-*	*-*	*Presence*
	3. AE	***0***	***1***	***2***	***3***
1	*OUV-STAT*	*Absence*	*-*	*-*	*Presence*
2	*ACCES-PUB*	*<5*	*<12*	*<22*	*>22*
3	*ACCES-PRIV*	*<3*	*<7*	*<12*	*>18*
4	*OCC-SOL-MAJ*	*Natural areas*	*Infrastructure/ Activities*	*Light structures*	*Hard-wall structures*
	4. MI	***0***	***1***	***2***	***3***
1	*Nmax-Run50*	*<1*	*>1*	*>2.8*	*>=8*

Partial and total vulnerability indices were calculated for each sector. For each vulnerability group (GCD,MI,VC,AE), the sum of the ranked and normalized variables, thus divided by the sum of the maximum possible rankings within each group, resulted in a vulnerability index expressed as a percentage. The overall vulnerability index (VIG) has been calculated as an unweighted average of the four partial vulnerability indices.

2.2 Site and model calibration

Xbeach model is applied in surfbeat mode at the beach of Canet Nord by choosing a recent huge storm for calibrating some selected parameters. The site chosen is located at the north of Canet-en-Roussillon harbor jetty, up to the north of the river Têt (1 km norther), included. The coastline of the sector has north-south orientation and the nearshore has a system of rhythmic bars. The dominant longshore drift is towards the north. The river mouth is characterized by strong spatial and temporal morphological variability, controlled by both alluvial and marine dynamics (BALOUIN, 2019).
Figure 1 presents the time series of the significant height Hs, period Tp and peak direction during the storm Gloria (20-24th January 2020), recorded at the buoy of Banyuls. The flows at Tet river during the storm reached exceptional values, with peak values of hourly flow at around 1200 m^3/s.
The erosion impact of the storm is high, distributed over the entire beach with very straight beach scarps particularly at the south, near the port dike (dune foot retreat decreased of 2 m around). The back dune is not affected (no overwash observed) due to the relatively low water levels during this event.

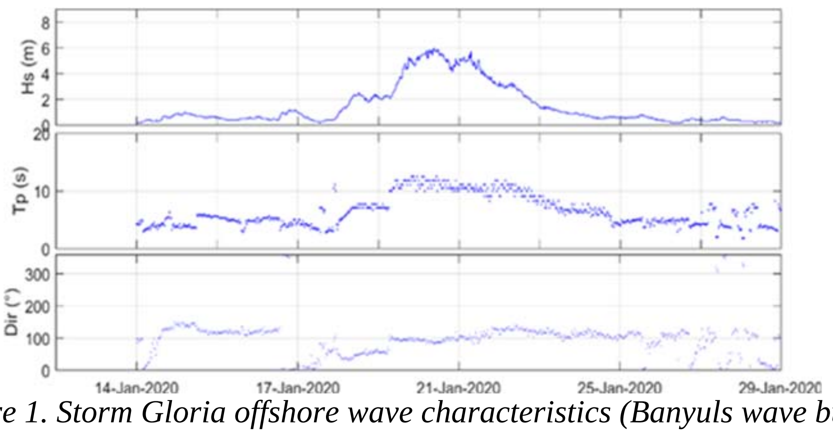

Figure 1. Storm Gloria offshore wave characteristics (Banyuls wave buoy).

The grid set up for XBeach model consists of a 347 x 524 rectilinear grid (2400 m x 1900 m extension) with variable spatial resolution. The average resolution in the cross-shore direction is 35 m at the offshore limit, decreasing to 2 m at the beach. The longshore resolution is 20 m on the lateral area down to 3 m on the inner part, in the main sector of the North Canet beach. A coupling strategy with a SWAN model grid has been implemented. The river outflow is also included in simulation. Model calibration has been performed by optimizing the Brier Skill Score (BSS), which quantifies the performance of the model by comparing the model results to the post-storm observations, at the emerged beach in the form of a DSM, by including the initial condition (SUTHERLAND, *et al.,* 2004). The calibrated model is applied, then, for simulating a 50-year return period storm, called S_{c0}, with a duration of 72 hours, a Hs at the peak of 6.9 m, better discussed in BALOUIN & BELON (2012). The same calibration strategy and projected scenarios have been applied at Frontignan-plage site (not reported here).

3. Results

3.1 Vulnerability index

With respect to the vulnerability analysis, a matrix of 17 variables for the 81 coastal sectors, covering the entire region, was subjected to an ascending hierarchical classification method (OGIER, 2020) to create homogeneous sector groups from the similarity matrix of sector variables. The analysis of the 81 sectors identified two major clusters and six secondary clusters. Beyond a strong disparity between the different clusters obtained in the analysis, it appears that the overall vulnerability index VIG, is high (value greater than 0.5) for a significant part of the regional coastline (35% of coastal sectors). Most important, the average value of the GCD index is 0.51, with low standard deviation, the best fitting of GCD partial indices is Weibull-distributed, with a left-skewed curve (skew=-0.29) and a scale parameter equals 0.55, indicating an important vulnerability derived from the geomorphological conditions. The two major clusters calculated highlight two different distribution of partial indexes. Very low vulnerability from vegetation condition and low human influence characterize the first cluster, while important anthropic effects and the absence or low presence of vegetation on the dune characterize the second. From the first cluster, the site of Canet is selected because of one of the highest values of GCD among the sites, the presence of vulnerable areas in the back dune (camping and port area), the availability of historical data (topo-bathymetry from Obscat observatory) and indirect data from “Reseau tempete” (http://www.littoral-occitanie.fr/). Frontignan is chosen from the second cluster, Litto3D data (2015) and indirect information’s from “Reseau tempete” are then used. Finally, it is important to emphasize that since 2015, some sectors evolved due to urban development or natural changes, which may have an impact on the partial indexes, presented herein. In this context, an update of these data at a frequency that remains to be determined is necessary to ensure the relevance of the vulnerability indices produced.

3.2 Numerical analysis

The Xbeach model was implemented in surfbeat mode and a sensitivity analysis performed on some parameters (i.e. morphological acceleration factor, *facua*, the critical wet slope, *wtslp*, *gamma, delta*, *sedcal* and *gwflow*) allows minimizing the BSS on the 2D setup. The systematic error (Bias) over the whole sector is of -0.35 m and the global mean square difference is 0.57 m. A much important erosion is modeled on the northern zone, at the mouth side (mean difference of -2.3 m compared to the observations), most probably resulting from the absence in XBeach of the fluvial contribution in sediments, which was important during the storm flood. The evaluation of the performance of the model for the choice of model parameters was performed on six profiles, in figure 2.

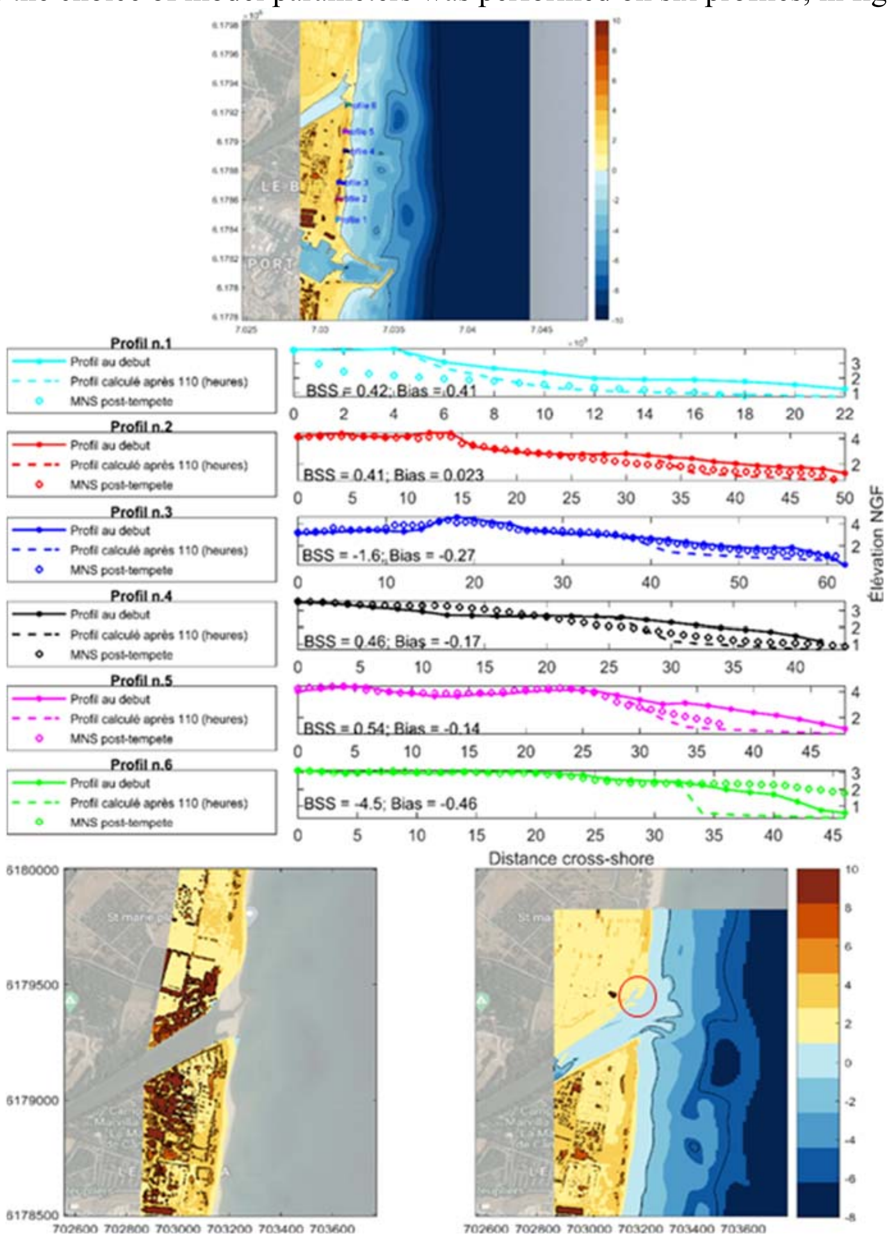

Figure 2. Top: Comparison between the beach profiles measured after the storm and simulated with XBeach at the end of the storm. BSS performance and Bias averaged over the profiles. Bottom: MNS mesuré post-tempête dans la zone de l'embouchure de la Têt (à gauche), résultat de l'évolution de l'embouchure calculé par XBeach à la fin de la simulation.

The central part of the sector is better modeled with biases between -0.3 and 0.4 m. BSS is around value of 0.45 except for profiles 3 and 6 (near the river mouth). A complete rupture of the sandy spit of the Têt mouth has been observed. This important modification is correlated with the extended flood episode. These evolutions are well simulated by the model, which correctly reproduces the final morphology of the environment, at least qualitatively, since unfortunately, no bathymetric data just after the storm for internal river is available. Despite a good general reproduction, we can mention a difference in the important erosion observed north of the mouth corresponding to a channel excavation phase, which is not completely reproduced by the model, where two small accumulation areas are observed (in red in figure 2). Part of the sediment accumulated at the mouth by Xbeach model, in reality have been eroded and flushed during the flood in larger quantities, and later accumulated in very moderate quantities along the southern shore under the effect of later swells.

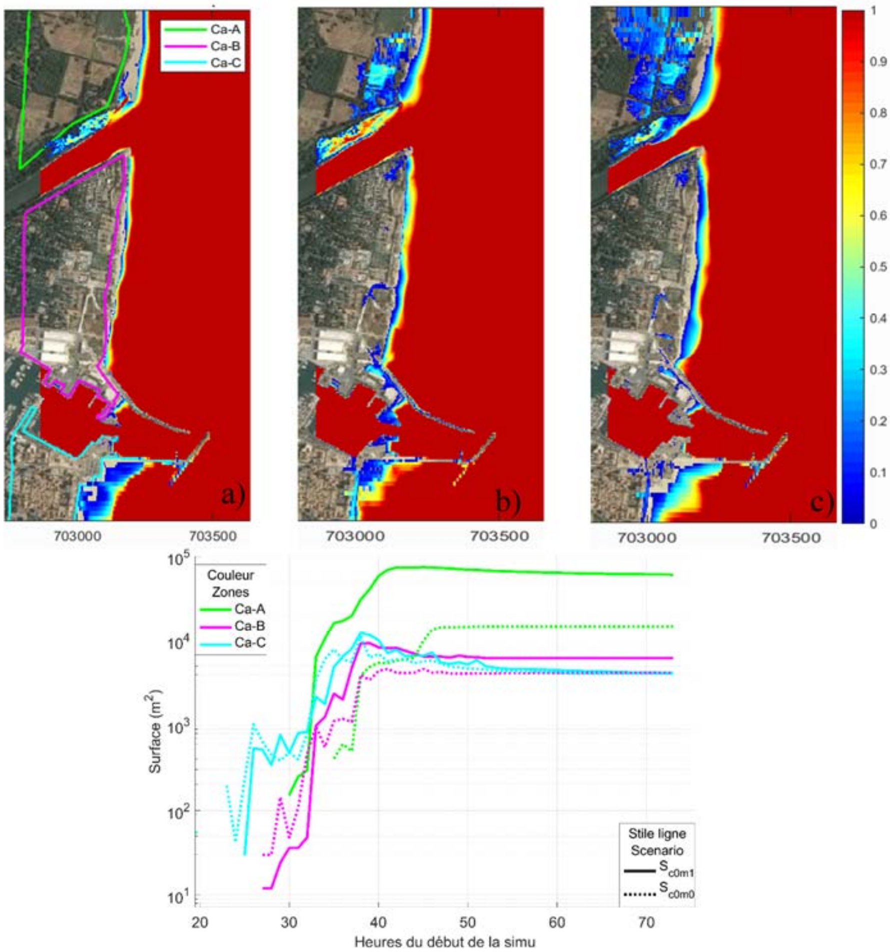

Figure 3. Flooding results for the Sc0_m1 scenario. a) 2h before the peak of the event, b) at the peak of the event, c) 10h after the peak. Bottom, the variation of flooding areas calculated by XBeach for the two scenarios Sc0_m1 and Sc0_m0, over time and for the three areas. The Y-axis is logarithmic.

The 50-year return period scenario has been modelled with Xbeach with the morphodynamic module activated S_{c0_m1} and not, S_{c0_m0}, in order to compare the differences. The morphodynamic evolutions simulated for the Sc0m1 scenario are shown in figure 4, on three smaller areas investigated, at three moments of the simulation. A very strong erosion of the emerged beach is already visible 2 hours before the peak of the event. Looking at the peak of the event at t0+36h, a transition between the collision and the overwash regime is reached on the three zones of the sector; an increase in the extent and height of erosion at the Sardinal beach is shown, up to -1.7 m of lowering in the southern side of the mouth and in the southern part of the beach, near the breakwater; the mouth, which is completely eroded, shows the accretion of the deposit on the north shore, which becomes important, in height up to 1.5 m above the initial level.

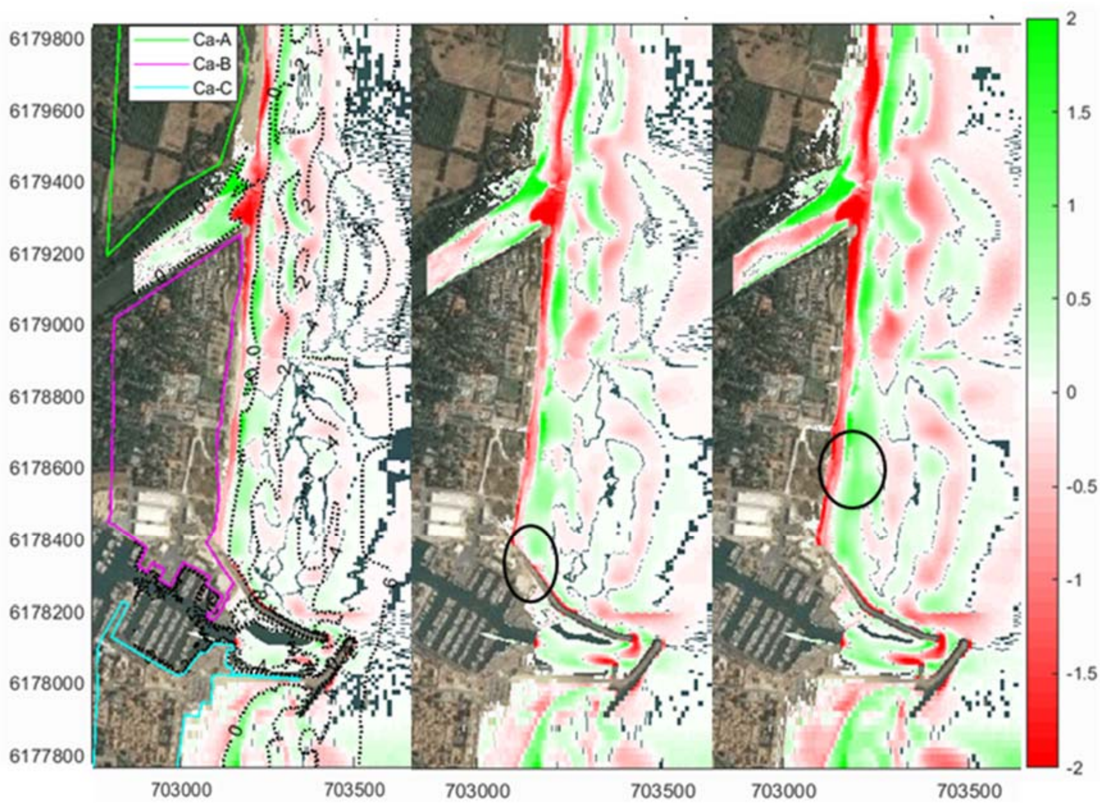

Figure 4. Simulation of cumulative erosion/accretion for the Sc0_m1 scenario. a) 2h before the peak of the event (t0+29h), c) at the central peak of the event (t0+36h), c) at the end of the event (t0+73h).

Sediment overwash at the back dune is observed in some points on the whole sector, mainly north of the mouth, at the Sardinal beach area as well, although to a lesser amount. The calculations of flooded surface are presented in the time series in figure 3. It can be observed, in the three investigated areas, that the effects of erosion (morphodynamic module activated, S_{c0_m1}) are very noticeable on the differences in flooding area calculated for the two scenarios. Flooded surface at storm peak in the northern area (Ca-A) is about 75,000 m^2 for S_{c0_m1}, but only 14,500 m^2 for S_{c0_m0}. The effects of a major sediment displacement at the river mouth can explain this difference. In the Ca-B zone, of the Sardinal beach, the calculated flooding at storm peak is 9,300 m^2 for S_{c0_m1}, while it is only 4,500 m^2 for S_{c0_m1}. Finally, the more south zone, Ca-C is characterized for a flooded surface of 12,500 m^2 with activated morphodynamic module, the value going down to 11,200 m^2 for the S_{c0_m0} scenario.

4. Conclusions

This study is a methodological work that focuses on using an objective strategy for assessing the vulnerability of the Occitan coastal-dune systems. The clustering results show that global vulnerability is high and strongly, rather homogeneously, affected by the geomorphological variables. The beach of Canet Nord is a sector in recurrent erosion, with a high vulnerability index, is here presented for evaluating the effects of storm-induced erosion on marine flooding during extreme events, by using Xbeach. The storm Gloria, which caused a significant beach erosion, and the river mouth opening observed as well, is used for model calibration. A scenario of a 50-year return period storm is presented to assess the influence of storm-induced erosion in flooding amplification. The results indicate that the extension of flooding area increases in the central beach of the Sardinal by 50%, and in the northern area of the mouth up to 6 times, as a result of the morphological evolution of the Têt river mouth, by the effect of waves.

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