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Testing storm impact modelling at São Pedro de Moel beach.

Universidade do Algarve

Faculdade de Ciências e Tecnologia

2020

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Testing storm impact modelling at São Pedro de Moel beach.

Master in Marine and Coastal Systems

Work performed under the supervision of:

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Declaração de autoria de trabalho

Declaro ser o(a) autor(a) deste trabalho, que é original e inédito. Autores e trabalhos consultados estão devidamente citados no texto e constam da listagem de referências incluída.

Declaration of authorship of work

I declare to be the author of this work, which is original and unpublished. Authors and works consulted are duly cited in the text and are included in the list of references.

30th of September 2020

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Nomenclature

BSS	Brier Skill Score
CEM	Coastal Engineering Manual
CFL	Courant–Friedrichs–Lewy
ECMWF	European Centre for Medium-Range Weather Forecasts
EMODnet	European Marine Observation and Data Network
JONSWAP	Joint North Sea Wave Project
LIDAR	Light Detection and Ranging
LNEC	Laboratório Nacional de Engenharia Civil, I.P.
MATLAB	MATrix LABoratory
MICORE	Morphological Impacts and Coastal Risks induced by Extreme storm events
RTP	Rádio e Televisão de Portugal
SWAN	Simulating WAves Nearshore
SWASH	Simulating WAves till SHore
UNESCO-IHE	United Nations Educational, Scientific and Cultural Organization - Institute for Water Education
USACE	United States Army Corps of Engineers
XBEACH	EXtreme Beach Erosion

List of symbols

A	Wave action
Area	Cross-sectional area of seawall and foreshore between the wave breaking location and the runup level for Mase et al. (2013)
Cg	Wave group velocity
D50	Median grain size
Df	Wave dissipation due to bottom friction
Dir	Mean wave direction
Dv	Wave dissipation due to vegetation
Dw	Wave dissipation due to wave breaking
E	Energy spectral density
hb	Wave height at the wave breaking point

Hs	Significant wave height
PkDir	Peak Wave Direction
q	Water discharge
R	Runup of regular waves
tanβ	Tangent of the imaginary slope
tanθ	Tangent of the sea bottom slope
Tm01	Mean absolute wave period
Tm02	Mean absolute zero-crossing period
Tp	Wave peak period
tsim	Time of the simulation
x, y	Geographic coordinates
zb	Bed level
zs	Water level
γf	Permeability coefficient of the structure
θ	Wave propagation direction
σ	Intrinsic wave frequency.
ω	Absolute radial frequency

Acknowledgements

This thesis was supported by the National Laboratory of Civil Engineering (LNEC). A thank you to Paula Freire for the data provided from the Mosaic.pt project.

The author acknowledges the following projects: Mosaic.pt, Ref. PTDC/CTA-AMB/28909/2017, To-SEAlert, Ref. PTDC/EAM-OCE/31207/2017 and EWCoast ALG-LISBOA-01-145-FEDER-028657.

A thanks to Juan Hervas from Ualg and Liliana Pinheiro from LNEC for all the help.

A very special thanks to Andreia Ferreira from LNEC for the orientation and being always available to answer any questions.

Dedication

Firstly, I would like to thank my supervisor Conceição Juana Fortes for being always so kind and available to help me with anything. I am also very thankful to her for the opportunity and believing in me to work on this project at LNEC. Unfortunately, it was just one and a half month at LNEC, but I loved working there.

To Professor Óscar, not only for all the patient "wasted" on the correction of this thesis but to be one of the most important reasons that I am writing this thesis. You opened my eyes to my passion, and I am forever thankful for that. You were always available and comprehensive of all the limitations that I had. I see you not only as a mentor but as a friend. Thank you and "Viva ao Sporting".

A very special thanks to Andreia Ferreira for being a third supervisor during all the work. Thank you very much.

Thanks to all my friends, colleagues, and people that I meet during the whole journey.

I want to thank Morais, Santos and Zé Tó. Without knowing you were my main support in very hard moments during this past 2/3 years. Thank you for what you do.

To Miguel and my second family, thank you for all the laughs and moments that made me forget the problems. I am grateful for having you all in my life.

And finally, I would like to dedicate this work especially to my warriors and source of strength, to my mom and dad (and of course my dog). You are the reason that I want to be better, to give you better. Thank you for everything.

Abstract

Numerical models are very powerful tools to predict the effects of the extreme conditions associated with coastal storms.

The main objective of this work was to simulate the effects of coastal storms in São Pedro de Moel beach, in terms of overtopping and morphological evolution associated, by using XBeach. To simulate the coastal storms using XBeach, it was necessary to have the data regarding the nearshore sea state. This was obtained by propagating offshore wave data conditions to nearshore using the SWAN model.

The XBeach model was divided into two setups to analyse two different situations, overtopping events (non-hydrostatic setup) and coastal evolution (surf beat setup). Sensibility tests were performed for both setups testing different model parameters. The model was also, calibrated and validated using information from past storms.

The non-hydrostatic setup demonstrated sensibility to the bathymetric resolution and for the intrinsic model parameters related to the bed friction and the non-hydrostatic correction. The results from the XBeach simulation of the overtopping event were compared against results from an empirical formula (Mase et al., 2013), which simulates the overtopping events associated with a seawall. The comparison of results showed lower values obtained with the empirical formula.

The surf beat setup demonstrated sensibility to the bathymetric resolution, and the intrinsic model parameters related to wave dissipation, sediment transport and morphology. The results from the calibration and past storm simulation of the coastal evolution setup point out to the necessity of having better field data before and after storms to improve the model settings and accuracy.

Keywords: XBeach, SWAN, overtopping, coastal storm, beach evolution, empirical formula.

Resumo

Os modelos numéricos constituem uma ferramenta muito útil para prever os efeitos associados à ocorrência de tempestades na zona costeira.

O objetivo principal deste trabalho foi simular os efeitos de tempestades costeiras na praia de São Pedro de Moel, em termos do galgamento e da evolução morfodinâmica, através do uso do modelo XBeach. Ao usar o modelo numérico XBeach para simular as tempestades costeiras, é necessário ter dados relativos às condições do mar na zona costeira. Esses dados foram obtidos através da propagação do clima de ondas ao largo para a zona costeira, utilizando o modelo numérico SWAN.

Neste trabalho, utilizaram-se duas configurações do modelo XBeach para simular duas situações diferentes: ocorrência de galgamento (configuração não hidrostática) e evolução do perfil de praia (configuração surf beat). As duas configurações foram submetidas a testes de sensibilidade para diferentes parâmetros e de seguida o modelo foi calibrado e validado, usando informação de tempestades já passadas.

A configuração não-hidrostática demonstrou maior sensibilidade associada à resolução batimétrica e aos parâmetros relacionados com a fricção de fundo e correção não-hidrostática. Os resultados obtidos através do XBeach relativos aos eventos de galgamento foram comparados com os resultados da fórmula empírica desenvolvida por Mase et al. (2013). Esta fórmula empírica simula os galgamentos numa praia com estrutura de proteção. A comparação de resultados demonstrou que os valores obtidos pela fórmula empírica eram inferiores aos obtidos pelo XBeach.

A configuração surf beat demonstrou maior sensibilidade associada à resolução batimétrica e aos parâmetros relacionados com dissipação de ondas, transporte de sedimentos e morfologia. Os resultados da calibração e da simulação de tempestade anterior desta configuração realçaram a necessidade de se obter dados com melhor qualidade pré e pós tempestade para melhorar a configuração e precisão do modelo.

Palavras-Chave: XBeach, SWAN, galgamento, formula empírica, evolução da praia, tempestade costeira.

Resumo Alargado

Este trabalho teve como objetivo a aplicação do modelo numérico XBeach (EXtreme Beach Erosion) para simular os efeitos de tempestades costeiras na praia de São Pedro de Moel.

A praia de São Pedro de Moel situa-se na costa oeste de Portugal e durante o inverno está exposta a tempestades durante aproximadamente 19.9 dias o que torna-a interessante para o estudo dos efeitos na zona costeira. A presença de uma proteção costeira nesta praia também torna a área interessante para o estudo de eventos de galgamento costeiro em estruturas.

Para simular o efeito das tempestades costeiras na praia de São Pedro de Moel através do XBeach foi necessário ter informação da agitação marítima próxima da costa. Para isso foi utilizado o modelo SWAN (Simulating WAves Nearshore). Neste trabalho, o modelo SWAN serviu para simular da propagação das condições da agitação marítima ao largo para a zona costeira de São Pedro de Moel. Os dados iniciais da agitação marítima ao largo foram obtidos através da base de dados do Centro Europeu de Previsões do Tempo a Médio Prazo (*European Centre for Medium Range Weather Forecast, ECMWF*) para um total de 20 anos (2000-2019). A simulação foi efetuada através do SWAN com o sistema de três malhas encaixadas sobre uma batimetria obtida no portal EMODnet (European Marine Observation and Data Network). Os resultados obtidos são relativos a um ponto na zona costeira de São Pedro de Moel (-9.045143º W 39.75535º N) com 10 metros de profundidade.

Após a obtenção dos resultados do modelo SWAN, foi necessário construir a batimetria inicial da zona de estudo para a aplicação do modelo XBeach. Essa batimetria resultou da combinação de três batimetrias diferentes (EMODnet, LIDAR 2011 e perfis de praia efetuados pelo LNEC no mês de fevereiro de 2019).

Neste trabalho, foram usadas duas configurações do modelo XBeach de modo a avaliar as consequências derivadas de tempestades costeiras em termos de: galgamentos na estrutura e da evolução costeira. Para os galgamentos, foi utilizada uma configuração não hidrostática com o processo não-hidrostático ativado, e para evolução do perfil de praia foi usado uma configuração surf beat com o processo de morfologia ativado. Para ambas as configurações, foram feitos primeiramente testes de sensibilidade para diferentes

parâmetros intrínsecos ao modelo, seguindo-se a calibração de cada configuração e finalmente, a simulação de tempestades passadas usando as calibrações efetuadas.

Nos testes da configuração não hidrostática, os resultados analisados foram o runup e o valor do caudal médio galgado associado ao galgamento na estrutura. Nos testes de sensibilidade deste tipo de configuração foram testados os seguintes parâmetros: resolução batimétrica, *nhlay*, *CFL*, *bedfriccoef* and *maxbrsteep*. A resolução batimétrica demonstrou influência tanto na extensão do runup como nos galgamentos. Os parâmetros *nhlay*, *bedfricooef* e *maxbrsteep* demonstraram influência nos resultados (runup e galgamentos). No caso do parâmetro *CFL* apenas demonstrou alguma influência no runup, mas essa influência não demonstrou uma correlação lógica com os valores utilizados para *CFL* e, por esse motivo, o seu valor nunca foi alterado durante o processo de calibração.

Para a analise da configuração surf beat a variável que foi observada foi o efeito no perfil de praia, ou seja, a comparação do perfil da praia inicial com o perfil da praia final. Neste tipo de configuração foi analisado um maior número de parâmetros quando comparado com o não hidrostático. Foram testados os seguintes parâmetros: *alpha*, resolução batimétrica, *bermslope*, *beta*, *CFL*, *delta*, *dryslp*, *dtheta_s*, *dzmax*, *facua*, *gamma*, *gammax*, *hswitch*, *lws*, *morfac*, *n*, *thetamax*, *thetamin*, *turb* e *wetslp*. Neste caso os parâmetros que demonstraram uma maior influência nos resultados foram *alpha*, resolução batimétrica *beta*, *delta, facua, gamma*, *morfac, n, lws* e *bermslope*. Os restantes parâmetros não demonstraram influência relevante na variação do perfil de praia.

Para calibrar e validar ambas as configurações, foi necessário selecionar as tempestades que iram servir para esses propósitos. As tempestades foram selecionadas de acordo com as informações disponíveis para a área de estudo. Para calibrar e validar a configuração não hidrostática as tempestades selecionadas foram Elsa (2019) e Hercules (2014), respetivamente. Para a calibração da configuração surf beat a tempestade selecionada foi uma tempestade que ocorreu em fevereiro de 2019. A tempestade Hercules (2014) foi utilizada para testar a configuração após a sua calibração.

A calibração da configuração não hidrostática foi feita através da comparação dos resultados do runup e do caudal com informação retirada de vídeos obtidos após os eventos de galgamento (reportagem jornalística) e proviniente da tabela fornecida pelo Coastal Engineering Manual. A calibração do modelo permitiu estabelecer um conjunto de parâmetros que conduziram a um runup a partir do topo da estrutura da ordem de, aproximadamente, 18 metros e a um valor de caudal no topo da estrutura entre os 10^{-3} e os 10^{-4} $m^3/s/m$, valores associados com a tempestade Elsa (2019). Os valores dos parâmetros alterados que demonstraram melhores resultados na calibração foram *bedfriccoef*=0.0195 *nhlay=0.33*, *maxbrsteep*=0.6 e uma resolução batimétrica de 0.5 metros. A calibração foi validada atrás da simulação da tempestade Hercules. Os valores da tempestade Hercules foram deduzidos através de informação recolhida de vídeos disponíveis na internet, notícias e da tabela fornecida pelo Coastal Engineering Manual (Runup=29 m a partir do topo da estrutura e caudal$\geq 10^{-3}$ $m^3/s/m$ no topo da estrutura).

Os resultados obtidos na configuração não hidrostática relativos ao caudal na estrutura foram também comparados com uma fórmula empírica (Mase et al., 2013). Esta fórmula empírica foi selecionada por ter sido desenvolvida para o cálculo do caudal associado ao galgamento em praias com proteção costeira como é o caso de São Pedro de Moel. Ao comparar os resultados foi possível observar que tanto o XBeach como a fórmula empírica demonstraram galgamento nas tempestades Elsa e Hercules, mas os valores do caudal foram diferentes para cada um dos métodos em ambas as tempestades. As fórmulas empíricas demonstraram valores inferiores aos do modelo XBeach.

No modelo morfodinâmico, a calibração foi efetuada através da comparação dos resultados do modelo com o perfil pós-tempestade efetuado pelo LNEC a 19 de fevereiro 2019. Após vários testes, os parâmetros que demonstraram melhores resultados na calibração, com um Brier Skill Score (BSS) de 0.8516, foram *alpha*=0.8, *beta*=0.8, *gamma*=0.8, *bermslope*=0.1*, facua*=0.15, *morfac*=5 e resolução batimétrica de 1 m. O perfil pós tempestade utilizado para calibrar esta configuração demonstrava recuperação da praia. Assim, a calibração foi efetuada para que os resultados do XBeach dessem recuperação. Ao simular a tempestade Hercules os resultados deram recuperação da praia, não correspondendo ao observado no local.

A configuração não hidrostática demonstrou capacidade de simular eventos de galgamentos em São Pedro de Moel com alguma precisão. No entanto, a utilização de dados de carácter não científico faz com que a calibração do modelo tenha de ser confirmada com resultados mais quantitativos. No caso da configuração surf beat havia dados científicos disponíveis, mas a qualidade dos mesmos, tendo em conta os objetivos, tornaram a configuração inviável. É, assim, necessário possuir dados disponíveis de qualidade para ambas as configurações, por forma a melhorar os resultados, no futuro.

1. Introduction

1.1.Motivation

Coastal storms are events that can produce intense coastal erosion and are considered one of the most energetic and violent hazards in nature (Harley, 2017). Coastal storms have possible outcomes on the coast (wave overtopping, flooding, and erosion) that can have harmful consequences to the local and regional economy, infrastructures, human wellbeing or, in the worst cases, even take human lives (Ciavola et al., 2014; Vousdoukas et al., 2011).

In the United States of America, storms are associated with the vast majority of monetary losses over the last half-century, with a value of 267 billion dollars between 1960 and 2014 (Harley, 2017). This issue is even more critical within a climatic change scenario, where the sea-level rise and storminess of some regions can lead to an increase of overtopping, flooding, and erosion events. According to Bertin et al. (2013), there was an increase in significant wave height in the North Atlantic Ocean during the past century. Bricheno and Wolf (2018), also observed an increase in annual wave height maximum (0.5-1m) in some areas. Those factors and the concentration in population in the coastal zones (being 13% of the world's urban areas located in low elevation coastal zones (McGranahan et al., 2007)), has led not only to an increase of interest but also a need for understanding and predict the effects of storms in coastal zones (Plomaritis et al., 2018).

The Portuguese coast is directly exposed to the action of the Atlantic Ocean waves. High-energy storms are quite frequent, endangering populations/ports/critical infrastructure and causing local severe economic and environmental consequences. Moreover, a large part of the Portuguese population, economic activities and construction are concentrated and constantly growing along the coast, increasing shorelines pressures and human vulnerability to coastal hazards.

Portugal has a significant historical record of such serious incidents caused by extreme wave conditions, wave overtopping and flooding. The Portuguese west coast (according to data from Figueira da Foz buoy) is exposed to storm conditions for 19,9 days per winter (Costa et al., 2001). Almost every year, mainly during the winter season, several emergency situations involving overtopping, flooding and erosion events occurred in different sites of the Portuguese coast, for instance, Faro 2009, Esmoriz 2011, Ericeira

2014, Paços de Arcos 2018, Foz do Douro 2018, Ericeira 2019, São Pedro de Moel 2019 (examples collected from newspapers and internet sites), with severe economic and environmental consequences. One of the most significant storms occurred in 2014 (the so-called Hercules storm (Santos et al., 2014)) and led to extensive coastal damage along the western European coast, Portugal included.

Situated on the west coast of Portugal, São Pedro de Moel is one area that has been exposed to different storms causing seawall overtopping, flooding, and erosive events. Hercules (2014)(Santos et al., 2014) and Elsa (2019), for example, were two storms with known impacts in that area.

A way to predict and understand the impacts of a storm in beaches and associated areas is by using empirical formulas or numerical modelling (Vousdoukas et al., 2011).

When concerning the empirical formulas, Mase et al. (2013) developed an empirical formulation that calculates the mean overtopping discharge based on runup at seawalls constructed on the land. The formula uses wave height, period and direction. It also uses, as input information, an imaginary beach slope and a uniform bottom slope. This formula represents simple processes, and it is of fast use, but the lack of detail related to the beach bathymetry can have an influence on the results (Heleno, 2017).

In terms of numerical modelling, XBeach (Roelvink et al., 2009) is a hydrodynamic and morphodynamic model that evaluates the wave runup, overwash and beach morphodynamics in a coastal area during storm conditions. However, the use of this model is restricted to small areas due to the significant computational effort. Moreover, the model results dependent on some intrinsic parameters which have to be calibrated for each coastal area. The application of XBeach to different coastal areas considering different storm incident conditions permits an assessment of the coastal hazard and also contributes to getting a better knowledge of the model itself, its limitations and advantages and especially on its intrinsic parameters.

1.2.Objectives

The main objective of this work was to evaluate the impact of storms on the runup and overtopping at São Pedro de Moel beach, as well as to access the morphodynamic evolution of the beach during storm events. For this, an empirical formula and two different setups of the numerical model (XBeach) were used. Three storms were considered for this work: Hercules (2014), Elsa (2019) and an unnamed storm that occurred in February of 2019 (herein called February storm).

This work was divided into sub-objectives: perform sensibility tests for different model parameters according to the type of setup, calibrate the two types of XBeach setups, simulate past storms using those calibrations and compare the overtopping results with the empirical formula of Mase et al. (2013).

The knowledge obtained from the results from both the XBeach model and the empirical formula (erosion, runup, overtopping and flooding) can be used in the future when preparing the area with safety measures to lower the impact of coastal hazards.

1.3. Thesis framework and outline

The work performed within this thesis is divided into four major parts. The first part of the work was the download and treatment of the offshore wave conditions and bathymetric data of São Pedro de Moel beach. The second part was the propagation of the offshore wave conditions to nearshore using the SWAN model (Booij et al., 1997). The third part was the simulation of the conditions on the beach using XBeach model and the empirical formula from Mase et al. (2013). The final part was the analyses and interpretation of the results (Figure 1.1).

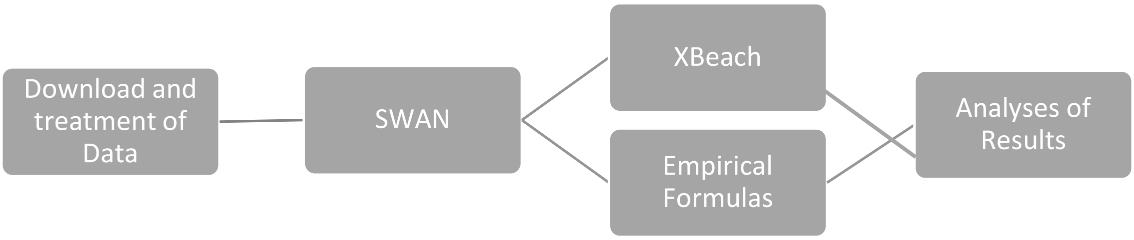


Figure 1.1 – Thesis workflow.

After this introduction (Chapter 1), in Chapter 2 we can find a literature review on coastal storms, the models used in this work (XBeach and SWAN) and a review of the empirical formulas developed by Mase et al. (2013). Chapter 3 describes the study area (São Pedro de Moel). Chapter 4 presents the methodology of this work. The results of the models and empirical formulas can be found in Chapter 5.

2. Literature review

2.1.Basic concepts

For a better understating of the work, in this chapter, the terms and concepts used are described. The sea wave conditions are usually characterised in 3 parameters: Significant wave height (Hs), peak period (Tp) and mean wave direction (Dir). These characteristics have two main ways of being obtained, from *in situ* measurements or from numerical modelling. The *in situ* measurements are usually done at buoys, which then transmits the data. The *in situ* data is more precise than the numerical modelling data but have some disadvantages. For instance, the cost of an *in situ* measurement is higher than a model. Another disadvantage, when compared to the numerical modelling, is the missing information from *in situ* measurements that can occur due to system fails (bad communication or maintenance of the system). The numerical modelling is less precise but provides all information without gaps (Heleno, 2017; Pires, 2017).

When the waves reach the beach, they can have different effects/regimes. Those together with wind, currents and tides will influence the morphology of the beach profile. There are many definitions/configurations of beach profiles, but for this work, four zones were highlighted (Figure 2.1): Backshore, foreshore, nearshore and offshore (USACE, 2002).

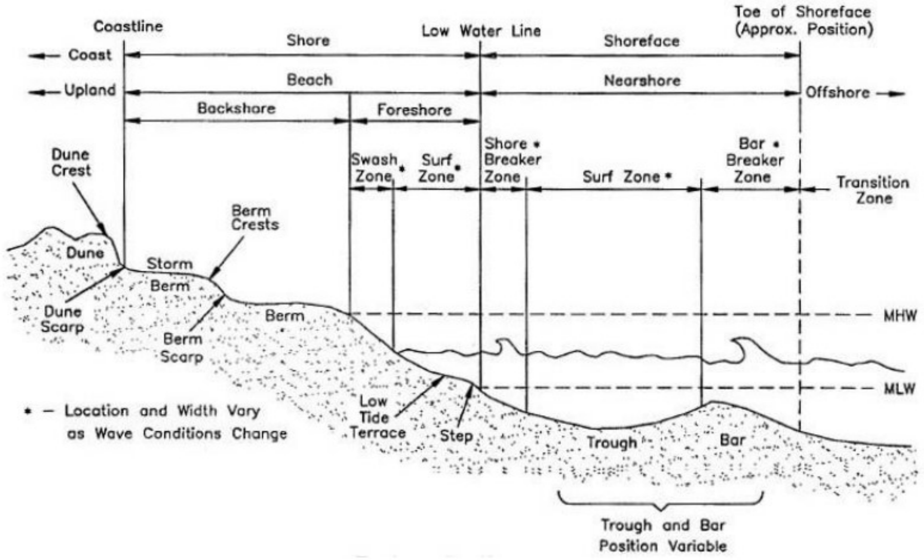


Figure 2.1 - A typical beach profile with the four main hydro/morphodynamic zones (USACE, 2002).

Backshore is the highest zone of the beach; it is only exposed to wave in extreme conditions. Dunes, cliffs, or structures usually constitute the upper limit of this area.

Foreshore, also known as beach face, is the area between the mean high water and the mean low water.

Nearshore is situated between the mean low water and the wave breaker zone.

Offshore is not easy to define, but in this case, it is considered to be the zone off the breaker zone.

Some terms need to be defined for correct use along with the thesis. Those can be found in Table 2.1, which includes additional terms useful when reading this work.

Table 2.1 - Terms used in this work based on Coastal Wiki and EurOtop (van der Meer et al., 2018).

Terms	Description
Runup	The upper level reached by a wave on a beach, or coastal structure
Seawall	A structure separating land and water areas. It is designed to prevent coastal erosion and other damage due to wave action and storm surge, such as flooding.
Overtopping	Wave runup levels reach and pass over the crest of the structure
Mean overtopping discharge	The average discharge per linear meter of width

2.2.Coastal storms definition and storm impact regimes

Coastal storms are considered a set of meteorological conditions that have the potential to damage the coastal zone and surrounding hinterland (Ciavola et al., 2014). Although the storms have positive impacts in the ecosystem, they are usually characterised by the destruction they cause (Harley, 2017). Coastal storms can cause an impact in infrastructures, buildings and even take human lives, ranked as the second deadliest natural disaster (Ciavola et al., 2014; Harley, 2017; Poelhekke et al., 2016; Santos et al., 2014). These events and the associated destruction affects mostly sandy coasts, promoting not only flooding but also coastal erosion (Poelhekke et al., 2016).

Coastal storms are not simple to define quantitatively because each system can have different behaviour for the same forcing conditions. Also, the timing of the storms and the ability for the sandy beach to recover can cause difficulties to define different storms quantitatively. Another reason why the storms are difficult to define is related to the generation of storms conditions (Ciavola et al., 2014). One of the most common techniques for defining individual storm events from wave data is the peak-over-threshold (P.O.T.) method (Ciavola et al., 2014). This method is based on a certain threshold of wave height (defined locally). For the west coast of Portugal, the study area of this work, the storm threshold is 4.5 meters of significant wave height, Hs (Costa et al., 2001). However, the threshold for wave height cannot define a storm by itself, and it is necessary to have other criteria coupled with the previous one to have a good and reliable definition of a coastal storm. The storm duration criterion is used to avoid short pikes of wave height to be considered a storm event. Another criterion to define a storm is the meteorological independence criteria. This criterion is to avoid the same event being considered as two separated events. This criterion varies from place to place (the period between storms can vary from a range of 6 hours to two weeks) (Ciavola et al., 2014) (Figure 2.2).

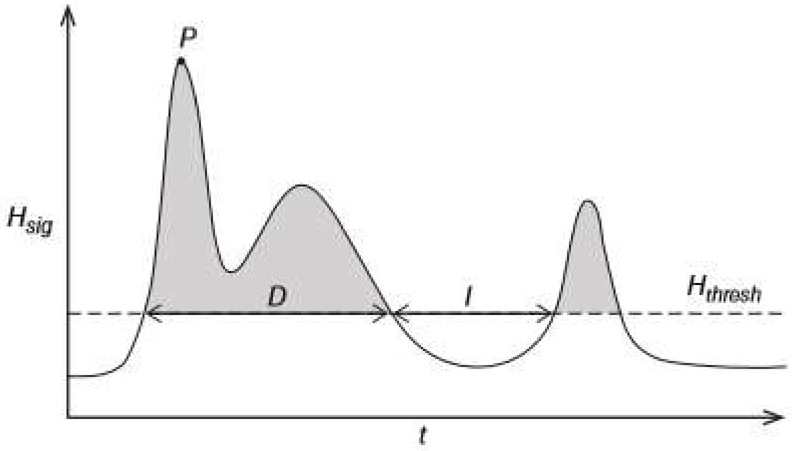


Figure 2.2 - Peak-Over-Threshold method for defining individual storms. P- Peak of significant wave height; D- Storm duration; I- Meteorological independence criterion between to storms (Figure from Harley, 2017).

Different storms have different impacts on the coast. Sallenger (2000) defined four regimes, which define the impact scale of a storm: swash, collision, overwash, inundation (Figure 2.3). Swash regime occurs when the maximum runup does not reach the base of the dune. Collision regime is when the maximum runup is in contact with the dune (maximum runup is between dune base and dune crest). Overwash regime is when the maximum runup exceeds the dune crest. Inundation regime is when the lower runup (sea level during a storm) exceeds the dune crest, and thus promotes dune submersion. An example of the regime’s definition was applied in Harter and Figlus (2017) where a hurricane was modelled using XBeach (Roelvink et al., 2009) and SWAN(Booij et al., 1997). The authors were able to identify the different types of the regime and at what time they occur (Table 2.2).

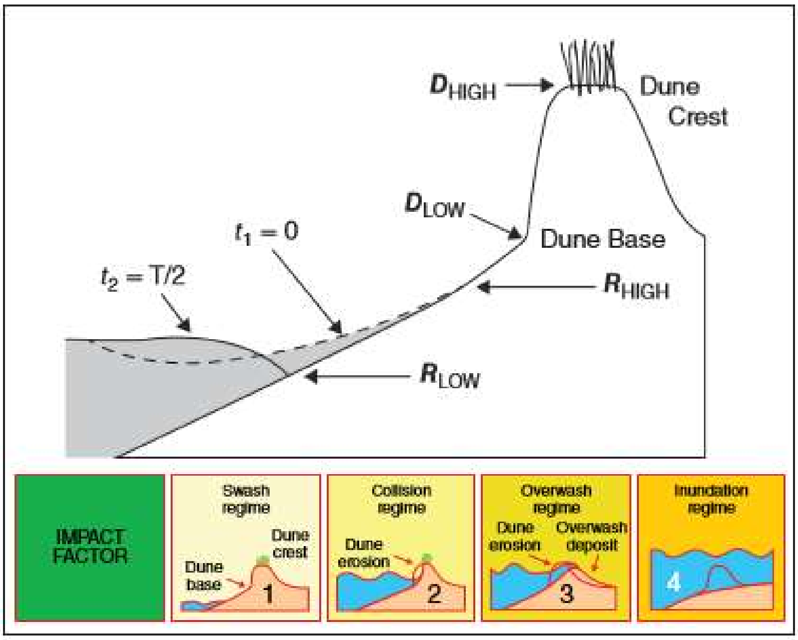


Figure 2.3 - Impact regimes of storms, according to Sallenger (2000). (Figure from Ciavola et al., 2014).

Table 2.2 - Simulated impact regimes from the hurricane Ike using XBEACH and when they possibly occurred during the modelled storm (adapted from Harter and Figlus, 2017).

	Time (hours)	Hydrodynamic Characteristics	Morphological Response	Schematic
Collision	0-32	Wave runup attacks the dune face.	Sediments from the dune toe and dune face are pulled offshore.	
Overwash	32-52	Wave runup level exceeds the dune crest.	Sediments from the dune crest are washed over to the back-barrier	
Inundation	52-62	Surge level exceeds the dune crest.	Significant washover of dune sediments to the back-barrier.	

2.3.Models and Tools

2.3.1. SWAN

One of the models used in this work was the third-generation spectral wave model SWAN (Simulating WAves Nearshore)(Booij et al., 1997) and it was used for the transformation of offshore wave conditions to nearshore conditions.

The Delft University of Technology developed SWAN based on the WAM model, and it was developed to improve the accuracy of the spectral wave model in the nearshore zone. SWAN is fully spectral in frequencies and directions. It computes short-crested wind-generated waves. SWAN is an open-source phase averaging model, and it uses the Eurelian approach and has the processes of wave generation, spatial propagation, shoaling and dissipation well represented and the action balance equation models it.

There are different processes represented in SWAN according to the SWAN Scientific and Technical documentation (The SWAN team, 2019).

- Propagation through geographic space.
- Refraction due to spatial variation in bottom current.
- Diffraction.
- Shoaling due to spatial variations in bottom and current.
- Blocking and reflections by opposing currents.
- Transmission through, blockage by or reflection against obstacles.

The waves generation and dissipation processes included in SWAN are:

- Generation by the wind.
- Dissipation by white capping.
- Dissipation by depth-induced wave breaking.
- Dissipation by bottom friction.
- Wave-wave interaction in both deep and shallow water.

The model requires inputs to simulate the propagation of waves from offshore to nearshore. Those inputs are bathymetric information, initial wave conditions, boundary conditions and, if necessary, the atmospheric forcing conditions (wind and pressure), ocean forcing (tide and currents) and a command file. SWAN uses a system of mesh nesting scheme that allows the system to have a higher precision in the area of interest.

This mesh-nesting scheme is the usage of the smaller nesh grids inside of a larger grid, the results from the larger grid are transferred to the border of the smaller grid resulting in higher precision in the smaller grid due to higher resolution. This system is used to reduce the computation time if a large grid has high detailed information that results in considerable computation time, by using a smaller resolution in the large grid and a higher resolution in a smaller grid the computational time is reduced.

SWAN can be run either in serial mode or in parallel mode. One example of the usage of SWAN in parallel mode was done by Fanti (2019) with the usage of Medusa cluster infrastructure, at LNEC. Using the parallel mode reduce the simulation time.

This model has been used in different studies with different purposes, as for wave propagation like in Heleno (2017); Pires (2017) and Vousdoukas et al. (2012) or used to assess the impact of wave energy converters (Fanti, 2019; Ozkan et al., 2020).

As mentioned before SWAN needs input files in order to simulate the conditions. According to the SWAN manual, the inputs files needed are:

- Command file
- File(s) with information about grid, bottom, current, friction and wind (if relevant)
- File(s) with the wavefield in the model boundaries

Before the start of the simulation, the user also needs to select some information related to the output.

- Output geographic location (individual output location or specified lines)
- Times of the outputs in nonstationary runs
- Type of outputs (wave parameters, currents, and others)

SWAN manual present all information about SWAN model and its application, namely input and output files.

2.3.2. XBeach

2.3.2.1. XBeach description

If an inundation event occurs in an area with no previous measures of protection (even a “simple” warning to the population) could have severe consequences. A way to understand and predict what kind of hazards and risk can occur during a coastal storm is through morphodynamic process-based models like XBeach (Roelvink et al., 2009). XBeach is an open-source numerical model that was developed with significant financial support from the *United States Army Corps of Engineers*, *Rijkswaterstaat* and the European Union. The project was also supported by *UNESCO-IHE*, *Deltares*, *Delft University of Technology* and the *University of Miami*. XBeach is a potent numerical tool initially developed to simulate the coastal response of sandy beach systems. The model includes all relevant hydrodynamic and morphodynamic processes for nearshore zones and storms with different durations(Ciavola et al., 2014; Harter and Figlus, 2017; Roelvink et al., 2009). Being a 2D process-based prediction tool, XBeach can model complex systems with artificial inlets, sea walls, or variable dune height along the coast (Ciavola et al., 2014) and that turns XBeach to a unique and special model. Nowadays, XBeach continues to be tested and developed to simulate different times of coast.

As mentioned before XBeach includes all hydrodynamic and morphodynamic processes. From the hydrodynamic processes, the model includes short wave transformation, longwave transformation, bottom configuration due to waves and currents action, overwash and inundation regimes. The morphodynamic processes include transport of sediments by drag or suspension, avalanching and changes in the bottom and erosion of the dunes. The effects of structures and vegetation can also be simulated.

XBeach has two working modes: hydrostatic (or surf beat) and non-hydrostatic. The hydrostatic mode is a lower computational cost mode since the short-wave action is not simulated. The opposite occurs in the non-hydrostatic model, first developed in the model SWASH (Zijlema et al., 2011), which has a high computational cost because it resolves all the processes. XBeach aims to model processes in the different regimes described by (Sallenger, 2000) and previously mentioned.

XBeach has many different processes which are correlated to specific parameters that can be adjusted to reach the final objective. The physical processes that are presented in XBeach can be active or inactive by default.

The physical processes that are active by default are:

- Short wave processes balance (*swave)*

Swave is the keyword that allows the model to activate short wave action balance through the wave action balance equation (the same base has the SWAN equation).

$$\frac{\partial A}{\partial t}+\frac{\partial c_{gx}A}{\partial x}+\frac{\partial C_{gy}A}{\partial y}+\frac{\partial C_{\theta}A}{\partial \theta}=\frac{D_w+D_f+D_v}{\sigma} \qquad (1)$$

In the equation, the variable A represents wave action, θ represents the angle of incidence concerning the x-axis, σ is the intrinsic wave frequency, c_θ is the propagation speed in directional space, and c_g represents the group velocity. In the second term of the equation, it is represented the short-wave dissipation processes (D): wave breaking(w), bottom friction(f) and vegetation(v).

- Avalanching (*Avalanching*)

Avalanching is the keyword for the slumping of sandy material from the dune to the foreshore during storm-induced dune erosion. This process is included and connected with bottom updating processes. The two most important variables of these physical processes are the critical slopes for the dry and wet area (*dryslp* and *wetslp*). Since the wet area is more prone to slumping than the dry area, it is necessary to separate the two types of material. When the critical slope is exceeded, the material is transported to the adjacent cells occurring the process of avalanching until the slopes do not exceed the values anymore.

- Flow calculation(*flow*)

Flow is the physical processes that implement all the equations that resolve the movement of water in shallow waters.

- Short wave forcing on nonlinear shallow water equations and boundary continuous (*lwave*)

Lwave is the keyword that turns on or off the calculation of longwave through short wave forcing on nonlinear shallow waters equation stated on *Generalised Lagrangian Mean* formulation(Andrews and Mcintyre, 1978). The equations are resolved at a temporal scale of the wave group simulating the movement of infragravity waves.

- Morphology(*morphology)*

They keyword *morphology* includes all morphology related processes with changes in morphology like avalanching. The model permits the user to turn on or off this option as the user wants. In this test, numerous parameters can be changed, like the velocity of the morphological process when compared with the hydrodynamic. It is also possible to define the presence of a non-erodible layer simulating the presence of a structure, for example.

- Sediment transport (*sedtrans)*

The *sedtrans*, as the name suggests, controls the activation of the sediment transport in the model. The process contains a different number of equations that influence sediment transport.

The inactive processes are:

- Groundwater flow (*gwflow*+)

This process utilises the principle of Darcy flow for laminar flow conditions and a parameterisation of the Forchheimer equations for turbulent groundwater flow in order to simulate the interaction between groundwater and surface water.

- Non-hydrostatic (*nonh*+)

With this type of module activated, the model accounts all the wave motions within the shallow water equation. For this to happen, the *swave* needs to be turned off (*swave* = 0).

- Time series of bathymetry input (*setbathy*)

With this module, it is possible to impose the alterations of bathymetry along time by implementing a time series from an external file.

- Shipe waves (*ship*+)

The model is also capable of computing non-hydrostatic waves from ships. Here a moving ship is represented as a pressure head that moves along a pre-defined track. The waves formed by the ships will propagate through the domain of the model.

- Stationary mode for refraction (*single_dir+*)

It calculates the direction of waves at regular intervals using the stationary solver and propagates the wave energy along a mean direction.

- Snell's law for wave refraction(*snells+*)

With the *snells*=1, the model will calculate the mean wave direction based on the Snells law. This process is useful in cases that the waves are oblique to the bathymetry.

- Short wave runup(*swrunup+*)

When turned on (*swrunup*=1), it allows the short wave to influence runup and overwash.

- Interaction of waves and flow with vegetation(*vegetation+*)

It simulates the dissipation of short waves by the influence of vegetation. The dissipation is calculated as a function of local wave height and vegetation parameters. Those parameters can be the number of vegetation elements, drag coefficient, vegetation stem diameters, density, and relative height.

Each process mentioned above has different parameters associated, for example, the *wetslp* and *dryslop*. Those parameters can be adjusted according to the result that the users want. Nevertheless, the users must be careful and use values of the parameters that are within the limits of the model. For that reason, the XBeach developers created a list of every parameter with the description of what they do and the ranges of values that they have. In previous studies, different authors tested the parameters of XBeach and determined different parameters that influenced the final result (Deltares, 2018). Vousdoukas et al. (2011) showed that for Faro Beach (a reflective beach) the parameters that had a direct impact in the results were *facua*, *wetslp*, *form* and *lws*.

XBeach requires specific input data/files in order to start simulation (can be consulted in the XBeach manual). In this work, the following inputs were used:

- Coordinate System and Grid

XBeach uses a coordinate system where the x-axis is towards the coast, and the y-axis is along the coast (alongshore). It is defined according to worlds coordinates through the origin and the orientation *alfa*, defined counter-clockwise (Roelvink et al., 2009)(Figure 2.4). Normally the grid is rectangular and characterized by the number of steps between the points in x and y (*nx and ny*). The smaller the steps, the more detail the simulation.

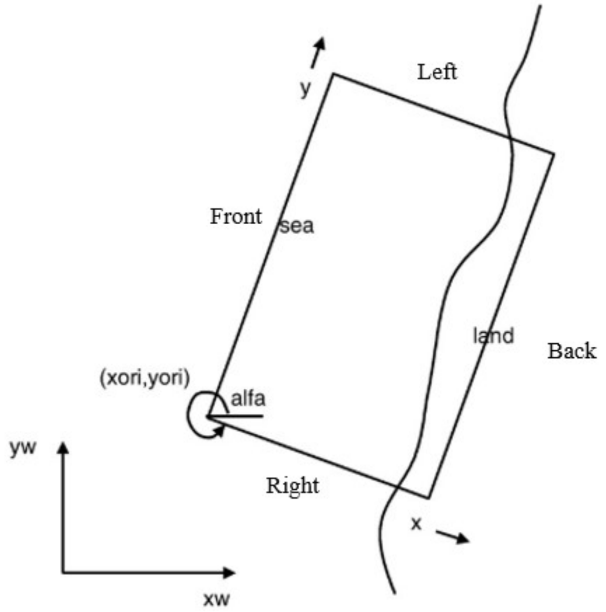


Figure 2.4 - XBeach coordinate system (Roelvink et al., 2009).

- Bathymetry

It is an external file (bed.dep), which is associated with two other files (x.grd and y.grd), and it describes the depth at each point.

- Wave boundary conditions

It is necessary to define the wave conditions at the boundary. Usually, this condition is also in a separated file (waves.txt). The characterization of the conditions can be spectral, non-spectral and special.

- Sea level (Tide and Surge)

It defines the water elevation along the time (there is an option to be constant). The tide and surge levels can be imposed in 1 to 4 boundaries of the grid.

- Morphology

Can contain information about the system, like the width of the erosion layer. In the case of structures, the erosion layer is 0.

- Simulation time

It is related to the wave conditions, and for that, the simulation is the time duration of the storm.

Before the user starts the model (and after compiling all the information and files), it is necessary to establish which outputs are wanted from the simulation. XBeach gives the option to select four different output types: instantaneous spatial output, time-averaged output, fixed-point output or runup gauge output. It is necessary to indicate the time that the outputs start to register, what types of result we want and the time interval that the result is registered.

At the end of the simulation, XBeach generates four files:

- Output.nc (Simulation results)
- XBlog.txt (with the information about the parameters and processes used, and the complete log of the simulation)
- XBerror.txt (Shows the errors if those existed)
- XBwarning.txt (Shows a warning about the values of parameters when they are out of the range recommended)

2.3.2.2. XBeach Tests & Validation

Since it was developed, XBeach has been subjected to different types of test (analytics, laboratory and field tests) to improve the model. XBeach has been used in several cases along the years for simulation past storms as well as to predict potential consequences from future ones (Harter and Figlus, 2017; Suh et al., 2017).

In project MICORE (Van Dongeren et al., 2009), several countries tested the morphological impact using XBeach and comparing with off-the-shelf packages models. One of those countries was Portugal, with the selected area being Praia de Faro located in a barrier island system (Vousdoukas et al., 2011). The model tested storm conditions regarding the winter of 2008/2009 that caused overtopping and some damage in the area. XBeach showed excellent results from the simulations but with overestimations in some areas of the beach.

As it was mentioned before XBeach is often compared with other models, Oliveira(2013, 2012a, 2012b, 2011) demonstrated in multiple testes that XBeach frequently shows more realistic results than the other models when observing the morphology changes.

In some cases, the XBeach model is calibrated according to the respective area and then a large number of different conditions is tested and stored in a Bayesian Network. This Bayesian Network allows a quick response from the authorities that do not need to wait for the simulation to be done (Plomaritis et al., 2018; Poelhekke et al., 2016; Vousdoukas et al., 2011).

The XBeach model is not only tested for the morphological behaviour of the areas, but it can also show the overtopping and simulate the effects of an artificial structure. With the increase of population in coastal areas there is also an increase in interest on developing and building artificial structures (seawalls, coastal levees, dykes, sea-breakers) that protect those areas (Troch et al., 2004). The number of research on this topic has also increased in general with the creation and testing of different empirical formulas (Carrasco et al., 2014; Ferreira et al., 2013; Mase et al., 2013). As previously mentioned XBeach is in constant developing in order to improve the results, Roelvink et al. in 2018 showed an improvement in accuracy of predicting overtopping rates by improving the swash dynamics (with a maximum of 15% of deviation), this was tested and improved by using data from (Vousdoukas et al., 2012). Phillips et al., (2017) using XBeach model showed that the morphology behaviour during a storm is significant in order to predict overtopping hazards.

2.4.Empirical Formula

Multiple authors have developed different empirical formulas either for runup or for overwash at beaches. However, if the study area presents an artificial structure, the beach dynamics and morphology will be influenced by those structures. According to the study site and the presence or absence of structures, there are specific formulas for each case.

Mase et al. (2013) used data from previous experiments (Mase et al., 2004) and results obtained from 3 beaches with seawalls. The formulas were compared with the experimental results from Tamada et al. (2002) and showed a good correlation. The models of artificial reefs and seawalls had a scale of 1:45 and had different uniform sea bottom slopes tested. The proposed methodology adopts the use of deep-water characteristics and application of a concept of imaginary slope for easy application of formulas. This imaginary slope is a line that connects the water depth at the onset of breaking for regular waves and the limit of runup(Saville, Jr., 1957). Mase et al. (2013) take in account the cross-sectional configuration of the foreshore seawall, so the concept of the imaginary slope was adapted (Figure 2.5).

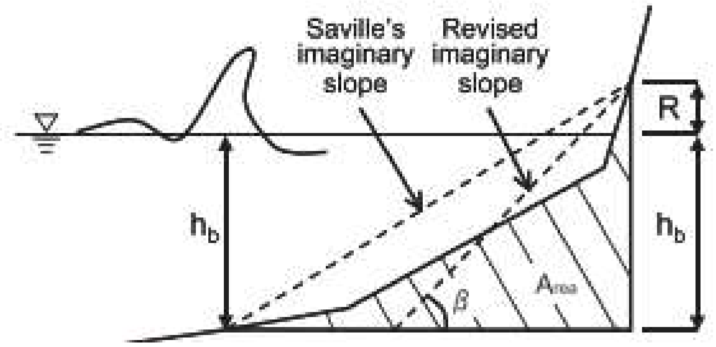


Figure 2.5 - Adaptation of the Imaginary slope (Figure from Mase et al., 2013)

The following formula determines this adapted imaginary slope:

$$\frac{1}{tan\beta} \approx cot\beta = \frac{2Area}{(h_b + R)^2} \tag{2}$$

where $tan\beta$ is the imaginary slope, h_b corresponds to the water depth at the onset of breaking for regular waves, and the $area$ is the cross-sectional area of seawall and foreshore between the wave breaking location and the runup level (R). It is necessary to know the slope to know the runup and vice-versa. To determine the h_b, a simple model for determination of wave parameters for irregular waves, developed by (Mase and Kirby, 1993), is applied. Through the two sets of experimental data, Mase et al. (2013) developed equations for overtopping discharge for seawalls and presented the conditions for the application of the formulas.

According to (Pullen et al., 2007), it is necessary to do a correction of maximum runup (R_{max}) before the calculation of the mean overtopping discharge, due to the permeability and rugosity of the structure. If the berm is permeable, it is necessary to calculate a reduction factor on the overtopping discharge and apply it to the calculated overtopping discharge.

This empirical formula has been used in different works (Heleno, 2017; Martinho, 2014; Neves et al., 2013; Pires, 2017).

3. Study Area

The village of São Pedro de Moel is located in the Portuguese central west coast, between the Mondego River mouth and the Nazaré Cape (Figure 3.1). The beach is an embedded narrow beach with 400 m of length, located south of a rocky headland and has a seawall with different heights at the backshore (LNEC, 2019), between the beach and the cliff or houses/infrastructures (Figure 3.2).

Figure 3.1 - Location of São Pedro de Moel. Figure from LNEC (2019).

Figure 3.2 - São Pedro de Moel beach in 12/Feb/2019. Figure from LNEC (2019).

According to Oliveira et al. (2002), Figueira da Foz (the closest tidal gauge to São Pedro de Moel) has a mean tide of 2.2 m and a maximum tidal level the chart datum of 3.6 m.

According to Costa et al. (2001), using the Figueira da Foz buoy data (from July 1990 to January of 1996), the closest to São Pedro de Moel, now inactive, the mean annual values for the wave climate offshore conditions are:

- Significant height: 2.2 m;
- Period: mean of 7.2 s and peak of 11.4 s;
- Direction: 90% from NW and W.

São Pedro de Moel is exposed to high energy wave conditions and an average of 19,9 days of storm conditions during the winter months (October to March) (Costa et al., 2001). Carvalho and Capitão (1995), characterized the wave conditions associated with a storm that have return periods of 10, 50 and 100 years at the location of the Figueira da Foz buoy (Table 3.1). According to the values presented in Table 5, the difference in offshore conditions concerning those return periods are only in wave height. With the increase of return periods, there is an increase in maximum wave height and maximum significant wave height. The zero-upcrossing wave period and mean direction are the same for the three return periods.

Table 3.1 - Wave conditions associated with storms with return periods of 10,50 and 100 years. Adapted from Carvalho and Capitão (1995).

T (years)	**Offshore Conditions**			
	Maximum Significant Wave Height (m)	**Maximum Wave Height (m)**	**Mean Direction(º)**	**Zero-upcrossing Wave period (s)**
10	11.3	19.0	330	16.1
50	13.7	23.2		
100	14.8	24.9		

Nowadays, the Figueira da Foz buoy is inactive, and a buoy that can be used to see the conditions offshore is the Leixões buoy. Although they are located in different areas, the results from both are very similar, having just significant differences in the increasing contribution of waves from NNW and an increase of significant wave height during storm events of 0.1 m at Leixões buoy (Costa and Esteves, 2009).

During storms conditions, São Pedro de Moel beach is exposed to overtopping and inundation events. For example, in 22nd of December 2019, national news reported the occurrence of overtopping, associated with storm conditions from Elsa storm (2019). In Figure 3.3, it is possible to see an example of where the water reached from the overtopping event during Elsa storm, reported by national news. The Elsa storm occurred from the 19th to the 23rd of December 2019, and it presented mean Hs values around ~4.9 m and mean peak periods of 14.2 s. In this storm, there were no negative effects on the population besides the road being cut to vehicles.

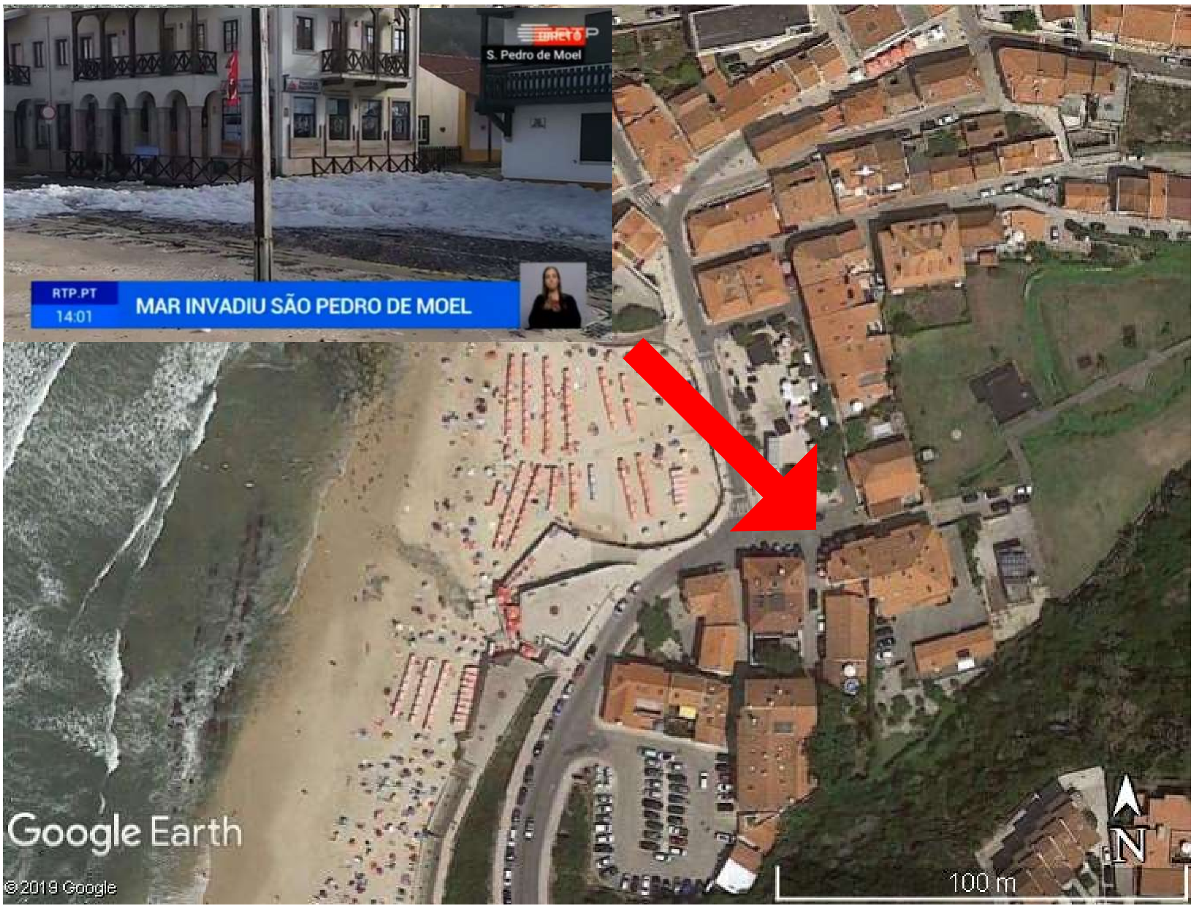


Figure 3.3 - Overtopping situation reported by national news (RTP) (Images from RTP and Google Earth).

Another example of overtopping event occurred in the Hercules storm in 2014 (Santos et al., 2014). Hercules storm occurred between the 3rd to the 8th of January 2019. This storm had mean Hs values of 5.1 and mean Tp of 16.3 s. The Hercules storm had a negative impact on the area. It caused damage and flooded to houses and restaurants and public infrastructures were destroyed (Santos et al., 2014).

4. Methods

4.1. Data acquisition and treatment

The first step done in this work was the download of the bathymetric data regarding São Pedro de Moel area. This information was obtained through the EMODnet (European Marine Observation and Data Network) Bathymetry portal in conjunction with data from LIDAR 2011 and topographic data from the field campaigns done in February of 2019 by LNEC for the MOSAIC.pt Field Campaigns report (LNEC, 2019).

The EMODnet digital terrain model (D.T.M.), 2018 version, creates a grid using different data providers (plummets, single beam, multi-beam, LIDAR observations, composite digital terrain models, Satellite-Derived Bathymetry) and it is the less detailed bathymetric data. The topographic profiles used were from the field campaigns done in São Pedro de Moel on the 12th (pre-storm) and 19th (post-storm) of February of 2019, and they were obtained from the GNSS receiver. The topographic files have high resolution. The Lidar 2011 data is the intermediate resolution and is used as a transition from the EMODnet data (lowest resolution) to the topographic profiles data (highest resolution).

Those three types of bathymetric data were used and adapted according to the different models and empirical formulas. For the SWAN model, the bathymetric grids were based upon the EMODnet bathymetric data. The XBeach model is concentrated in a more restricted area, so it was necessary to have a detailed bathymetry and topography of the area. In this case, the three types of data were combined into one file in order to have the best data file and therefore, results closest to reality (Figure 4.1). EMODnet data was used to represent the offshore data with higher depth values since neither the LIDAR nor beach profiles reached those depths. LIDAR was used for depths between 12 m to 0.5 m below the MSL, and the pre-storm beach profile was used for values higher than 0.5 m below the MSL. Note that, according to Simmons et al. (2019), the offshore bottom data has less influence than the parameters and onshore data. The bathymetric file built for the empirical formula was a compilation of the LIDAR 2011 and the pre-storm profile from LNEC survey. LIDAR 2011 data were used in depths between 11 m and 0.5 m below the MSL and the field data from LNEC's campaigns (P1 from Figure 4.2) from 0.5 m to 7.5 m above the MSL (Figure 4.3).

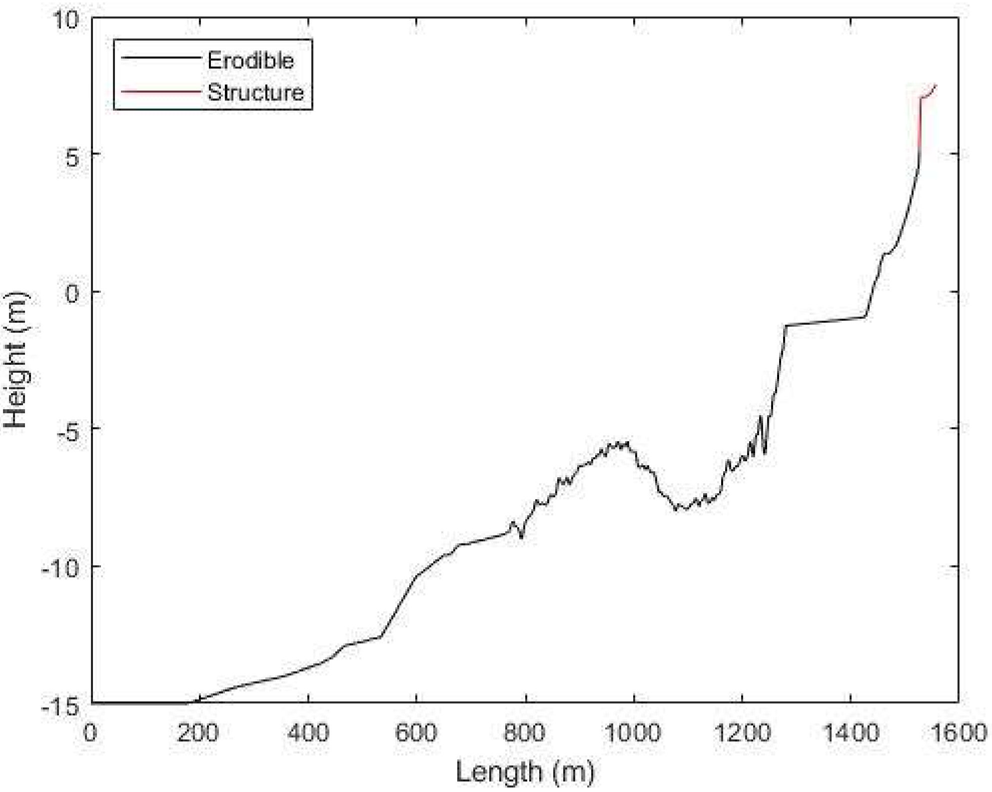


Figure 4.1 - Bathymetry profile used in the XBeach model. Combination of EMODnet, LIDAR 2011 and LNEC's Surveys (P1).

Figure 4.2 - Location of the surveys done during the campaigns at São Pedro de Moel (LNEC, 2019). For this work, the only profile used was the P1.

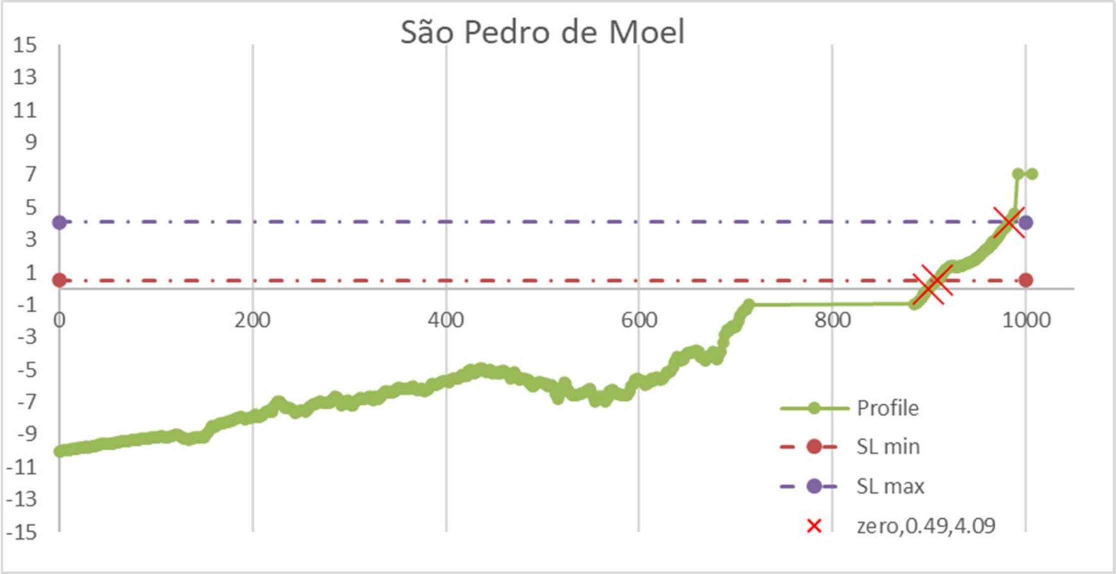


Figure 4.3 - Bathymetry used for the empirical formula. Combination of LNEC surveys and LIDAR 2011. The x-axis corresponds to distance from the original point in (m), and the y-axis is the height (m).

After having all the bathymetry information necessary for the simulations, it was necessary to have the data from wave conditions. This wave data was downloaded from the ECMWF Centre (Richardson et al., 2013), and it contained data from 2000 to 2019 (20 years) at an offshore point of São Pedro de Moel (-9.6º W, 40º N in the coordinate system EPSG:3763 ETRS89/Portugal TM06) at a depth of 185 meters below the mean sea level (MSL) (Figure 4.4). The data contained information on the significant wave height, mean wave period, peak wave period, and wave direction with an interval of six hours. The data was analysed according to the monthly mean and annual maximum (a year is considered to be from August to July of the next year).

It was also necessary to have the water level information; in this case, the data was obtained at a point near Peniche using WXTide32 (Flater, 2007), tide and current prediction program.

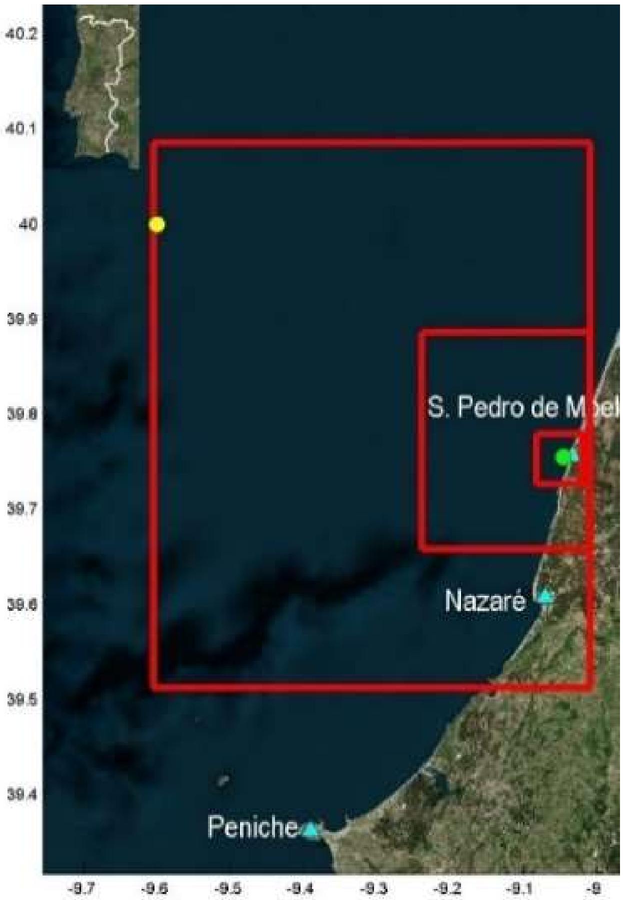


Figure 4.4 - Map with the computational grids using in SWAN. The larger is the main grid and the other two are the nested grid. The yellow point corresponds to the wave conditions input, and the green point corresponds to the location of the wave conditions output (Figure made using MIRONE (Luis, 2007)).

4.2.SWAN model

The SWAN model was used to simulate the propagation of waves from offshore to nearshore. The organization and combination of data to be used in SWAN as input files were done by using Microsoft Access database – SOPRO (Fortes et al., 2007; Pinheiro et al., 2005). The database program constructs the input files necessary for SWAN by processing the data (Figure 4.5). In this case, a three-nested model domain was applied. This same system was used by Fanti (2019) to reduce the simulation time. The grid system is demonstrated in Figure 4.4. The computational grids were regular and rectangular; the first grid was the one with the lowest resolution with 300 m (300x300). The other two grids have higher resolution of 100 m and 50 m (Table 4.1). Since the bathymetry file only used one source (EMODnet), there were no differences in the information related to the three bathymetric grids (Table 4.2).

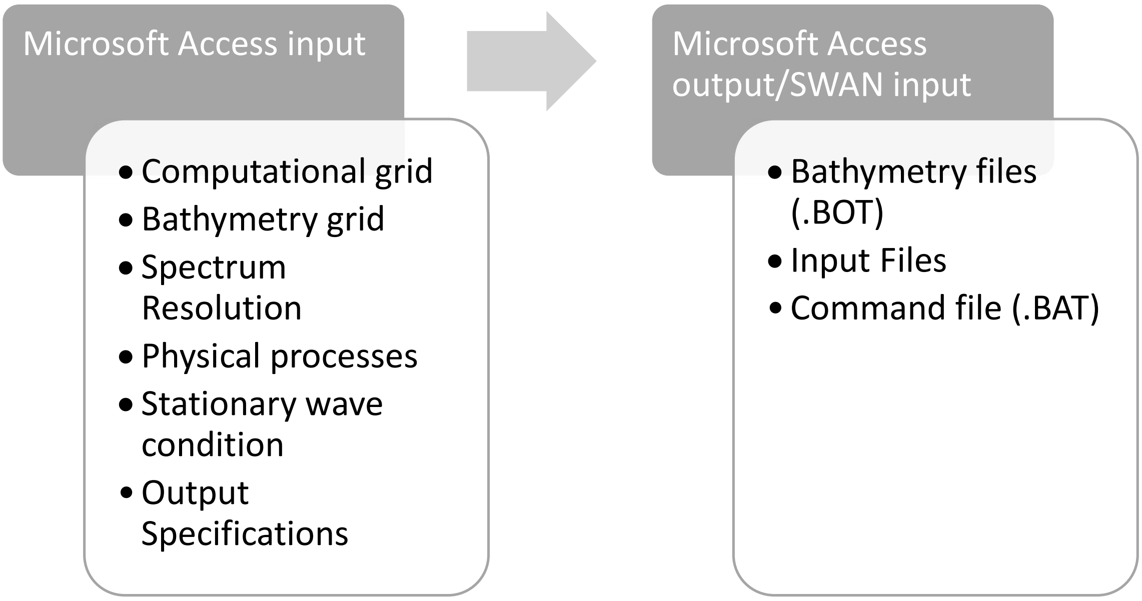


Figure 4.5 - Microsoft Access database and SWAN files.

Table 4.1 - Computational grids details used in SWAN. The coordinate system used is the EPSG:3763 ETRS89/Portugal TM06.

Computational grids	Main Grid	Nested Grid	Nested Grid 2
X Initial	-126574.95	-94704.61	-81205.31
Y Initial	-16183,48	-481,78	6951,73
Grid rotation	0	0	0
Grid length x (m)	51500	19760	5320
Grid length y (m)	63440	25290	5850
DX	300	100	50
DY	300	100	50

Table 4.2 - Bathymetry grids details used in SWAN. The coordinate system used is the EPSG:3763 ETRS89/Portugal TM06.

Bathymetry grid	Main Grid	Nested Grid	Nested Grid 2
X Initial	-139073.37	-139073.37	-139073.37
Y Initial	-16772.24	-16772.24	-16772.24
Grid rotation	0	0	0
nº DX	715	715	715
nº DY	575	575	575

DX(m)	89.55	89.55	89.55
DY(m)	115.51	115.51	115.51

After the input files of SWAN were ready through Microsoft Access database, the SWAN model was executed. The model ran with a constant input of hydrodynamic conditions at the offshore boundaries (stationary mode). These conditions are transferred from the main grid to the first nested grid and from the first nested grid to the second. The initial conditions applied in the boundary of the SWAN model were the conditions extracted from the ECMWF database that was mentioned before. The model ran for the 20 years (2000-2019) using MEDUSA cluster, the final results show the values were associated with a selected point in front of São Pedro de Moel at 10 m depth in relation to the MSL (-9.045143º W 39.75535º N) (Figure 4.4). The same process of data analyses done for the offshore data was performed in the SWAN results.

4.3.XBeach model

In this work, XBeach was used to simulate the morphological evolution and the overtopping events at São Pedro de Moel. As mentioned before, two different types of setups (non-hydrostatic and surf beat) were used to analyse both events. In this chapter, it is explained the differences and similarities on the input files.

Both setups used a 1D model, and the domain was defined by three files, “x”, “y” and “bed”. These files are correspondent to the coordinate system and the correspondent bathymetry and topography. In this case, y is 0 because the used model is 1D, x is the distance from the first point (offshore), and the bed is the bathymetry correspondent to x. The bathymetry file used has the configuration mentioned before (using the data from the three sources: EMODnet, LIDAR and field campaigns) (Figure 4.1). For the surf beat setup, it was necessary to define a file with the non-erodible layers that represent the structures (Figure 4.1); for this, it is also necessary to activate the parameter *structure*.

The four domain limits of XBeach represented in Figure 2.5, were defined with different functions according to the type of model. The *front* boundary was different for the two models. For the non-hydrostatic setup, the *front* boundary condition was *nonh_1d* (specific for non-hydrostatic runs). For the surf beat setup was *abs_1d* in this boundary condition, the boundary allows the water level variation along time to be specified while a wave that is coming towards the boundary is absorbed. The *abs_1d* is also applied in the back boundary for both types of runs.

The lateral boundaries (*right* and *left*) do not have a global influence on the numerical model. The conditions were different for the two setups, in the non-hydrostatic, the condition for the lateral boundaries was *wall*, and this means that there is zero flux in the boundary. For the surf beat setup, the option *neumann* was selected; this condition state that there are no changes in velocity or surface elevation locally.

The wave conditions were obtained through SWAN. Due to the XBeach's high computational effort, it is not possible to run all the data resulted from SWAN (twenty years of data). For that reason, it was necessary to select data associated with storms (this matter will be further discussed). However, for the two different setups, the wave-conditions files were prepared differently. For the non-hydrostatic, the wave condition file was *parametric.* The associated file had single parametric spectrum data with the different wave characteristics (Significant wave height, peak frequency, peak enhancement factor, directional spreading coefficient, the highest frequency used to create JONSWAP). For the surf beat setup, the option of *jonstable*. The associated file has a timeline with the wave characteristics associated with every hour (significant wave height, peak period, wave direction, directional spreading coefficient, peak enhancement factor, duration, timestep). The tide input was fixed for the non-hydrostatic setup. However, for the surf beat setup, was associated with the water levels of every hour.

For each setup, sensibility tests were performed to establish the parameters more relevant. This was done by testing the range of values indicated in XBeach manual for each parameter. The parameters for the non-hydrostatic sensibility tests were *bedfriccoef*, *CFL*, *nhlay*, *maxbrsteep,* see Table 4.3, and the bathymetry resolution; it is also important to mention that the *morphology* parameter was turned off and the *nonh+* was turned on for this type of setup. The surf beat setup's parameters tested were *alpha*, bathymetry resolution, *bermslope*, *beta*, *CFL*, *delta*, *dryslp*, *dtheta_s*, *dzmax*, *facua*, *gamma*, *gammax*, *hswitch*, *lws*, *morfac*, *n*, *thetamax*, *thetamin*, *turb* and *wetslp*. The meaning and range values for each parameter recommended by the manual are represented in Table 4.3, except for the bathymetric resolution. The bathymetric resolution tested was 0.5 m, 1 m, 1.5 m, 2 m and 5 m, those resolutions were done using interpolations from the files built (Figure 4.1).

Table 4.3 - List of parameters tested in this work and its description and associated range of values (Deltares, 2018).

Process	Parameter	Description	Units	Range of Values	Default value
Bed friction and viscosity	bedfriccoef	Bed friction coefficient		$3.5\text{x}10^{-05}$; 0.9	0.01
Non-hydrostatic correction	maxbrsteep+	Maximum wave steepness criterium		0.3 ; 0.8	0.4
	nhlay+	Layer distribution in the non-hydrostatic model		0.0 ; 1.0	0.03
Time parameters	CFL	Maximum courant-friedrichs-lewy number		0.1 ; 0.9	0.7
Wave Dissipation	alpha+	Wave dissipation coefficient in Roelvink formulation		0.5 ; 2.0	1.0
	delta+	The fraction of wave height to add to water depth		0.0 ; 1.0	0.0
	gamma	Breaker parameter in Baldock or Roelvink formulation		0.4 ; 0.9	0.55
	gammax+	Maximum ratio wave height to water depth		0.4 ; 5.0	2.0
	n+	Power in Roelvink dissipation model		5.0 ; 20.0	10.0
Roller	beta+	Breaker slope coefficient in roller model		0.05 ; 0.3	0.1

Sediment transport	tsmin+	Minimum adaptation time scale in advection diffusion equation sediment	s	0.01 ; 10.0	0.5
	bermslope	Swash zone slope for (semi-) reflective beaches		0.0 ; 1.0	0.0
	facua+	Calibration factor time-averaged flows due to wave skewness and asymmetry		0.0 ; 1.0	0.1
	lws+	Switch to enable long wave stirring		0 or 1	1
Morphology	dryslp	The critical avalanching slope above water (dz/dx and dz/dy)		0.1 ; 2.0	1.0
	dzmax+	Maximum bed level change due to avalanching	m/s/m	0.0 ; 1.0	0.05
	hswitch+	Water depth at which is switched from wetslp to dryslp	m	0.01 ; 1.0	0.1
	morfac	Morphological acceleration factor		0.0 ; 1000.0	1.0
	wetslp	Critical avalanching slope underwater (dz/dx and dz/dy)		0.1 ; 1.0	0.3
Grid and Bathymetry	dtheta_s	Directional resolution in case of stationary refraction	deg	0.1 ; 20.0	10.0

	thetamax	Higher directional limit (angle w.r.t computational x-axis)	deg	-360.0 ; 360.0	90.0
	thetamin	Lower directional limit (angle w.r.t computational x-axis)	deg	-360.0 ; 360.0	90.0

The global and point located outputs were almost the same for both runs. In this study, the results that were analysed were *zb*, *zs* for both types of runs and *nrugauge* and *qx* for the non-hydrostatic setup (Table 4.4). All the outputs were analysed by using MATLAB.

Table 4.4 - List of outputs used in this work.

Type	**Outputs**		
	keyword	**Description**	**Units**
Instantaneous spatial output	Zb	Bed level	m
	zs	Water level	m
Fixed point output	qx	Discharge in u-points, x component	m^2/s
Runup gauge output	nrugauge	Number of outputs runup gauge locations (associated with a point to track the waterline)	

One of the outputs analysed in this work was: *runup gauge output*. For this type of output, it is necessary to select a point of the grid (below the mean sea level), and it creates a temporal series of the sea level variation. In the end, the model provides information about runups in the simulation (Figure 4.6).

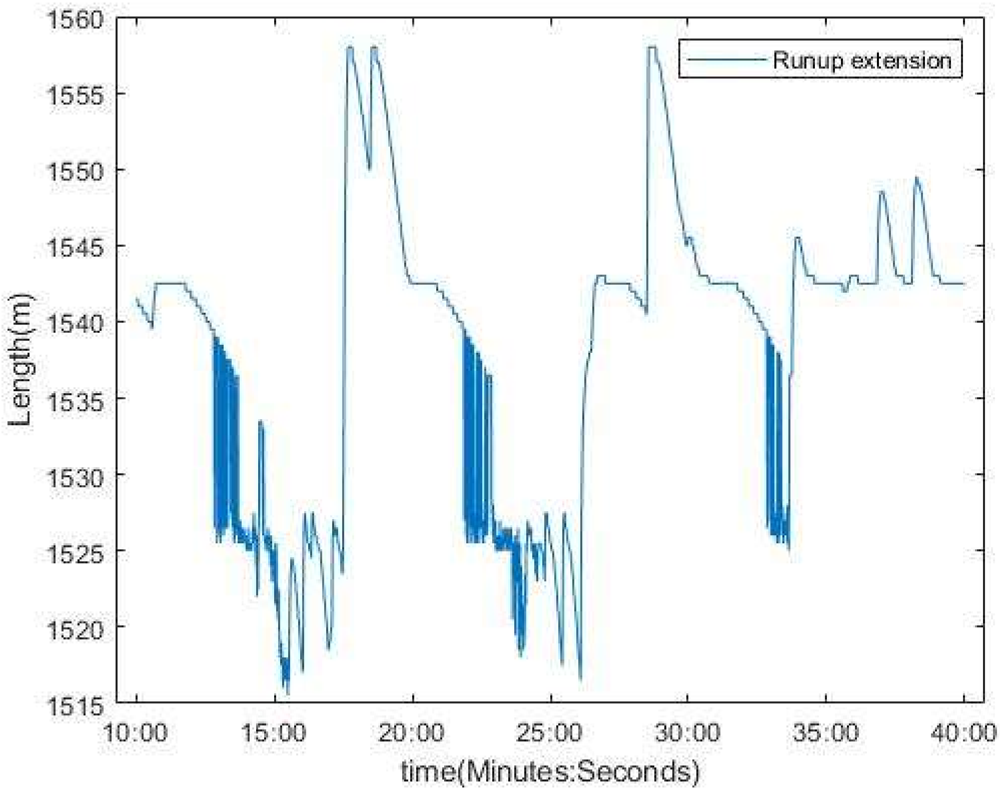


Figure 4.6 – Runup extension during a simulation.

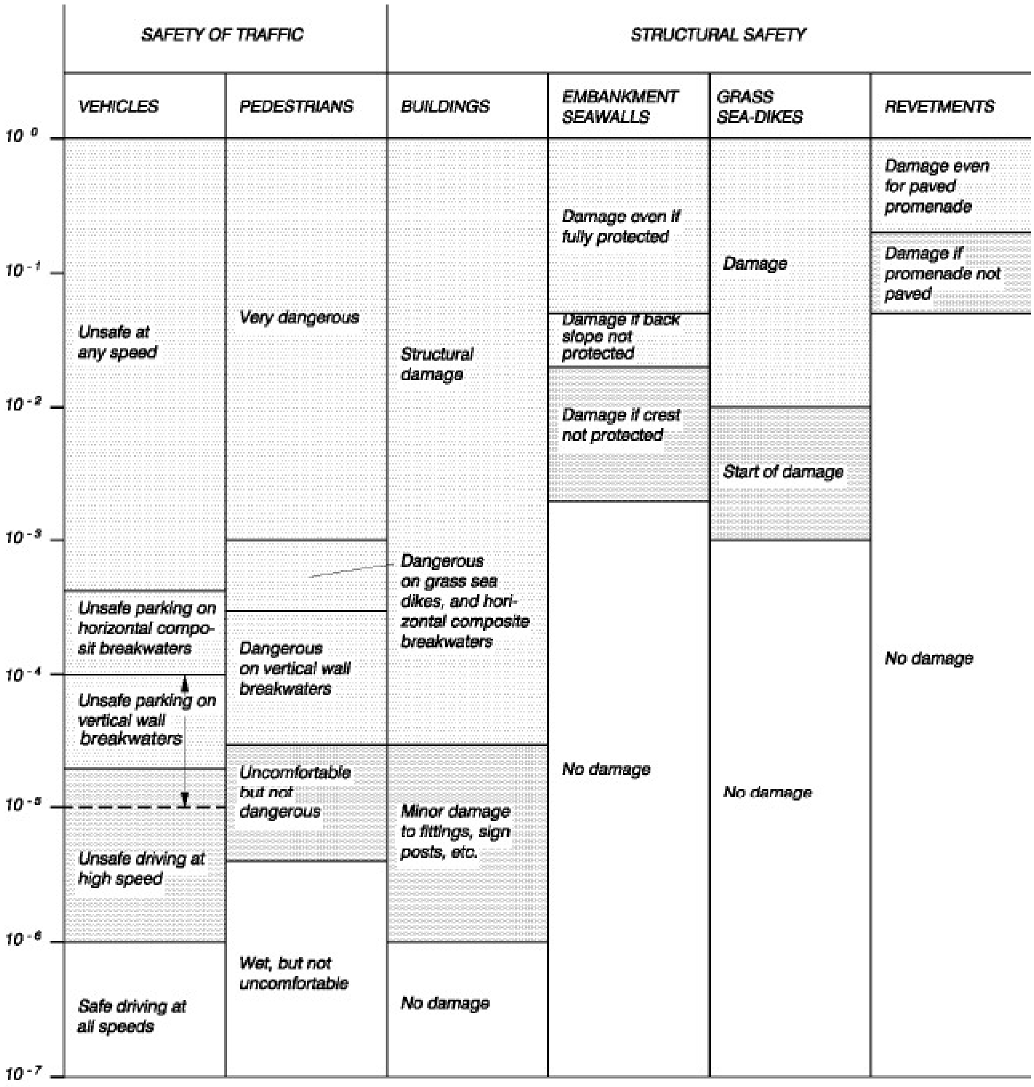
The other variable that was important to calibrate and validate the model was the water discharge at a fixed point (qx). This point was vital for not only the calibration and validation but is also useful for future safety measures regarding the overtopping events (if the model is used). In this parameter, physical modelling shows good results due to the ability to simulate complex processes (Neves et al., 2013). However, due to the high costs of those physical models and the difficulty of understanding specific processes, numerical models have been more used (Silva et al., 2012).

In XBeach, it is possible to see the discharge values at one point by choosing the qx in the output section. This option shows in the results the horizontal movement that the water did in the points selected. By removing the water from backwash and summing all the values from qx and dividing it by the time of the simulation, we get the values for discharge per second.

$$q = \frac{\sum qx}{t_{sim}} \tag{3}$$

The processes of calibration and validation of the non-hydrostatic setup are based on the q at the crest of the structure and maximum runup extension in relation to the crest of the structure, those two values are compared with a CEM table regarding the critical mean overtopping discharge values (USACE, 2002) (Table 4.5) and historical data.

Table 4.5 - Table used to compare the values of overtopping discharge(Table from the Coastal Engineering Manual (USACE, 2002)).



SAFETY OF TRAFFIC

VEHICLES
Unsafe at any speed
Unsafe parking on horizontal composit breakwaters
Unsafe parking on vertical wall breakwaters
Unsafe driving at high speed
Safe driving at all speeds

PEDESTRIANS
Very dangerous
Dangerous on grass sea dikes, and horizontal composite breakwaters
Dangerous on vertical wall breakwaters
Uncomfortable but not dangerous
Wet, but not uncomfortable

STRUCTURAL SAFETY

BUILDINGS
Structural damage
Minor damage to fittings, sign posts, etc.
No damage

EMBANKMENT SEAWALLS
Damage even if fully protected
Damage if back slope not protected
Damage if crest not protected
No damage

GRASS SEA-DIKES
Damage
Start of damage
No damage

REVETMENTS
Damage even for paved promenade
Damage if promenade not paved
No damage

For the surf beat setup, the variable analysed was the bed level (*zb*). This variable shows the bed level at all the output intervals. In this work, the final output of *zb* was used to compare the modelled *zb* and the post-storm *zb* from field campaigns. This allows adjusting the parameters until the *zb* from the simulation and field campaigns have similar results. This process is firstly done by visual comparison, and then, the best results were analysed using the Brier Skill Values (BSS) (Weigel et al., 2007).

$$BSS = 1 - \frac{(z_{bresult} - z_{bfinal})^2}{(z_{binitial} - z_{bfinal})^2} \tag{4}$$

4.4. Empirical Formula

The empirical formula (Mase et al., 2013) was used to determine the overtopping at the structure of São Pedro de Moel. The empirical formula was applied by using a Fortran program (Fortes et al., 2013). This program needs three complementary files regarding the wave and tide conditions, structure conditions, beach and bathymetry conditions.

The file regarding the wave and tide conditions has the information that resulted from the SWAN model. The file related with the bathymetry is based on the LIDAR 2011 and pre-storm field campaign, as it was mentioned before. The final file needed is a file with the information necessary to the empirical formula, for example, bottom slope, beach profile degree, beach orientation, the height of the structure crest, length of the structure, structure slope, permeability coefficient of the structure (γ_f, 0.8 was considered in this case) (Annexe A).

The empirical formulas gave the result for overtopping according to an interval of 6h (associated with the interval of the wave input data).

4.5. Storm selection

The two setups were calibrated using different storms and validated or tested using the same storm. The main objective for the non-hydrostatic setup and empirical formulas was to predict the induced storm runup extension and overtopping. In this case, there was no quantitative data for those events. Hence, besides the coastal storm "minimal" characteristics mentioned in chapter 2.2, the factor of the selection of the coastal storm was the qualitative information available (news, people, videos, internet).

The storm selected for the calibration was Elsa storm (from 19th to the 23rd of December 2019). In this storm, there was no damage due to overtopping, but there is visual evidence of the runup maximum reached (Figure 3.3). In the non-hydrostatic setup, the only values used to simulate the storm were correspondent to the maximum significant wave height and associated tide level during the night of 21st to 22nd. That period was selected due to the available information from the RTP news report (during the morning of 22nd of December). The conditions occurred on the 22nd of December at 1 h (Table 4.6).

Table 4.6 - Nearshore wave conditions for the Elsa storm. The conditions that occurred at 1h of the 22nd of December were used in the non-hydrostatic.

Storm	**Date**			**Wave conditions**			
				Morphodynamic			
	Day	Month	Hour	Hs (m)	Tp (s)	Dir (º)	Tide (m)
Elsa (2019)	19	12	6	3.8	12.1	275	2.24
	19	12	12	4.4	12.1	275	1.62
	19	12	18	4.7	12.1	265	1.76
	20	12	1	5.0	12.1	275	1.86
	20	12	6	4.8	13.4	275	1.77
	20	12	12	4.7	14.9	275	2.11
	20	12	18	4.9	13.4	275	1.32
	21	12	1	4.5	13.4	275	2.29
	21	12	6	4.5	13.4	275	1.31
	21	12	12	4.6	12.1	275	2.54
	21	12	18	4.9	12.1	285	0.96
	22	12	1	5.9	14.9	285	2.65
	22	12	6	5.5	16.5	285	0.97
	22	12	12	5.9	16.5	285	2.81
	22	12	18	5.0	16.5	285	0.77
	23	12	1	4.5	16.5	285	2.85
	23	12	6	4.0	14.9	285	0.82
	23	12	12	3.5	14.9	285	2.84

The calibration of the surf beat setup was differently performed because, in this case, there was quantitative information about the effects on the beach profile since it was obtained *in situ* profiles before and after the storm. The storm occurred between the 12th and the 19th of February 2019. With this data, it is possible to calibrate the model by comparing its results with the data from the campaign of 19th (post-storm). For the surf beat setup, the wave input conditions correspond to wave conditions data during the whole storm (Table 4.7).

After calibrated, both setups were tested using a well-known storm in Portugal, Hercules storm (2014) (Table 4.7) that cause significant damages all over the continental Portuguese coast. The Hercules storm was selected due to the information available from different sources (internet videos, news report and scientific articles (Santos et al., 2014)). For the non-hydrostatic setup, the conditions were related to the 6th of January at 18h and the surf-beat simulated all the conditions represented.

Table 4.7 – Nearshore wave conditions used in the morphodynamic run’s wave input file.

Storm	**Date**			**Wave conditions**			
				Morphodynamic			
	Day	Month	Hour	Hs (m)	Tp (s)	Dir (º)	Tide (m)
“February storm” (2019)	18	2	1	3.6	14.8	295	2.76
	18	2	6	4.4	14.8	295	1
	18	2	12	4.7	14.8	295	2.4
	18	2	18	4.5	14.8	295	1.21
	19	2	1	4.0	14.8	295	2.43
	19	2	6	3.5	14.8	295	1.47
Hercules (2014)	3	1	18	4.3	14.8	295	2.79
	4	1	1	4.8	14.8	285	0.88
	4	1	6	5.6	14.8	285	3.17
	4	1	12	5.1	14.8	285	0.5
	4	1	18	5.8	14.8	285	3.08
	5	1	1	5.0	14.8	285	0.6
	5	1	6	5.0	14.8	285	3.35
	5	1	12	4.5	14.8	285	0.43
	5	1	18	4.2	14.8	285	3.07
	6	1	1	3.9	14.8	285	0.63
	6	1	6	4.3	13.4	275	3.19
	6	1	12	5.5	20.3	285	0.67
	6	1	18	6.4	20.3	285	2.77
	7	1	1	5.6	20.3	285	0.94
	7	1	6	6.0	18.3	285	2.76
	7	1	12	5.2	18.3	285	1.1

	7	1	18	4.8	16.5	285	2.3
	8	1	1	4.5	16.5	285	1.37
	8	1	6	4.3	14.8	275	2.23

5. Results

In this chapter, the results from the SWAN model, XBeach runs, and empirical formulas are presented and compared.

5.1.Offshore wave conditions

Based upon the ECMWF wave data from 2000 to 2019 (20 years) at an offshore point of São Pedro de Moel (-9.6º W, 40º N), it was obtained the mean values for Hs, Tp and Dir for each month in order to characterise seasonality changes (Table 5.1). The wave height was higher in the winter months and lowered in the summer months. The same happened with the peak period. When analysing the wave direction, it is possible to see that it varies from west-northwest (WNW) and northwest (NW), WNW dominates during winter and NW during summer.

Table 5.1 - Wave Characteristics - Monthly mean.

Months	H_s (m)	T_p (s)	Dir (º)
January	2.68	13.1	294
February	2.61	12.9	296
March	2.28	12.2	296
April	1.99	11.2	299
May	1.63	10	304
June	1.38	9.2	306
July	1.33	8.6	314
August	1.34	8.8	314
September	1.53	10.6	304
October	2.01	11.5	295
November	2.37	12.0	301
December	2.45	12.6	292

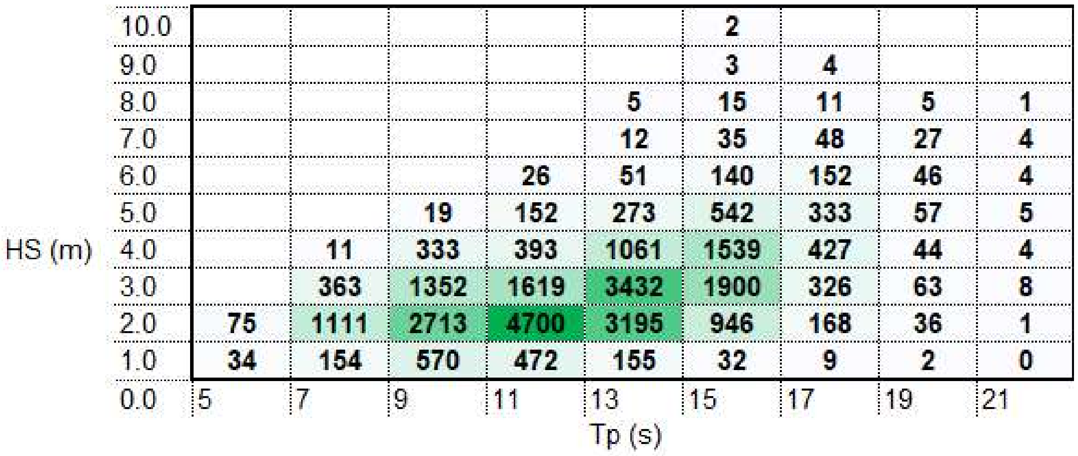
The highest annual maximum of Hs was registered in 2012-2013 and the highest maximum Tp in 2004-2005 (Table 5.2).

Table 5.2 - Wave Characteristic - Annual Maximum.

Interval of years	H_s (m)	T_p (s)
2000-2001	8.28	14.7
2001-2002	7.31	17.9
2002-2003	7.27	14.7
2003-2004	8.02	16.3
2004-2005	7.00	18.7
2005-2006	7.01	13.6
2006-2007	6.61	15.4
2007-2008	7.46	16.9
2008-2009	7.20	15.0
2009-2010	6.74	11.4
2010-2011	9.50	14.9
2011-2012	6.41	12.0
2012-2013	9.90	13.3
2013-2014	8.40	13.2
2014-2015	5.92	16.8
2015-2016	7.10	12.5
2016-2017	7.09	16.7
2017-2018	7.71	14.5
2018-2019	8.04	15.2

The relation between Hs and Tp for the twenty years of data is represented in Table 5.3. This table shows that waves with wave heights of two meters are more frequently correlated with wave periods of 9 s to 13 s. In relation to the wave direction, the more frequent waves come from 300º and 360º (Figure 5.1).

Table 5.3 - Number of occurrences of sea state for the 20 years (2000-2019) for the offshore wave conditions (-9.6º W, 40º N). Y-axis corresponds to the significant wave height in meters, and the x-axis is the peak period in seconds. The data was downloaded from ECMWF dataset. The darker colours represent a higher occurrence state.



HS (m)									
10.0						2			
9.0						3	4		
8.0					5	15	11	5	1
7.0					12	35	48	27	4
6.0				26	51	140	152	46	4
5.0			19	152	273	542	333	57	5
4.0		11	333	393	1061	1539	427	44	4
3.0		363	1352	1619	3432	1900	326	63	8
2.0	75	1111	2713	4700	3195	946	168	36	1
1.0	34	154	570	472	155	32	9	2	0
0.0	5	7	9	11	13	15	17	19	21

Tp (s)

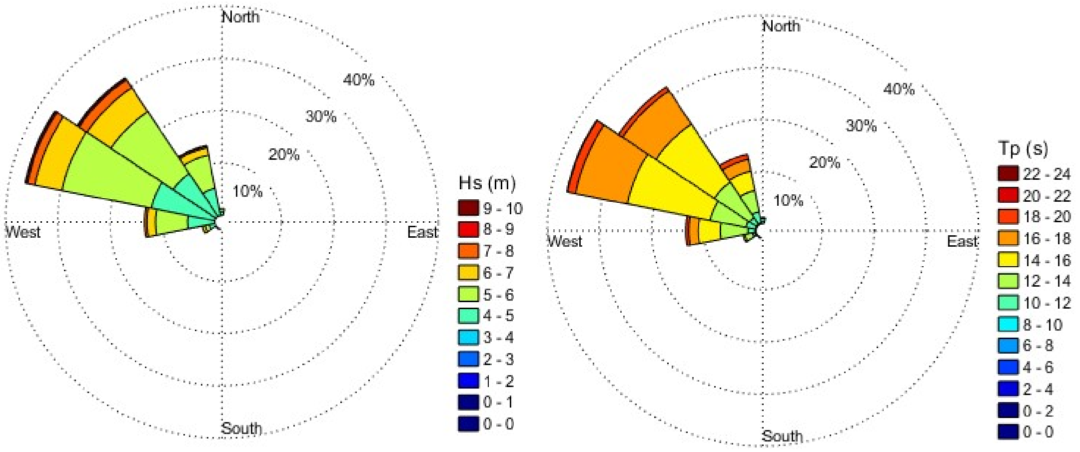


Figure 5.1 - Wave roses for the 20 years (2000-2019 representing the offshore wave conditions (-9.6º W, 40º N). One the left the significant wave height (in meters). On the right the peak period (in seconds). The data was downloaded from ECMWF dataset. Each sector has a division of 22.5º.

The offshore conditions for the storms studied in this thesis are represented in Table 5.4. The development of Hs and Tp during each storm is represented in Figure 5.2.

Table 5.4 - Offshore general conditions for the three storms studied.

	Elsa			Hercules			February storm		
	Hs (m)	Tp (s)	Dir (º)	Hs (m)	Tp (s)	Dir (º)	Hs (m)	Tp (s)	Dir (º)
Maximum	7.2	17.3	292.9	7.4	20.9	300.9	4.8	15.6	312.6
Minimum	3.7	12.0	249.3	4.0	13.8	270.1	4.5	15.2	304.4

Mean	5.4	14.2	273.9	5.6	16.2	289.0	4.7	15.4	309.0

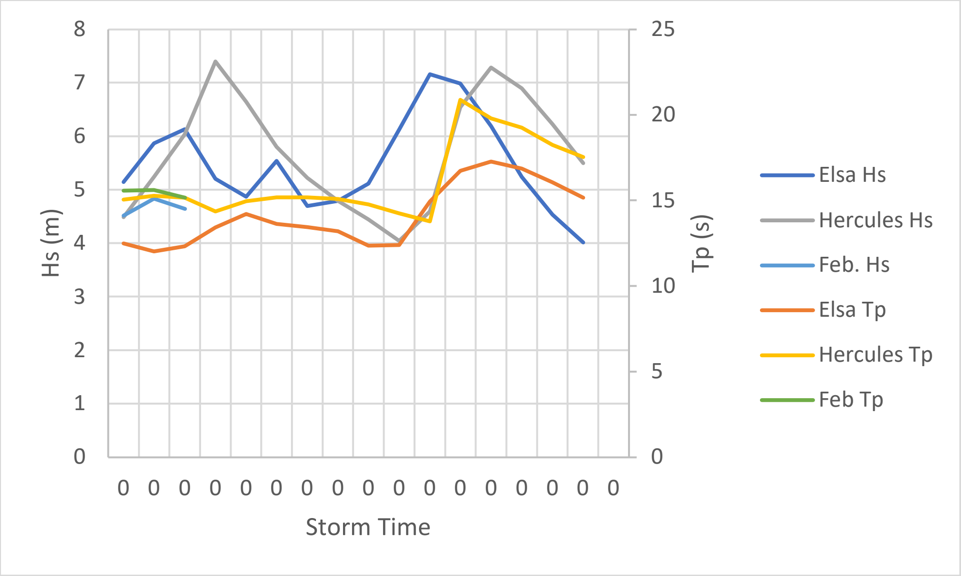
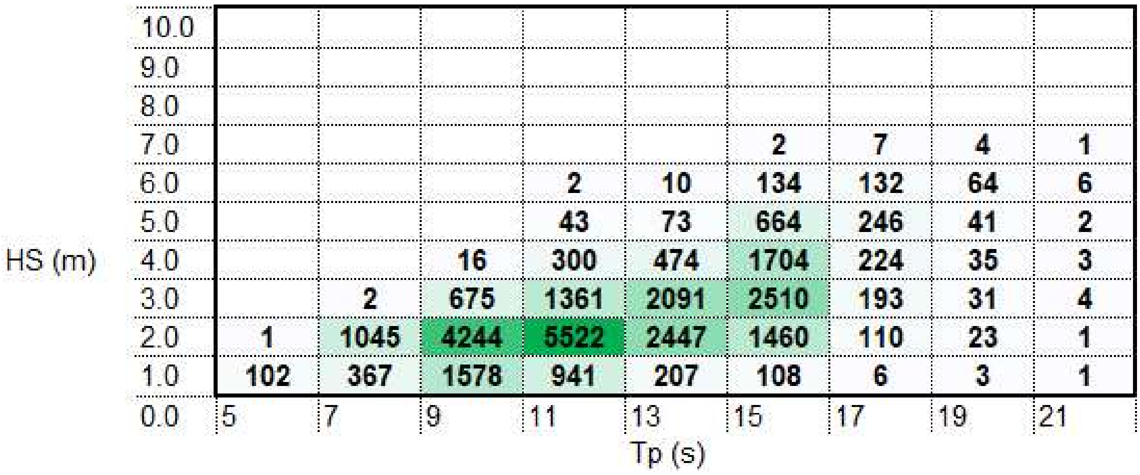


Figure 5.2 - Offshore Hs and Tp in relation to time for the three storms studied

5.2.Nearshore wave conditions

The wave propagation from offshore to nearshore using SWAN, namely to the point (-9.045143º W 39.75535º N) in front of São Pedro de Moel at 10 m depth in relation to the MSL, permitted to obtain the 20 years local wave climate. The most frequent waves are, still, waves with Hs=2 m and Tp between 9 s to 13 s. The significant wave heights presented in Table 5.5 show a general decrease when compared with results from Table 5.3. The maximum value is above 7 meters. The peak wave periods showed a general decrease, having less waves with higher periods. The wave direction is even more concentrated between NW and WNW when comparing with the offshore wave condition (Figure 5.3).

Table 5.5 - Number of occurrences of sea state for the 20 years (2000-2019) for the nearshore wave condition (-9.045143º W 39.75535º N). Y-axis corresponds to the significant wave height in meters, and the x-axis is the peak period in seconds. This data is the result of the wave propagation from offshore to nearshore using SWAN. The darker colours represent a higher occurrence state.



HS (m)									
10.0									
9.0									
8.0									
7.0						2	7	4	1
6.0				2	10	134	132	64	6
5.0				43	73	664	246	41	2
4.0			16	300	474	1704	224	35	3
3.0		2	675	1361	2091	2510	193	31	4
2.0	1	1045	4244	5522	2447	1460	110	23	1
1.0	102	367	1578	941	207	108	6	3	1
0.0	5	7	9	11	13	15	17	19	21

Tp (s)

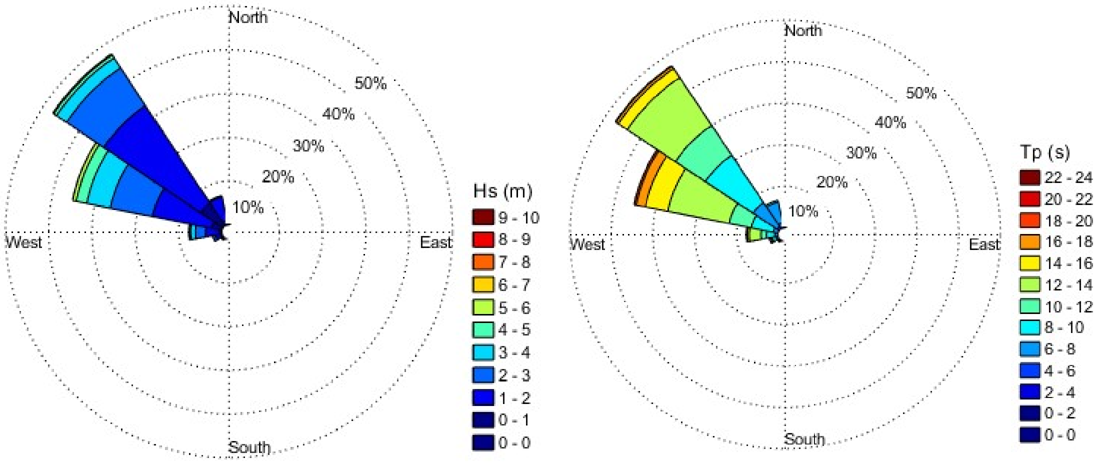


Figure 5.3 Wave roses for the 20 years (2000-2019 for the nearshore wave condition(-9.045143º W 39.75535º N). One the left the significant wave height (in meters). On the right the peak period (in seconds). This data is the result of the wave propagation from offshore to nearshore using SWAN. Each sector has a division of 22.5º.

The nearshore conditions for the storms studied in this thesis are represented in Table 5.6. The development of Hs and Tp during each storm is represented in Figure 5.4.

Table 5.6 – Nearshore general conditions for the three storms studied.

	Elsa			Hercules			February storm		
	Hs (m)	Tp (s)	Dir (º)	Hs (m)	Tp (s)	Dir (º)	Hs (m)	Tp (s)	Dir (º)
Maximum	5.9	16.5	285.0	6.4	20.3	295.0	4.7	14.9	295.0

Minimum	4.0	12.1	265.0	3.9	13.4	275.0	4.4	14.9	295.0
Mean	4.9	14.0	278.8	5.1	16.3	285.0	4.6	14.9	295.0

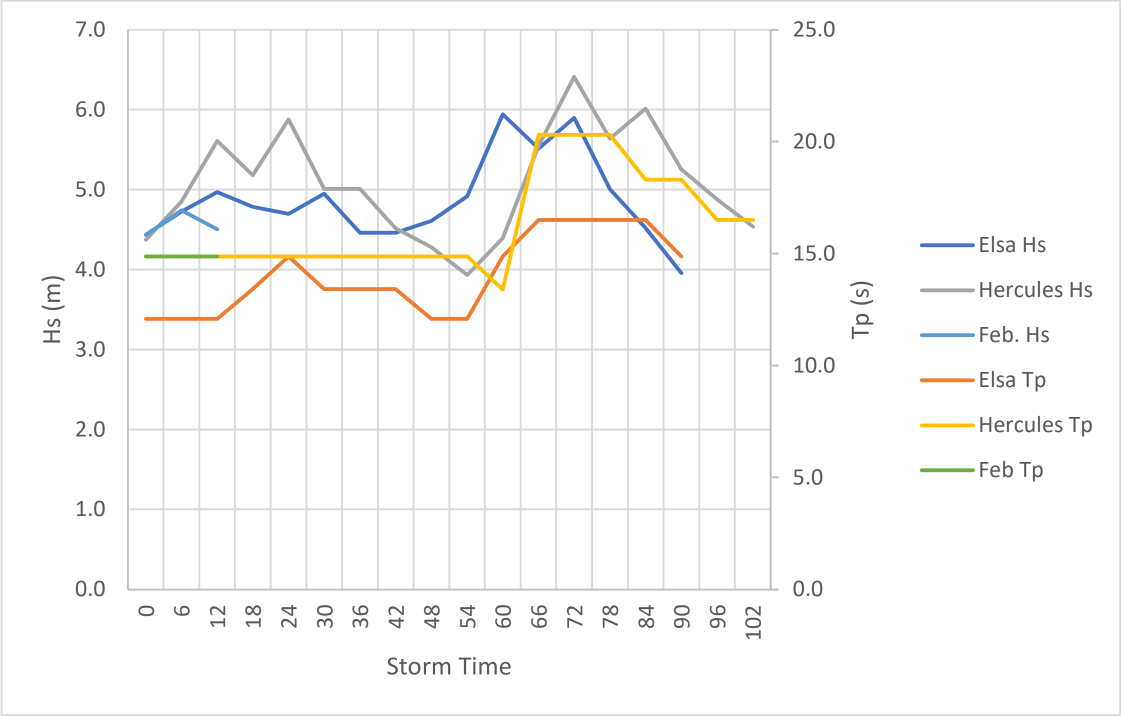


Figure 5.4 - Offshore Hs and Tp in relation to time for the three storms studied.

5.3.Empirical Formula

The use of the empirical formulation for the nearshore wave conditions obtained at the point at 10 m depth below MSL, permits to obtain the overtopping discharge results along the 20 years period. In particular, one is interested in the results of Elsa and Hercules storm since they are the same wave conditions input of XBeach simulations.

The variation of the mean overtopping discharge q ($m^3/s/m$) during Elsa and Hercules storm is presented in Figure 5.5.

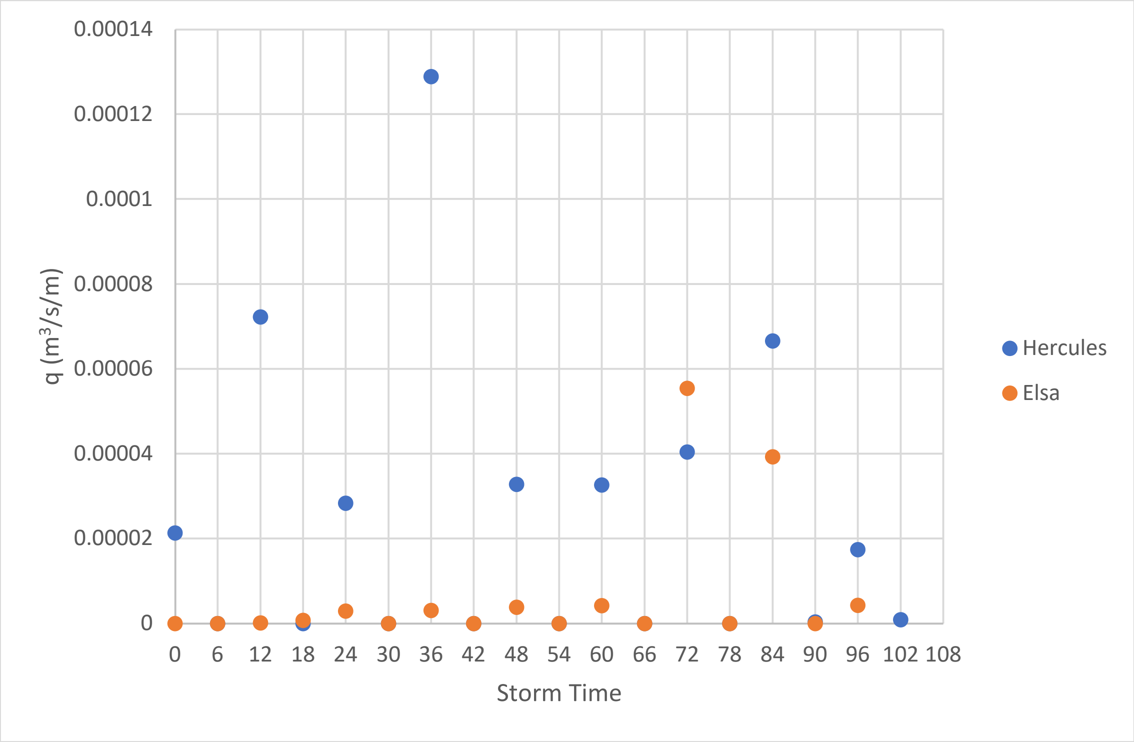


Figure 5.5 - q results during Elsa and Hercules storm using the empirical formula.

5.4.XBeach

5.4.1. Non-hydrostatic setup

5.4.1.1. Sensibility tests

The sensibility tests were made to observe how the model reacts and the results changes according to the modification of each model parameter. The analysis of the results was based on the runup maximum extension from the structure crest and the mean overtopping discharge at the crest of the structure. The range of values for the parameters tested was selected according to the XBeach manual (Deltares, 2018), except for the bathymetric resolution.

The wave conditions were simulated with a single parametric spectrum with the data related to the 22nd of December of 2019 at 01h (Table 4.6). During the sensibility tests, the random factor was inactive (*random*=0).

It was tested 6 different resolution of the bathymetry, varying from 0.5 m to 5 m. The parameters tested were bathymetric resolution, *nhlay*, *CFL*, *bedfriccoef* and *maxbrsteep*.

The results show that the bathymetric resolution has an influence on the runup extension and mean overtopping discharge. Both runup extension and overtopping discharge tend to have lower values as the grid spacing increases. The resolutions of 2 m and 5 m demonstrated no mean overtopping discharge (Figure 5.6).

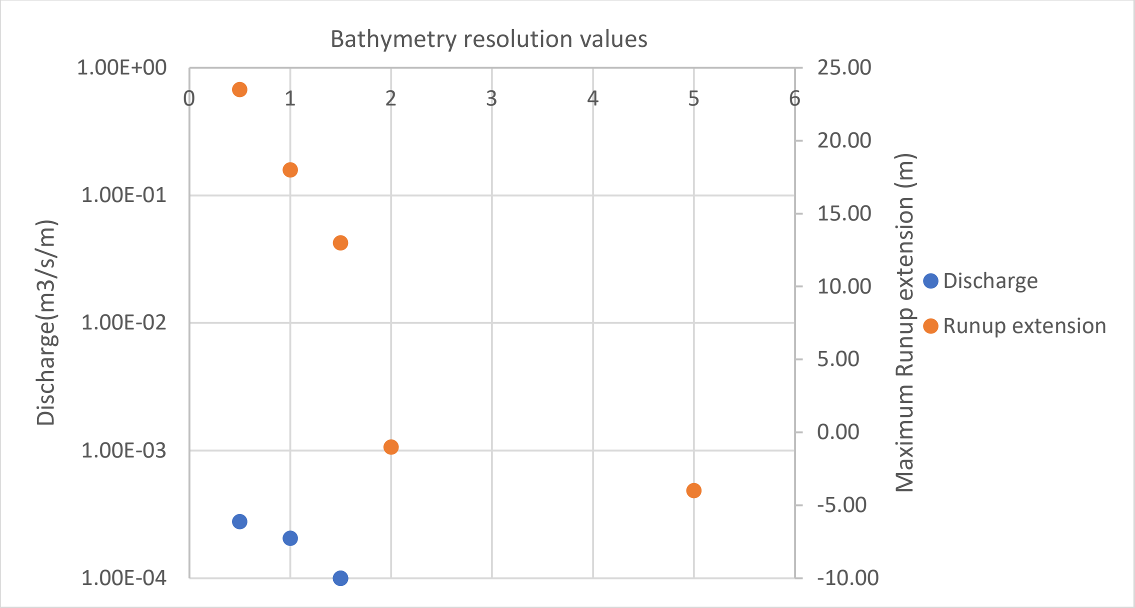


Figure 5.6 - Bathymetric resolution's sensitivity test results from the hydrodynamic run. Discharge is evaluated at the structure crest, and the runup distance is in relation to the structure crest.

Several values of *nhlay* were considered, namely 0.1, 0.11, 0.125, 0.143, 0.166, 0.2, 0.25, 0.33, 0.5. The values of the parameter *nhlay* influences in both mean overtopping discharge and runup extension (Figure 5.7). In relation to the mean overtopping discharge, q, and for lower *nhlay*, there is an increase of the q values as the parameters *nhlay* increases from 0.1 to 0.166. For higher values of *nhlay,* there is a stabilization of q. In general, the runup extension values show a positive correlation with the increase of values tested of *nhlay*.

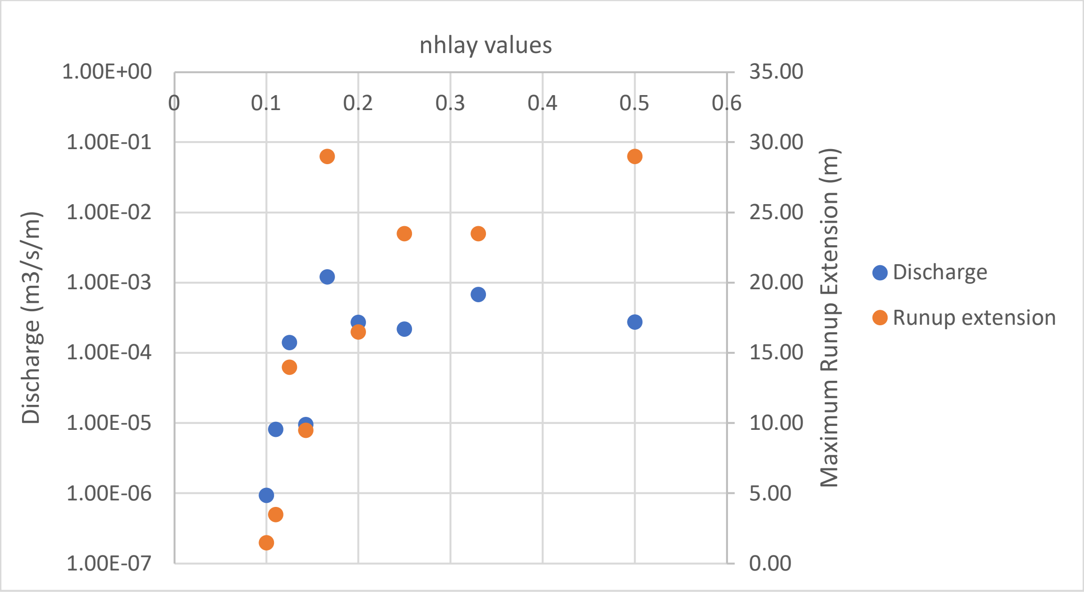


Figure 5.7 - *nhlay*'s sensitivity test results from the hydrodynamic run. Discharge is evaluated at the structure crest, and the runup distance is in relation to the structure crest.

The variation of *CFL* between 0.2 and 0.8 showed almost no influence on the results for the mean overtopping discharge (Figure 5.8). The values of q are of the same magnitude. In relation to the runup, the variation *CFL* lead to significant changes in the maximum runup extension but without a particular relation.

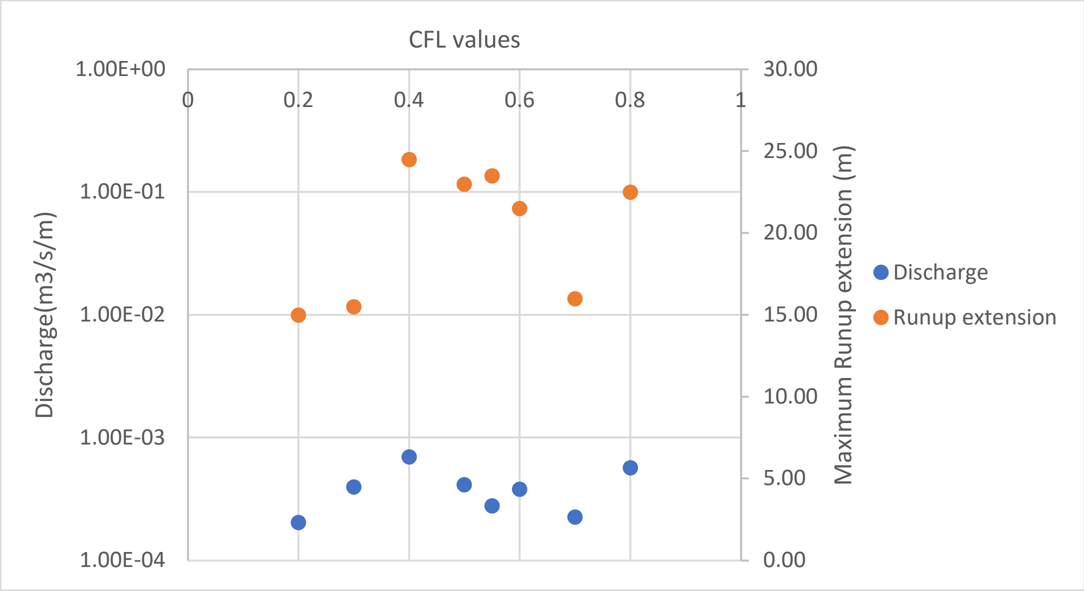


Figure 5.8 - *CFL*'s sensitivity test results from the hydrodynamic run. Discharge is evaluated at the structure crest, and the runup extension is in relation to the structure crest.

The *bedfriccoef* results (Figure 5.9) showed that the range of values between 0 and 0.1 have influence in both runup extension and mean overtopping discharge. For the rest higher values of *bedfriccoef*, the results of the runup extension and mean overtopping discharge were constant.

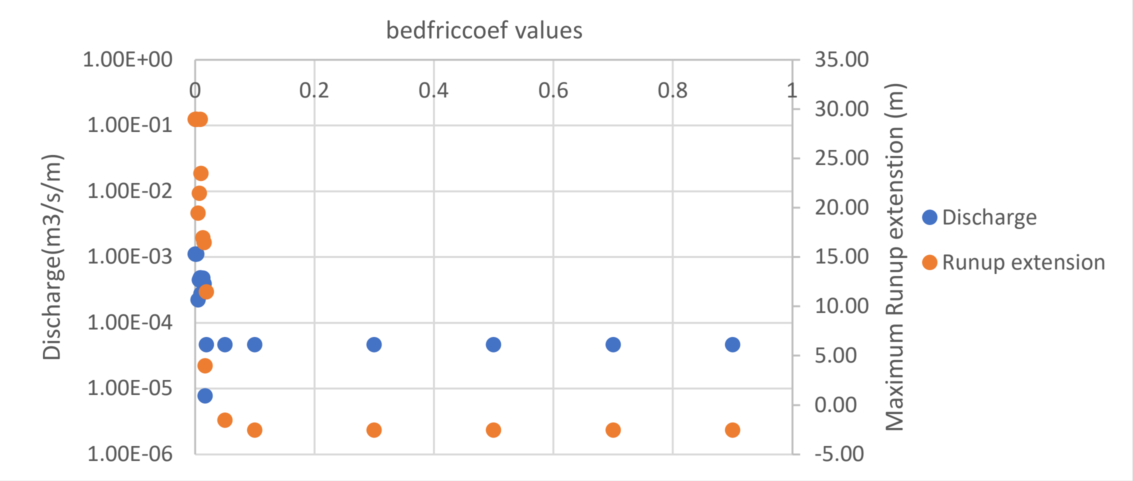


Figure 5.9 - *bedfriccoef*'s sensitivity test results from the non-hydrostatic setup. Discharge is evaluated at the structure crest, and the runup extension is in relation to the structure crest.

The *maxbrsteep* varied between 0.3 and 0.8. That variation influences both runup extension and mean overtopping discharge (Figure 5.10). In general, the results demonstrate a positive correlation with the increase of the values used in the parameter, in both cases.

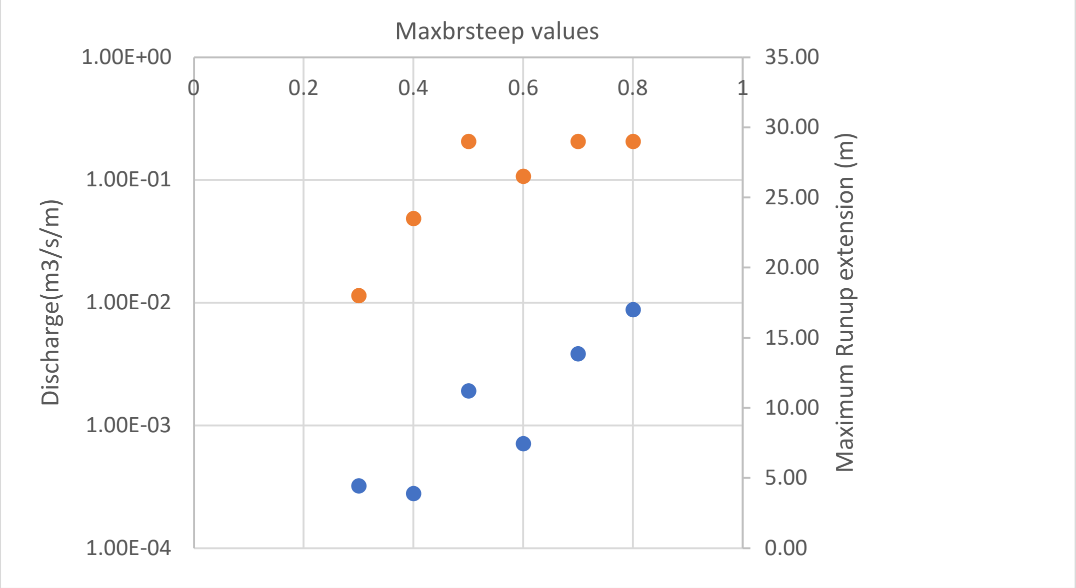


Figure 5.10 - *maxbrsteep*'s sensitivity test results from the non-hydrostatic setup. Discharge is evaluated at the structure crest, and the runup extension is in relation to the structure crest.

5.4.1.2. Calibration

As mentioned, the Elsa storm data was used to calibrate the non-hydrostatic setup. The model results were compared with:

a) Estimated (*in situ*) maximum runup extension reached at the São Pedro de Moel beach, that was visible in the RTP news (Figure 3.3). It was established that the maximum runup reaches the point marked by the arrow in Figure 3.3 (RTP) (~18 m from the crest of the structure).

b) The mean overtopping discharge values from CEM table (Table 4.5) that can put in danger people and vehicles. The mean overtopping discharge at the crest of the structure computed by CEM table was between 10^{-3} and 10^{-4} $m^3/s/m$. This discharge values showed to be dangerous for the population or vehicles near the berm of the structure but caused no damages to infrastructures.

From the sensibility tests, it was decided to use of 0.5 m for the bathymetry resolution. With this resolution defined, the first tests were performed with the default values of the parameters. During the calibration, the *random* factor was on. This factor causes randomness of waves during the runs. That can cause the results from two different runs using the same inputs to be different. For that reason, each test was run ten times. The final results presented here are the average of the ten model runs.

The results of those first tests were lower than the estimated values. So, it was necessary to test and try different values for the *maxbrsteep*, *bedfriccoef* and *nhlay* (all the other values remain as default values). The combination of parameters that gave better results were *bedfriccoef*=0.0195 *nhlay=0.33* and *maxbrsteep*=0.6. The results from this combination were the ones closer to the estimated values mentioned above (Table 5.7).

Table 5.7 - Comparison between results from the model (runup extension related to the structure crest and the mean overtopping discharge at the structure crest (Disch)) against the estimated values for Elsa storm.

	Runup landward extension form the structure crest (m)	**Mean overtopping Discharge($m^3/s/m$)**
Estimated	~18	10^{-4} - 10^{-3}
Model Result	16.1	9.74×10^{-4}

5.4.1.3. Validation

The validation was done using Hercules storm data. For this validation, the *in situ* estimated values were obtained by the analysis of videos available on the internet for the period of Hercules storm. The estimated runup extension value was ~29 m which corresponds to a point near the houses (last point of the bathymetric file). The mean overtopping discharge values were considered to be dangerous to drive at any speed and could cause structural damage ($\geq 10^{-3}$ $m^3/s/m$).

The simulation of the Hercules storm considered the same final parameters used during the calibration. In this case, the obtained results were similar to the estimated ones (Table 5.8).

Table 5.8 - Comparison between results from the model (runup extension related to the structure crest and the mean overtopping discharge at the structure crest (Disch)) against the estimated values for the Hercules storm.

	Runup landward extension form the structure crest (m)	**Mean overtopping Discharge($m^3/s/m$)**
Estimated	~29 (maximum)	$\geq 10^{-3}$
Model Result	27.9	5.15×10^{-3}

5.4.1.4. Model Results vs Empirical Results

In this section, the results for the mean overtopping discharge at the crest of the structure, from the XBeach non-hydrostatic setup and the empirical formula are compared, for the Hercules and Elsa storm.

The wave conditions were the same for both the empirical formula and XBeach. The results demonstrate a lower overtopping value for the empirical formula in both storms (Table 5.9). This difference can be a consequence of the different methodologies and different detail in the beach profile.

Table 5.9 - Comparison of results from Mase et al. (2013) formula and XBeach regarding the overtopping discharge.

Storm	**Mean overtopping Discharge($m^3/s/m$)**	
	Empirical Formula	XBeach

Elsa (2019)	$4.27\text{x}10^{-06}$	$9.74\text{x}10^{-4}$
Hercules (2014)	$4.05\text{x}10^{-05}$	$5.15\text{x}10^{-3}$

5.4.2. Surf beat setup

In the surf beat setup, the main characteristic analysed was the final bed level (*zb*).

5.4.2.1. Sensibility tests

As it was done for the non-hydrostatic setup, multiple parameters were tested to see its influence on the results, in this case, changes in *zb*. For the sensibility tests, multiple parameters related to different physical processes were tested using the range of values available in the XBeach manual (Deltares, 2018), as it was mentioned before.

Like the in non-hydrostatic sensibility tests, the first parameter to be tested was the bathymetric resolution. Grid spacing from 0.5m to 5 m were considered. It was possible to visualise the differences when simulating the same storm using the different bathymetric resolution (Figure 5.11). The bathymetric resolution that showed less quality of data, compared to the others, was the 5 m resolution. For the other grid resolutions, the differences are not so evident.

So, two factors were crucial for deciding which resolution to use, the quality of resolution and time consumed to simulate. The highest the resolution, the higher the quality of data but computation time increases also significantly. By the conjunctions of those two factors, the bathymetric resolution used was the 1-meter resolution. Although it was not the highest resolution, it showed similar results when compared with 0.5 m resolution, and it was more time-efficient (1 m =504 seconds, 0.5 m =3631 s) (Figure 5.12).

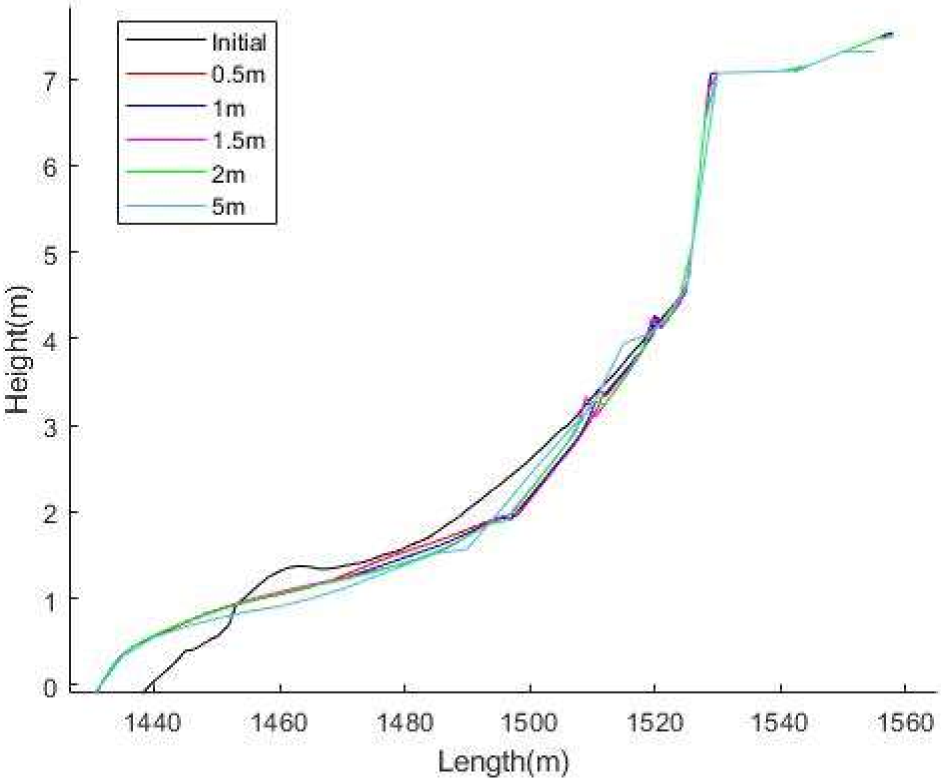


Figure 5.11 - Bathymetric resolution sensibility test results (*zb*).

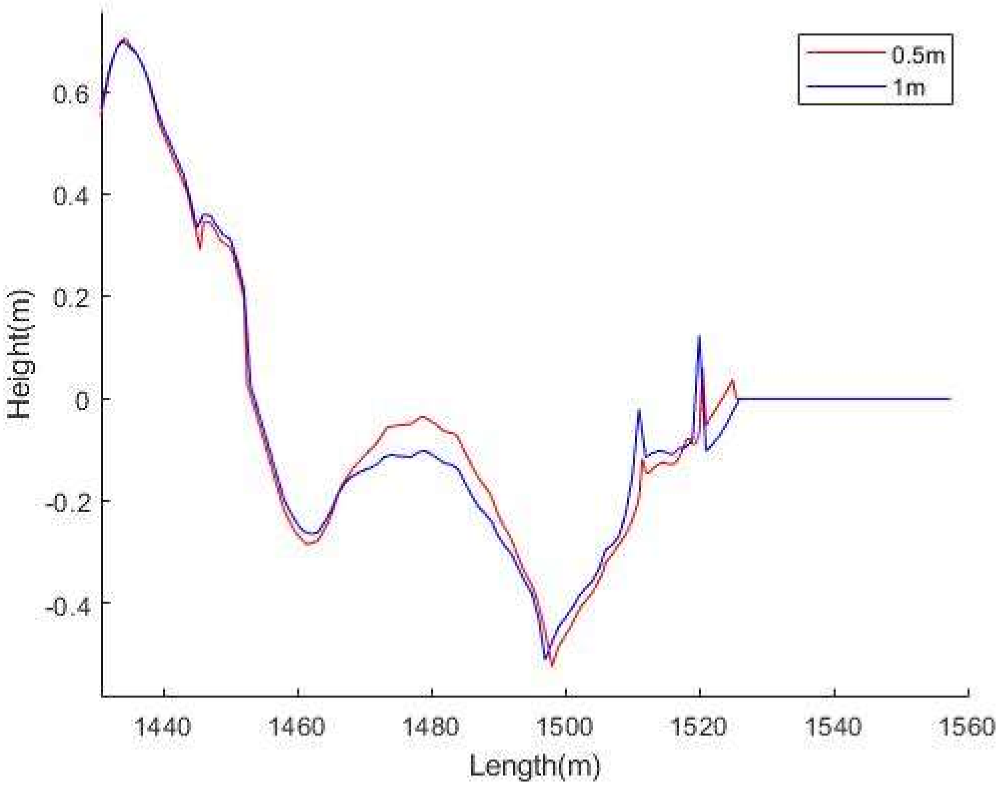


Figure 5.12 - Differences between Initial and Result profiles for the higher bathymetry resolution. This graph was used to choose the resolution used for all the remaining XBeach runs.

After the bathymetric resolution, the sensibility tests for the other parameters were performed. One parameter that showed influence in the results was the *morfac* (Figure 5.13). The results showed that *morfac* values of 1, 5 and 10 lead to differences in the final results. Otherwise, *morfac* values equal or above 50 does not influence the final results and there are no changes from the initial profile. Note also that this parameter influences the simulation time. The usage of lower values of *morfac* results in a more realistic simulation, but with lower values, the longer the simulation takes to run. To have a more realistic and time-efficient simulation, the *morfac* value used in the rest of the work equal to 5.

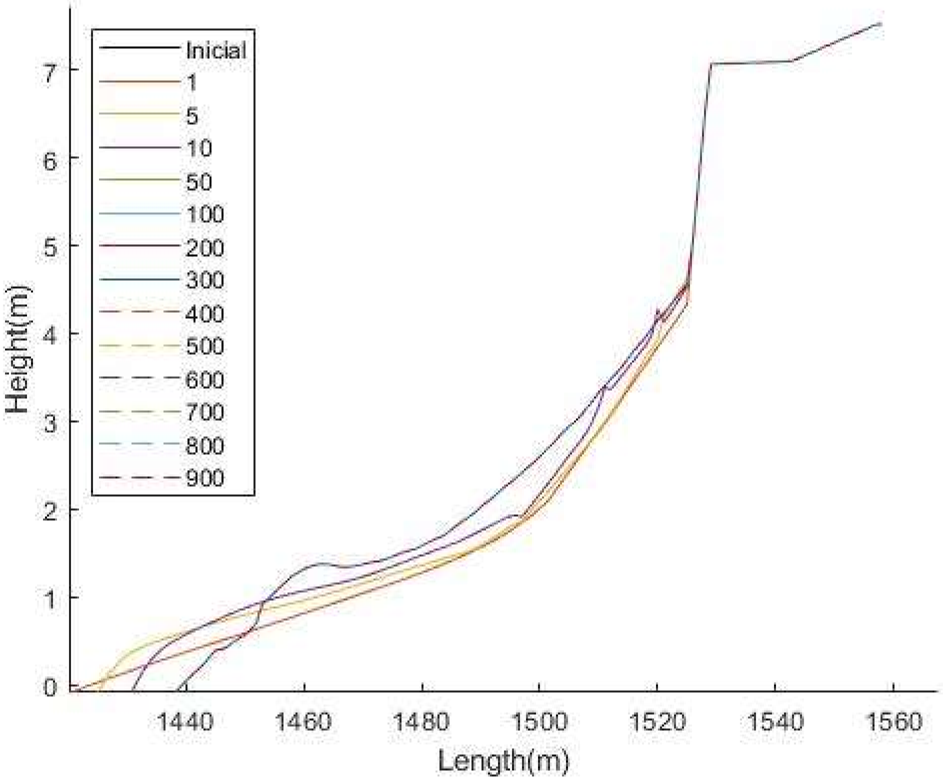


Figure 5.13 - Sensitivity test for the parameter *morfac*.

The variation of the parameter *facua* (ranging from0.1 to 1) lead to significant changes in the final bed level, Figure 5.14. It is clear that the final profiles depend on *facua* values.

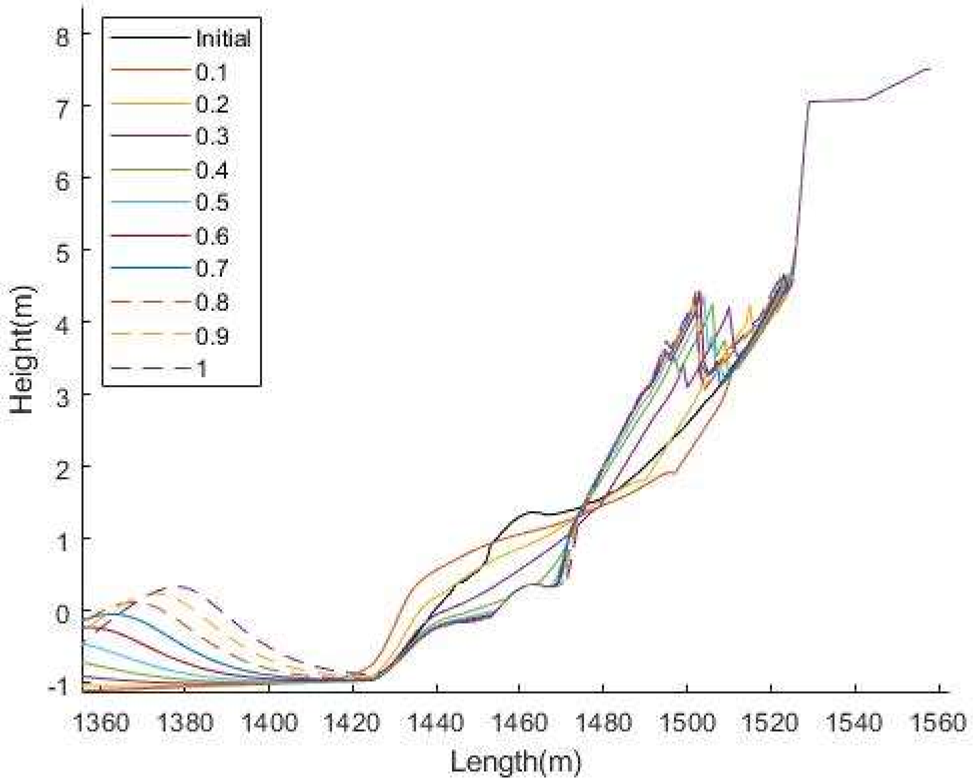


Figure 5.14 - *facua*'s sensibility test results on the bed level (*zb*).

The other parameters that influence the final result of *zb* are *alpha*, *beta*, *delta, gamma*, *n, lws* and *bermslope*.

In contrary, the variation of the parameters *gammax*, *tsmin*, *lws, dryslp*, *dzmax*, *hswitch*, *wetslp*, *CFL*, *dtheta_s*, *thetamax* and *thetamin* does not lead to significant changes in the *zb*. In fact, for certain parameters, there are no changes (as an example for *dzmax* in Figure 5.15 where there were no differences using the different values).

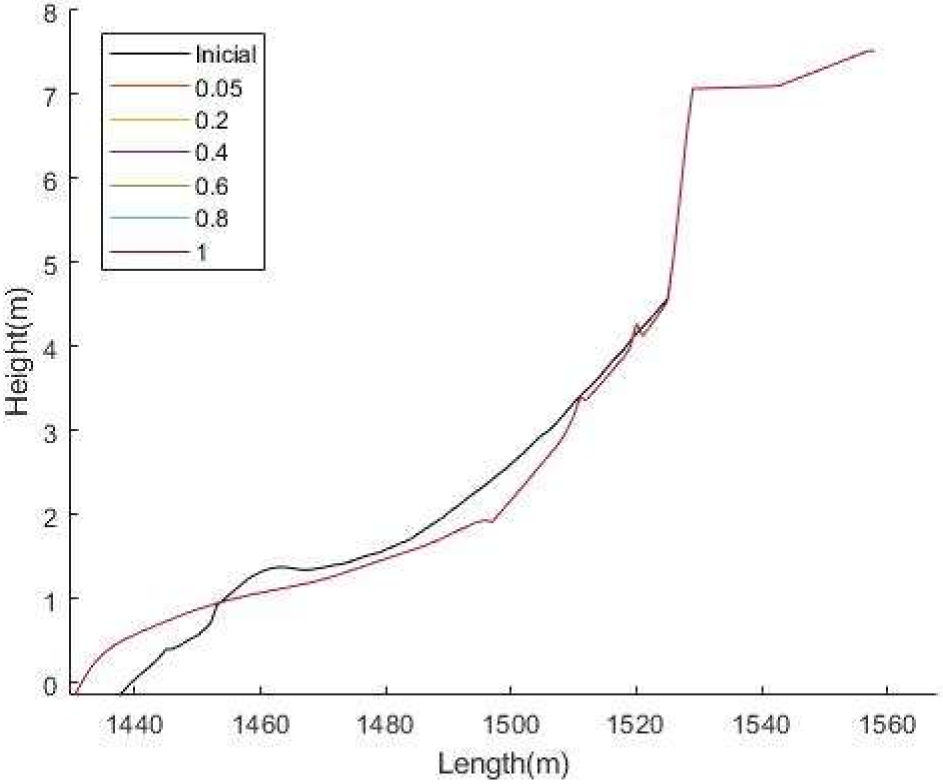


Figure 5.15 - *dzmax*'s sensibility test results on the bathymetry(*zb*). In this test, there were no changes by using different values.

5.4.2.2. Calibration

Considering the February storm (2019), the calibration was done by comparing the model results with the post-storm profile obtained by LNEC on the 19th of February 2019 (Figure 5.16). This comparison was realised firstly visually, and for better detail, the best visual results were compared using the BSS formula.

The comparison was only made for values above the mean sea level because it is where measured data were obtained before and after the February storm. For the calibration, it was also necessary to indicate the mean grain diameter (*D50*), which for São Pedro de Moel was 0.00032 m. It must be stated that the post-storm profile available denotes beach recovery.

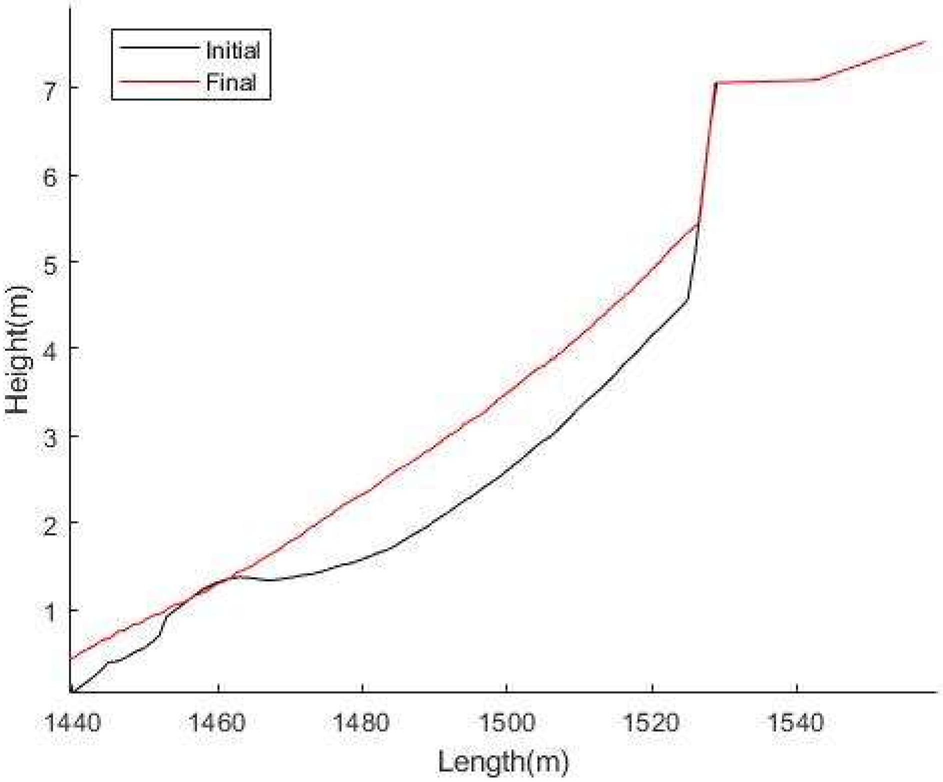


Figure 5.16 - Beach profiles made by LNEC from 12th of February (Initial) and the 19th of February (Final). The results from the morphodynamic runs were compared to the final profile.

The first tests were performed with the default values for the different parameters, except for *morfac* one (*morfac*=5). The results obtained show that the model parameters needed some adjustments/calibration (Figure 5.17) to reproduce field results since almost no changes were observed.

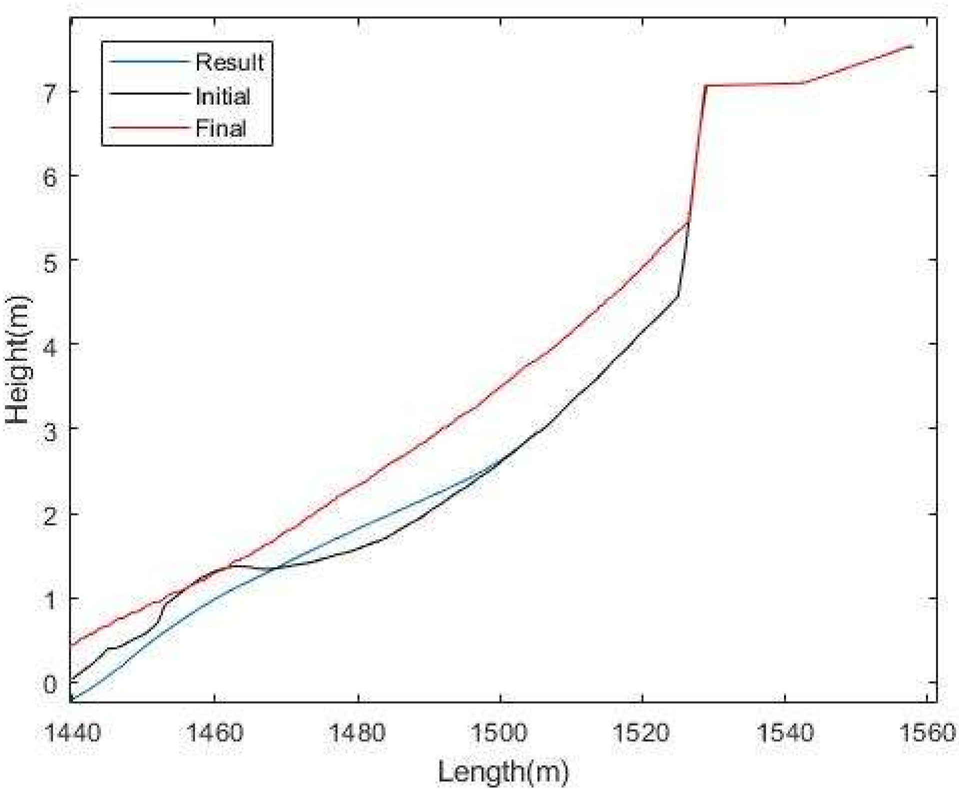


Figure 5.17 - Results of the run with the default parameters compared with the initial and final beach profiles.

The results obtained with the model considering a set of parameters that lead to the closest results to the post-storm profile is represented in Figure 5.18. In this case, the values of *alpha*=0.8, *beta*=0.8, *gamma*=0.8, *bermslope*=0.1*, facua*=0.15, *morfac*=5, were considered. The obtained BSS is very high, reproducing well the beach recovery mimicking the post-storm observations.

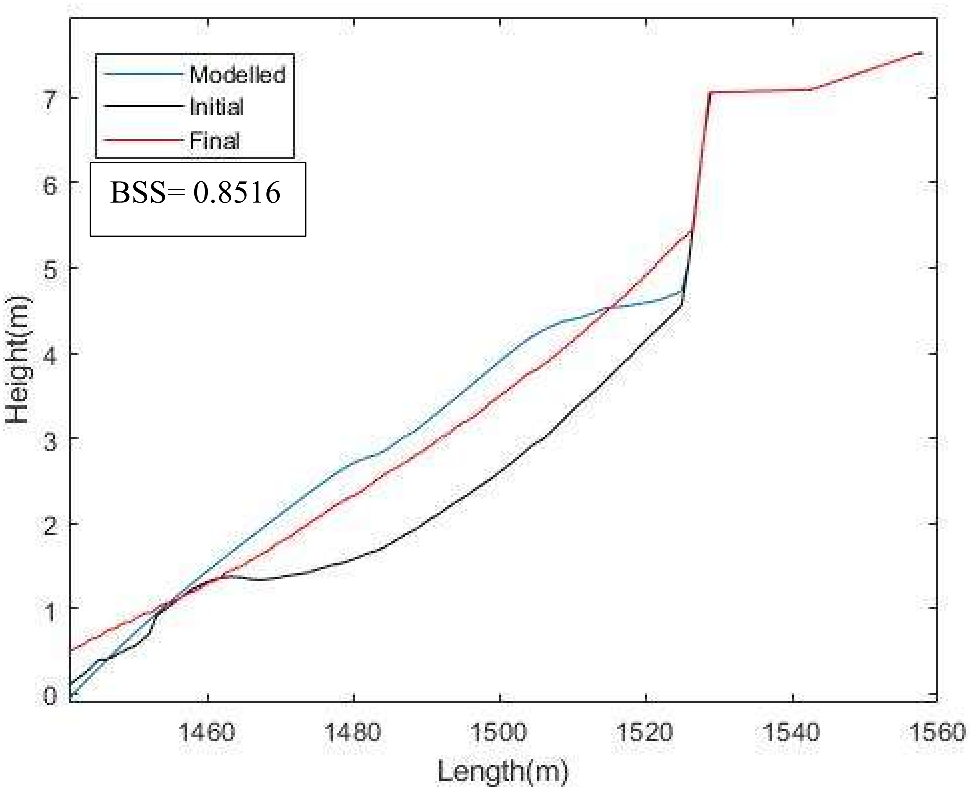


Figure 5.18 - Best results from calibration runs (closest to the post-storm profile). BSS is the Brier Skill Score from the test.

5.4.2.3. Application to Hercules storm

With the Hercules storm, it was not possible to have a validation of the XBeach morphological behaviour since there was no information about the post-storm beach profile. So, it was only demonstrated the results for the simulation of the Hercules storm using the parameters from the calibration (Figure 5.19). The simulation resulted in beach accretion, a result that is opposite to the field observations, newspapers and video footages records, all showing strong erosion. It must be noticed that, according to the post-storm profile used for calibration, the beach showed recovery for that particular storm (February 2019) either because it occurred beach accretion or because there was a strong recovery after the storm (not possible to be defined).

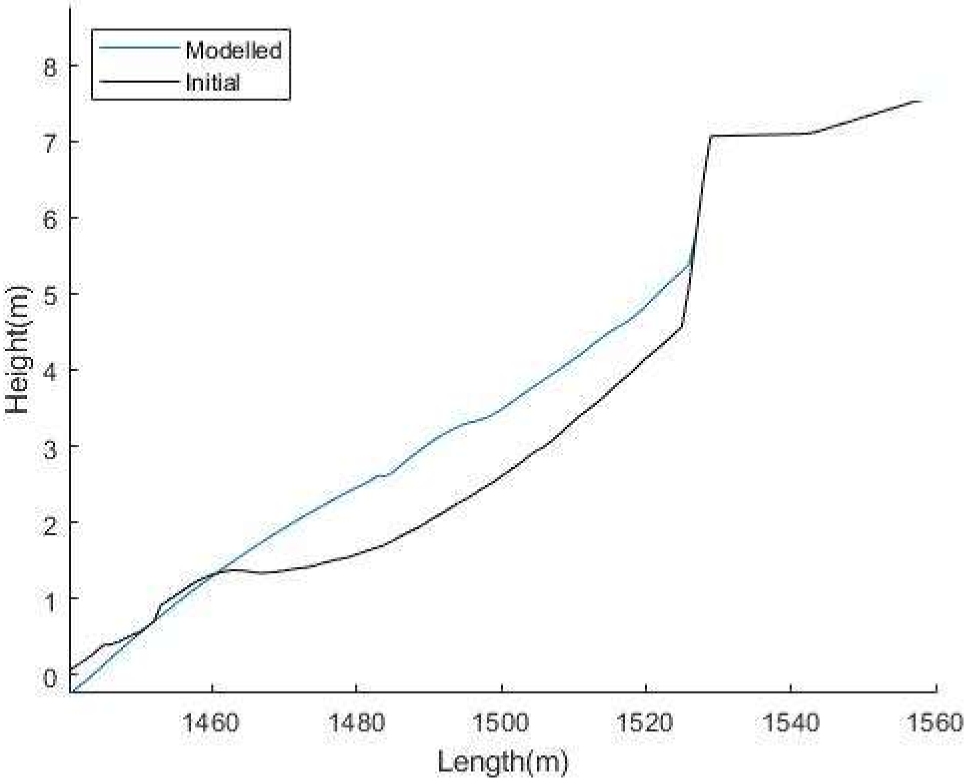


Figure 5.19 - Result from the simulation of the Hercules storm using the calibration’s parameter values.

6. Discussion

The main objective of this work was to model the effects of overtopping and morphological evolution associated with coastal storms at São Pedro de Moel beach using XBeach.

The used model (XBeach) was divided into two setups, the non-hydrostatic setup that was focused on the overtopping events and the surf beat setup that was focused on the morphological evolution of the beach. For each setup, sensibility tests were performed for some intrinsic parameters using the range of values demonstrated in the manual. Those sensitivity tests were done to see which parameters had more influence in the model's results.

The non-hydrostatic setup was the first to be analysed in this work. In this setup, the characteristics that were used to analyse the results were the runup extension from the crest of the structure and the mean overtopping discharge at the crest of the structure. The sensibility tests executed for this case were bathymetric resolution, *nhlay*, *CFL*, *bedfriccoef* and *maxbrsteep*. The bathymetric resolution showed influence in both mean overtopping discharge and runup extension, having lower values of runup and overtopping with lower resolution. The parameter *nhlay* also showed influence in both overtopping discharge and runup extension, in this case, the discharge results had higher variation in the lower values tested and tended to stabilise with higher values. The runup extension shows a positive correlation with the increase of the tested values. *CFL* results showed no significant changes when analysing the mean overtopping discharge. In the runup extension results, *CFL* demonstrated changes using the different values but there was no particular correlation between the results and the tested values. The *bedfriccoef* only show variation in values between 0 and 0.1, after 0.1 the results are constant and have no alteration. The final parameter tested was the *maxbrsteep*. This parameter showed influence in both runup extension and overtopping discharge. The *maxbrsteep*'s results demonstrated a positive correlation with the increase of the value used in the parameter. The results from the sensitivity tests determined the parameters that were adjusted for the calibration. In this case, the only parameter that did not suffer any changes during the calibration was *CFL*. The other four parameters were changed until the model reached good results.

The calibration of the non-hydrostatic setup was done for Elsa storm, and the used information about this storm was from non-scientific sources. With the non-scientific information, it was estimated that during the storm the maximum runup extension was ~18 m from the crest of the structure and the mean overtopping discharge at the crest was in an interval of 10^{-4} to 10^{-3} $m^3/s/m$. The process of calibration showed that the test with the best results had the following values for the parameters *bedfriccoef*=0.0195 *nhlay=0.33* and *maxbrsteep*=0.6. The model results using those parameter values were 16.1 m for runup extension and 9.74×10^{-4} $m^3/s/m$ for the mean overtopping discharge.

After the calibration, the non-hydrostatic setup was validated using the Hercules storm. The estimated values for this storm (~29 m for runup extension and $\geq 10^{-3}$ for mean overtopping discharge) were also obtained from non-scientific sources. Using the calibrated setup, the results were close to the estimated values, runup equal to 27.9 m and mean overtopping discharge was equal to 5.15×10^{-3} $m^3/s/m$. The validation of the model is highly valuable since it allows the further use of the setup to estimate discharge values and runup extension to other storms at the study area. However, the usage of non-scientific information was a limitation cause the model to be not completely accurate. So, this setup can be improved even further to replicate overtopping events during storms with the usage of scientific data during the calibration and validation of the model.

The mean overtopping discharge results from the non-hydrostatic setup were compared with the results from an empirical formula (Mase et al., 2013). The results from XBeach and the empirical formulas showed differences, being the overtopping discharge presented from the XBeach higher than the empirical formulas. A difference in results from XBeach and the Mase et al. empirical formula also occurred in Heleno (2017) but in that case, the empirical formula had higher values for mean overtopping discharge. This suggests that by validating a process-based model, the obtained values can be more accurate than using a more generic formulation.

The surf beat setup had the objective to simulate the morphological evolution of the beach during a storm. In this setup, the parameters that were observed in the sensitivity tests were *alpha*, bathymetry resolution, *bermslope*, *beta*, *CFL*, *delta*, *dryslp*, *dtheta_s*, *dzmax*, *facua*, *gamma*, *gammax*, *hswitch*, *lws*, *morfac*, *n*, *thetamax*, *thetamin*, *turb* and *wetslp*. In this case, the analysis was done to the beach profile, comparing the initial profile with the final profile (that resulted from the simulation). The parameters that showed impact in the beach profile when testing a range of values were bathymetry resolution, *morfac*, *facua*, *alpha*, *beta*, *delta, gamma*, *n, lws* and *bermslope*. The other parameters did not show significant changes to the beach profile. In Vousdoukas et al. (2011) it was also demonstrated that the parameters *facua, lws* influenced the beach profile, however, the *wetslp* also demonstrated influence which did not happen in this work.

The calibration for the surf beat setup was done by comparing the results from the simulation with the post-storm profile from the February 2019 storm. This comparison was done using the Brier Skill Score (BSS) that was previously used in other studies regarding the XBeach (Elsayed and Oumeraci, 2017; Roelvink et al., 2009; Vousdoukas et al., 2012, 2011). The surf beat setup that had the results closer to the post-storm profile had the following parameters: *alpha*=0.8, *beta*=0.8, *gamma*=0.8, *bermslope*=0.1, *facua*=0.15, *morfac*=5, the rest that of the parameters that were considered sensitive for this setup had the default values as "best values". The surf beat setup demonstrates the limitations of applying a morphodynamic model without proper validation and calibration. The available data for this work was associated with a storm that caused beach recovery, showing accumulation on the post-storm profile regarding the February 2019 storm. The calibration was done using the only available data, and thus the model setup is tuned towards beach recovery. When applied to the Hercules storm, it also gave beach accretion (Figure 5.19), not allowing to mimic the generic observation of erosion caused by that storm. Thus, model calibration requires adequate data sets and a strong field effort, without which the obtained values are not trustable.

In addition to the limitation mentioned before the bathymetric file with the information from the 3 sources shows an abnormal profile in the transition area (Figure 4.1). That could cause a limitation especially in the surf beat setup that was focused on the morphological evolution of the beach.

7. Conclusion

The occurrence of a coastal storm can have negative effects in an area due to associated events like flooding and erosion. Due to the exposition to coastal storms, the Portuguese coast have experienced those negative effects. The modelling of coastal storms can provide information to predict the impacts associated with coastal storms like overtopping and coastal evolution. In the present work, a numerical model called XBeach was used to simulate coastal evolution and overtopping associated with storm events at São Pedro de Moel beach.

The XBeach was "divided" into two setups, one for the overtopping events (non-hydrostatic setup) and the other to evaluate the morphological evolution of the coast (surf beat setup). For each setup, multiple parameters were tested to see how the results would respond to their changes, the setups were also calibrated using the tested parameters and the calibrated setups were used to simulate past storms. The non-hydrostatic setup was also compared to an empirical formula (Mase et al., 2013).

The sensibility test for the non-hydrostatic setup demonstrated that the parameters that caused most changes in the final results were bathymetric resolution, *nhlay.*, *bedfriccoef* and *maxbrsteep*. Those parameters were adjusted until the results from the model reached the estimated results related to the Elsa storm (2019). The calibration was then tested by simulating the Hercules storm (2014). The non-hydrostatic setup showed that it is possible to simulate overtopping events at São Pedro de Moel with good accuracy when compared to estimates. Nevertheless, the non-hydrostatic model still presented limitations due to the lack of quantitative information on overtopping events. Improvements will require in situ measurements using current meters, videos or holding tanks.

For the surf beat setup, it was also performed different sensibility tests, the results from those tests showed that the parameters that cause more changes in the beach profile were bathymetry resolution, *morfac*, *facua*, *alpha*, *beta*, *delta, gamma*, *n, lws* and *bermslope*. The model was calibrated using the post-storm beach profiles from a storm that occurred in February 2019. In fact, that storm caused accumulation of sediment (recovery). The surf beat setup provided erroneous results for the Hercules Storm simulation as a consequence of the performed calibration (against a post-storm recovery profile). This demonstrates the need for having suitable field data immediately before and after storms. It also suggests that morphological data from low energy storms (with smaller erosion and quick recovery) might not be enough to promote adequate calibration for high energy events (like Hercules).

It is important to emphasise the need for field data with good quality. Without this good quality data, it is hard to develop a proper model setup that can be used as a tool for coastal management decisions.

8. References

Andrews, D.G., Mcintyre, M.E., 1978. An exact theory of nonlinear waves on a Lagrangian-mean flow. J. Fluid Mech. 89, 609–646. https://doi.org/10.1017/S0022112078002773

Bertin, X., Prouteau, E., Letetrel, C., 2013. A significant increase in wave height in the North Atlantic Ocean over the 20th century. Glob. Planet. Change 106, 77–83. https://doi.org/10.1016/j.gloplacha.2013.03.009

Booij, N., Holthuijsen, L.H., Ris, R.C., 1997. The "Swan" Wave Model for Shallow Water, in: Coastal Engineering 1996. American Society of Civil Engineers, New York, NY, pp. 668–676. https://doi.org/10.1061/9780784402429.053

Bricheno, L.M., Wolf, J., 2018. Future Wave Conditions of Europe, in Response to High-End Climate Change Scenarios. J. Geophys. Res. Ocean. 123, 8762–8791. https://doi.org/10.1029/2018JC013866

Carrasco, A.R., Reis, M.T., Neves, M.G., Ferreira, Ó., Matias, A., Almeida, S., 2014. Overtopping hazard on a rubble mound breakwater. J. Coast. Res. 70, 247–252. https://doi.org/10.2112/si70-042.1

Carvalho, M., Capitão, R.P., 1995. Extreme wave heights off the western coast of Portugal. Proc. Int. Conf. Offshore Mech. Arct. Eng. - OMAE 2, 41–49.

Ciavola, P., Ferreira, O., Van Dongeren, A., Van Thiel de Vries, J., Armaroli, C., Harley, M., 2014. Prediction of Storm Impacts on Beach and Dune Systems. Hydrometeorol. Hazards Interfacing Sci. Policy 9781118629, 227–252. https://doi.org/10.1002/9781118629567.ch3d

Costa, M., Esteves, R., 2009. Clima de agitação marítima na costa oeste de portugal continental. Comun. das XI Jornadas Técnicas Eng. Nav. 15p.

Costa, M., Silva, R., Vitorino, J., 2001. Contribuição Para O Estudo Do Clima De Agitação Marítima Na Costa Portuguesa. 2^{a}s Jornadas Port. Eng. Costeira e Portuária, AIPCN/PIANC Secção Port. 20.

Deltares, 2018. XBeach Documentation: Release XBeach v1.23.5527 XBeachX FINAL.

Elsayed, S.M., Oumeraci, H., 2017. Effect of beach slope and grain-stabilization on coastal sediment transport: An attempt to overcome the erosion overestimation by XBeach. Coast. Eng. 121, 179–196. https://doi.org/10.1016/j.coastaleng.2016.12.009

Fanti, V., 2019. Application of Snl-Swan Model on the Effect of Wave Farms in the Wave Propagation.

Ferreira, Ó., Reis, M.T., Carrasco, A.R., Neves, M., Neves, D., Didier, E., 2013. Small overtopping at Albufeira harbour: field measurements and modelling.

Fortes, C.J., Pinheiro, L., Palha, A.C., 2007. O pacote sopro_3.1: evoluções recentes 1–21.

Fortes, C.J.E.M., Reis, M.T., Neves, P., 2013. Programa Calcula_Runup_Galgamento_Mase.f.

Harley, M., 2017. Coastal Storm Definition, in: Coastal Storms. John Wiley & Sons, Ltd, Chichester, UK, pp. 1–21. https://doi.org/10.1002/9781118937099.ch1

Harter, C., Figlus, J., 2017. Numerical modeling of the morphodynamic response of a low-lying barrier island beach and foredune system inundated during Hurricane Ike using XBeach and CSHORE. Coast. Eng. 120, 64–74. https://doi.org/10.1016/j.coastaleng.2016.11.005

Heleno, A.J.P., 2017. Avaliação do espraiamento e inundação nas praias da Costa da Caparica: modelação com o modelo XBEACH. https://doi.org/http://hdl.handle.net/10400.21/7108

LNEC, 2019. Mosaic.pt field campaigns - Cova-Gala, Vieira and São Pedro de Moel beaches, January-March 2019.

Luis, J.F., 2007. Mirone: A multi-purpose tool for exploring grid data. Comput. Geosci. 33, 31–41. https://doi.org/10.1016/j.cageo.2006.05.005

Martinho, M.F.M.A., 2014. Avaliação e gestão de riscos em áreas litorais. Contributo para o desenvolvimento de um sistema de previsão e alerta de inundação em zonas costeiras. https://doi.org/hdl.handle.net/10362/14764

Mase, H., Kirby, J.T., 1993. Hybrid frequency-domain KdV equation for random wave transformation. Proc. Coast. Eng. Conf. 1, 474–487. https://doi.org/10.1061/9780872629332.035

Mase, H., Miyahira, A., Hedges, T.S., 2004. Random wave runup on seawalls near shorelines with and without artificial reefs. Coast. Eng. J. 46, 247–268. https://doi.org/10.1142/S0578563404001063

Mase, H., Tamada, T., Yasuda, T., Hedges, T.S., Reis, M.T., 2013. Wave Runup and Overtopping at Seawalls Built on Land and in Very Shallow Water. J. Waterw. Port, Coastal, Ocean Eng. 139, 346–357. https://doi.org/10.1061/(ASCE)WW.1943-5460.0000199

McGranahan, G., Balk, D., Anderson, B., 2007. The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. Environ. Urban. 19, 17–37. https://doi.org/10.1177/0956247807076960

Neves, P., Poseiro, P., Fortes, C.J.E.M., Reis, T., Capitão, R., Antunes do Carmo, J., Raposeiro, P., Ferreira, J.C., 2013. Aplicação da metodologia de avaliação do risco de inundação/galgamento na praia de São João da Caparica. 8ªs JPECP. https://doi.org/: https://www.researchgate.net/publication/258149983 Aplicação

Oliveira, F.S.D.B.F. De, 2013. EROSÃO DE DUNAS DURANTE TEMPESTADES: APLICAÇÃO DE DIFERENTES MODELOS NUMÉRICOS. Congr. Métodos Numéricos en Ing.

Oliveira, F.S.D.B.F. De, 2012a. Erosão de dunas com os modelos Xbeach e Litprof. Rev. Gestão Costeira Integr. 12, 195–222. https://doi.org/10.5894/rgci314

Oliveira, F.S.D.B.F. De, 2012b. Modelação numérica da erosão de dunas durante tempestades.

Oliveira, F.S.D.B.F. De, 2011. Avaliação Do Modelo De Erosão De Praias E Dunas Xbeach : Resultados Preliminares 1–18.

Oliveira, F.S.B.F., Freire, P.M.S., Larangeiro, S.H.C.D., 2002. Characterisation of the dynamics of Figueira da foz beach, Portugal. J. Coast. Res. 36, 552–563. https://doi.org/10.2112/1551-5036-36.sp1.552

Ozkan, C., Perez, K., Mayo, T., 2020. The impacts of wave energy conversion on coastal morphodynamics. Sci. Total Environ. 712, 136424. https://doi.org/10.1016/j.scitotenv.2019.136424

Phillips, B.T., Brown, J.M., Bidlot, J.R., Plater, A.J., 2017. Role of beach morphology in wave overtopping hazard assessment. J. Mar. Sci. Eng. 5, 1–18. https://doi.org/10.3390/jmse5010001

Pinheiro, L., Fortes, C., Santos, J., Neves, M., Capitão, R., Braga Coli, A., 2005. SOPRO - Caracterização da agitação marítima. Aplicações.

Pires, B.A.A., 2017. Vulnerabilidade e Riscos de Galgamento oceânico em Litorais Baixos e Arenosos.

Plomaritis, T.A., Costas, S., Ferreira, Ó., 2018. Use of a Bayesian Network for coastal hazards, impact and disaster risk reduction assessment at a coastal barrier (Ria Formosa, Portugal). Coast. Eng. 134, 134–147. https://doi.org/10.1016/j.coastaleng.2017.07.003

Poelhekke, L., Jäger, W.S., van Dongeren, A., Plomaritis, T.A., McCall, R., Ferreira, Ó., 2016. Predicting coastal hazards for sandy coasts with a Bayesian Network. Coast. Eng. 118, 21–34. https://doi.org/10.1016/j.coastaleng.2016.08.011

Pullen, T., Allsop, N.W.H., Bruce, T., Kortenhaus, A., Schüttrumpf, H., der Meer, J.W., 2007. EurOtop, European Overtopping Manual-Wave overtopping of sea defences and related structures: assessment manual. Coast. Eng. 178.

Richardson, D.S., Bidlot, J., Ferranti, L., Haiden, T., Hewson, T., Janousek, M., Prates, F., Vitart, F., 2013. Evaluation of ECMWF forecasts, including 2012--2013 upgrades 55.

Roelvink, D., McCall, R., Mehvar, S., Nederhoff, K., Dastgheib, A., 2018. Improving predictions of swash dynamics in XBeach: The role of groupiness and incident-band runup. Coast. Eng. 134, 103–123. https://doi.org/10.1016/j.coastaleng.2017.07.004

Roelvink, D., Reniers, A., van Dongeren, A., van Thiel de Vries, J., McCall, R., Lescinski, J., 2009. Modelling storm impacts on beaches, dunes and barrier islands. Coast. Eng. 56, 1133–1152. https://doi.org/10.1016/j.coastaleng.2009.08.006

Sallenger, A.H., 2000. Coastal of Florida Summer Storm Impact Scale for Barrier Islands. Coast. Educ. Res. Found. Inc. 16, 890–895.

Santos, Â., Mendes, S., Corte-Real, J., 2014. Impacts of the storm Hercules in Portugal, Finisterra. https://doi.org/10.18055/Finis6468

Saville, Jr., T., 1957. WAVE RUN-UP ON COMPOSITE SLOPES. Coast. Eng. Proc. 1, 41. https://doi.org/10.9753/icce.v6.41

Silva, D.M.F., Fortes, C.J., Reis, M.T., Carmo, J.S.A. do, Simões, A., Rodrigues, C., 2012. Avaliação do galgamento de estruturas portuárias: porto de Ponta Delgada. Rev. Recur. Hídricos 33, 37–51. https://doi.org/10.5894/rh33n2-3

Suh, S.-W., Kim, M.-J., Kim, H.-J., 2017. Prediction of Sand Beach Variations by

Coupling of Hydrodynamic and Morphological Models during Extreme Storms. J. Coast. Res. 79, 284–288. https://doi.org/10.2112/si79-058.1

Tamada, T., Tezuka, T., Inoue, M., 2002. EXPERIMENTAL STUDIES ON THE CHARACTERISTICS OF WAVE OVERTOPPING ON GENTLE SLOPE-TYPE SEAWALLS. Proc. Civ. Eng. Ocean 18, 239–244. https://doi.org/10.2208/prooe.18.239

The SWAN team, 2019. Scientific and tehcnical documentation, SWAN Cycle III version 41.31A. https://doi.org/10.1007/s13398-014-0173-7.2

Troch, P., Geeraerts, J., Van de Walle, B., De Rouck, J., Van Damme, L., Allsop, W., Franco, L., 2004. Full-scale wave-overtopping measurements on the Zeebrugge rubble mound breakwater. Coast. Eng. 51, 609–628. https://doi.org/10.1016/j.coastaleng.2004.06.004

USACE, 2002. Coastal Engineering Manual. Coast. Eng. Man. 1100, 1–62.

van der Meer, J.W., Allsop, N.W.H., Bruce, T., De Rouck, J., Kortenhaus, A., Pullen, T., Schüttrumpf, H., Troch, P., Zanuttigh, B., 2018. EurOtop.

Van Dongeren, A., Bolle, A., Vousdoukas, M.I., Plomaritis, T., Eftimova, P., Williams, J., Armaroli, C., Idier, D., Van Geer, P., Van Thiel de Vries, J., Haerens, P., Taborda, R., Benavente, J., Trifonova, E., Ciavola, P., Balouin, Y., Roelvink, D., 2009. 82. MICORE: DUNE EROSION AND OVERWASH MODEL VALIDATION WITH DATA FROM NINE EUROPEAN FIELD SITES, in: Proceedings of Coastal Dynamics 2009. WORLD SCIENTIFIC, pp. 1–15. https://doi.org/10.1142/9789814282475_0084

Vousdoukas, M.I., Almeida, L.P., Ferreira, Ó., 2011. Modelling storm-induced beach morphological change in a meso-tidal, reflective beach using XBeach. J. Coast. Res. 1916–1920.

Vousdoukas, M.I., Ferreira, Ó., Almeida, L.P., Pacheco, A., 2012. Toward reliable storm-hazard forecasts: XBeach calibration and its potential application in an operational early-warning system. Ocean Dyn. 62, 1001–1015. https://doi.org/10.1007/s10236-012-0544-6

Weigel, A.P., Liniger, M.A., Appenzeller, C., 2007. The discrete Brier and ranked probability skill scores. Mon. Weather Rev. 135, 118–124. https://doi.org/10.1175/MWR3280.1

Zijlema, M., Stelling, G., Smit, P., 2011. SWASH: An operational public domain code for simulating wave fields and rapidly varied flows in coastal waters. Coast. Eng. 58, 992–1012. https://doi.org/10.1016/j.coastaleng.2011.05.015

9. Web References

Flater, Dave. (2007). “WXTide 32” from http://www.wxtide32.com/

Annexes

Annexe A – Input data used for the Empirical formula.

Parameter	Value used
Bottom slope	240
Beach profile degree	2.53486902498933
Beach orientation with N	258.3
The height of the crest of the structure	-7.077500
Length of the structure	14.31504491294630
Structure slope	1.26550231943601
The permeability coefficient of the structure	0.8