Modelling the morphological response of beaches with groynes

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Abstract: The construction of breakwaters on the Mondego river mouth had a huge impact on the coastline configuration both north and south of Figueira da Foz, blocking, for some time, the main source of sediments arriving in the area – between the inlets of the Mondego and the Lis rivers. A few interventions had to be implemented to reverse the erosion process occurring in the last years. To make them more effective, it is necessary to study the local sediment dynamics and the impact of such interventions on that dynamics, using models based on numerical modeling, which are an alternative to physical models, because of both economic and time factors. This investigation aims to study the capability of one of these models, DELFT3D, to simulate the morphological evolution in the area of influence of a groyne. To make this possible, the mean wave of the study zone was propagated above a simplified bathymetry of the area. Default parameters were used to set up the model, and a sensitivity analysis was done as regards parameters with a major impact on the modeling, such as the direction of the incident wave and directional spreading. To evaluate the model performance, a line model was used – the LITLINE, included in the LITPACK model, which had been applied in the study area in previous studies. The comparison between the two models led to the conclusion that DELFT3D is more complete and more complex than LITLINE. However, LITLINE enables simpler simulations and takes less time.

Keywords: Figueira da Foz Erosion, Numerical Modeling, Morphological evolution, DELFT3D, LITPACK.

1. Introduction

Portugal, despite its small geographical area when compared with other countries, has a very long shoreline. The coastal zone, with all its resources, has always had a huge economic and social impact on the development of the country. Hence, the management of the coastal zone has been gaining growing importance.

Climate changes have had a huge effect on the planet, and Portugal is no exception. Erosion resulting from such changes has become evident in many regions of the Portuguese shoreline. This process carries a bigger impact when it occurs near towns or villages, given the damage it may cause to local populations, thus making the need for protection even more necessary. In order to protect people from the negative effects of erosion, interventions on the shoreline have to be implemented. Because these interventions may have both a positive and a negative impact, it is imperative to model the different options available, so as to study the impact of each of them on the shoreline. Only after these modeling studies is it possible to make decisions based on reliable data.

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These studies can be done using software based on numerical modeling. Numerical modeling is an alternative to physical models, because it is more economic, more practical, and simulations take less time.

The main aim of this dissertation was to determine the ability of a specific numerical modeling software (DELFT3D) to model the effect of a groyne in the coastline evolution. To test this software, the modeling focused on a particular study area, located between the mouth of the Mondego and the Lis rivers, near Figueira da Foz, Portugal.

2. Study Case

The building of a numerical model requires previous knowledge of the study area, in order to obtain essential data for the model input. For a study like the present one, the critical factors to define the study zone in the model are **wave climate**, **topo-hydrography** and **sedimentology**.

The study area is located between the Mondego and the Lis rivers' inlets. It has an extension of approximately 32 kilometers and an orientation of 19ºN (clockwise) (Oliveira e Brito, 2015). There are four villages in this stretch: Gala-Cova, Leirosa, Costa de Lavos and Pedrogão. In Figure 1, it is possible to see the location of the four villages in the stretch examined.

Figure 1 – Study area and detail of the main structures and adjacent urban centers. Source (Oliveira, 2016).

The construction of the breakwater in Figueira da Foz resulted in erosion in the south stretch. In order to protect the villages located in the study area from the erosion process, groynes were built near each village, except in Pedrogão, where no further protection was needed, because it already has a natural headland. Groynes built near these villages have successfully protected them by counteracting the erosion process in that zone. Locally, some erosion occurred on the downdrift side of each groyne; yet, on the updrift side, there was sediment accretion, which has worked as a natural protection of the adjacent villages ever since.

2.1. Wave Climate

As mentioned above, it is imperative to know the wave climate in order to set up a numerical model. As regards the models used in this dissertation, it was necessary to collect data such as significant wave height (Hs), peak period (Tp) and the direction (Dir) of the incident wave. There are several studies of the wave climate in the study area of this dissertation. Table 1 gives an overview of the previous studies upon which this research draws and the time span covered by each of them. For each of these studies, the table also displays the major frequency class of each parameter (Hs, Tp, Dir):

Table 1 - Major frequent classes of Hs, Tp and Dir, for each study of wave climate in the study area located between the Mondego and the Lis rivers' inlets.

	Wave climate studies			
	Simões & Castanho (1978)	Cunha *et al* (1997)	Capitão *et al* (1997)	Oliveira (2016)
	Major frequent classes			
Hs	1-2	1-2 (41,9%)	1,00-1,50 (19,0%)	1,00-1,50 (25,64%)
			1,5-2,0 (22,0%)	1,50-2,00 (23,32%)
Tp	9-11	8-10 (24,7%)	-	10-12 (27,24%)
		10-12 (30,3%)	-	12-14 (26,97%)
Dir	280-290ºN	265-275ºN (32,7%)	290-300ºN (16,3%)	290-300Nº (21,03%)
		275-285ºN (10,4%)	300-310ºN (15,0%)	300-310Nº (22,61%)
	1954-1960		1984-1996	1952-2010

From the analysis of Table 1, it is possible to verify that the most frequent class for the significant wave height (Hs) was between 1 and 2 meters in all studies. As for the peak period (Tp), there are some differences in the conclusions drawn by each study. However, it is possible to conclude that the most frequent class is between 10 and 12s. For the wave direction (Dir), there is some divergence between the results presented in the studies, which may be related to the fact that the studies by Simões and Castanho (1978), Cunha *et al* (1997) and Capitão *et al*. (1997) cover a shorter period than the one conducted by Oliveira (2016).

As the table shows, Oliveira (2016) carried out a study over a longer period (1952-2010), thus providing an analysis of 59 years. This is the most complete study for the study area. Therefore, the data considered to set up both models used in this dissertation (DELFT3D and LITPACK) was from Oliveira (2016).

Since the main objective of this research was to test the ability of the DELFT3D model to model the influence of a groyne on a beach, it was considered that the study should be based on propagating a mean wave (i.e., a wave with mean characteristics), instead of on propagating a chronological series of wave climate. Hence, this study used the mean parameters obtained in the investigation carried out by Oliveira (2016), for the model input, which are 2,15m for the Hs, 11,5s for Tp and 299,5ºN to Dir.

Given that the coastline has an orientation of 19,6ºN, to make the introduction of data in the model easier, it was defined that the coastline should be aligned with the north direction, so the wave direction had to be corrected from 299.5ºN to 280ºN (Figure 2).

Figure 2 – a) Coastline alignment of the study area, and mean wave direction. b) Correction of the coastline alignment and mean wave direction

2.2 Topo-hydrography and sedimentology

The sediment transport is directly related to the beach profile. Oliveira (2014) conducted a study about the topography of the study area of the present dissertation, in which several profiles were obtained. In a subsequent study, Oliveira (2016) concluded that for all those profiles, it is possible to consider only one profile as representative of the whole study area. Oliveira (2016) also obtained equilibrium profiles, for several values of $d_{50.}$ By comparing the first profiles with the equilibrium ones obtained, Oliveira (2016) concluded that one of the profiles (P7 from Oliveira (2014)) of the study area was similar to the equilibrium profile for 0,3mm of d_{50}. Based on this comparison, that profile was determined to be the representative profile of the study area in the present study.

In addition, in a real profile, there are changes of slope that influence directly the transport capacity. Using a simplified profile makes the results easier to analyse, because it minimizes the influence of several slope changes. Therefore, a simplified profile of the study area was made. In this dissertation, a simplified profile with a d_{50} of 0,3mm was used. Figure 3 represents the three profiles mentioned above.

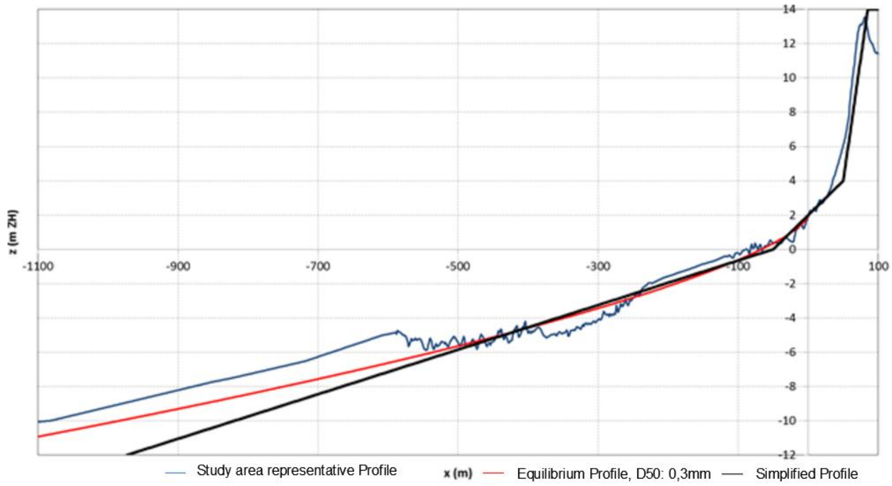


Figure 3 –Representative profile (Oliveira, 2014), equilibrium profile, d50= 0,3mm and simplified profile (Oliveira, 2016), of the study area located between the Mondego and the Lis inlets.

3. DELFT3D

3.1. Introduction

DELFT3D allows the simulation of hydrodynamic and morphologic processes, because it can reproduce not only the flow, but also the sediment transport, the wave propagation and the morphodynamics (Deltares, 2011d).

The model is divided into modules, which can be characterized distinctly, but work together when applying simulations. Although the main module is FLOW, in this dissertation, it had to be coupled with the WAVE module, so that the wave could be introduced in the model. This combination makes it possible to consider the wave effects on the FLOW module, and it also allows the WAVE module to receive the boundary conditions imposed by the FLOW module for wave transformation.

The sediment transport brought about by wave and currents is calculated by the advection-diffusion equation, in three directions.

3.2. Setting-up the model

A grid for the DELFT3D model was created. The grid had to be more wide-ranging than the study area, in order to keep the boundaries away from the area under analysis. The grid resolution and the distance between the study area and the boundaries influence the modeling. A grid with 4000m (longshore direction) and 1100m (cross-shore direction) was created for the WAVE module, and a grid with 2000m (longshore direction) and 785m (cross shore direction) for the FLOW module. The grid resolution in both grids is 5x5m.

The WAVE bathymetry was generated based on the simplified profile, already presented in section 0. The FLOW bathymetry is equal to the WAVE one, but in the area where the groyne is located, the data were changed according to the groyne's height, in order to create a physical barrier to the flow.

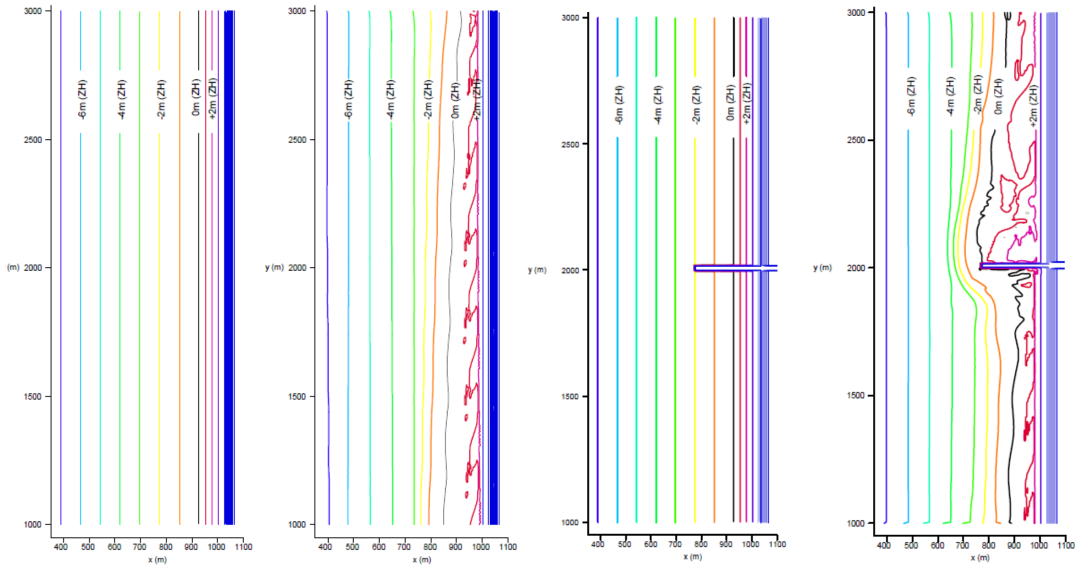
In the FLOW module, the model was defined for 30 days of simulation. As simulations are time consuming, the morfac factor was used, since this factor allows the acceleration of the modeling, by multiplying the results obtained in each time by the factor defined. In this study, a morfac of 30, with a simulation of 1 day, was used, which results in a 30 days simulation.

In regard to the boundary conditions, north and south boundaries were defined as Neumann boundaries, while the west boundary was defined in accordance with the water level, which was set 2m above the hydrographic zero.

In the WAVE module, the hydrodynamic conditions were defined according to the parameters described in section 2.1: Hs: 2,15, Tp:115, and Dir:280ºN. An obstacle for the groyne's area was also defined, because it had to be defined in both FLOW and WAVE modules, so that there could be a physical barrier in both modules.

3.3. Results

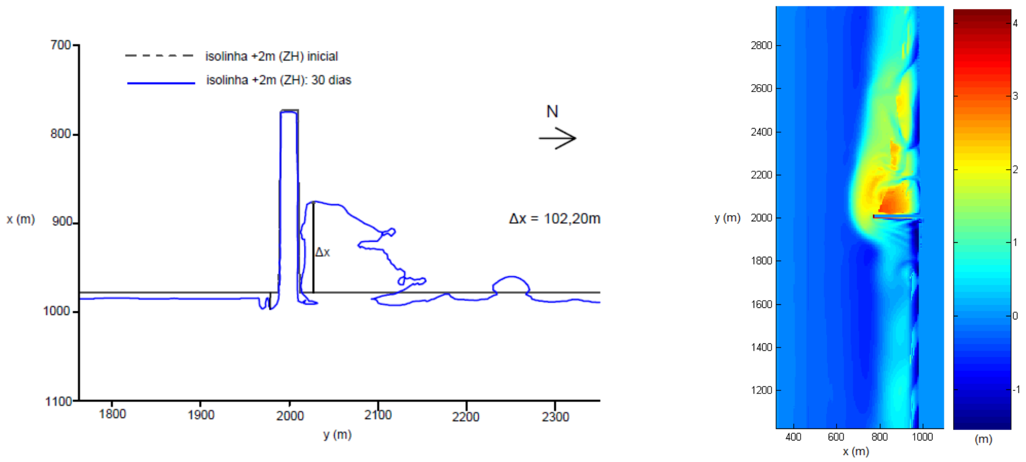
Firstly, a situation without a groyne was simulated, so as to test the evolution in the same period of time (30 days), caused only by the hydrodynamic conditions (without a structure influence). As it is possible to verify, the incident wave has the capability to make bed changes for itself. In 30 days, there was a smoothing of the beach profile, and a regression of the coastline (bathymetric +2m (ZH) of about 16meters (Figure 4a) and b)). When considering a groyne, the whole morphological evolution is different. The groyne has a direct impact on the sediment transport, which results in a lot of morphological changes (Figure 4c) and d)). The groyne works as a barrier to the natural sediment drift, so, for these hydrodynamic conditions, on the updrift side there is a coastline progress, while on downdrift one, the evolution is much different. There is a lack of sediments in the downdrift area.



a) b) c) d)

Figure 4 - Results obtained for a 30 days simulation with DELFT3D model, for the study area located between the Mondego and Lis inlets, for Hs:2,15m, Tp:11,5s and Dir: 280ºN. a) Initial bathymetry without groyne. b) Bathymetry after 30 days without groyne c) Initial bathymetry with groyne. d) Bathymetry after 30 days with groyne.

To make a more specific analysis of the coastline, the initial coastline was compared with the one obtained after 30 days (Figure 5a)). There was a progress of approximately 100m on the updrift side, and no progress on the downdrift one. There was a regression of the coastline on the downdrift side, but since it is so small, it is not possible to determine whether it was a numerical error or a consequence of the groyne.



a) b)

Figure 5 – Results obtained for 30 days with DELFT3D model, for the study area located between the Mondego and Lis inlets, for Hs:2,15m, Tp:11,5s and Dir: 280ºN a) Initial coastline and coastline after 30 days b) Erosion and sedimentation.

Figure 5b) shows the erosion and sedimentation occurred after 30 days, with the hydrodynamic conditions imposed. The yellow and red colors represent sedimentations and the dark blue, erosion. As it is possible to observe, all sedimentation occurs on the updrift side of the groyne, and the erosion on its downdrift side, which proves that the groyne has a direct influence in the morphological changes.

Both previous simulations were made with a directional spreading value of 4. The effect of this parameter was studied by changing that value to the following ones: 0.1, 2, 4, 6 and 8. The results from each value are represented in Figure 6:

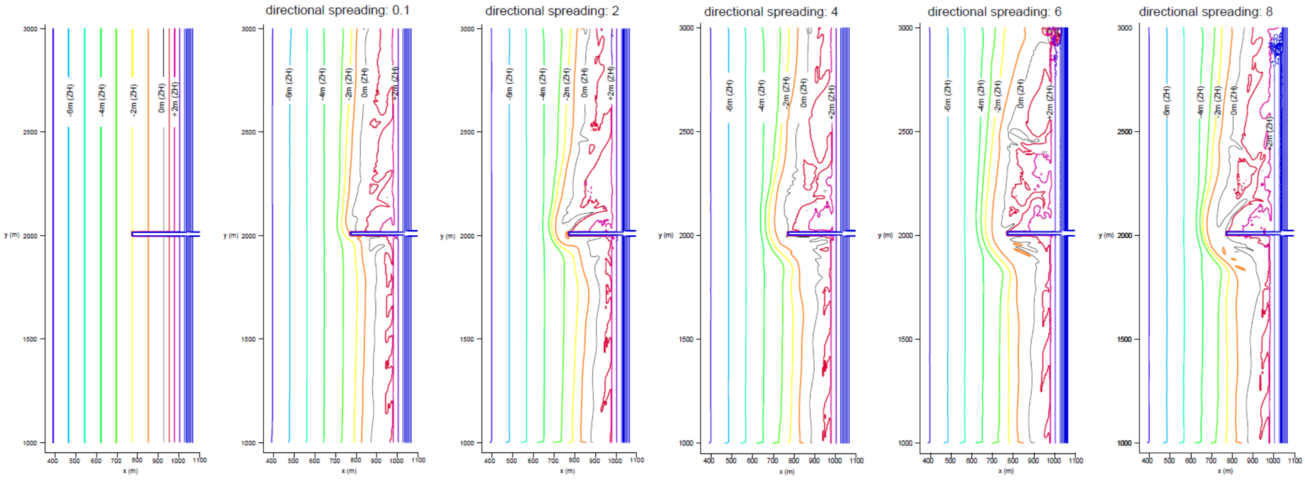
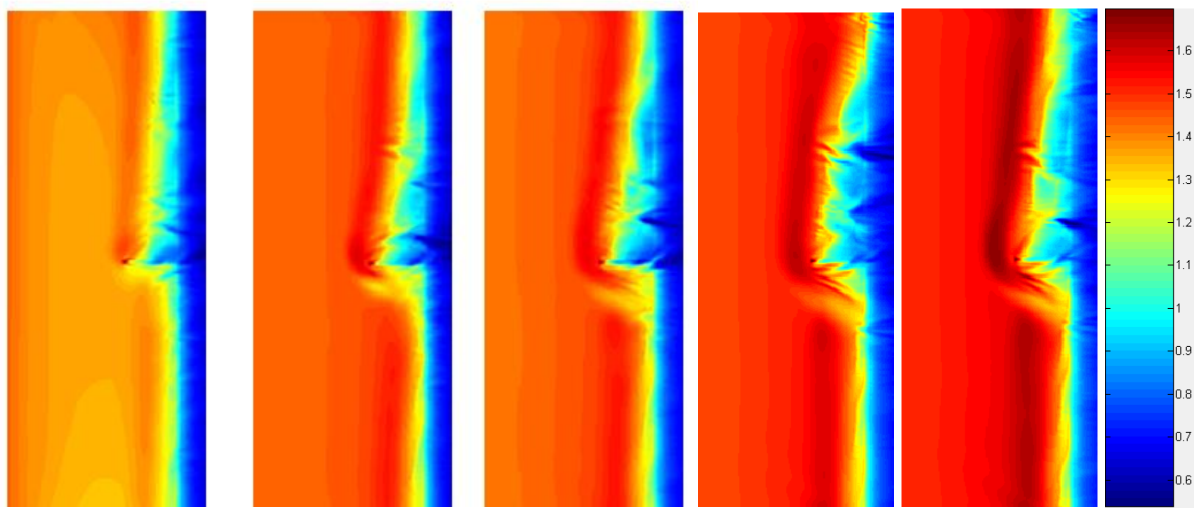


Figure 6 – Influence of directional spreading in DELFT3D model, for the study area located between the Mondego and Lis inlets, for Hs: 2,15m, Tp: 11,5s and Dir:280º

Figure 6 also shows that bed changes are significant with the change of directional spreading, which can be explained with the influence of this effect on the root mean square height, represented in Figure 7.



a) b) c) d) e)

Figure 7 - Hrms for different values of d.s,, after 30 days, obtained with DELFT3D model for the study area located between the Mondego and Lis inlets, for Hs: 2,15m, Tp: 11,5s and Dir:280º a) d.s: 0,1 b) d.s: 2 c) d.s: 4 d) d.s: 6 e) d.s: 8

The directional spreading has a great influence on the wave height. A higher value of directional spreading causes a greater wave height. These waves carry more energy and, consequently, have more ability to make bed changes.

In this dissertation, the influence of the wave direction was also studied in order to determine whether the model was sensitive to it or not. Two simulations were made for 315ºN, one with a direction spreading of 0.1 and the other one with 4.

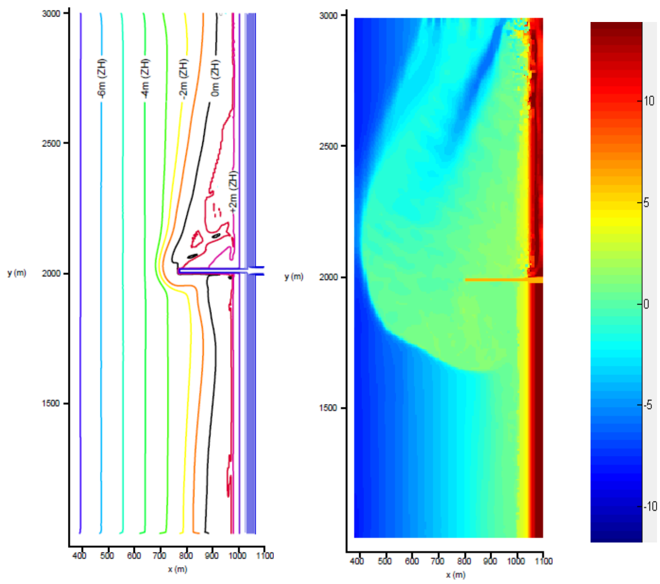


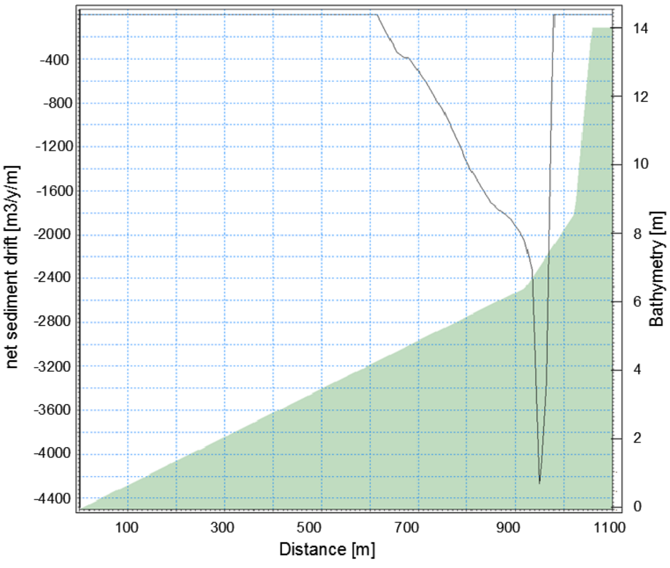
Figure 8 – Bathymetry obtained after 30 days, with DELFT3D model, for the study area located between the Mondego and Lis inlets, for Hs: 2,15m, Tp: 11,5s and Dir:315º. a) directional spreading: 0,1. b) directional spreading: 4.

As Figure 8 shows, the model is very sensitive to both parameters: wave direction and directional spreading. For the first case, with a directional spreading of 0,1 and a wave direction of 315ºN, the bathymetry obtained is more regular than the one present for 280ºN. This is because 280ºN is a direction almost perpendicular to the coastline, thus causing some instabilities. As for the second case, for 315ºN and a directional spreading of 4 (which is the value used in the main simulation), the model develops so many instabilities in the north boundary, that it ends in error before the simulation reaches the finishing time. The solution for this problem lies beyond the scope of this dissertation, but future research could, for example, refine the grid on the north boundary side, where such instabilities occur.

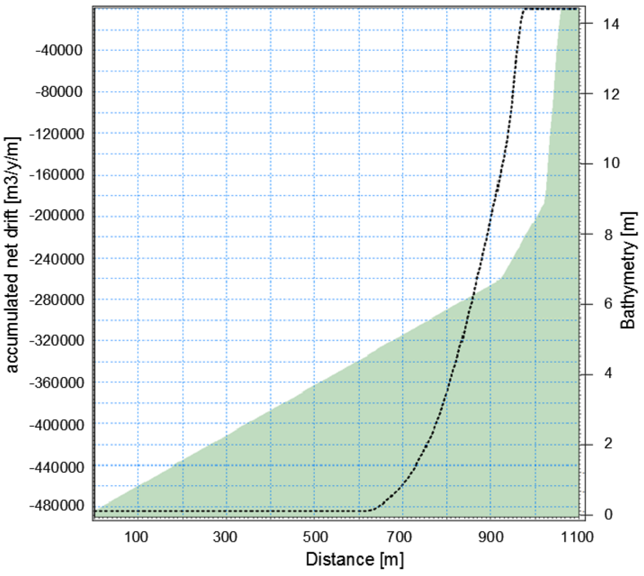
4. LITPACK model

In order to understand if the results obtained with DELFT3D were plausible, the model system LITPACK was used. This model system works with modules too, but in a different way from DELFT3D. LITPACK has already been used in previous studies (Oliveira, 2016; Fonseca, 2015), including studies about this study area. It is divided into modules, and in this dissertation the modules used were: **LITDRIFT** (longitudinal sediment drift due do waves and currents) and **LITLINE** (coastline evolution based on 1-line model) (DHI, 2016)

With the LITDRIFT module, the net sediment drift (m^3/y/m) and the accumulated net drift (m^3/year/m) were obtained. Both drifts were combined with the profile, in order to evaluate the sediment transport according to the profile (Figure 9).



a)



b)

Figure 9 – Results obtained with the LITDRIFT application for the study area located between the Mondego and Lis inlets, for Hs: 2,15m, Tp: 11,5m and Dir: 280ºN. a) net sediment drift (m3/y/m) and beach profile. B) accumulated net drift (m3/y/m) and beach profile.

By analyzing Figure 9, it is possible to confirm that the sediment transport occurs over an extension of approximately 400m, for the stretch between 600m and 1000m of the beach profile, which corresponds to the bathymetries between -4m (ZH) and 2m (ZH).

After obtaining the sediment transport results caused by the propagation of the wave in the beach profile, the LITLINE module was set up, and the coastline evolution for the study period (30 days) was obtained (Figure 10).

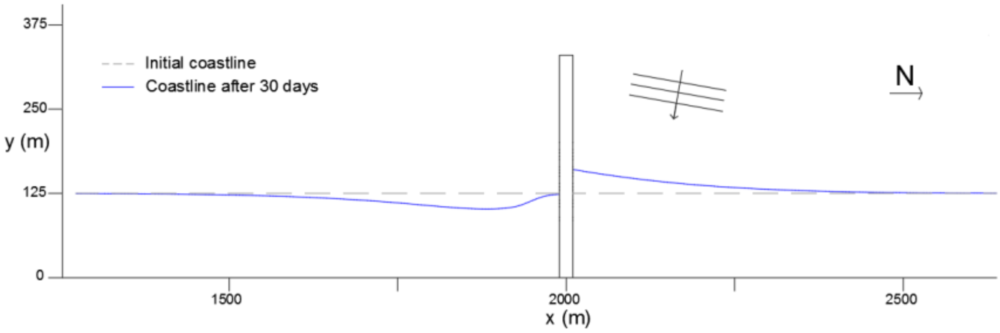


Figure 10 – Initial coastline and coastline after 30 days, obtained with LITLINE, for the study area, located between Mondego and Lis' inlets, for Hs: 2,15m, Tp: 11,5m and Dir: 280ºN.

From the analysis of Figure 10, it is possible to verify that there is a sediment accumulation on the updrift side, and erosion on the downdrift area, resulting from the fact that the groyne works as a barrier to the natural sediment drift. The coastline evolution for 30 days occurs only due to the existence of the groyne. With these study parameters, there is neither progress nor regression of the coastline due solely to the hydrodynamic conditions.

5. Comparison between DELF3D and LITPACK Results and Final Considerations

In order to examine the reach of both models, as well as the main differences between them for the same hydrodynamic and morphology conditions, the two coastlines obtained for the study period (30 days) with the two models were overlapped with the initial coastline (Figure 11).

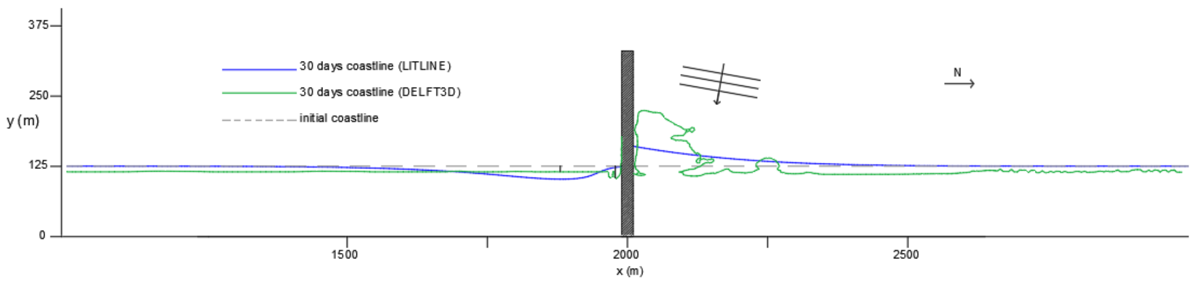


Figure 11 - Comparison of the coastline obtained for 30 days in DELF3D and LITLINE models with the initial coastline of the study area located between the Mondego and Lis inlets, for a wave with Hs: 2.15m, Tp: 11,5s and Dir: 280ºN.

The analysis of Figure 11 shows that both models describe the sediment accumulation on the updrift side. The length of influence on the updrift side is almost the same in the two models, approximately 500m. On the downdrift side, no influence of the groyne in the coastline was registered in the DELFT3D model, whereas in the LITLINE model an influence with also 500m is perceptible. On the updrift side, it is possible to confirm that DELF3D presents a greater coastline progress than the LITLINE model (approximately 60m more).

The DELFT3D model works in 3 dimensions simultaneously, which means that it can represent the processes of nature better. Besides the 3 dimensions, the wave propagation, the sediment transport calculation and the morphological update are completed in each time-step, which means that the model is always updated for next time-step. The LITPACK model works differently from DELFT3D: first, the longitudinal sediment transport is calculated in a beach profile (LITDRIFT), and then the coastline evolution is calculated based on these results, by moving these beach profiles parallel to themselves (LITLINE).

Another important difference is that in DELFT3D, both directions of sediment transport are taken into account (cross-shore and longitudinal directions). In LITDRIFT, only the longitudinal direction is considered, and LITLINE mode, using results from LITDRIFT, draws the coastline evolution by considering only the longitudinal direction, in other words, neglecting the cross-shore one.

The comparison of the results in the two models makes it possible to identify and understand the major differences between them. It was concluded that DELFT3D is more complete, which can model the evolution of bathymetria according to hydrodynamic conditions and structures’ influence. Being a more complete model implies that its application is more difficult, because of its complexity and of the long time simulations. LITPACK is a simpler model, but for the parameters used in this study, it can only model the coastline evolution due the groyne’s influence. Because of being simpler, it can make faster simulations, so it is a good tool to evaluate the influence of structures in the coastline.

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