COASTAL EROSION MITIGATION BASED ON ARTIFICIAL NOURISHMENTS AND SAND BYPASSING SYSTEMS: BARRA-VAGUEIRA, PORTUGAL

M. Ferreira[1], C. Coelho[1], and P. A. Silva[2]
[1]RISCO and Civil Engineering Department, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal. margarida.ferreira@ua.pt, ccoelho@ua.pt.
[2]CESAM and Department of Physics, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal. psilva@ua.pt.

1. Introduction

Barra-Vagueira coastal stretch (Figure 1), located downdrift of the Aveiro Harbour, NW coast of Portugal, is an erosion hotspot, presenting, in the last 50 years, erosion rates that reached 8 m/year (Santos *et al*., 2014). This coast is subject to a very energetic wave climate, inducing a net littoral transport from North to South that reaches values around 10^6 m^3/year (Santos *et al*., 2014). In the last two decades, artificial nourishments have become the most common coastal erosion mitigation strategy at this site, being performed low-frequency shots, summing several million cubic meters of sediments (Pinto *et al*., 2020). In 2014, the Portuguese Littoral Working Group (Santos *el al*., 2014) has recommended artificial nourishments as the main strategy to reduce the deficit of sediments on the littoral drift and to counter the shoreline retreat.

The present study aims to assess both the impact of artificial nourishments performed at south of the Aveiro harbour inlet and sand bypassing systems at the inlet, on the morphological evolution of the stretch Barra-Vagueira, considering their performance and longevity. The study was performed through the application of the numerical models LTC - Long Term Configuration (Coelho, 2005), to simulate the shoreline evolution, and CS - Model (Larson *et al*., 2016), to simulate the cross-shore profile evolution, both in a 30 years perspective (2020-2050). The methodology adopted in this study and the assessed scenarios is primary described, in the next section. The following sections describe the calibration and validation of the models and the results of the impact of the intervention scenarios in the morphology of the coastal stretch. Finally, the major conclusions are presented.

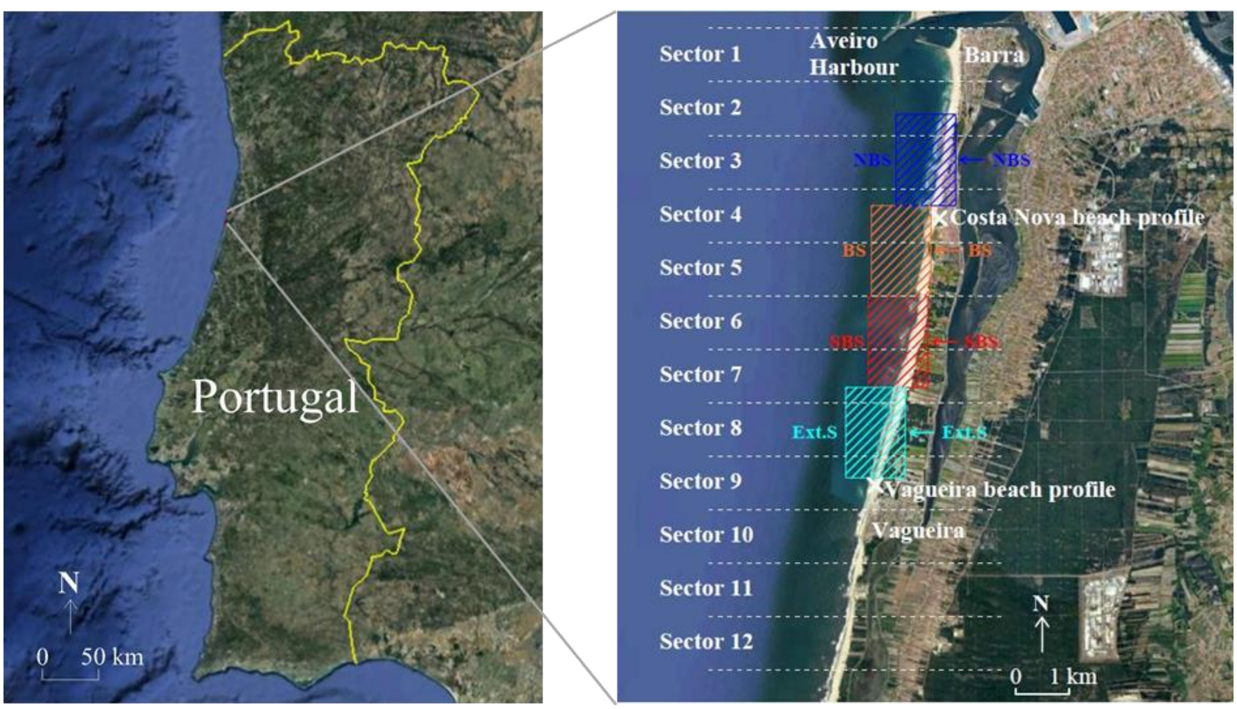


Figure 1. Study area (Google Earth, 2020)

2. Methodology

The current study addresses the impact of artificial nourishments interventions and sand bypassing systems on the morphological evolution of the coastal stretch Barra-Vagueira, Figure 1, in a long-term perspective (30 years). Two numerical models, namely LTC and CS-Model were selected. Based on the modelling capacities of each model, LTC was applied to study the shoreline position evolution considering artificial nourishments and sand bypassing systems. CS-Model was considered to identify the impact of artificial nourishments in the cross-shore beach profile evolution of two profiles located in the study area (Costa Nova beach profile and Vagueira beach profile, see Figure 1).

LTC, developed at Aveiro University by Coelho (2005), is a one-line model special designed for sandy beaches. The model applies a sediment continuity equation, considering that the main causes of medium-term shoreline evolution is the longshore sediment transport gradients and the domain boundary conditions. Through LTC it is possible to simulate the shoreline evolution considering different coastal defense interventions such artificial nourishments, groins, breakwaters and sand bypassing systems. To simulate artificial nourishments the user defines the parameters related to total nourishment volume, area covered by the intervention and the time to perform the nourishment (starting and ending instants of the intervention). To simulate sand bypassing systems the user defines the hourly volume added by the system (considered constant during all the simulation) and the outlet location alongshore.

CS-Model, developed at Lund university by Larson *et al.* (2016), is a cross-shore numerical model to simulate the cross-shore exchange of sand at a decadal scale. The model uses a schematic representation of the beach profile through a key of morphological features and apply a set of equations to characterize the cross-shore processes relevant in a long-term perspective, namely (Larson *et al.*, 2016; Marinho, 2018): dune erosion, overwash, wind-blow sand and the material exchange between the berm and bar. Figure 2 presents the schematic profile used by the model that include the parameters: dune height (S), the locations of the landward and seaward dune feet (Y_L and Y_S respectively), the berm crest location (Y_B), the longshore bar volume (V_B), the berm height (D_B), the depth of closure (D_C), the dune face slopes (β_L and β_S) and the foreshore slope (β_F). The forcing parameters used by the model are the waves characteristics at offshore, winds and still water levels characteristics.

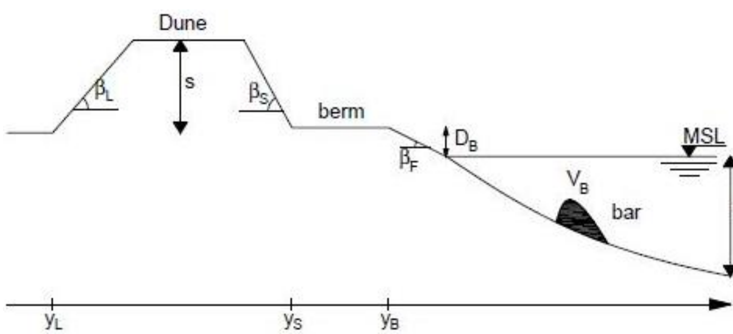
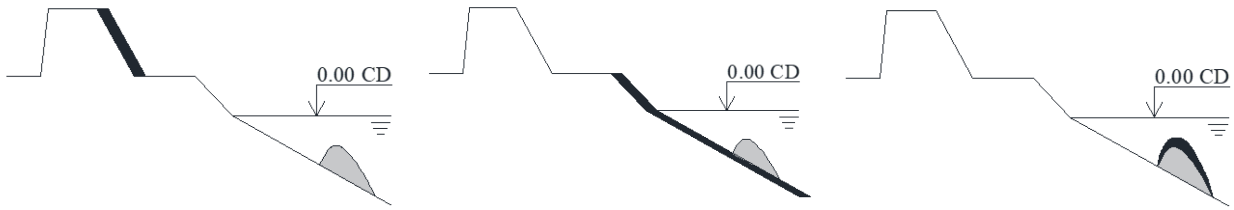


Figure 2. Scheme of the profile given by CS-Model (from Marinho, 2018)

Following the approach adopted by Marinho (2018), in the CS-Model, the artificial nourishments were simulated through the manipulation of the morphological parameters that define the beach profile (Figure 3), resulting from the sectional fill volume that the nourishment represents in the profile (total nourishment volume divided by the longitudinal extension of the deposition). Dune nourishment was simulated by considering an advance of the seaward dune foot position (Y_S) and when necessary was also imposed an advance for the berm position (Y_B). The beach nourishment scheme was set through an equivalent seaward advance of the berm position (Y_B) and the nourishment at the bar was simulated by adding the total fill volume to the bar volume input parameter. All the nourishment schemes were configured at the beginning of each year of simulation.



a) Dune b) Beach c) Bar

Figure 3. Different types of nourishment schemes, varying the sediments deposition location

A total of 10 scenarios tested the impact of sand bypassing systems at the inlet in the shoreline evolution, allowing to make considerations about the bypassed volume, location of the discharge outlet and number of outlets. Regarding artificial nourishments, shoreline and cross-shore profile evolution impacts were tested, for different design fill schemes, considering the volume, frequency of intervention and placement site (both the longshore location and cross-shore profile location, dune, bar or beach). A baseline scenario was adopted and the alternative scenarios have been defined through changes in one of the factors at a time (volume, frequency or location of the nourishments interventions, or location and number of outlets of the bypassing systems). For the scenarios that tested the impact of the interventions in the shoreline evolution, the baseline scenario was defined as the deposition of 500 000 m^3/year of sediments, in front of a groin field, referred as BS in Figure 1. The baseline scenario for the scenarios that tested the impact of the artificial nourishments in the cross-shore beach profile evolution was defined as the deposition of 500 000 m^3/year of sediments at the submerged bar.

Figure 4 summarizes the assessed scenarios and Figure 1 shows the placement sites alongshore considered to deposit the sediments.

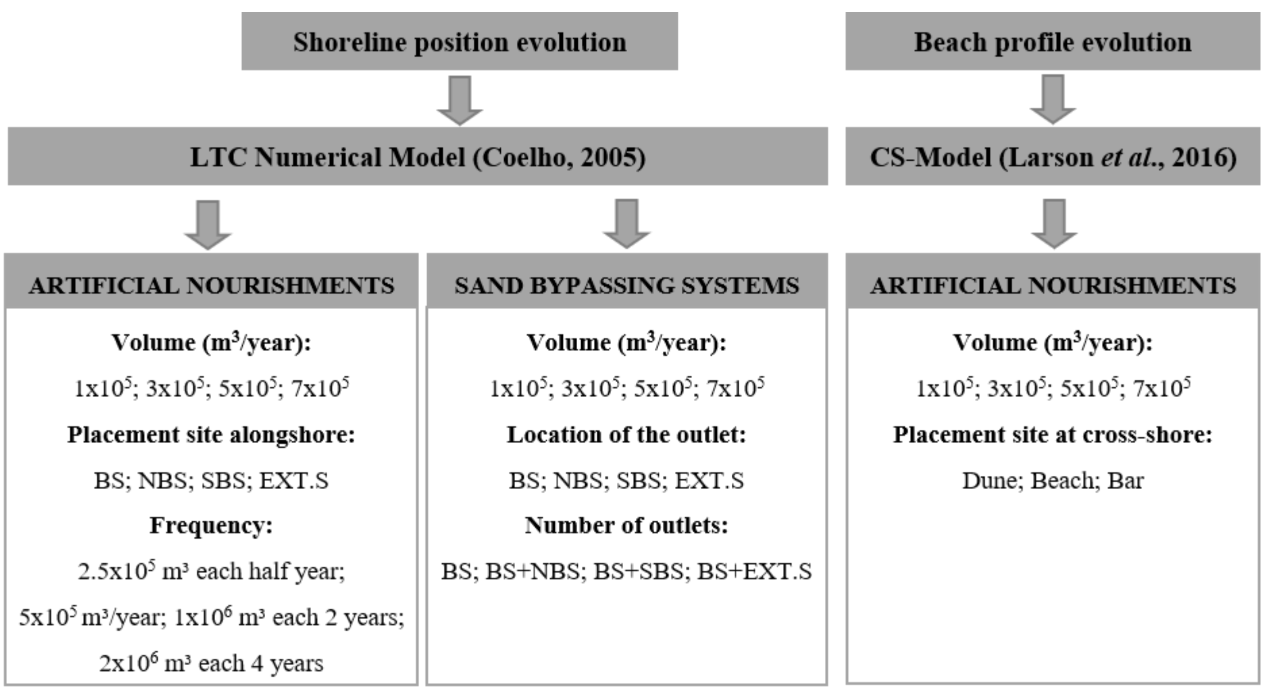


Figure 4. Assessed scenarios (nourishment placement site alongshore and bypassing location are shown at Figure 1, being the nourishments location represented by rectangles and the bypassing outlet's locations represented by arrows)

3. Shoreline position evolution: LTC numerical model

This section describes the LTC model setup and the calibration and validation results. The results of the impact of future intervention scenarios in the shoreline evolution for a time horizon of 30 years (2020-2050) are also presented. To analyze these results the position of the shoreline considering its natural evolution (without nourishment or bypassing interventions) was compared with the position of the shoreline in the different intervention scenarios, at the same time instants.

3.1 Model setup, calibration and validation

The calibration and validation of the LTC model include the definition of the numerical domain, wave climate, boundary conditions and computational parameters related with formulas and physical properties of sediments and water.

The numerical domain was defined based on the identification of the shoreline position through the analysis of the digital elevation model of the study area provided by COSMO (2020). Based on the shoreline position, the bathymetry and topography of the stretch was represented by a regular grid of points spaced 20 m in both directions (West-East and North-South), with an extension of 6x12 km^2. The bathymetry, based on the COSMO (2020) surveys was adjusted to Dean profile shape, being considered regular and parallel. The topography was approximate to a constant slope equal to 3%. The numerical domain includes the 19 coastal structures existing on the stretch Barra-Vagueira (8 groins and 11 longitudinal revetments). In this study was considered the wave series presented in Fernández-Fernández *et al.* (2020). In the model, the sediment transport was defined according to CERC formula (CERC, 1984).

The shoreline change rate was selected to calibrate the model. The empirical coefficient of the CERC formula was defined equal to 0.0025 representing the best shoreline projections considering a 10 years period. The shoreline change rates were obtain alongshore at 12 coastal sectors with 1 km of extension (Figure 1). Table 1 presents the mean shoreline retreat by sector. Most of the sectors present shoreline retreats rates near to 3 m/year, resulting in a global mean shoreline retreat in the study area equal to 2.52 m/year. The numerical results are in accordance with the values referred in the literature; according to Veloso Gomes *et al.* (2006) the shoreline retreat at Costa Nova and Vagueira was estimated equal to 3.7 and 3.9 m/year, respectively.

Table 1. Mean shoreline retreat rates by sector, at the end of 10 years of simulation

Sector	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Retreat (m/year)	0.59	2.82	3.18	0.48	2.34	3.66	3.32	3.39	3.18	1.41	2.25	3.63

To validate the model setup, the artificial nourishments performed on the stretch in the period from 2008 to 2017 were considered, based on the analysis of the data provided by Pinto *et al.*, 2020. The addiction of the artificial nourishments in the model decreases the shoreline retreat rates, leading to a global mean shoreline retreat on the study area of around 1.89 m/year. This result suggests that the model is sensitive to artificial nourishment interventions and the shoreline retreat rate due to artificial nourishments is in accordance with monitoring works, decreasing the erosion in the study area (Fernandéz-Fernandéz *et al.*, 2019).

3.2 Results

The shoreline position projection considering its natural evolution (without nourishment) shows that if no actions are taken to mitigate coastal erosion, the coastal stretch Barra-Vagueira will continue to retreat, representing a loss of territory of more than 400 000 m^2, in a time horizon of 30 years (2050), which represents an average shoreline retreat rate of about 1 m/year (Figure 5).

Artificial nourishments and sand bypassing systems allow to mitigate the coastal erosion, decreasing the shoreline retreat rate. Table 2 presents the results of the percentage of coastal area not lost due to the interventions at the end of 30 years of simulation, considering all the tested scenarios. For both type of interventions, the scenarios corresponding to the largest volumes of deposited sediments are the ones with the best performance to mitigate the erosion, being the sand bypassing systems the most effective solutions.

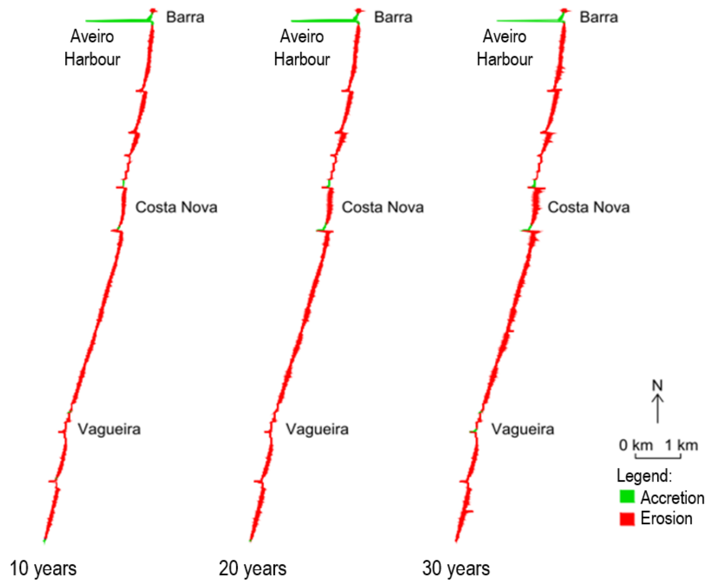


Figure 5. Shoreline position projections at different instants of time

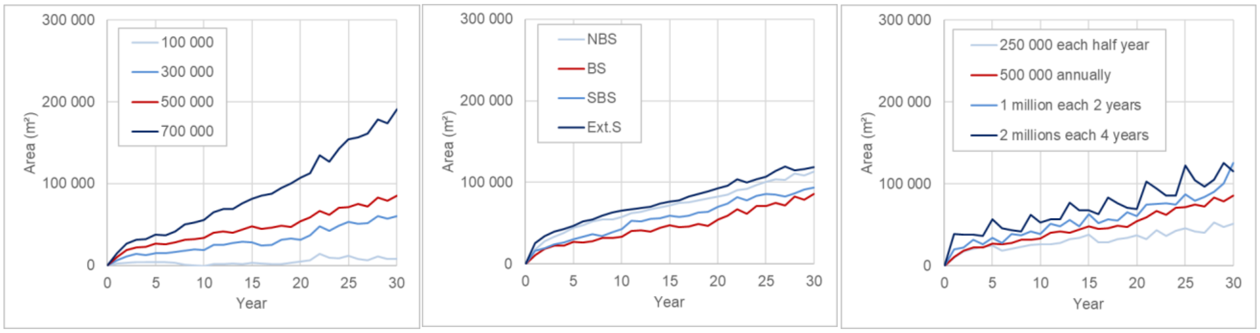
Table 2. Percentage of coastal area not lost, at the end of 30 years of simulation

Artificial Nourishment		%
Volume (m³/year)	1x10^5	2
	3x10^5	15
	5x10^5	21
	7x10^5	47
Placement site	NBS	28
	BS	21
	SBS	23
	Ext.S	30
Frequency	2.5x10^5 each half year	13
	5x10^5 by year	21
	1x10^6 each 2 years	31
	2x10^6 each 4 years	29

Bypassing System		%
Volume (m³/year)	1x10^5	4
	3x10^5	20
	5x10^5	42
	7x10^5	74
Location of the outlet	NBS	49
	BS	42
	SBS	37
	Ext.S	46
Number of outlets	BS+NBS	28
	BS	42
	BS+SBS	27
	BS+Ext.S	31

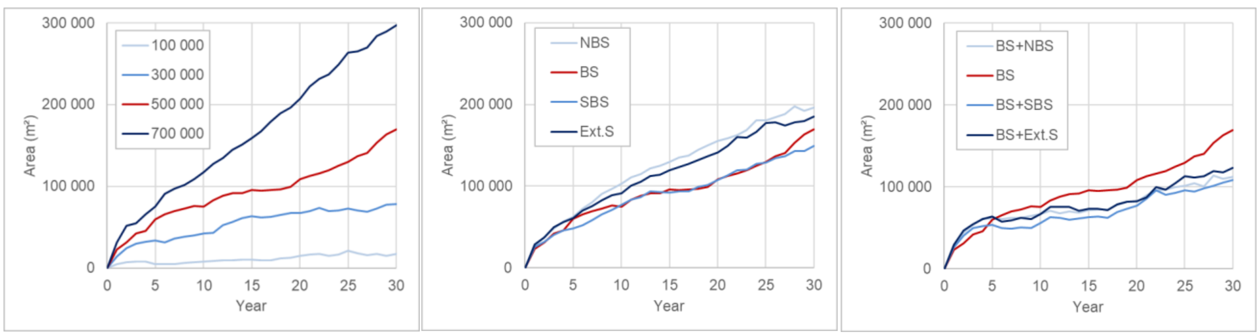
Figure 6 and Figure 7 present the intervention scenarios impact in terms of territory not lost. The results show that the impact of the interventions increases over time, being greater for the biggest volume of sediments deposited or transposed (Figure 6a and Figure 7a). The results also suggest that the study area presents greater benefits if the sediments are deposited or transposed in the locations defined as NBS and Ext.S corresponding to the northern and southern tested scenarios (Figure 6b and Figure 6c). Finally, the numerical model results indicate that it is more efficient to carry out fewer artificial nourishment interventions, with larger volumes (Figure 6c).

The number of outlets affect the performance of the bypassing system. Greater benefits are observed if the total volume of sediments transposed is transferred by only one outlet, as opposed to the scenario that divides the total transposed volume by two outlets (Figure 7c).



a) Volume (m^3/year) b) Placement site c) Frequency

Figure 6. Territory not lost over time, for the scenarios that assessed the artificial nourishments impacts in the shoreline evolution



a) Volume (m^3/year) b) Location of the outlet c) Number of outlets

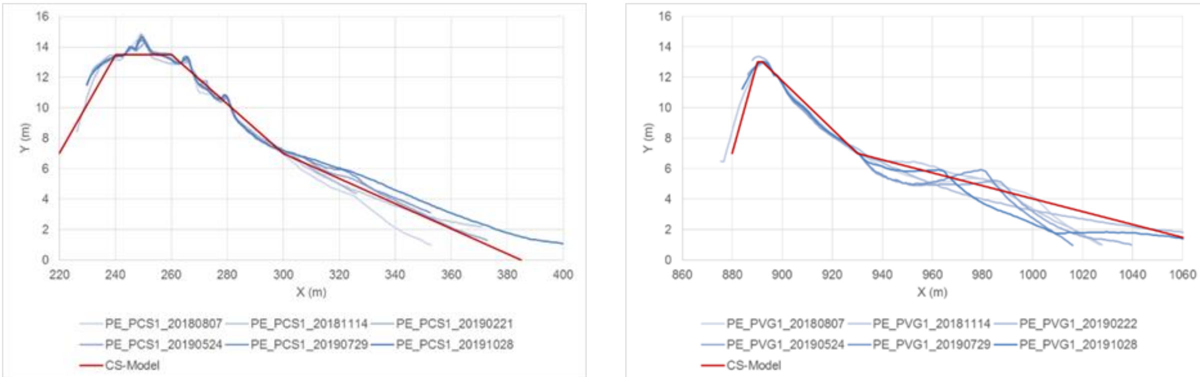
Figure 7. Territory not lost over time, for the scenarios that assessed the sand bypassing systems impacts in the shoreline evolution

4. Cross-shore beach profile evolution: CS-Model

This section describes the CS-Model application to Barra-Vagueira, beginning by referring the calibration and validation results. Later the results of the impact of future intervention scenarios in the evolution of the beach profiles are presented, supported by the analysis of the evolution of the parameters that defined the cross-shore morphology (foot dune position, berm position and consequent berm width). To evaluate the impact of the artificial nourishments in the beach profile's morphology, the evolution of the parameters considering its natural evolution (without nourishment) was compared with the parameter's evolution in the different intervention scenarios.

4.1 Model setup, calibration and validation

The calibration and validation of the model was performed through the data analysis of the field surveys provided by COSMO (2020), covering approximately a year and half period (from July 2018 to October 2019). Based on the surveys, the scheme of each beach profile was defined, being the calculation parameters used to adjust the model to obtain a good correlation between numerical modeling results and survey data. Figure 8 presents the cross-shore scheme adopted for each beach profile (red line) and the field surveys that supported the calibration and validation process (blue lines). Table 3 summarizes the values adopt for the initial morphological parameters, sediments characteristics and aeolian sediment transport rate. The wave series was equal to the one applied to LTC model.



a) Costa Nova b) Vagueira

Figure 8. Field surveys and CS-Model scheme adopted for each beach profile

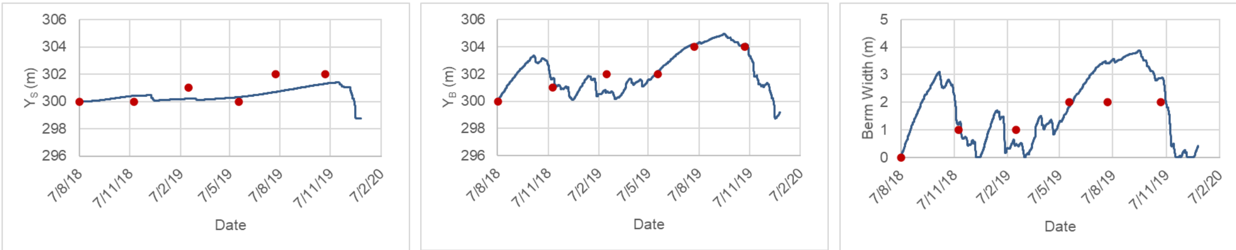
Table 3. Initial beach profiles morphological parameters, sediments characteristics and aeolian sediment transport rate

Cross-shore profile	Y_L	Y_S	Y_B	S	S_{max}	D_B	V_B	β_L	β_S	β_F	D_c	D_{50}	Q_{winds}
	(m)	(m)	(m)	(m)	(m)	(m)	(m^3)	(rad)	(rad)	(rad)	(m)	(mm)	(m^3/s)
Costa Nova	220	300	300	6.5	6.5	7	180	0.31	0.16	0.08	17	0.5	$0.1x10^{-5}$
Vagueira	880	930	930	6.0	6.0	7	100	0.54	0.16	0.04	18	0.5	$0.9x10^{-5}$

CS-Model performance was evaluated using the statistical parameters mean error and the refined Willmott's concordance index (Willmott *et al.*, 2012). The results of the statistical analysis are presented in Table 4. Generally, the results presented a mean error lower than 1 m and the Willmott concordance parameter varies from 0 to 0.8, allowing to conclude that the model is able to reproduce with accuracy the cross-shore evolution of the profiles studied. Figure 9 and Figure 10 compare the evolution of the morphological parameters used to calibrate the model, obtained through numerical modeling, with the values resulting from the analysis of the field surveys.

Table 4. Results of the statistical parameters applied to evaluate CS-Model performance

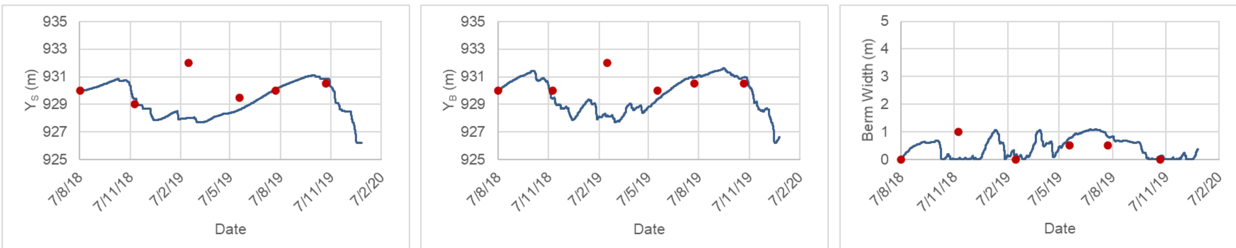
	Mean error			**Willmott concordance error**		
	Y_S	Y_B	Berm width	Y_S	Y_B	Berm width
Costa Nova	0.59	0.40	0.53	0.65	0.84	0.60
Vagueira	0.95	0.98	0.32	0.34	0.02	0.52



a) Seaward foot dune position b) Berm crest c) Berm width

CS-Model Surveys

Figure 9. Morphological evolution of Costa Nova beach profile parameters obtained through numerical modeling and field surveys



a) Seaward foot dune position b) Berm crest c) Berm width

CS-Model Surveys

Figure 10. Morphological evolution of Vagueira beach profile parameters obtained through numerical modeling and field surveys

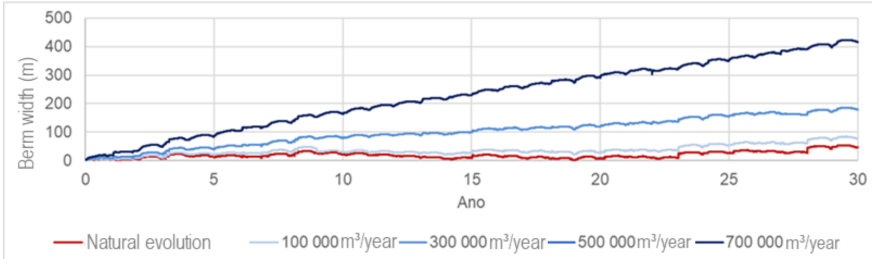
4.2 Results

The impact of the artificial nourishments on the cross-shore profile is mainly reflected in the increase of the berm width and/or increase of the dune volume.

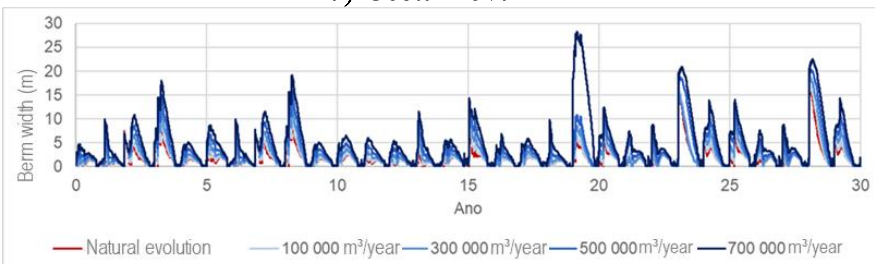
Figure 11 presents the berm width evolution for the scenarios that tested different nourishment volumes deposited in the submerged bar. For both profiles, it is verified that the impact on the profile evolution increases with higher volumes deposited. However, it is observed to occur different morphological evolutions between the two profiles. The results at Costa Nova profile show that adding sediments to the profile leads to considerable gains in berm width over the 30 years of simulation, when compared to the natural evolution (red line in the Figure 11a), but at Vagueira profile, the gains are not so large (Figure 11b). This difference is attributed to the profile morphology (dune and berm slopes) and to the parameter adopted for the calculation of wind transport of sediments from the berm to the dune, since these were the only parameters that varied in the numerical modelling evolution of each profile.

The artificial nourishment placement site in the Costa Nova cross-shore profile shows that the deposition of sediments on the beach and at the submerged bar leads to a positive impact and to larger berm width over the 30 years of simulation, when compared to the natural evolution (Figure 12a). Artificial adding of sediments to the dune contributes to increase the dune volume, making it more robust, but dune nourishment has no significant impact in terms of berm gain (the dune foot advance decreases the potential berm width gains).

At Vagueira beach profile, for the three deposition location tested, it is observed that the Y_S and Y_B seaward advance is similar, during the total time of computation, and thus, bar and beach nourishment have a slightly impact in terms of gain of berm width, being the major impact of the interventions reflected in the gain of dune volume, independently of the placement site selected to deposit the sediments (Figure 12b).

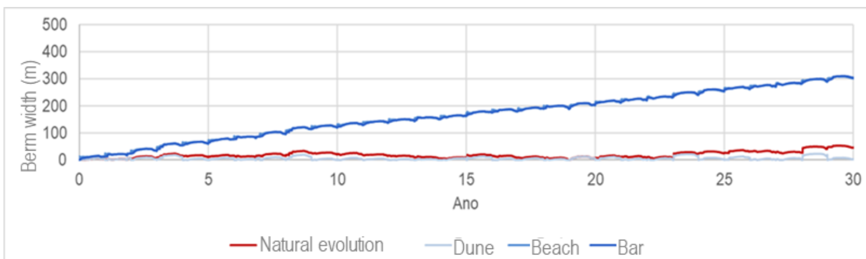


a) Costa Nova

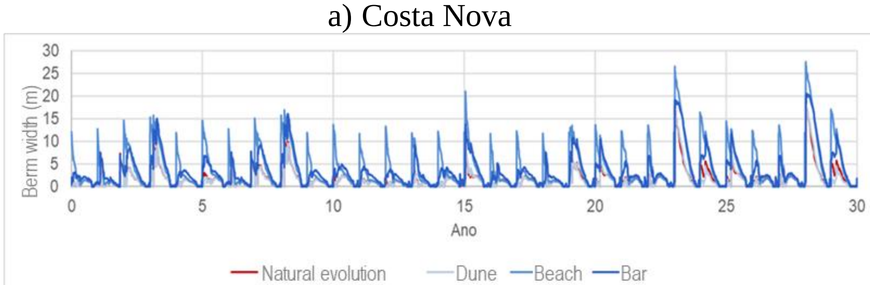


b) Vagueira

Figure 11. Berm width evolution for different deposition volumes scenarios, in the submerged bar



a) Costa Nova



b) Vagueira

Figure 12. Berm width evolution for different deposition scenarios, in the cross-shore profile

5. Conclusions

This work aimed to numerically simulate the impact of artificial nourishments and sand bypassing systems on the morphological evolution of the coastal stretch Barra-Vagueira in a long-term perspective (30 years). The study compromise two main phases: 1st) selection, calibration and validation of the numerical models; 2nd) application of the models to evaluate the impact of future intervention scenarios in the study area. With this purpose, different scenarios were defined and the performance of the interventions was studied in function of different design parameters.

The simplified numerical models LTC and CS-Model were selected to develop the study. The model's calibration and validation results demonstrate that, despite the uncertainties, the models are able to reproduce the observed trends of the Barra-Vagueira coast, being the numerical models results aligned with monitoring works carried out in the study area.

Regarding the results of the impact of future intervention scenarios, the LTC numerical model results demonstrated that both artificial nourishments interventions and sand bypassing systems allow to decrease the coastal territory lost by comparison with the scenario of no intervention. However, none of the interventions for the tested scenarios allows to fully eliminate the loss of territory. The CS-Model results show that artificial nourishments may serve different purposes: to increase the width of the beach berm and/or to increase the dune volume.

This study aims to help planning and decision-makers process in the establishment of more efficient coastal management to mitigate coastal erosion on the Barra-Vagueira coastal stretch. Additionally, this study represents a first step forward numerical models' improvement capacity, to have more efficient models, merging long-shore and cross-shore process in a medium to long-term perspective, without compromising the required computational efforts.

Acknowledgements

This work has been developed in the scope of the research project Sandtrack (POCI-01-0145-FEDER-031779) funded by FEDER, through COMPETE2020 - POCI, and by national funds (OE), through FCT/MCTES. The authors gratefully acknowledge FCT by the financial supported provided to RISCO (FCT/UIDB/ECI/04450/2020) and CESAM (UID/AMB/50017/2019) and APA - Portuguese Environmental Agency in the aim of the project Feasibility Study of Sand Bypassing at Aveiro and Figueira da Foz Tidal Inlets for providing the data necessary to develop the study.

References

CERC 1984. Shore Protection Manual. Vol. 1. DC: U.S. Army Corps of Engineers. Coastal Engineering and Research Center. U.S. Government Printing Office.

Coelho, C. 2005. "Riscos de Exposição de Frentes Urbanas para Diferentes Intervenções de Defesa Costeira." PhD Thesis, University of Aveiro, Aveiro, Portugal, 404 p. (in Portuguese).

COSMO 2020. Monitoring Data. Coastal Monitoring Programme of Continental Portugal: COSMO, APA - Portuguese Environmental Agency. https://cosmo.apambiente.pt/data (visited in May of 2020).

Fernandéz-Fernandéz, S., Baptista, P., Bernardes, C., Silva, P., Fontán-Bouzas, Á., Lópes_Olmedilla, L., Ferreira, C. 2019. "Variação da Linha de Costa em Praias Arenosas: Aveiro (Portugal)." *IX Congresso sobre Planeamento e Gestão das Zonas Costeiras dos Países de Expressão Portuguesa*, Lisbon, Portugal (in Portuguese).

Fernández-Fernández, S., Silva, P.A., Ferreira, C.C., Carracedo-García, P.E. 2020. "Longshore sediment transport estimation at Areão Beach (NW Portugal) under climate change scenario." *Journal of Coastal Research*, Special Issue No. 95, pp. 479-483. Coconut Creek (Florida), ISSN 0749-0208

Google Earth 2020. Visited in November of 2020

Larson, M., Palalane, J., Fredriksson, C., Hanson, H. 2016. "Simulating Cross-Shore Material Exchange at Decadal Scale. Theory and Model Component Validation." *Coast. Eng. J.*, 116, 57-66.

Marinho, B. 2018. "Artificial Nourishments as a Coastal Defense Solution: Monitoring and Modelling Approaches." PhD Thesis, University of Aveiro, Aveiro, Portugal.

Pinto, C., Silveira, T., Teixeira, S. 2020. "Beach Nourishment Practise in Mainland Portugal (1950-2017): Overview and retrospective." Elsevier. *Ocean and Coastal Management* 192 105211.

Santos, F., Lopes, A., Moniz, G., Ramos, L., Taborda, R. 2014. "Gestão da Zona Costeira: O Desafio da Mudança. Relatório do Grupo de Trabalho do Litoral."; 237 p. (in Portuguese).

Veloso-Gomes, F., Taveira Pinto, F., Das Neves, L., Pais Barbosa, J. 2006. "Pilot site of River Douro - Cape Mondego, and case studies of Estela, Aveiro, Caparica, Vale de Lobo and Azores." EUrosion. IHRH, FEUP. ISBN: 972 752 074-x.

Willmott, C., Robeson, S., Matsuura, K. 2012. "A Refined Index of Model Performance." *International Journal of Climatology*. 32, 2088-2094.