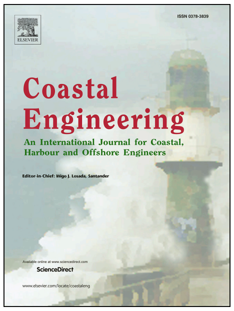

# An integrated physical and cost-benefit approach to assess groins as a coastal erosion mitigation strategy

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# **TITLE:** An integrated physical and cost-benefit approach to assess groins as a coastal erosion mitigation strategy

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## ABSTRACT

Future investments required for the construction and maintenance of coastal defense interventions are expected to increase, due to increasing coastal erosion issues along social, environmental and economically valuable coastal areas. The high costs related with coastal defense interventions require improved knowledge on their performance, considering impacts, costs and benefits. Despite the existence of several cost-benefit approaches applied to coastal zones, in this study a well-defined, sequential and integrated methodology supported by already existent numerical models is developed and applied to assess the effectiveness (shoreline evolution impacts), costs and benefits of different coastal defense interventions. This methodology encompasses three integrated modules, including a shoreline evolution module (to estimate areas of territory maintained, gained or lost over time), a coastal structure pre-design module (to estimate material volumes of coastal works) and a cost-benefit evaluation module (to assess cost-benefit evaluation criteria). The approach allows for the physical and economic comparison of different coastal defense intervention scenarios, helping coastal management and planning entities to define strategies. In this study, the proposed methodology was applied to evaluate the performance of different groin scenarios, based on a hypothetical case study. The case study allowed highlighting the importance of the physical and economic analysis of different scenarios. Results show that the definition of coastal defense interventions is complex where, on the one hand, best physical solutions are sometimes related to very high costs and, on the other hand, best economic scenarios lead to high territory losses. Thus, the innovative approach presented in this study shows that an integrated analysis of shoreline evolution, coastal intervention design and subsequent costs and benefits allows to improve the physical and economic performances of coastal defense interventions.

**KEYWORDS**

Shoreline evolution, coastal structural design, cost-benefit analysis, coastal defense interventions, numerical modelling

## 1. INTRODUCTION

A growing trend of erosion issues in coastal areas is being observed worldwide (Basco, 1992; Coelho *et al.*, 2009; Narra *et al.*, 2017; Escudero-Castillo *et al.*, 2018). Sediment deficits, increasing urban pressure and continuous shoreline retreat along coastal areas, are expected to require increased investments to build and maintain coastal protection structures, to perform artificial nourishments or to allow retreat of urban coastal fronts. Hudson et al. (2015) refer that construction costs for coastal protection works are highly variable due to the varied nature of required works, site conditions, local prices and values, and availability and sources of materials used. Coastal works involve high costs and, thus, the definition of erosion mitigation measures require integrated studies, namely concerning coastal interventions performance based on cost-benefit analysis (Roebeling et al., 2011; Lima, 2018).

Coastal management entities should justify their coastal defense interventions strategies based on scientific knowledge, reasoned analysis and cost-benefit considerations. The choice for specific coastal defense interventions can be based on physical criteria (maximize the area and type of territory to be protected), economic criteria (maximize the returns on coastal defense investment), or through the combination of both. Integrated tools to assess different coastal defense interventions scenarios, helping decision-making and leading to cost reductions, are critical for efficient coastal management.

One of the most applied coastal erosion mitigation strategies is based on coastal structures, such as groins. Groins interfere with coastal dynamics (Figure 1) and sediment transport, leading to accretion and sediments accumulation at the updrift side (valuable area to be protected), while at downdrift side (where the provided value of the ecosystems is lower) the erosive process is anticipated due to the lack of sediments (Guimarães et al., 2016).

Figure 1: Groin impact on shoreline evolution (green hatched area represents accretion while red hatched area represents erosion).

Shoreline evolution assessment associated with groins allows to evaluate the benefits, considering the maintained or accreted areas resulting from the groins positive impact, minus the eroded areas caused by the groins. The structures design allows to define the groins dimensions and material volumes and, consequently, the required direct investment and maintenance costs. Finally, by assigning monetary values to the territory (taking into account, simultaneously, social, environmental and/or economic values), it is possible to assess the economic viability based on total costs and total benefits (see e.g. Roebeling *et al.*, 2011).

The main objective of this study is to present a well-defined and sequential approach, applied in an integrated way, to assess the effectiveness (shoreline evolution impact), costs and benefits of different coastal defense intervention scenarios. The methodological approach considers a shoreline evolution model (to estimate territory maintained, gained or lost over time), a coastal structures pre-design model (to estimate structures dimensions and material volumes) and a cost-benefit evaluation model (to define values for land and coastal interventions as well as to assess cost-benefit evaluation criteria). To show the sequential approach and highlight the potential impacts of different coastal intervention scenarios, a hypothetical case study is presented. Thus, the proposed approach was applied to assess the effectiveness, costs and benefits of different groins scenarios to mitigate coastal erosion issues in an urban coastal waterfront study area that is characterized by sediment deficits and erosion problems.

The next section provides a short review on cost-benefit analyses applied to coastal erosion mitigation strategies. Then, the integrated methodology and underpinning modules of the developed approach to assess the effectiveness of different coastal erosion mitigation strategies are described. Next, the case study is presented, including the reference scenario description, the groin baseline scenario and all assessed groin scenarios. Finally, the obtained results are presented, analyzed and discussed, and key conclusions are derived.

## 2. COST-BENEFIT ANALYSIS APPLIED TO COASTAL EROSION MITIGATION STRATEGIES

Engineering approaches are, traditionally, used to assess coastal erosion problems and responses and, thus, the physical effectiveness of coastal intervention measures are assessed without taking cost and benefit considerations into account (see Roebeling *et al.*, 2018). Shoreline evolution models, such as the Long-Term Configuration (Coelho, 2005), GENESIS (Hanson and Kraus, 1989), ONELINE (Dabees and Kamphuis, 1998), LITMOD (Vicente and Clímaco, 2003), LITPACK (DHI, 2009) and UNIBEST (Deltares, 2018a), and coastal structure design models, such as the Xpress Design of Coastal Structures (XD-Coast; Lima *et al.*, 2013), BREAKWAT (Deltares, 2018b), CRESS (CRESS, 2018), and CLI (CLI, 2018), can be used for these physical effectiveness analyses. However, with the emergence of Integrated Coastal Zone Management (2002/413/EC), the focus of studies moved from physical effectiveness of coastal intervention measures to a more comprehensive management of coastal zones. This gave rise to various economic studies evaluating coastal intervention measures, considering economic tools such as cost-effectiveness, cost-benefit and efficiency analyses (Breil *et al.*, 2007; Roebeling *et al.*, 2018).

Cost-effectiveness analyses provide insight in what coastal intervention measures achieve coastal protection objectives at least cost. For example, some studies assessed the expected costs of no interventions, associated with ecosystem service value losses in Central Portugal (Alves *et al.*, 2009) and expected tourism revenue losses in the Greek island of Crete (Alexandrakis *et al.*, 2015). Other studies assessed the cost-effectiveness of groin fields and beach nourishments in Central and South Portugal (Taborda *et al.*, 2005) and the cost-effectiveness of beach nourishments in the U.S. State of Florida (Chu *et al.*, 2014).

Cost-benefit analyses provide insight in what coastal intervention measures/scenarios provide largest net benefits, assessing costs (construction and maintenance) and benefits (avoided costs) of intervention measures. Turner *et al.* (2007) evaluated the costs and benefits of various managed realignment scenarios in North-East England. Roebeling *et al.* (2011) performed a cost-benefit assessment of a wide range of hard and soft protection scenarios in Central Portugal. Martino and Amos (2015) assessed the net benefits from a beach nourishment project along the Tyrrhenian coast of Italy. Finally, Coelho *et al.* (2016) assessed the costs and benefits of several longitudinal revetment scenarios in Central Portugal, while

Campos *et al.* (2016) and Vizinho (2018) assessed the costs and benefits of stakeholder-defined climate change adaptation pathway scenarios for a case study in Central Portugal.

Efficiency analyses enable the identification of optimal coastal intervention measures/strategies and, thus, provide largest welfare benefits. Efficiency studies, that enable the identification of optimal adaptation measures/strategies (*i.e.* that provide largest net benefits and, thus, maximize welfare), have mainly been applied at the regional and global scale (Darwin and Tol, 2001; Bosello *et al.*, 2007; Costa *et al.*, 2009; Neumann *et al.*, 2011). Few efficiency studies have been applied at the local and landscape scale. Those include studies by Smith *et al.* (2009) and Landry (2011), that developed conceptual optimization models (capital-theoretic and optimal-control, respectively) to assess optimal artificial beach nourishment sizes and intervals. Tsvetanov and Shah (2013) applied a stochastic optimization approach to assess the optimal investment timing of increases in the height of seawalls/levees in Connecticut (U.S.). Roebeling *et al.* (2018) applied a deterministic combinatorial optimization approach to explore the dimensions and locations of groins that provide largest welfare gains in Central Portugal.

The cost-benefit methodology approach and the numerical tool developed and presented in this study differs from the abovementioned costs-benefit analyses in the following three main aspects. Firstly, it is a well-defined, sequential and integrated analysis that entails the impact of the coastal interventions on shoreline evolution (by applying the LTC numerical model), the pre-design of the coastal structures (applying XD-Coast model) and, finally, the quantification of related costs and benefits. The integration of these three components in a single numerical tool adds important value to the global analysis of coastal intervention measures, based on their simultaneous physical and economic performance. Secondly, this numerical tool allows for an easy and quick comparison between different coastal defense intervention scenarios, helping coastal management entities in evaluating coastal erosion mitigation strategies. Finally, it allows to easily perform sensitivity analyses on all relevant variables that determine the intervention scenarios – including physical characteristics (such as length, location, number of structures, crest elevation, volume, etc.) and/or economic features (such as land values and materials unit costs).

## 3. METHODOLOGY

The proposed integrated methodology to assess the effectiveness, costs and benefits of different coastal defense interventions encompassed three modules (Figure 2). Shoreline evolution in a medium-term scenario (using LTC numerical model; Coelho, 2005) that allows to calculate benefits (territory maintained, gained or lost); pre-design of the coastal structures and its dimensions for quantification of material volumes (with the support of XD-Coast model; Lima *et al.*, 2013) that allows to calculate costs (structures construction and maintenance); and, finally, cost-benefit analysis resulting from the land and materials values, and the estimates obtained from the previous steps. This section describes in detail the three integrated modules.

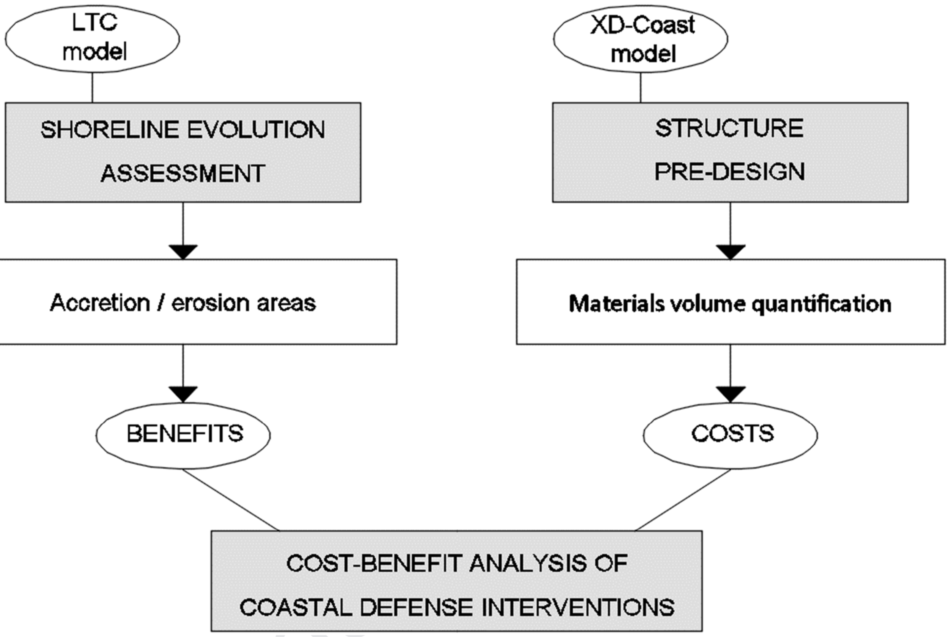


Figure 2: Integrated methodology to assess the effectiveness, costs and benefits of different coastal defense interventions.

### 3.1 SHORELINE EVOLUTION ASSESSMENT

The effectiveness of benefits from coastal mitigation interventions are estimated through the shoreline evolution numerical modelling and consequent evaluation of territory maintained, gained or lost along the time (typically at a decadal time scale). For this purpose, the numerical model LTC (Long-Term Configuration; Coelho, 2005) was used, a shoreline evolution model that allows to easily define and evaluate scenarios as well as test sensitivity to different parameter values. Naturally, the application of the proposed model to specific situations requires numerical models calibration and validation. Complex morphodynamics models are not adequate to model the intended spatial and temporal scales required by the approach. LTC was developed to support coastal zone planning and management in relation to coastal erosion problems (Coelho *et al.*, 2005; 2007; 2013; Guimarães *et al.*, 2016; Lima and Coelho, 2017). It was firstly presented at the ICCE 2004 (Coelho *et al.*, 2004) and has been improved and extensively applied since then (Coelho, 2005; Coelho *et al.*, 2006, 2007, 2013, 2016; Silva *et al.*, 2007a, 2007b; Silva, 2010; Roebeling *et al.*, 2011, 2018; Silva *et al.*, 2011; Pereira and Coelho, 2013; Guimarães *et al.*, 2016; Lima and Coelho, 2017; Lima, 2018). LTC combines a simple classical one-line model with a rule-based model for erosion/accretion volumes distribution along the beach profile (Coelho *et al.*, 2007). This model was designed for sandy beaches, where the main cause of shoreline evolution is the alongshore sediment transport gradients, dependent on the wave climate, water levels, sediment sources and sinks, sediment characteristics and boundary conditions. The model inputs are the wave climate, water level and the bathymetry and topography of the landward adjacent zones (updated during calculation).

The sediment transport volumes are estimated by formulae that consider the shoreline's angle to oncoming breaking waves (CERC formula; SPM, 1984) and the breaking wave height (Coelho *et al.*, 2009). The sediment volume variation in a coastal stretch is caused by sediment transport gradients between modeled cells where, similar to one-line models, the balance of volumes is defined through the continuity equation. This equation states that the variation in the volume of sand, along an infinitesimal length of the shoreline, is the same as the variation of sediments in transport, in that same length, added or subtracted by eventual external sediments supplements or extractions (Silva et al., 2017b). This difference between sediment transport volumes represents a variation in the depth level of the grid points in the same profile of the modeled domain (Coelho *et al.*, 2007). Thus, these sediment deficits along a coastal stretch represent shoreline retreat over time. LTC assumes a uniform cross-shore distribution of the alongshore sediment transport along the active extension of the beach cross-shore profiles, between the depth of closure (DoC) and the wave run-up limit. Thus, LTC performs a uniform variation of the vertical coordinates of the active profile grid points, adjusting the active profile limits based on the sediments friction angle (Coelho et al. 2013; Baptista et al. 2014). Thus, the sediment volumes distribution respect the sediment volumes balances but do not correspond exactly to the same accretion and erosion areas defined by the shoreline position, due to the differences between bathymetry and topography (see Coelho et al., 2013). Summarizing, the variation of the shoreline position depends, not only, on the sediment volume variation, but also, on the topography and bathymetry associated with each cross-shore profile (Coelho, 2005). With the LTC numerical model, the 3D topographic data are continuously updated during simulation, allowing the model to distribute erosion or accretion sediment volumes for each wave action (computational time step).

The wave transformation by refraction, diffraction and shoaling is modelled in a simplified manner (Coelho *et al.*, 2007), always taking into consideration the updated bathymetric data in each time step. According to Coelho (2005), the refraction effects in LTC are estimated through the use of Snell's law, while the shoaling effect is calculated following Airy's linear theory of sinewaves (Airy, 1845). The diffraction effects are calculated for beach extensions located downdrift of groins using a simplified method, based on Sorensen *et al.* (2003).

Due to the importance of the boundary conditions in the model simulations, several options can be made: constant sediment volumes going in or out the study area; constant volume variations in the border sections; extrapolation from nearby conditions (Silva *et al.*, 2007b). Moreover, different coastal protection works combinations may be considered with almost no limitation for the number of groins (i.e. the structure considered in this study), breakwaters and seawalls, the number of sediment sources/sinks sites, and artificial nourishments.

### 3.2 STRUCTURES PRE-DESIGN

The estimation of costs associated with coastal protection works (construction and maintenance) was based on the structures' design and corresponding definition of volumes and materials. This is achieved considering the geometry of the structure (cross-section and length) and its volume (depending on local bathymetry and topography). The numerical pre-design tool XD-Coast was applied (Lima, 2011). XD-Coast software (Xpress Design of COAstal Structures) and developed in Microsoft Visual C# language, whose main objective is the calculation of armor layer blocks unit weight of coastal structures exposed to wave actions, considering different formulations and types of structures. Furthermore, the model allows for the calculation of the main characteristics of the cross-section, in function of the armor layer blocks unit weight (Lima *et al.*, 2013).

XD-Coast is divided into two main parts: estimative of the armor layer blocks unit weight; and cross-shore geometric characteristics definition, based on the previous results. In the first part, the user starts by choosing the type of structure in analysis and the formulation required to calculate the block weight of the resistant layer. Afterward, in the second part, depending on the adopted block weight, a schematization of the cross-section can be obtained (Lima, 2011). The software allows to consider three different formulations for calculations related to non-overtopped structures: Hudson (1974), van der Meer (1988a) for rocks and van der Meer (1988b) and De Jong (1996) for tetrapods. For low-crested and submerged structures, the model presents one available formulation: van der Meer (1991) for rocks. The coastal structures are exposed to several energetic actions, such as waves, currents and tides, but the software only considers the wave height for block weight calculations. Once the cross-section is defined, knowing the bathymetry and topography at the structures location, the volume of each structure layer and material is calculated (Lima, 2018).

### 3.3 COST-BENEFIT ANALYSIS

To compare and assess the economic viability of different coastal intervention measures/scenarios, a cost-benefit analysis is performed (following Roebeling *et al.*, 2011), using net present value (NPV) and the benefit-cost ratio (BCR) evaluation criteria (Zerbe and Dively, 1994). Costs and benefits are estimated relative to the situation without intervention, where costs ($C_t$) are defined as the additional initial investment and recurrent maintenance costs associated with the intervention (in €/year) and benefits ($B_t$) are defined as the value of territory maintained, gained or lost due to the intervention (in €/year). Initial investment and recurrent maintenance costs are determined by applying XD-Coast (Lima, 2011; see Section 3.2), and territory gains/losses are determined considering the LTC numerical model results (Coelho, 2005; see Section 3.1) .

The NPV evaluation criterion is given by the sum of discounted benefits minus the sum of discounted costs that occur in each period *t* over the lifetime of the project *T* (Zerbe and Dively, 1994), and is given by:

$$\mathrm{NPV} = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} - \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \qquad (1)$$

where *r* is the time discount rate. The project is considered economically viable when the NPV > 0, *i.e.* when the present value benefits (first term on right-hand side of Equation 1) exceed the present value costs (second term on right-hand side).

The BCR evaluation criterion is given by the sum of discounted benefits relative to the sum of discounted costs that occur in each period *t* over the lifetime of the project *T* (Zerbe and Dively, 1994), and is given by:

$$\mathrm{BCR} = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} \Bigg/ \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \qquad (2)$$

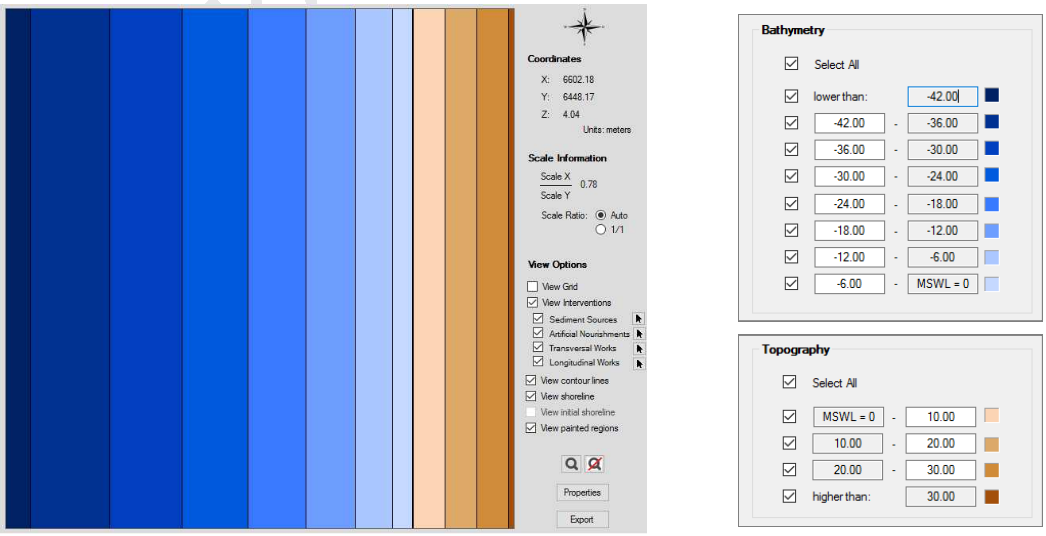
A project is considered economically viable when the BCR > 1, *i.e.* when the present value benefits (numerator on right-hand side of Equation 2) exceed the present value costs (denominator on right-hand side). Note that the BCR = 1 when the NPV = 0.

## 4. THE CASE STUDY

This study aimed to assess the effectiveness of different groin scenarios applied to a hypothetical case study, through an integrated cost-benefit analysis. Cost-benefit analysis requires the comparison of two different scenarios: the reference scenario and the coastal intervention scenario to mitigate erosion. The reference scenario corresponds to the "do-nothing" scenario, which represents the natural shoreline evolution without any intervention in a coastal stretch forced by significant sediments deficit and erosion problems. To allow the comparison between the different proposed scenarios, a baseline scenario with a single groin with a length of 200 meters was also defined – i.e. a typical situation along many sandy coastal areas where groins are constructed in front of urban settlements. Starting from this baseline scenario, by changing length, location, number of groins, in total 10 groin scenarios were defined, tested and analyzed.

### 4.1 REFERENCE SCENARIO

The reference scenario represents a hypothetical study area, characterized by a regular topo-bathymetry, where a regular square grid (spacing 20 meters), with 401 x 501 points (respectively, in the perpendicular and parallel direction to the shoreline) results in a spatial domain area of the 8 000 x 10 000 m$^2$ (Figure 3). The bathymetry data was generated according to the Dean profile (Dean, 1991), considering the parameter $A$ and $m$, respectively 0.127 and 2/3. For the topography data (above reference level, 0.0 m) a constant slope of 2% was considered.



**Coordinates**

X: 6602.18

Y: 6448.17

Z: 4.04

Units: meters

**Scale Information**

Scale X / Scale Y 0.78

Scale Ratio: ● Auto ○ 1/1

**View Options**

☐ View Grid
☑ View Interventions
  ☑ Sediment Sources
  ☑ Artificial Nourishments
  ☑ Transversal Works
  ☑ Longitudinal Works
☑ View contour lines
☑ View shoreline
☐ View initial shoreline
☑ View painted regions

**Bathymetry**

☑ Select All
☑ lower than: -42.00
☑ -42.00 - -36.00
☑ -36.00 - -30.00
☑ -30.00 - -24.00
☑ -24.00 - -18.00
☑ -18.00 - -12.00
☑ -12.00 - -6.00
☑ -6.00 - MSWL = 0

**Topography**

☑ Select All
☑ MSWL = 0 - 10.00
☑ 10.00 - 20.00
☑ 20.00 - 30.00
☑ higher than: 30.00

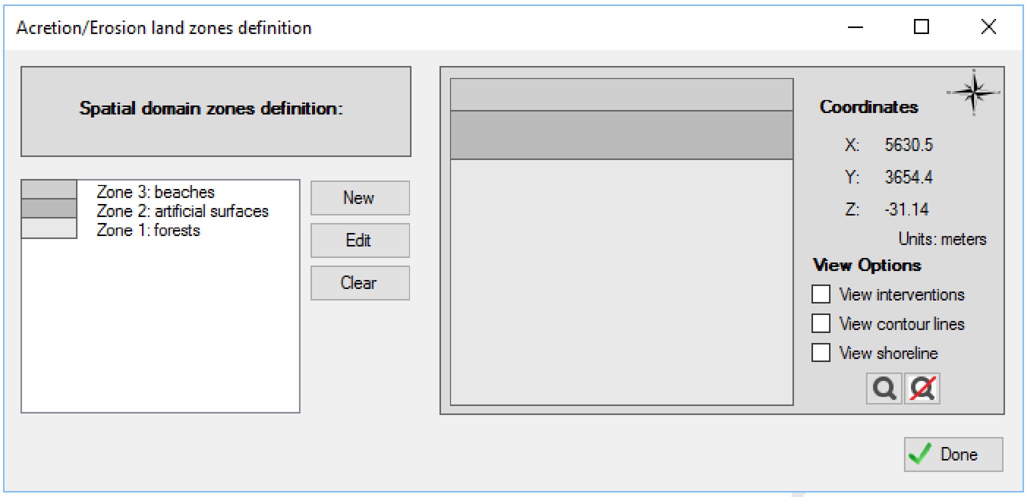
Figure 3: LTC numerical model representation of the topo-bathymetric data.

To perform the LTC numerical modelling, the wave climate was considered constant along all the simulations, with offshore characteristics of 2 meters wave height ($H_0$) and 10 degrees wave direction with West, clockwise ($\alpha_0$). The active cross-shore profile was limited by the closure depth ($DoC$ = 8 m) and by the wave run-up ($R_u$ = 2 m), which result in a total active height of 10 meters (considered constant along all simulations). The DoC also works as a calibration parameter of the model, by defining the cross-shore extension of the active profile width. The uniform cross-shore distribution of the alongshore sediment transport is assumed to occur in the active width of the cross-shore profile, between the DoC and the wave run-up limit. The adopted CERC sediment transport coefficient ($k$) was 0.03. At the northern boundary, a null input of sediments was considered and in the southern boundary, an extrapolation of the sediment transport nearby conditions was imposed. The described conditions correspond to a coastal stretch where a sediment deficit is imposed by the northern boundary conditions and significant erosion and shoreline retreat is expected to occur along the domain, propagating from North to South due to the littoral drift corresponding with the potential longshore sediment transport capacity of the wave climate. A time-step of one hour and a time horizon of 20 years were adopted for the simulations. Annual model outputs were registered, allowing the evaluation of every year eroded and accreted areas of territory.

To estimate territory values, the provided services of the coastal areas and ecosystems, which are important to human well-being, health and livelihoods, should be considered. For the case study, the land value of the territory was divided in three zones along the coast with landward constant values (see Table 1 and Figure 4), with beaches (Zone 3), artificial surfaces (Zone 2) and forests (Zone 1) from north to south over an extension of 10 km. Beaches provide coastal protection and recreational uses, artificial surfaces provide residential, tourism and recreational uses and, finally, forests provide timber production, climate regulation and erosion control, habitat for biodiversity, and recreational services (Costanza *et al.*, 1997; 2014; Martinez et al., 2007; Roebeling *et al.*, 2013). It should be noted that the defined territory values encompass economic, environmental, social and cultural aspects that may vary largely between study locations. The time discount rate (r) was considered 3% (following Roebeling *et al.*, 2018).

Table 1: Economic land value defined in the case study (based on Roebeling *et al.*, 2018).

| | **Description (km)** | **Location** | **Extension (km)** | **Value (€/m$^2$/year)** |
|---|---|---|---|---|
| **Zone 3** | Beaches | North limit | 1.0 | 2.00 |
| **Zone 2** | Artificial surfaces | Intermediate | 1.5 | 10.00 |
| **Zone 1** | Forests | South limit | 7.5 | 0.20 |



Zone 3: beaches
Zone 2: artificial surfaces
Zone 1: forests

X: 5630.5
Y: 3654.4
Z: -31.14
Units: meters

Figure 4: Territory zones defined in the spatial domain of the case study.

### 4.1.1 Shoreline evolution

Based on the adopted conditions for the case study, the shoreline evolution results for the reference scenario show great losses of territory after 20 years of simulation, mostly at the northern boundary of the domain. Coastal erosion and subsequent shoreline retreat is propagating downdrift over time. Thus, if no interventions are implemented during the 20 years simulation period, shoreline retreat can reach about 230 meters on the northern border and all the extension of the urban waterfront is affected by erosion. Figure 5 shows the shoreline position after 5, 10 and 20 years of simulation as well as the total area lost in each zone (beaches, urban and forest).

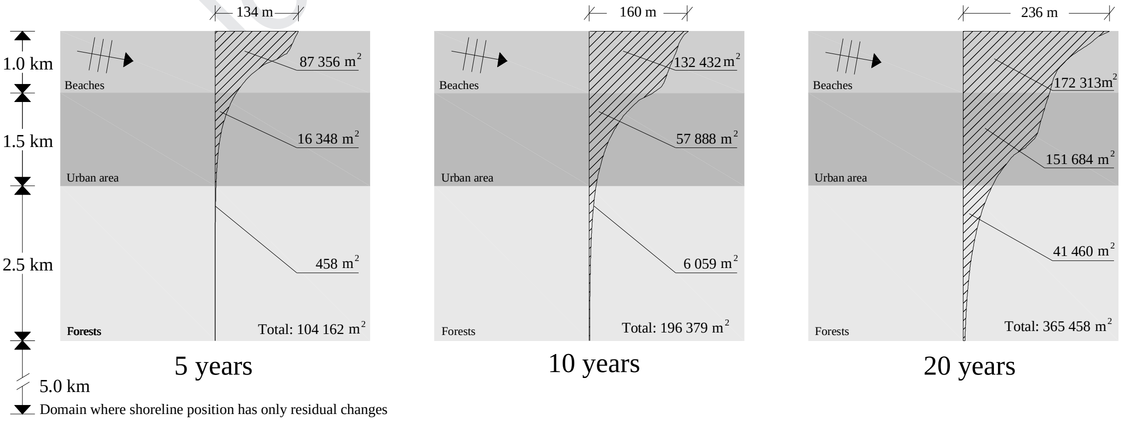


Figure 5: Shoreline position in the reference scenario, after 5, 10 and 20 years (horizontal scale 10 times greater than the vertical scale).

### 4.1.2 Coastal erosion impacts

Based on the attributed land values for each zone, the NPV for each year of simulation is calculated. After 5 years of simulation, the losses of territory represent about 0.8 m€, and after ten years the losses already exceed 3 m€. At the end of the 20 years simulation, the results show about 12 m€ losses, representing the erosion trend along the coast and subsequent losses over time.

Although representing a hypothetical case study, the reference scenario shows that in sandy coastal areas subject to erosion (i.e. where the sediment volumes available for the littoral drift are below the potential sediment transport capacity), there is a high potential for economic losses if no mitigation strategies are considered. Thus, in this study, different groin intervention scenarios are proposed to mitigate the erosion problems identified in the reference scenario. First, a groin baseline scenario was defined and then, other scenarios considered different groin extensions and locations, and combined different number of groins.

## 4.2 BASELINE SCENARIO

The establishment of groins to mitigate coastal erosion does not result in a reduction in sediment deficits along the coastal stretch but, instead, only transfers coastal erosion to lower-value areas. LTC evaluates the active cross-shore width of the beach profile and its relationship with the groin extension (creating a barrier to the longshore sediment transport). This relationship defines the share of sediments trapped by the groin, causing accumulation updrift and accelerating the sediment deficit and erosion downdrift (Baptista *et al.*, 2014; Guimarães *et al.*, 2016; Lima and Coelho, 2017). To evaluate the reasonability of this type of intervention, the baseline scenario was characterized by a groin with 200 meters length located 2.5 km south of the northern border and at the southern limit of the urbanized area (Zone 2; see Figure 6).

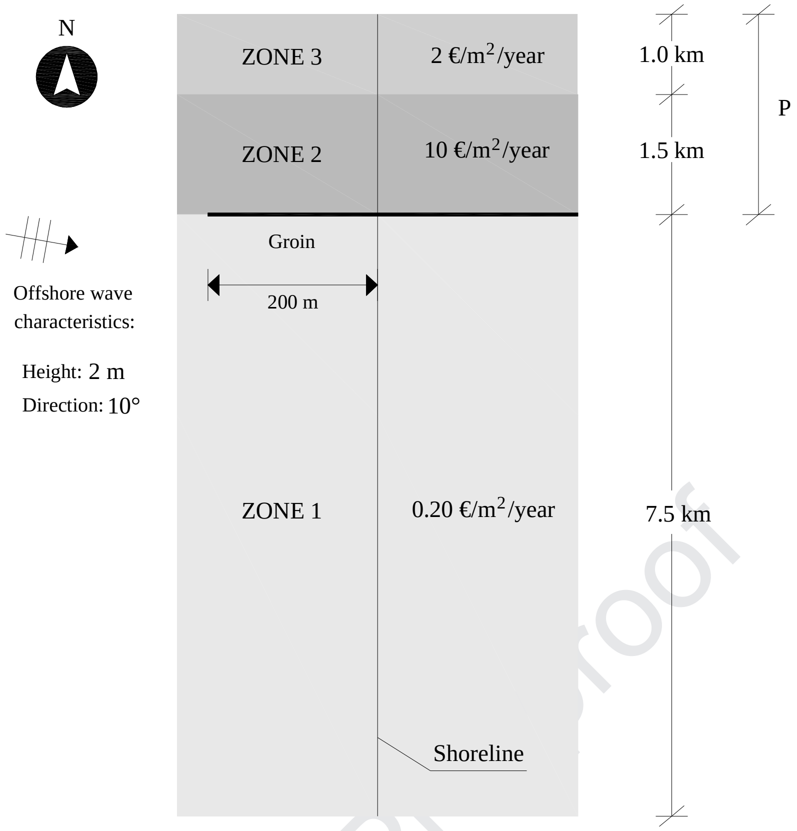


Figure 6: Plan schematization of the baseline scenario.

### 4.2.1 Shoreline evolution

Considering the parameter values of the reference scenario, LTC was applied to the baseline scenario to predict the shoreline evolution over the 20 years' time horizon. Given the sediment deficit in the study area, a global erosion trend in the modelled domain is again observed. However, results show smaller shoreline retreat rates near the northern border and accumulation of sediments near the urban waterfront, updrift of the groin (Figure 7). In contrast, the sediment deficits, erosion trends and shoreline retreat rates are higher at downdrift (Zone 1), where the erosion impacts represent lower economic consequences. However, to evaluate if the proposed scenario is in fact economically advantageous, it was necessary to estimate the groin construction and maintenance costs, by designing the structure's characteristics (by applying XD-Coast model).

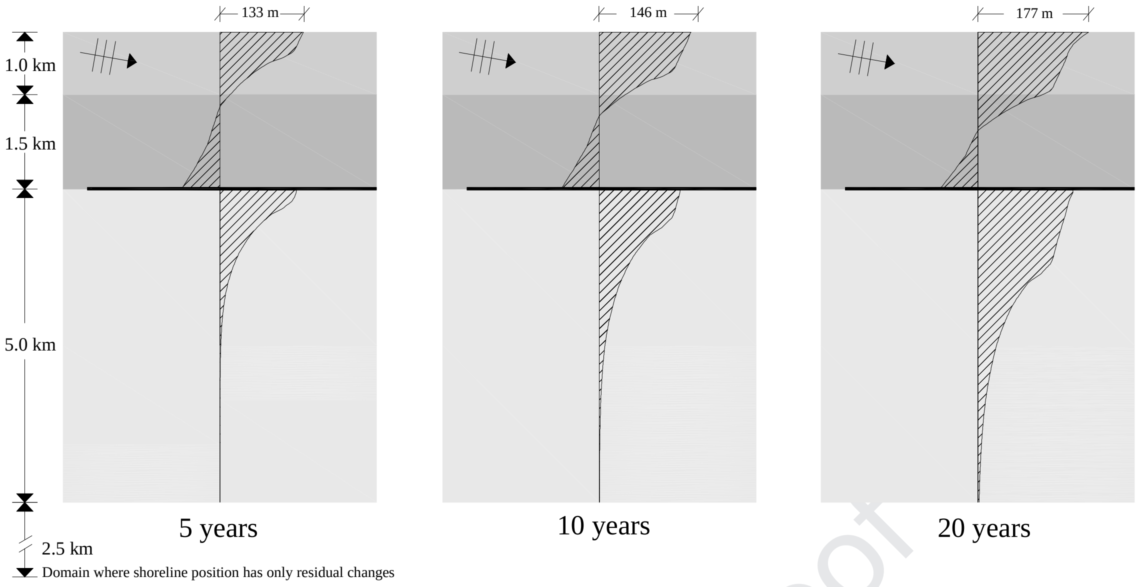
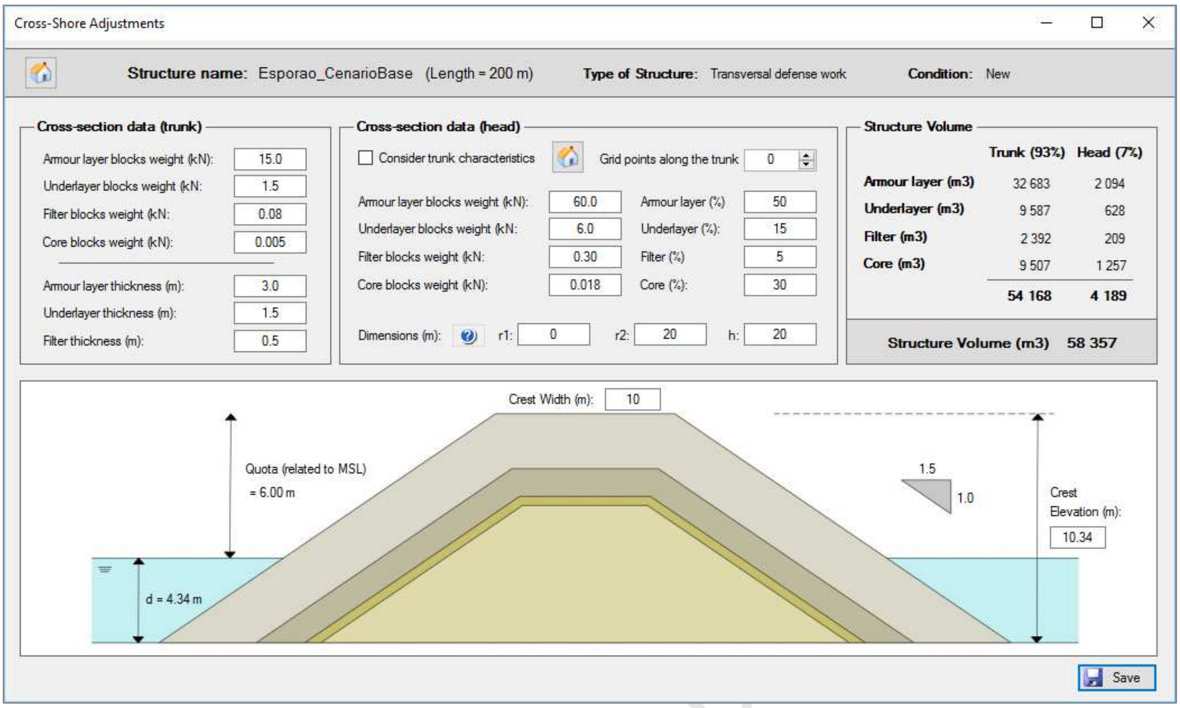


Figure 7: Shoreline position in the baseline scenario, after 5, 10 and 20 years (horizontal scale 10 times greater than the vertical scale).

### 4.2.2 Structure pre-design

The groin cross-section corresponding to the head of the structure was defined based on XD-Coast results. The Hudson (1974) formula was applied, considering a 2 m wave height, a structure slope of 2/3 (V/H) and the stability coefficient ($K_D$) of 3.5, characteristic of rock material. The cross-section characteristics (resistant layer and filters, crest width and elevation, and slope) were considered constants along the structure length. The structure height varied, depending on the bathymetric and topographic data. A crest width of 10 m and a crest elevation of 6 meters were considered (above the reference level). Considering that the structure head was located at a depth of about 4.5 meters, the total volume of the structure is around 58 000 $m^3$ (Figure 8).



Cross-Shore Adjustments

**Structure name:** Esporao_CenarioBase (Length = 200 m) **Type of Structure:** Transversal defense work **Condition:** New

**Cross-section data (trunk)**

Armour layer blocks weight (kN): 15.0
Underlayer blocks weight (kN: 1.5
Filter blocks weight (kN: 0.08
Core blocks weight (kN): 0.005
Armour layer thickness (m): 3.0
Underlayer thickness (m): 1.5
Filter thickness (m): 0.5

**Cross-section data (head)**

☐ Consider trunk characteristics
Grid points along the trunk: 0
Armour layer blocks weight (kN): 60.0
Underlayer blocks weight (kN: 6.0
Filter blocks weight (kN: 0.30
Core blocks weight (kN): 0.018
Armour layer (%): 50
Underlayer (%): 15
Filter (%): 5
Core (%): 30
Dimensions (m): r1: 0 r2: 20 h: 20

**Structure Volume**

| | Trunk (93%) | Head (7%) |
|---|---|---|
| **Armour layer (m3)** | 32 683 | 2 094 |
| **Underlayer (m3)** | 9 587 | 628 |
| **Filter (m3)** | 2 392 | 209 |
| **Core (m3)** | 9 507 | 1 257 |
| | **54 168** | **4 189** |

**Structure Volume (m3) 58 357**

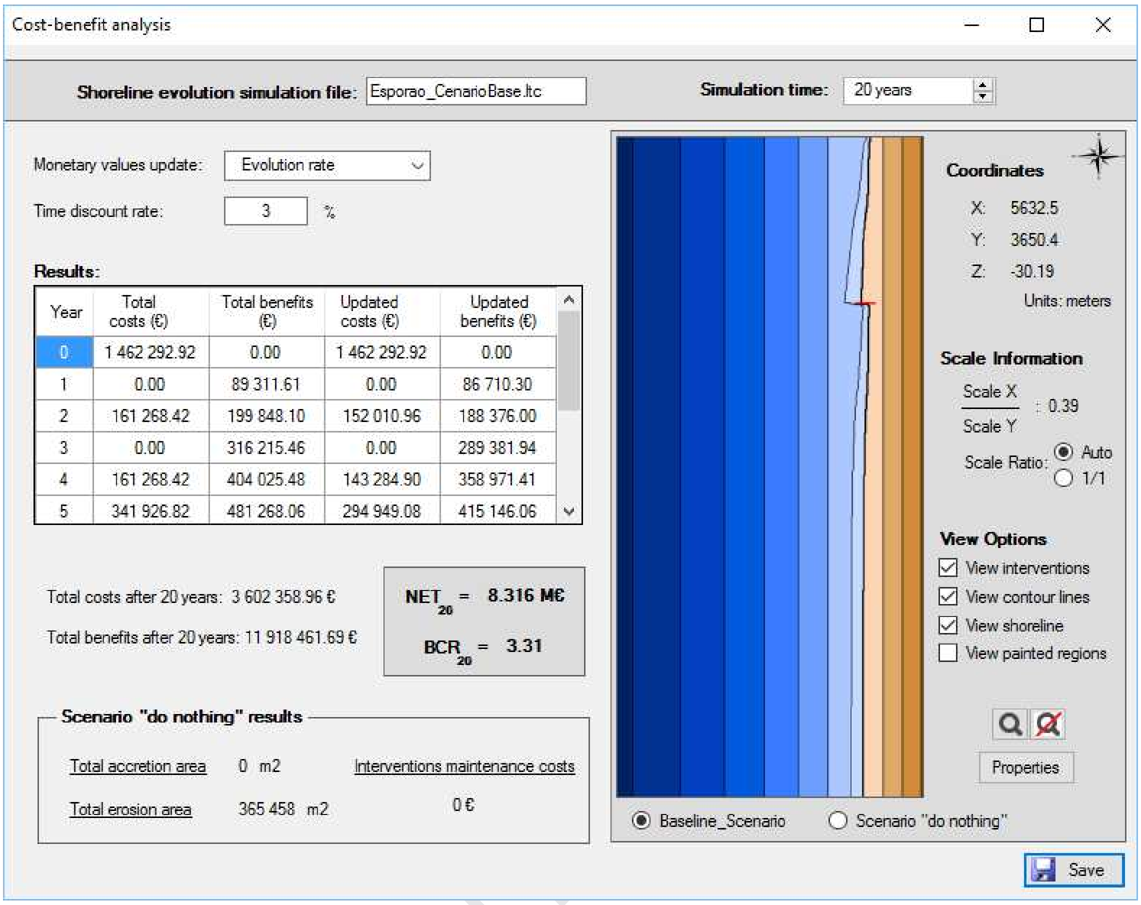
Crest Width (m): 10
Crest Elevation (m): 10.34

Figure 8: Groin head cross-section in the baseline scenario.

### 4.2.3 Cost-benefits results

Considering the groin material volumes, costs were calculated. The total initial investment costs for the groin construction was € 1 462 200. Maintenance costs were based on a percentage of the cost of each part of the structure (head and trunk). For the trunk, maintenance works were considered to take place every five years and corresponding costs are about € 340 000 (30% of trunk construction costs). For the head, maintenance works were considered to take place every two years and corresponding costs are about € 160 000 (50% of head construction costs).

Benefits were defined based on shoreline evolution model results, taking into account the accretion and erosion areas obtained every year, and the land values defined in the reference scenario (Figure 7 and Table 1). Given all costs and benefits associated to the baseline scenario, the economic indicators (NPV and BCR) were determined for every year. Figure 9 represents the results obtained at the end of the 20 years simulation.



**Shoreline evolution simulation file:** Esporao_CenarioBase.ltc

**Simulation time:** 20 years

Monetary values update: Evolution rate

Time discount rate: 3 %

**Results:**

| Year | Total costs (€) | Total benefits (€) | Updated costs (€) | Updated benefits (€) |
|---|---|---|---|---|
| 0 | 1 462 292.92 | 0.00 | 1 462 292.92 | 0.00 |
| 1 | 0.00 | 89 311.61 | 0.00 | 86 710.30 |
| 2 | 161 268.42 | 199 848.10 | 152 010.96 | 188 376.00 |
| 3 | 0.00 | 316 215.46 | 0.00 | 289 381.94 |
| 4 | 161 268.42 | 404 025.48 | 143 284.90 | 358 971.41 |
| 5 | 341 926.82 | 481 268.06 | 294 949.08 | 415 146.06 |

Total costs after 20 years: 3 602 358.96 €

Total benefits after 20 years: 11 918 461.69 €

**$NET_{20}$ = 8.316 M€**

**$BCR_{20}$ = 3.31**

**Scenario "do nothing" results**

Total accretion area 0 m2

Total erosion area 365 458 m2

Interventions maintenance costs 0 €

**Coordinates**

X: 5632.5

Y: 3650.4

Z: -30.19

Units: meters

**Scale Information**

Scale X / Scale Y : 0.39

Scale Ratio: ● Auto ○ 1/1

**View Options**

☑ View interventions

☑ View contour lines

☑ View shoreline

☐ View painted regions

● Baseline_Scenario ○ Scenario "do nothing"

Figure 9: Cost-benefit results for the baseline scenario.

## 4.3 GROIN SCENARIOS

Three main parameters were considered to test different groin scenarios: length, location and number of groins. Adequate groin length is one of the main issues in its design. Longer structures promote a bigger barrier to the littoral drift and provide effective protection to extensive areas located updrift of the structure, but increase the intervention costs and the negative impacts in the downdrift areas. Global and integrated assessment of groin location should correspond to a groin located at the downdrift limit of the higher valuable zone (which was adopted in the baseline scenario). However, this groin location scenario is not always possible and, thus, structure location was also tested. Depending on the size of the most valuable zones, some interventions may consider the combination of several structures, resulting in different groin field scenarios. In view of the previous, Table 2 presents the 10 different groin scenarios tested: influence of the length of the structure (group $i$, with three different scenarios); influence of the location of the structure (four scenarios in group $ii$); and, finally, influence of the number of the structures (three combinations in group $iii$).

Table 2: Definition of groin's scenarios tested (L is the length and P is the distance of the groin to the northern boundary of the modelled domain).

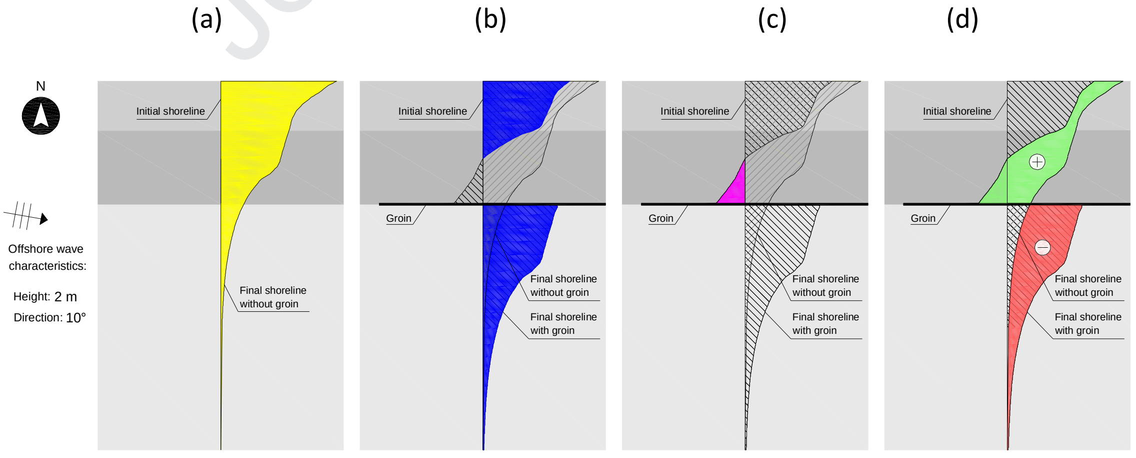
| | | 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| Groin length | *i* | $L$ = 100 m | $L$ = 300 m | $L$ = 400 m | - |
| Groin location | *ii* | $P$ = 1.5 km | $P$ = 2.0 km | $P$ = 3.0 km | $P$ = 3.5 km |
| Number of groins | *iii* | 2 groins spaced by 500 m | 2 groins spaced by 1000 m | 3 groins spaced by 500 m | - |

## 5. RESULTS AND DISCUSSION

This section presents and discusses the main results obtained for the groin baseline scenario and the 10 alternative groin scenarios. Final remarks highlight the major outlines of the obtained results.

### 5.1 BASELINE SCENARIO

Baseline scenario shoreline evolution results show the positive updrift impact of the groin, with an accretion area of 2.4 ha (which partially protects the urbanized zone). However, in total, the baseline scenario presents higher erosion than the reference scenario, increasing land losses in around 4 ha, which represents a general negative physical balance. The physical balance is here understood as the difference between the erosion areas of the reference scenario and the groin scenario under analysis, added to the accretion area resulting from the groin scenario under analysis, after the 20 years of simulation (Figure 10).



Erosion at reference scenario

Erosion at intervention scenario

Accretion at intervention scenario

Physical balance
= 🟨 - 🟦 + 🟪

Figure 10: Schematization of physical balance and corresponding benefits (reference and baseline scenarios, after 20 years).

The benefits (positive if territory is maintained or gained; negative if territory is lost) are obtained taking into account the land value and comparing the shoreline evolution of the two scenarios (Figure 10). In the reference scenario, after 20 years simulation, shoreline retreat in the most northerly section is 236 meters, which represents an average retreat rate of 11.8 m/year (yellow area). This high erosion rate is due to the absence of sediment input from the northern boundary and an initial domain far from the equilibrium between wave climate and sediment input (see Figure 10a). In the case of a groin the northern boundary is also retreating, as there are no sediments coming into the domain. However, the boundary is near the influence of the deposition updrift the groin and, thus, the retreat rate is lower than in the reference scenario (blue area). Due to the barrier effect of the groin, however, part of the sediments deposited updrift are missing downdrift, where the erosion area increases significantly (blue area; Figure 10b). The accretion area resulting from the groin effect updrift the structure corresponds to the pink area (see Figure 10c). The positive benefits (green hatch) encompass the accretion area and the area that was not lost due to the groin. The negative benefits correspond to the losses that would not occur in the reference scenario (red hatch; Figure 10d). Despite the negative physical balance of the baseline scenario, this scenario is economically advantageous, reaching the break-even point after seven years. Break-even represents the time instant when the total benefits are equal the total costs of the coastal protection intervention (BCR = 1 and NPV = 0).

As previously referred, the 200 meter groin represents an initial cost of around 1.5 m€ and a total cost of about 3.6 m€ (considering maintenance costs) over the 20 years of simulation. However, the benefits resulting from the groin impact represent economic gains in the order of 12 m€, at the end of the 20 years of simulation (due to the protection of the valuable urbanized zones of the coastline). Thus, the groin baseline scenario net present value (NPV) over the 20-year time horizon was about 8 m€. Table 3 summarizes the total accreted and eroded areas after 20 years and presents the benefit-cost ratios (BCR) after 5, 10 and 20 years.

Table 3: Physical (after 20 years) and economic (after 5, 10 and 20 years) balance of the baseline scenario.

| | **Total areas after 20 years (ha)** | | **Benefit-cost ratio** | | |
|---|---|---|---|---|---|
| | Accretion | Erosion | 5 years | 10 years | 20 years |
| Baseline scenario ($BS$) | 2.4 | 43.1 | 0.65 | 1.51 | 3.31 |

Despite the global negative physical impact of the groin baseline scenario (increased erosion area), it is possible to conclude that this is an economically adequate intervention to mitigate erosion impacts in the medium- to long-term perspective (after 7 years of simulation).

## 5.2 GROIN LENGTH

Three different groin lengths were tested and compared to the baseline scenario (*BS*, 200 m long): 100 m, 300 m and 400 m groin lengths, respectively, scenario i.1, i.2 and i.3 (Table 2). Groin dimensions are different in each scenario and, thus, XD-Coast was applied to estimate the material volume in each scenario and corresponding costs (Table 4). Although the structures extend to different depths, by simplification, the same design wave height was considered in all scenarios (resulting in the same type of block).

Table 4: Groin material volume and construction cost, for different length scenarios.

| | | Volume ($m^3$) | Total cost (€) |
|---|---|---|---|
| $i.1$ | $L$ = 100 m | 34 600 | 975 627 |
| $BS$ | $L$ = 200 m | 58 357 | 1 462 293 |
| $i.2$ | $L$ = 300 m | 91 334 | 2 291 617 |
| $i.3$ | $L$ = 400 m | 130 756 | 3 263 128 |

Regardless of the length of the groin, shoreline evolution after 20 years results in a negative physical balance (Table 5). In the first scenario (i.1, L = 100 meters), sediment accumulation updrift of the groin results in a small accretion area (less than 0.1 ha). With increasing groin lengths, sediment accumulation updrift is larger, increasing protection effectiveness of the urbanized zone. Significant differences occur for groin lengths of 200 and 300 meters (accretion area increases by around 200%), while for groins of 300 and 400 meters the increasing impact is only 10%. Despite the urbanized zone protection, all the scenarios show generalized erosion at the northern border and downdrift of the groin. The total erosion area increases with the length of the structure, at an approximately linear rate of about 10 to 15% per 100 meters of groin length.

Knowing groins costs and the gained/lost areas, economic analysis of the different scenarios was performed (BCR results for 5, 10 and 20 years are shown in Table 5). At the end of the simulation (20 years), all intervention scenarios are economically viable, while noting that the baseline scenario presents the highest BCR.

Table 5: Physical and economic balance of the groin length scenarios.

| | | **Total areas after 20 years (ha)** | | **Benefit-cost ratio** | | |
|---|---|---|---|---|---|---|
| | | Accretion | Erosion | 5 years | 10 years | 20 years |
| $i.1$ | $L$ = 100 m | 0.9 | 38.0 | 0.23 | 0.57 | 1.48 |
| $BS$ | $L$ = 200 m | 2.4 | 43.1 | 0.65 | 1.51 | 3.31 |
| $i.2$ | $L$ = 300 m | 7.5 | 47.4 | 0.47 | 1.28 | 2.96 |
| $i.3$ | $L$ = 400 m | 8.2 | 47.9 | 0.32 | 0.88 | 2.06 |

The smaller groin is least economically viable, albeit still presenting positive returns to investment. However, if the initial financial availability is low, the scenario corresponding to the smaller groin (100 meters) may be a more feasible intervention option (as construction and maintenance costs are lower). The two longer groins are less economically viable, however, if the main intervention goal is the beach area increasing along the urbanized extension of the coast, these options will be more effective.

Summarizing, each studied scenario simultaneously presents advantages and disadvantages and, thus, the best option for the length of the groin will depend on the main objective of the intervention. The baseline scenario (200 meters) is the solution that most quickly reaches break-even and represents, at the same time, the greatest negative physical balance. The 100 m groin is the most effective solution in case few economic resources are available to perform coastal protection works. The groins with 300 and 400 meters results in larger accretion areas and, consequently, greater effectiveness in the protection of the urban waterfront, if this is the main goal of the intervention.

### 5.3 GROIN LOCATION

Four different groin location scenarios were tested and compared to the baseline scenario. The scenarios tested the position of the groin, located 500 and 1000 meters north and south of the groin position in the baseline scenario (resulting in scenario ii.1, ii.2, ii.3 and ii.4, Table 2, respectively at a distance P from the northern boundary of the domain of 1.5, 2.0, 3.0 and 3.5 km). The cost of the groin was considered the same for all the studied scenarios, reason why the economic indexes are only affected by the erosion and accretion areas. Table 6 summarizes the obtained results, showing the baseline scenario as the most economically viable albeit not resulting in largest accretion areas.

Table 6: Physical (after 20 years) and economic (after 5, 10 and 20 years) balance of the groin location scenarios.

| | | **Total areas after 20 years (ha)** | | **Benefit-cost ratio** | | |
|---|---|---|---|---|---|---|
| | | Accretion | Erosion | 5 years | 10 years | 20 years |
| $ii.1$ | $P$ = 1.5 km | 1.8 | 40.8 | -0.65 | -1.09 | -0.82 |
| $ii.2$ | $P$ = 2.0 km | 2.0 | 42.1 | -0.20 | 0.01 | 1.20 |
| $BS$ | $P$ = 2.5 km | 2.4 | 43.2 | 0.65 | 1.51 | 3.31 |
| $ii.3$ | $P$ = 3.0 km | 3.0 | 44.2 | 0.26 | 0.85 | 2.18 |
| $ii.4$ | $P$ = 3.5 km | 3.8 | 45.4 | 0.10 | 0.47 | 1.45 |

In the scenarios where the groin location is at the southern positions, the largest accretion areas will occur in less valuable zones of the domain. On the other hand, if the groin is located in the northern positions, erosion will occur in the most valuable zones. Thus, considering scenario ii.1 (groin located 1.5 km far from the northern border), the solution is not economically viable in the 20 years simulation. However, this is the scenario that presents better physical results. Scenario ii.2 is economically viable after 19 years of simulation and corresponds to the second best physical balance scenario. The scenarios where the groin position is located to the south of the groin of the baseline scenario (ii.3 and ii.4), are economically efficient after 20 years of simulation (although the BCR values are lower than those obtained in the baseline scenario). However, the erosion areas are larger than those obtained for the baseline scenario (erosion area increases with increasing distance from the groin to the northern border of the domain).

In sum, the most adequate location for the groin corresponds to the baseline scenario, where the groin is located at the downdrift limit of the most valuable zone. However, concerning the physical evaluation of the interventions, this is not the most advantageous scenario, as the total erosion area after 20 years of simulation increases with increasing distance from the groin to the northern border of the studied area. If the decision criteria for intervention is to avoid generalized erosion, the preferred location of the structure should be as far from the northern border as possible (although decreasing the accretion areas at the urbanized zone and consequently, obtaining lower protection to this zone).

### 5.4 NUMBER OF GROINS

Three different groin field scenarios were considered, always keeping the groin adopted in the baseline scenario: scenario iii.1, adding a groin with the same characteristics, located 500 meters to the north; scenario iii.2, adding a new groin with the same characteristics, located 1000 meters at north; and finally, scenario iii.3 considering three structures, combining the locations of the two previous scenarios. The number of groins in each scenario has a direct influence on the total construction and maintenance costs along the 20 years of simulation (Table 7).

Table 7: Groins material volume and construction cost, for different groin field scenarios.

| | | Volume ($m^3$) | Total cost (€) |
|---|---|---|---|
| $BS$ | 1 groin | 58 357 | 1 462 293 |
| $iii$.1 e $iii$.2 | 2 groins | 116 715 | 2 924 586 |
| $iii$.3 | 3 groins | 175 072 | 4 386 879 |

Table 8 shows greater accretion and erosion areas for the groin field scenarios, when compared to the baseline scenario. In the scenario iii.1, worst physical results were verified than in the baseline scenario, but scenarios iii.2 and iii.3 present a less negative physical balance (about 1 ha difference). The three groins scenario is the one that results in less losses of territory after the 20 years of simulation, representing a negative physical balance of about 3.3 ha.

Table 8: Physical (after 20 years) and economic (after 5, 10 and 20 years) balance of the groin field scenarios.

| | | Total areas after 20 years (ha) | | Benefit-cost ratio | | |
|---|---|---|---|---|---|---|
| | | Accretion | Erosion | 5 years | 10 years | 20 years |
| $BS$ | 1 groin | 2.4 | 43.2 | 0.65 | 1.51 | 3.31 |
| $iii$.1 | 2 groins spaced by 500 m | 3.8 | 44.7 | 0.32 | 0.87 | 2.01 |
| $iii$.2 | 2 groins spaced by 1000 m | 3.6 | 43.5 | 0.18 | 0.63 | 1.79 |
| $iii$.3 | 3 groins spaced by 500 m | 3.4 | 43.3 | 0.16 | 0.47 | 1.24 |

Although the largest accretion areas are associated with the groin field scenarios, the scenario with the highest BCR value corresponds to the baseline scenario. The three groins scenario presents the worst economic results, allowing to conclude that the increased investment associated with the construction and maintenance of the three groins, despite reaching break-even after 17 years, is not as economically viable as the baseline scenario.

In summary, the groin field scenarios (with two or three groins) do not provide economic benefits as compare to the baseline, because the benefits from the not eroded areas are not compensated by the increased construction and maintenance costs of the additional groins. However, all analyzed scenarios are economically adequate within the considered time horizon and the three groins field scenario corresponds to smaller losses of territory.

### 5.5 FINAL REMARKS

Considering all the assumptions adopted in the presented case study, several groin scenarios to mitigate coastal erosion were evaluated. A reference scenario was analyzed, corresponding to the “do-nothing” scenario, which would represent the natural shoreline evolution without coastal protection interventions. To allow the comparison between tested scenarios, a baseline scenario with a groin of 200 meters, was also defined. In turn, 10 other scenarios were defined and assessed, varying lengths, location and number of groins.

Table 9 summarizes the physical and economic results of all the scenarios: 1) 20 years physical balance, that is, the area lost as compared to the reference scenario (negative represents erosion); 2) net present value after 20 years; 3) initial and total investment costs; and 4) break-even points.

Table 9: Physical and economic summary results (after 20 years), for the analyzed groin scenarios.

| Scenario | | Physical balance (ha) | $NPV_{20\ yr}$ (€) | Costs | | Break-even** (years) |
|---|---|---|---|---|---|---|
| | | | | Initial (€) | Total* (€) | |
| $BS$ | Figure 6 | -4.2 | 8 316 103 | 1 462 293 | 3 602 359 | **7** |
| $i.1$ | $L$ = 100 m | **-1.4** | 1 263 061 | **975 627** | **2 615 491** | 15 |
| $i.2$ | $L$ = 300 m | -3.4 | **11 612 679** | 2 291 617 | 5 925 785 | 9 |
| $i.3$ | $L$ = 400 m | -3.1 | 9 150 555 | 3 263 128 | 8 670 313 | 11 |
| $ii.1$ | $P$ = 1.5 km | -2.5 | -6 556 228 | 1 462 293 | 3 602 359 | - |
| $ii.2$ | $P$ = 2.0 km | -3.5 | 714 226 | | | 19 |
| $ii.3$ | $P$ = 3.0 km | -4.7 | 4 259 681 | | | 11 |
| $ii.4$ | $P$ = 3.5 km | -5.1 | 1 624 686 | | | 16 |

| | | | | | | |
|---|---|---|---|---|---|---|
| $iii$.1 | 2 groins spaced by 500 m | -4.3 | 7 291 156 | 2 924 586 | 7 204 718 | 11 |
| $iii$.2 | 2 groins spaced by 1000 m | -3.4 | 5 678 216 | | | 13 |
| $iii$.3 | 3 groins spaced by 500 m | -3.3 | 2 560 639 | 4 386 879 | 10 807 077 | 17 |

*Values updated for initial simulation time, according to the discount rate (r).

** The **break-even** instant represents the instant, in the simulation time, when the investment balance is reached, that is, when the total benefits equal the total costs of the intervention (BCR = 1 and NPV = 0).

Table 9 shows that: 1) all scenarios result in a negative physical balance, with the 100 meter groin scenario showing the best global results at the physical level; 2) the largest net present value after 20 years of simulation was obtained for the 300 meters groin scenario; 3) lower initial and total investment costs are associated with the shorter groin (100 meters); and 4) the scenario that most quickly reaches break-even is the baseline scenario (groin with 200 meters, located at the south border of the urbanized zone).

Although the implementation of the groin induces greater losses of territory than that obtained in the reference scenario (after the 20 years of simulation), it provides economic benefits. Looking at the NPV value (Table 9) and based on the economic losses verified in the reference scenario (around 12 m€), after the 20 years of simulation almost all the economic losses can be avoided by the groin construction (11.6 m€ in the scenario i.2).

Results also show that it is difficult to combine, in the same intervention scenario, the best option taking into account both physical and economic factors. Thus, groin scenario definition depends on the main goals of the intervention, considering the urban waterfront extension to protect, the land values, the initial investment, the generalized erosion of the study area, the time required to reach the return to investment, the general physical balance or net present value, etc. All obtained cost-benefit results are dependent on defined territory values, which encompass economic, environmental, social and cultural aspects that may vary largely between study locations and, hence, a sensitivity analysis with respect to these values is recommended.

## 6. CONCLUSIONS

A well-defined and sequential cost-benefit analysis methodology, supported by existent numerical models to evaluate shoreline evolution and coastal structures design, was applied in an integrated way to a hypothetical case study. The main purpose of this study was to present the proposed approach by assessing the effectiveness of different groin scenarios to mitigate coastal erosion issues. The integrated methodology allowed to define, evaluate and discuss different scenarios, based on their physical and economic performance.

The proposed methodology considers that costs encompasses the investment and maintenance costs and that benefits are based on not eroded or accreted areas resulting from shoreline evolution.  A reference scenario corresponding to the “do-nothing” scenario was defined, which represents the natural shoreline evolution without any intervention. This scenario resulted in a significant loss of territory (around 37 ha) and large economic losses (above 12 m€). To compare different groin intervention scenarios, a baseline scenario with a 200-meter groin was also defined. Starting from this baseline scenario, 10 alternative groin scenarios were defined, tested and analyzed.

The groin baseline scenario results showed that with an initial cost of around 1.5 m€ (which represents a total cost of about 3.6 m€, when including maintenance costs), it is possible to obtain economic returns of about 11.9 m€, after 20 years. The net present value of this scenario is around 8 m€ and the break-even point was reached after 7 years. However, this solution results in a negative physical impact (additional 4 ha of land loss, as compared to the reference scenario). It should be noticed that groins do not solve the sediment deficit and, hence, to mitigate erosion the sediment deficit needs to be balanced. Nevertheless, the presented results show that it is possible to intervene with benefits by transferring the erosion from a more valuable area to a less valuable area. Lengths, locations and number of groins were analyzed, being possible to conclude that the preferable scenario will depend on the main goal of the intervention (e.g. lower cost, accretion areas or quicker economic return). The previous was evident when discussing the groin length scenarios. Regarding groin location, the baseline scenario is economically most advantageous, but physically not the best solution. It was verified that the groin field scenarios do not provide benefits as compared to the baseline scenario as the benefits from the gained areas are not compensated by the increased groin investment and maintenance costs. Therefore, the definition of the intervention scenario is complex, because sometimes the best physical solutions are associated with higher costs and economically advantageous solutions lead to higher land losses. However, the evaluation of the characteristics variation that defines the baseline scenario allowed to understand how the physical and economic performances can be improved, and shows that, with the same investment, significant improvements in the physical and economic performance of the adopted intervention scenarios can be achieved.

Worldwide, coasts present increasing erosion trends, regardless of the investments made. The preferred intervention is, generally, the solution that leads to least physical impacts and, simultaneously, largest economic benefits. In this process, the well-defined, sequential and integrated cost-benefit approach presented in this study can be very useful and important to help entities in coastal management, as it allows for: i) the easy definition and comparison of scenarios, ii) the performance of sensitivity analyses, and iii) the integrated assessment of several coastal defense scenarios from a physical and economic perspective. This approach allows to easily define and evaluate scenarios as well as test sensitivity to different parameter values – making it applicable to other study areas with similar coastal characteristics. Moreover, albeit not considered in the presented case study, the proposed method allows defining different land values in the landward direction and the land value can be updated over time, considering the socio-economic development of the coastal zone over the simulation time horizon. Those are important aspects to test, with implications for the decision-making process results.

As a final note, it must be noted that the values attributed to the different territories should include, simultaneously, all social, environmental and economic values. Also, the results obtained for this case study are dependent on the assumptions related to the shoreline evolution model and the structure design model, as well as the conditions of the considered spatial domain, namely, wave climate, topo-bathymetry data and land values. The potential application of the results from the presented hypothetical case study to real world situations is, naturally, limited by the specific conditions of each situation. However, the developed approach allows for easy and quick parametrization, calibration and sensitivity analysis to those conditions, allowing the approach to be easily applied to other study areas with similar coastal characteristics. Thus, the proposed methodology has the potential to contribute to a well-supported decision-making process, aiding in integrated coastal engineering, management and planning.

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## Highlights

1. An innovative integrated cost-benefit methodology and software application is developed and applied to analyze the impact of coastal defense interventions;
2. Three stages encompassed in the integrated methodology: shoreline evolution in a medium-term perspective; coastal structures pre-design; and finally, the cost-benefit assessment;
3. Groins performance was analyzed by assessing the effectiveness of different scenarios, in a physical and economic point of view;
4. Integrated global assessment of coastal defense interventions, discussing at the same time the best physical and economical solutions;
5. Worldwide coasts present increasing erosion trends, regardless the investment made, and when an intervention is performed, the solution simultaneously with less physical impact and economically more attractive performance is sought.

Conflict of Interest and Authorship Conformation Form

Please check the following as appropriate:

X All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

X This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

X The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript

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