# FEASIBILITY STUDY OF SAND BYPASS AT AVEIRO AND FIGUEIRA DA FOZ INLETS

Margarida Ferreira[1], Carlos Coelho[2], Márcia Lima[3], Cristina Bernardes[4], Paulo Baptista[5], Paulo A. Silva[6], Ricardo Carvalho[7], Malcolm Pound[8] and Celso Pinto[9]

To mitigate coastal erosion in the sectors Barra-Vagueira and Figueira da Foz-Leirosa (NW of Portugal), Portuguese coastal authority has promoted the discussion on the feasibility of implementing a sand bypassing system to restore natural littoral sediment transport. This study synthesizes the main results of the proposed solutions for Aveiro and Figueira da Foz tidal inlets. The methodology to develop the study compromised tree main phases that included the historical characterization of the study area, the preliminary design of different sand bypassing solutions for each coastal inlet and the discussion of their economic feasibility. The physical performance of the sand bypass solutions demonstrated that several bypassing solutions are technically viable to mitigate coastal erosion. However, it was found that the solution is economically viable only at the coastal sector Figueira da Foz-Leirosa.

*Keywords: coastal management; erosion; artificial sand bypassing, numerical modelling; cost-benefit; Portugal*

## INTRODUCTION

The Portuguese Northwest coast is exposed to the Atlantic Ocean wave climate, characterized by significant wave heights ($H_s$) between 2 m and 2.5 m, inducing a potential net longshore drift estimated to be around $1.1x10^6$ $m^3$/year directed towards South (Andrade *et al*., 2002; Coelho, 2005, Santos *et al*., 2014). Storms come predominantly from the NW sector and occur during the maritime winter months (from October to March) with significant wave heights that can exceed 8 m and can persist 5 days (Costa *et al*., 2001). This high-energy wave environment combined with existing sediment deficit (mostly due to anthropogenic actions such as dam construction, dredging in river basins, coastal engineering structures, etc.) has consequences in the shoreline evolution, namely coastal retreat/erosion in several areas (Coelho *et al*., 2009; Santos *et al.*, 2014; Lira *et al.*, 2015).

The coastal areas of Barra-Vagueira (Aveiro) and Figueira da Foz-Leirosa (Figueira da Foz), located downdrift the Aveiro estuarine-lagoon system and the Mondego river tidal inlets, respectively (NW coast of Portugal) are among the coastal extensions of the Portuguese coast most affected by the erosion issues (Figure 1). According to Lira *et al.* (2016), the shoreline retreat from 1958 to 2010 in the coastal sector Barra-Vagueira was in average 3.74 m/year and in the sector Figueira da Foz-Leirosa was 1.27 m/year. Sediment retention updrift of the harbor breakwaters, that define the northern border of the coastal sectors, is pointed out as one of the main causes for the sediment deficit and consequent shoreline retreat in these locations (Coelho *et al*., 2011; Costa and Coelho, 2013).

In the last decades, several coastal works have been carried out to mitigate shoreline retreat. Coastal management strategy in Portugal up to the late 1980s was based on the construction of fixed structures, such as groins and longitudinal revetments (Veloso-Gomes *et al*., 2004; Santos *et al.,* 2014). However, the paradigm as change since the 1990s and the coastal works began to be based on "soft measures", such as beach nourishments (Marinho *et al*., 2019; Pinto *et al*., 2020; Pinto *et al.* 2022).

To mitigate coastal erosion and the sediment deficit downdrift of Aveiro and Figueira da Foz tidal inlets, the Portuguese coastal management authority has promoted a feasibility study to implement a sand bypassing solution to restores the natural sediment transport in the inlets. This strategy could be achieved through dredging and deposition works (the sediments are dredged updrift of the harbor breakwaters, transported and deposited downdrift), or through continuous sand bypassing systems.

[1] RISCO & Department of Civil Engineering, University of Aveiro, Campus Universitário de Santiago, Aveiro, 3810-193, Portugal
[2] RISCO & Department of Civil Engineering, University of Aveiro, Campus Universitário de Santiago, Aveiro, 3810-193, Portugal
[3] R5 Marine Solutions, RISCO, University of Aveiro and Lusophone University of Porto
[4] CESAM & Department of Geosciences, University of Aveiro, Campus Universitário de Santiago, Aveiro, 3810-193, Portugal
[5] CESAM & Department of Geosciences, University of Aveiro, Campus Universitário de Santiago, Aveiro, 3810-193, Portugal
[6] CESAM & Department of Physics, University of Aveiro, Campus Universitário de Santiago, Aveiro, 3810-193, Portugal
[7] Oceaning Consulting Engineers, Estrada da Portela, Carnaxide, Oeiras, Portugal
[8] MALCPERL PO Box 2221, North Ipswich, QLD 4305, Australia
[9] APA - Portuguese Environment Agency, Rua da Murgueira, Amadora, 2610-124, Portugal

Sand bypassing systems, as the ones applied in Australia (e.g. in the Gold Coast - Tweed and Nerang rivers and Adelaide) and France (Capbreton), use fixed or mobile components to bypass sediments from accreted to eroded areas. Generally, sand bypassing systems are applied in coastlines affected by harbor breakwaters structures, with sediments being pumped from updrift to downdrift to mimic the naturally occurring longshore sediment transport before the breakwaters disrupted the littoral drift.

When compared with other solutions, such as groin fields, coastal protection based on adding or relocating sediments in the coastal zone has the advantage of maintaining beaches in a natural state and preserve their recreational/touristic functions (Pinto *et al.*, 2020; Kroon *et al.*, 2022). However, the performance and longevity of these sand nourishment works depend on several parameters related to volume, frequency of works, placement site (alongshore and in the beach profile) and sediment dynamics (Kamphuis, 2000; French, 2001; Coelho *et al.*, 2020; Ferreira and Coelho, 2021; Coelho *et al.*, 2022).

Coastal erosion mitigation solutions present positive and negative aspects with different costs and benefits. Cost-benefit analysis can be applied to compare costs and benefits to evaluate the economic feasibility of each scenario, allowing to support the decision-making process (Turner *et al.*, 2007; Slott *et al.,* 2008; Roebeling *et al*., 2011; Lima, 2018; Coelho *et al.*, 2022). Effective long-term coastal erosion management requires that all costs and benefits are quantified during the project life cycle. Total costs are dependent on the type of the works and must include construction, maintenance, operation and dismantling costs. The benefits of the works are linked to their capacity to slow down erosion trends and consequently to reduce coastal property loss, including damage to structures and loss of land, during the life cycle defined for the project (Penning-Rowsell *et al.,* 1992).

This work synthesizes the main results of the feasibility study of sand bypass solutions for Aveiro and Figueira da Foz tidal inlets, prepared for the Portuguese Environment Agency (APA). The study was headed by the University of Aveiro and R5 Marine Solutions consortium, which participation of Oceaning Consulting Engineers company and MALCPERL Engineering. The project aimed to evaluate the technical and economic viability of sediment bypassing from North of the jetties to downdrift, considering various solutions that involved both fixed solutions (system of pipes and pumps) and mobile solutions (dredging and deposition) and a life cycle for the project of 30 years.

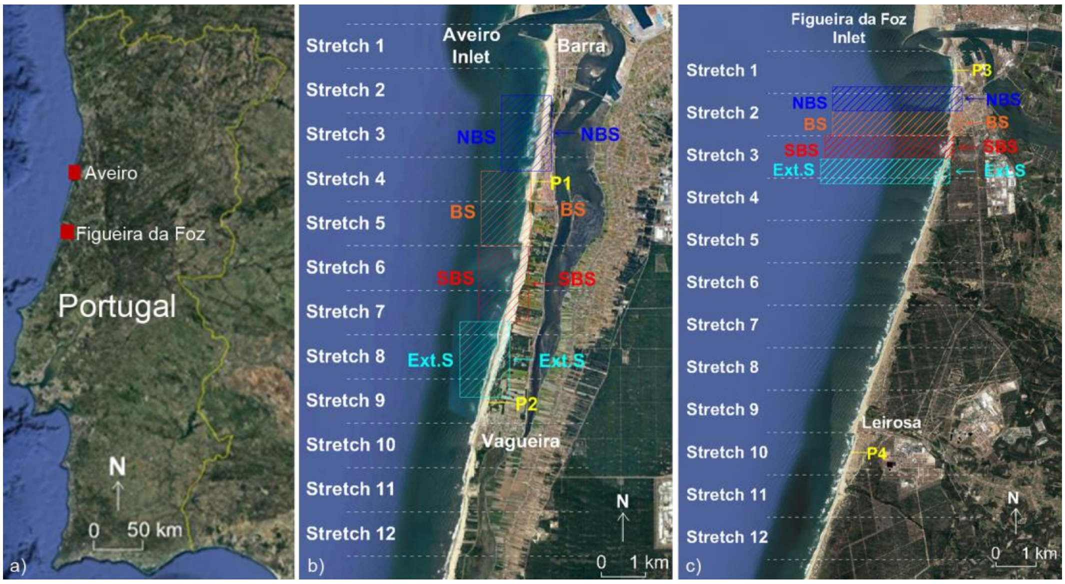


**Figure 1. Study areas: a) Portugal; b) Barra-Vagueira sector; c) Figueira da Foz-Leirosa sector. The rectangles BS, NBS, SBS and Ext.S are the nourishment placement sites and the arrows the outlet locations.**

## METHODOLOGY

The methodology to develop the study combines a sequence of seven tasks grouped in three mains stages. The goal of the first stage was to characterize the historical morphological evolution of the study areas. The second stage focused on the preliminary design of the bypass solutions. In the third phase, a cost-benefit analysis was developed to evaluate the economic feasibility of the sand bypassing solutions defined as technically viable. The sequence of the tasks and the main stages of the study are presented in Figure 2.

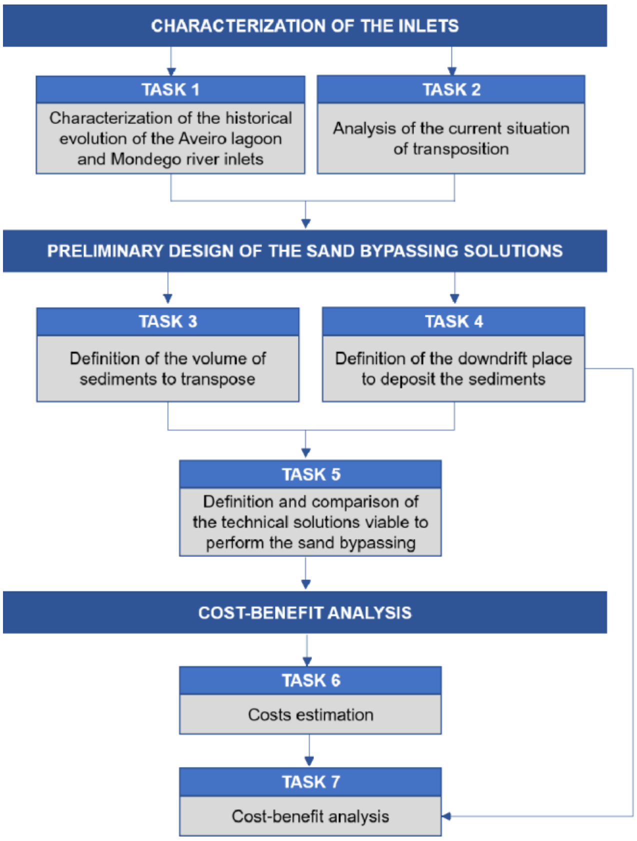


**Figure 2. Sequence of the tasks implemented to develop the study.**

### 1st Stage: Characterization of the inlets

This stage includes the historical morphological evolution of the coastal sectors (Task 1) and the analysis of the current situation of transposition (Task 2), in which the volume of sediments that transpose the harbor jetties was analyzed through satellite images and topo-bathymetric surveys. The current situation of transposition is focused on the periods before and after harbor works, namely jetty extension, including the adjacent areas. The evolution of the shoreline allowed to estimate shoreline change rates, essential to calibrate and validate the numerical models in subsequent tasks.

### 2nd Stage: Preliminary designed of the sand bypass solutions

Numerical studies were developed for preliminary design of the sand bypassing solutions. The studies aimed to assess the impact of the solutions on the morphological evolution (specifically, the shoreline and cross-shore beach profile evolution) of the coastal sectors. The effectiveness and longevity of the coastal erosion mitigation are dependent on the sediments distribution and transport rates. Therefore, the preliminary design of the sand bypassing solutions consisted of three tasks. Firstly, the potential longshore sediment transport was evaluated in the coastal sectors over the last twenty years and future periods, considering climate change effects (Task 3). Secondly, numerical models were applied to assess the impact of sand bypassing works on the morphological evolution of the study areas (Task 4). Based on the results of the previously tasks and a comprehensive review of sand bypassing projects developed worldwide, Task 5 defined the sand bypassing solutions technically viable to perform the sediment bypassing for Aveiro and Figueira da Foz inlets.

The estimation of the longshore sediment transport was developed based on numerical simulation of the wave's propagation and the application of bulk longshore sediment transport formulas. The simulation of the wave climate regimes was carried out with the WAVEWATCH III (WWIII) model (Tolman, 2009). The model was forced by ERA5 winds dataset (available at https://cds.climate.copernicus.eu) considering the period between 2000 and 2019 (last 20 years). For future periods the climatological winds of CMIP6 (Coupled Model Intercomparison Project) for the SSPs-8.5 scenario were considered, which assumes the highest emissions levels of greenhouse gases.

CMIP6 wind data were taken from the MPI-ESM-1 model (Max Planck Institute for Meteorology) for three periods: i) 2000 to 2015 (historic period) ii) 2020 to 2040 (SSPs 8.5 scenario) and iii) 2080 to 2100 (SSPs-8.5 scenario). The potential longshore sediment transport was calculated based on nine different formulations. As the grid of the WWIII model in the coastal zone has a resolution of 2 km, it is not possible to accurately describe the swell conditions in the surf zone. Thus, based on the solutions of the WWIII model obtained at 15 m depth, the linear wave theory and Snell's law were used to estimate the wave parameters at breaking (wave height and direction).

The morphological impact of the sand bypassing solutions in the study areas was assessed under a variety of scenarios, which included continuous sand bypass systems and dredging and deposition operations. These scenarios enabled the examination of factors such as bypass volumes, alongshore and cross-shore deposition sites, frequency of interventions and number of outlets for the fixed solutions. The LTC numerical model (Coelho, 2005) was applied to assess the shoreline evolution and the CS-Model (Larson *et al*., 2016) was used to evaluate the cross-shore beach profiles evolution over a period of 30 years (Figure 3). A baseline scenario (BS) was defined considering the results of the historical interventions performed on the coastal sectors, corresponding to the deposition of $5\times10^6$ $m^3$/year of sediments in the area designated as BS (Figure 1). Alternative scenarios were defined by modifying one factor at a time relative to the baseline scenario.

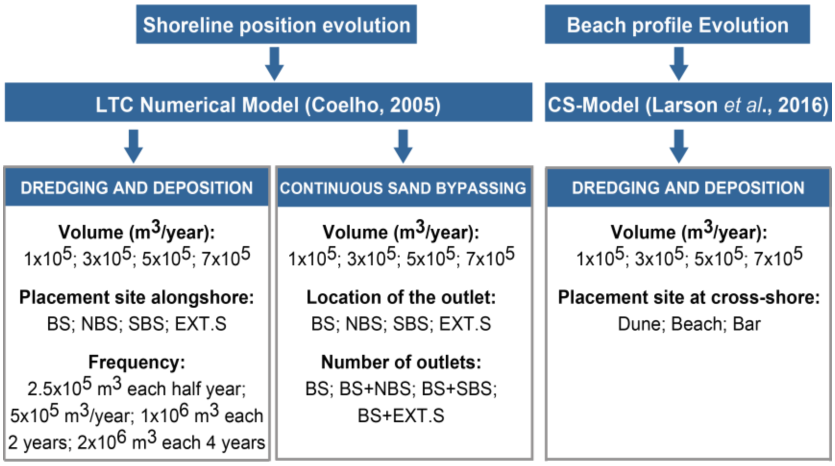


**Figure 3. Assessed scenarios (the placement sites and the outlets locations designated as BS, NBS - North BS, SBS - South BS and Ext.S - Extreme South are presented in Figure 1).**

**3rd Stage: Cost-benefit**

Cost-benefit analysis were developed to discuss the economic feasibility of the different sand bypassing solutions. For that, the COAST software, developed in the University of Aveiro (Lima, 2018; Lima *et al.*, 2020), was applied. This software, specifically designed to perform cost-benefits analysis of coastal erosion mitigation scenarios, applies a sequential approach based on three main steps (Coelho *et al.*, 2022):

1st: Assessment of the benefits of the coastal erosion mitigation measure;

2nd: Evaluation of all costs of the solutions during the life cycle of the project (construction, maintenance, exploration and dismantling);

3rd: Cost-benefit assessment of each intervention scenario, based on the analysis of the evolution of the economic parameters NPV (net present value), BCR (benefit-cost ratio) and break-even year (first year the benefits equal the costs).

The benefits of the sand bypassing solutions were obtained through the relationship between the physical impact of the solutions (areas of territory maintained or gained over time) and the monetary value of the coastal territories. The shoreline evolution projections to evaluate the physical impact of the works was obtained through the LTC numerical model, based on the results from the second stage of the study. The economic value of the coastal territories was evaluated based on a methodology combining the land uses and the ecological systems values, with benefit transfer (Coelho *et al.*, 2022).

## RESULTS

### 1st Stage: Characterization of the inlets

The current characterization of Aveiro lagoon and Figueira da Foz tidal inlets during the period 2008-2019 indicates that the physiography of the inlets is influenced by the coastal system's response to successive interventions that increased the length of the harbor jetties. Updrift sediment retention in the jetties at both inlets leads to significant sedimentary imbalances. As a result, the downdrift areas experience negative impacts such as shoreline retreat, reduction in beach width, decreased morphological robustness of the frontal dune/sandy dike and washover processes.

After the extension of the harbor jetty in 2013, nourishments were carried out downdrift of the Aveiro inlet, which helped to mitigate shoreline retreat, especially over the last five years. As a result, the rates of shoreline retreat in the Barra-Vagueira coastal sector have decreased to less than 0.5 m/year, while the beach width has remained relatively stable. Previous to 2018 the mean shoreline retreat was near 4.0 m/year (1958-2018).

The jetties at Figueira da Foz inlet restrict the position and the migration of the submerged bar of the ebb shoal to the South direction. Between 2010 to 2019, after the extension of the North jetty in 2009, the subaerial beach downdrift of the fifth groin (the southern one) of Cova Gala beach, presented a reduced width in an extension of approximately 2.5 km, almost a total destruction of the dune front and values of shoreline retreat close to 3.5 m/year (Pinto *et al.*, 2021). The immersion of dredged sediments from harbor dredging operations in the nearshore did not appear to benefit this area, likely due to low volumes deposited and poor placement location. Further South, erosion and shoreline retreat were more moderate with residual values.

Regarding the present sediment bypass situation, in Aveiro the results in terms of coastal processes indicate that the inlet is not completely adjusted to the new configuration. This result is justified by the accretionary trend that is observed updrift of the inlet, whose stabilization is not evident in the time series of data. Conversely, after 2013, the updrift sedimentary accretion tends to be progressively lower, while downdrift the erosive trend, recorded in the sedimentary balances, only is reversed through artificial nourishments intervention performed with volumes not lower than the mean value of the littoral drift considered in the coastal sector. It must be added that the results obtained for the relationship equation between the tidal prism (in spring tide conditions) and the average annual value of the littoral drift current near the mouth of Aveiro suggest the presence of a barrier effect to sedimentary transposition. The tidal prism values of Lopes *et al.* (2013) allow to define a value of r=139.7 (tidal prism of $139.7\text{x}10^6$ $m^3$), close to the threshold of r=150 defined by Bruun and Gerritsen (1959, 1960) for the cases of poor sediment transposers. In this context, the mouth of Aveiro constitutes a partial barrier to sedimentary transposition, although on a threshold close to a full barrier state.

At Figueira da Foz the results indicate that the coastal inlet has been adjusted to the new configuration of the harbor breakwaters after the last extension in 2009. This deduction is justified by the decrease of the accretionary trend between Buarcos and the North jetty, allowing to conclude that the sedimentary retention from North has been progressively lower.

Based on above, the results indicate that at Aveiro inlet the mouth constitutes a partial barrier to sediment transposition (there is no continuous bar formation in front of the inlet) while at Figueira da Foz is partial (a submerged bar is observed).

### 2nd Stage: Preliminary designed of the sand bypassing solutions

*Potential longshore sediment transport*

Considering the historical wave series, nine formulations were applied to calculate the potential longshore sediment transport: CERC (1984), Kamphuis (1991), Bayram *et al.* (2007), Silva *et al.* (2012), van Rijn (2014) and Shaeri *et al.* (2020). Furthermore, it was also considered the modifications indicated by Mil-Homens *et al.* (2013). Figure **4** presents the annual mean longshore sediment transport obtained through the different formulations.

Based on the results, it was concluded that the formulation of CERC (1984) with the modification of Mil-Homens *et al*. (2013) was the sediment transport formula that better reproduces the net littoral drift closer to the value referred in the bibliography for the Northwest coast of Portugal ($1\text{x}10^6$ $m^3$/year, according to Santos *et al*., 2014). Considering the previously indicated formula, the net longshore sediment transport was estimated to be approximately 746 000 $m^3$/year in Figueira da Foz and 996 000 $m^3$/year in Aveiro. In the two study areas, the sediment transport occurs predominantly from

North to South direction (Table 1) and the results show the effect of the seasonality. The higher values of the sediment transport occur during the maritime winter months and the lower values in the maritime summer months (Figure 5).

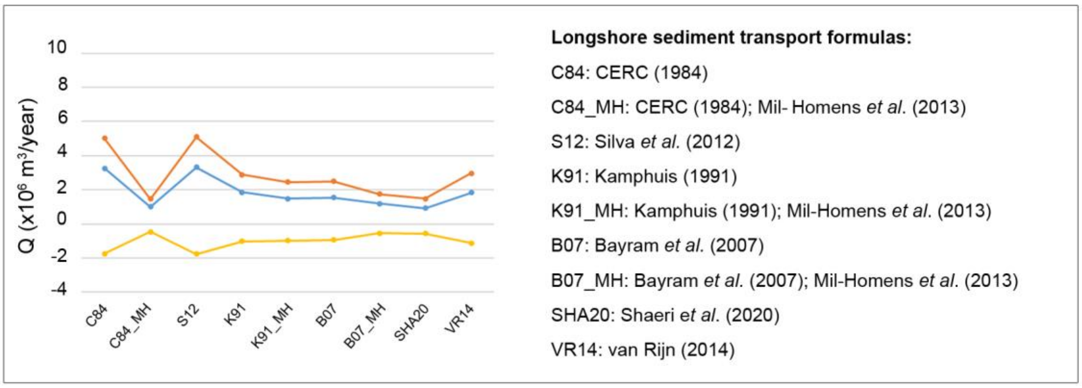


**Figure 4. Mean annual values of longshore sediment transport obtained through different longshore sediment transport formulas: sediment transport in North-South direction (orange line); sediment transport in South North direction (yellow line); and net sediment transport (blue line).**

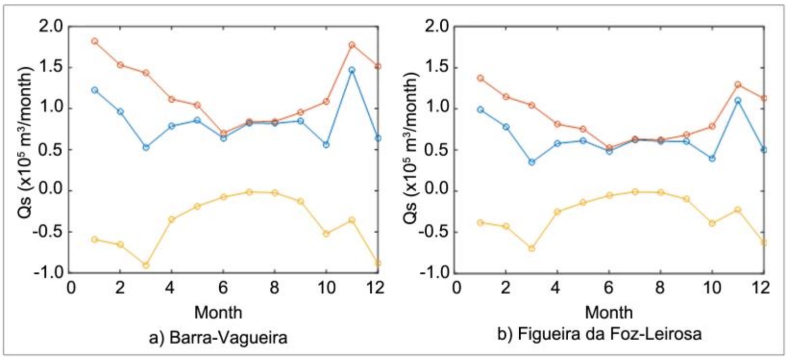


**Figure 5. Mean monthly values of sediment transport in the study areas computed with C84_MH formula (4 to 9 are maritime summer months): sediment transport in North-South direction (orange line); sediment transport in South-North direction (yellow line); and net sediment transport (blue line).**

For future periods (i.e. 2020-2039 and 2080-2099), the results show a decrease of the net longshore sediment transport. Table 1 presents the values of the potential longshore sediment transport obtained for the historical period and the ratios in the future periods in relation to the historical period. For example, considering the period from 2080 to 2099, the net longshore sediment transport decreases approximately 23% in Aveiro and 12% in Figueira da Foz, in relation to the value estimated for the historical period.

**Table 1. Potential longshore sediment transport in the historical period (x10$^6$ m$^3$/year) and ratio of the sediment transport in the future periods in relation to the historical period.**

| | Time period | North-South | South-North | Total | Net |
|---|---|---|---|---|---|
| Aveiro | Historical | 1.47 | 0.47 | 1.94 | 1.00 |
| | 2020-2039 | 0.89 | 1.21 | 1.02 | 0.11 |
| | 2080-2099 | 0.93 | 0.99 | 0.95 | 0.77 |
| Figueira da Foz | Historical | 1.08 | 0.33 | 1.41 | 0.75 |
| | 2020-2039 | 0.89 | 1.24 | 1.03 | 0.22 |
| | 2080-2099 | 0.94 | 0.98 | 0.96 | 0.88 |

The net longshore sediment transport reduction in the future periods results of changes in the future wave climate by comparison with the historical period. From the analysis of the wave parameters, it was observed a rotation in counterclockwise direction in the months of December, January and February and for storm conditions, with consequences on the longshore sediment transport. The decrease of the sediment transport during the maritime winter months are associated with an increase in the volumes transported in the South-North direction, with no evidence of an increase in transport in the positive direction (from North to South). Similar results related to the variability of the longshore sediment transport along the Northwest coast of Portugal and the sediment transport in future periods were presented by Ferreira *et al*. (2021; 2023).

*Shoreline and cross-shore beach evolution scenarios*

The shoreline projections obtained with LTC indicate that unless specific actions are implemented to mitigate erosion, the shoreline will continue to retreat, representing a loss of territory in each study area of about 40 ha, in 30 years (Figure 6).


**Figure 6. Shoreline projection for 2050: a) Barra-Vagueira; b) Figueira da Foz-Leirosa.**

Sediment bypass allows to mitigate the erosion problems, reducing the loss of territory over time. Regarding the shoreline evolution, the results suggest that continuous bypassing systems are most effective than dredging and deposition operations for erosion mitigation, being the bypass of higher volumes the most efficient solution (Table 2). For Aveiro inlet, none of the scenarios fully eliminate the total loss of territory. At Figueira da Foz, some of the intervention scenarios allow reversing the erosive trend.

**Table 2. Percentage of territory not lost after 30 years of simulation, for each coastal area.**

| Dredging and deposition | | | |
|---|---|---|---|
| | | **Aveiro** | **Figueira** |
| **Volume** (m³/year) | $1x10^5$ | 2 | 3 |
| | $3x10^5$ | 15 | 13 |
| | $5x10^5$ | 21 | 52 |
| | $7x10^5$ | 47 | 100 |
| **Placement site** (see Figure 1) | NBS | 28 | 37 |
| | BS | 21 | 52 |
| | SBS | 23 | 70 |
| | Ext.S | 30 | 73 |
| **Frequency** | $2.5x10^5$ each half year | 13 | 52 |
| | $5x10^5$ m³/year | 21 | 52 |
| | $1x10^6$ each 2 years | 31 | 57 |
| | $2x10^6$ each 4 years | 29 | 59 |

| Continuous sand bypassing | | | |
|---|---|---|---|
| | | **Aveiro** | **Figueira** |
| **Volume** (m³/year) | $1x10^5$ | 4 | 6 |
| | $3x10^5$ | 20 | 24 |
| | $5x10^5$ | 42 | 78 |
| | $7x10^5$ | 74 | 100 |
| **Outlet location** (see Figure 1) | NBS | 49 | 100 |
| | BS | 42 | 78 |
| | SBS | 37 | 100 |
| | Ext.S | 46 | 100 |
| **Number of outlets** (each outlet transposes half the total volume) | CB+NCB | 28 | 49 |
| | CB | 42 | 78 |
| | CB+SCB | 27 | 100 |
| | CB+Ext.S | 31 | 100 |

The study of nourishments impacts on the cross-shore beach profile evolution of four profiles (two located in Barra-Vagueira and two in Figueira da Foz-Leirosa - P1, P2, P3 and P4 in Figure 1) shows that different nourishment schemes serve different purposes. Submerged bar and beach nourishment are most effective in terms of berm gain, but with different order of magnitude between the profiles. Dune nourishment is most effective in terms of gains in the dune volume.

*Sand bypassing solutions*

Based on the obtained results and in comprehensive review of sand bypassing projects developed worldwide, five different bypass solutions were defined as technically viable to perform the sand bypassing for each inlet (Carvalho *et al.*, 2022). Thus, a Solution 0 (S0) was defined, corresponding to the current mitigation measures (based on dredging and deposition, resulting of the dredging operations developed by the harbor authorities) and 4 alternative solutions were evaluated, compromising fixed, mobile and mixed solutions, namely (Figure 7):

- Solution 1: fixed solution similar to Gold Coast Seaway or Tweed River (Australia);
- Solution 2: mixed solution similar to Adelaide (Australia);
- Solution 3: mixed solution similar to Capbreton (France);
- Solution 4: mobile solution based on dredging updrift the breakwaters and deposition downdrift. At Figueira da Foz, to complement this solution (named Solution 4.1 in this case), an option with a hydraulic circuit was also evaluated (Solution 4.2).


**Figure 7. Sand bypassing solutions.**

### 3rd Stage: Cost-benefit

*Costs*

Table 3 and Table 4 summarize the estimated costs of the sand bypassing solutions defined as technical viable to perform the sand bypassing for each coastal sector. The total costs are presented considering constant values and updated values assuming a discount rate equal to 2%.

For the coastal sector Barra-Vagueira, after 30 years, it was estimated a total volume of sediments transposed of approximately 9.9 $Mm^3$ for the Solution 0 and approximately 35.0 $Mm^3$ for the remaining solutions. The results show that the Solution 1 is the one that presents the lowest updated unit cost per $m^3$ of sand transposed (2.1 €/$m^3$), followed by the Solutions 2 and 3 that present a unit cost of approximately 2.3 €/$m^3$ and 2.4 €/$m^3$, respectively. The Solution 4 presents the highest unit cost (approximately 3.0 €/$m^3$). This solution, unlike Solutions 1 to 3, does not require a high initial investment in permanent or semi-permanent infrastructure.

**Table 3. Summary of the estimated costs of the sand bypassing solutions for Aveiro inlet (million euros).**

| | Life-cycle costs | | | | Total costs | |
|---|---|---|---|---|---|---|
| | Construction (year 0) | Exploration (years 1-30) | Maintenance (years 1-30) | Dismantling (year 30) | Constant prices | Updated prices (rate 2%) |
| **Solution 0** | 0.0 | 24.8 | 0.0 | 0.0 | 24.8 | 18.5 |
| **Solution 1** | 22.2 | 54.6 | 12.7 | 1.1 | 90.6 | 73.9 |
| **Solution 2** | 21.0 | 69.9 | 12.0 | 1.0 | 103.8 | 83.5 |
| **Solution 3** | 19.9 | 68.2 | 11.3 | 0.9 | 100.4 | 80.7 |
| **Solution 4** | 0.0 | 135.0 | 0.0 | 0.0 | 135.0 | 103.3 |

For the coastal sector Figueira da Foz-Leirosa, after 30 years, it was estimated a transposed volume of about 9.0 $Mm^3$ for the Solution 0, approximately 35.8 $Mm^3$ for Solutions 1 to 3 and 33.5 $Mm^3$ for Solutions 4. Solution 1 is the alternative that presents the updated lowest unit cost per $m^3$ of sand transposed (1.64 €/$m^3$), followed by Solutions 2 and 3, with similar updated unit costs of approximately 2.0 €/$m^3$.

**Table 4. Summary of the estimated costs of the sand bypassing solutions for Figueira da Foz inlet (million euros).**

| | Life-cycle costs | | | | Total costs | |
|---|---|---|---|---|---|---|
| | Construction (year 0) | Exploration (years 1-30) | Maintenance (years 1-30) | Dismantling (year 30) | Constant prices | Updated prices (rate 2%) |
| **Solution 0** | 0.0 | 30.0 | 0.0 | 0.0 | 30.0 | 22.4 |
| **Solution 1** | 18.1 | 43.0 | 10.3 | 0.9 | 72.2 | 58.9 |
| **Solution 2** | 17.7 | 61.2 | 10.1 | 0.8 | 89.8 | 72.1 |
| **Solution 3** | 16.6 | 59.6 | 9.5 | 0.8 | 86.3 | 69.2 |
| **Solution 4.1** | 0.0 | 127.5 | 0.0 | 0.0 | 127.5 | 97.7 |
| **Solution 4.2** | 2.1 | 127.5 | 1.2 | 0.1 | 130.8 | 100.7 |

*Benefits*

The benefits of sand bypassing solutions were obtained after considering the economic value of the territory and the areas maintained/gained due to the interventions. Table 5 presents the monetary values of the territories of both study areas (AV - Aveiro and FF - Figueira da Foz), obtained considering coastal stretches of 1 km (Figure 1).

**Table 5. Monetary value of the coastal stretches identified in Figure 1 (€/m²/year). AV - Aveiro; FF - Figueira da Foz; 1 to 12 are the coastal stretches.**

| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **AV** | 38.0 | 21.2 | 18.8 | 29.2 | 6.0 | 4.6 | 2.4 | 0.4 | 3.9 | 29.7 | 8.0 | 0.5 |
| **FF** | 29.9 | 33.4 | 12.2 | 11.4 | 0.4 | 7.1 | 0.3 | 2.5 | 1.5 | 18.9 | 5.3 | 0.3 |

At both study areas the stretches that combine urban and ecological areas are the most valuable in economic terms. At Aveiro the results indicate that the monetary value of the territory ranges from 38.0 to 0.4 €/m²/year. At Figueira da Foz the monetary values of the territory vary from 29.9 to 0.3 €/m²/year.

The areas of territory maintained/gained considered to assess the benefits of the sand bypassing solutions were obtained by the shoreline evolution numerical simulations. Based on the results of the previously stages of the study, that indicated the convenience of the systems to transpose an annually volume equal to $1x10^6$ $m^3$, the adopted scenario considered the bypassing of a $1x10^6$ $m^3$/year of sediments annually by two outlets. The outlets locations in each study area are identified in Figure 8. For each coastal sector, the evolution of territory maintained/gained over time was obtained for two situations of sediment bypassing:

- Situation A of sand bypassing (50/50): shoreline position along time was obtained considering that each outlet transposes half of the total volume;

- Situation B of sand bypassing (20/80): shoreline position along time was obtained considering that the northern outlet transpose 20% and the other 80% of the total volume.

To develop the cost-benefit analysis, for each study area, the benefits were considered the same independently of the sand bypassing solution. This approach was adopted based on preliminary studies that indicated that this methodology produces more conservative results, eliminating uncertainties linked to numerical modelling of the shoreline position (as discussed in Coelho *et al*, 2021a; 2021b).

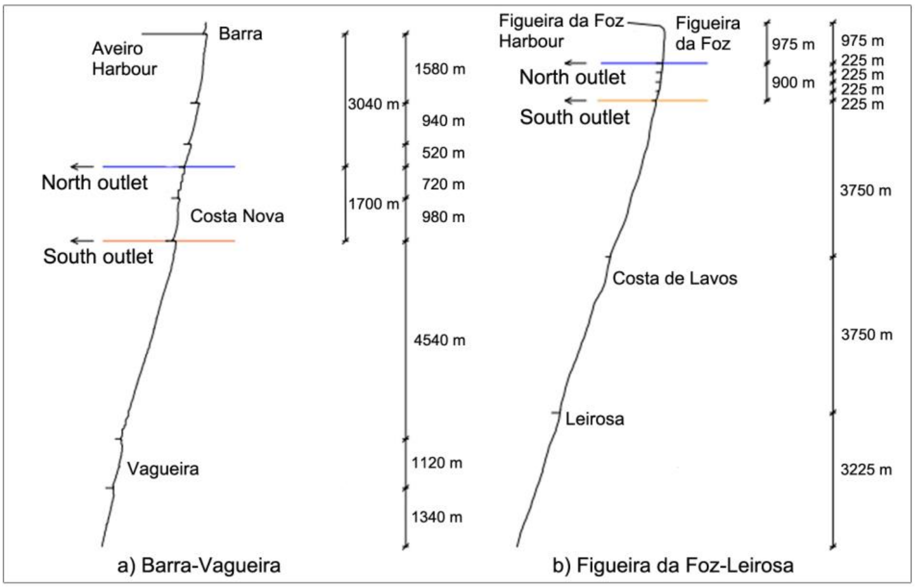


**Figure 8. Sand bypassing outlet locations in the study areas.**

In the coastal sector Barra-Vagueira the results suggest that the situation B of sand bypassing allows to reverse the erosion trend at the end of 30 years of simulation. At Figueira da Foz, the evolution of the areas of territory maintained/gained are similar for both bypassing situations and the area maintained/gained is higher than the areas loss in the non-intervention scenario (approximately 42 ha), allowing the sediment bypassing to eliminate the erosion trend that is observed in the coastal sector Figueira da Foz-Leirosa. **Figure 9** presents the evolution of the area of territory maintained/gained for each study area, considering the two transposition situations.

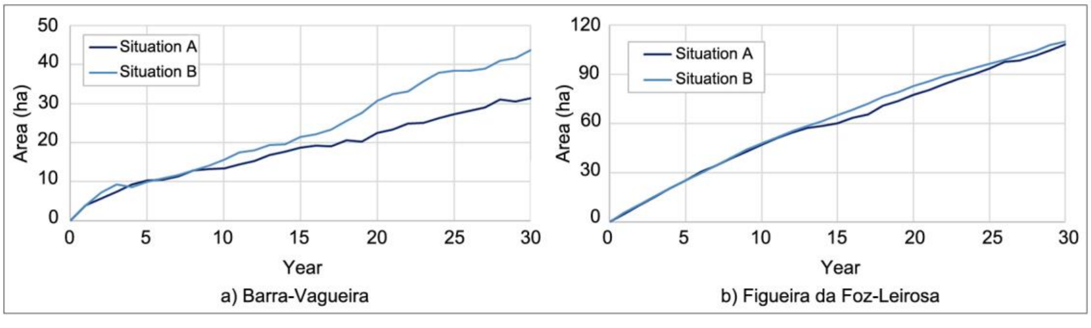


**Figure 9. Time evolution of the area of territory maintained/gained in the coastal sectors, considering the two situations of sediment bypassing.**

Based on the presented results, it is concluded that the sand bypassing solutions have distinct impacts on the shoreline evolution of the coastal sectors. The coastal sector Figueira da Foz-Leirosa shows gains of area significantly higher than the obtained for the Aveiro coastal sector Barra-Vagueira. The explanation for this difference is related to the net longshore sediment transport that was estimated to be significantly higher in Aveiro by comparison with the value obtained at Figueira da Foz, with consequences on the sediment's distribution in the coastal zone (996 000 $m^3$/year in Aveiro and 746 000 $m^3$/year in Figueira da Foz).

*Cost-Benefit*

Based on the costs and benefits it was obtained the economic viability of each sand bypassing solution. The cost-benefit analysis assumes the comparison of the intervention scenario with the reference situation. Thus, first it was obtained the economic balance of the reference situation (Scenario 0). The reference situation is assumed to be the scenario where the current coastal management policy in the study areas is maintained (perform artificial nourishments downdrift of the inlet jetties with sediments from the dredging operations carried out by the harbor authorities). Subsequently, a cost-benefit analysis of the different bypassing solutions was carried out considering a 2% discount rate and the maintenance costs of the bypassing systems equal to 2% of the total construction cost.

Table 6 summarizes the physical and economic performance of the reference scenario. At the end of 30 years, in Aveiro is predicted an economic loss of approximately 82 M€, resulting of the loss of approximately 40 ha of territory, representing an economic loss of 64 M€, plus the 18 M€ invested in the implementation of the artificial nourishments performed on the Solution 0.

At Figueira da Foz was obtained a negative economic balance of 64 M€, resulting of the loss of approximately 42 ha of territory, representing around 42 M€, combined with the 22 M€ of investment in present dredging/deposition operations carried out.

**Table 6. Evolution of the physical and economic evolution of the reference scenario (scenario 0).**

| | Aveiro | | | Figueira da Foz | | |
|---|---|---|---|---|---|---|
| | 10 years | 20 years | 30 years | 10 years | 20 years | 30 years |
| Area lost ($m^2$) | 270 482 | 347 114 | 401 703 | 145 165 | 305 747 | 426 650 |
| Value (million €) | 17.77 | 41.41 | 64.36 | 14.30 | 30.09 | 42.39 |
| Investment (million €) | 7.41 | 13.49 | 18.48 | 8.98 | 16.35 | 22.40 |
| NPV (million €) | -25.18 | -54.90 | **-82.83** | -23.29 | -46.44 | **-64.79** |

As previously mentioned, the cost-benefit analyzes of the bypassing solutions were carried out for two estimations of benefits that varies in the volume transposed in each outlet and designated as Situation A (50/50) and Situation B (20/80).

The results of the cost-benefit analysis of the bypassing solutions evaluated for Aveiro show that none of the solutions are economically compensatory in relation to the reference scenario (Figure 10).

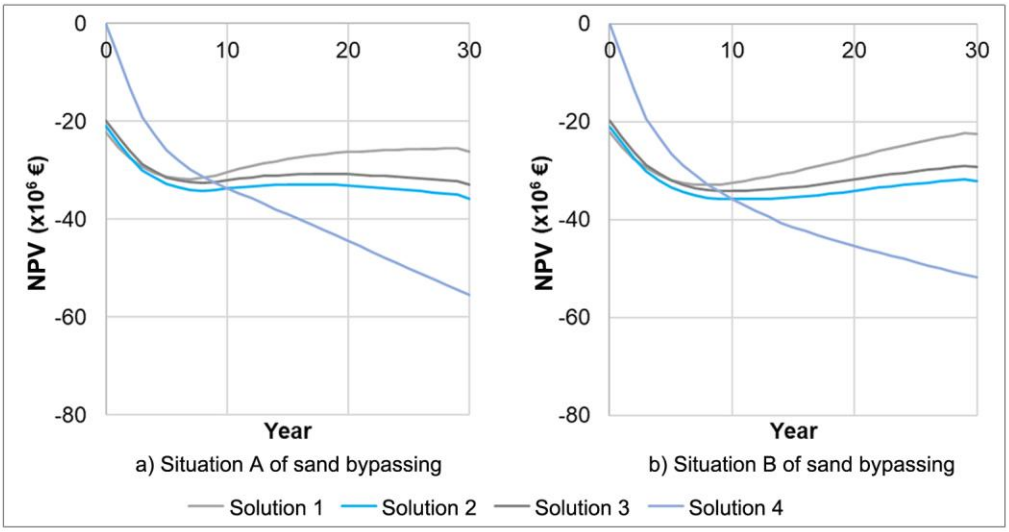


**Figure 10. Evolution of the economic indicator NPV for the bypassing solutions studied in the Barra-Vagueira sector.**

Although all solutions are technical viable to perform the sand bypassing in the Aveiro inlet, allowing to mitigate the loss of territory, the costs of the solutions are not equilibrated by the benefits. The Situation A of sand bypassing (50/50) allows to maintain approximately 33 ha, corresponding to an economic value of 47.7 M€. The Situation B of sand bypassing (20/80) allows to maintain approximately 45 ha, corresponding to an estimated economic value of 51.4 M€.

After 30 years, the Solution 1 is the one that presents the best benefit-cost ratio (BCR equal to 0.65 in the Situation A and 0.70 for the Situation B). For the remaining bypassing solutions, the benefits are slightly higher than half of the costs after 30 years (BCR values close to 0.5). Thus, for the sector Barra-Vagueira, the break-even is not reached in the time horizon defined for the project (30 years).

The results of the cost-benefit analysis of the bypassing solutions studied for Figueira da Foz inlet show that it is economic viable to implement any of the solutions (Figure 11). It is verified that for all bypassing solutions the costs are compensated by the benefits, reaching the break-even between the 7$^{th}$ and the 10$^{th}$ year of the project.

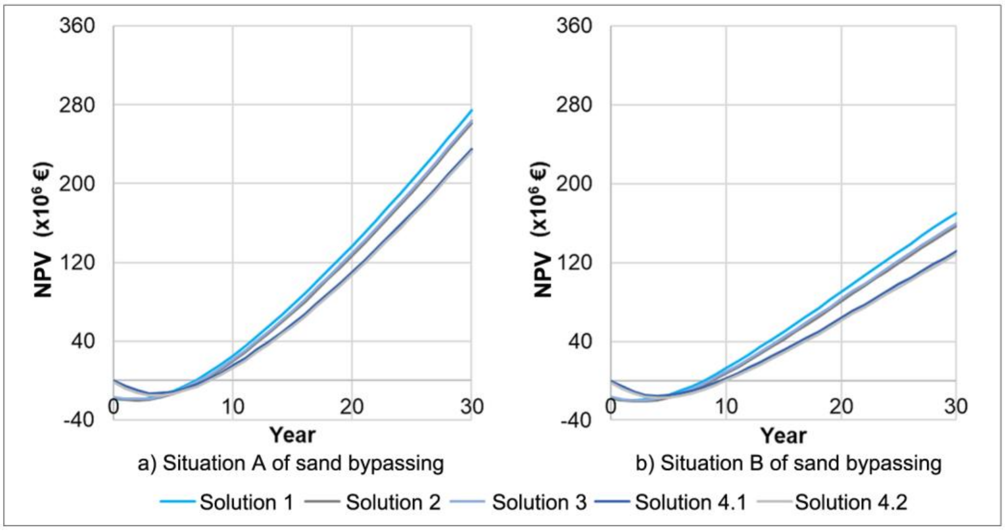


**Figure 11. Evolution of the economic indicator NPV for the bypassing solutions studied in the sector Figueira da Foz-Leirosa.**

At the end of the life cycle defined for the project, the Situation A of sand bypassing (50/50) allows to preserve approximately 108 hectares, corresponding to an economic value of 333 M€, while the Situation B allows to maintain 110 ha, representing an economic value of approximately 229 M€. Table 7 presents the break-even year and the benefit-cost ratio (BCR) at the end of 30 years, for the evaluated bypassing scenarios.

**Table 7. Benefit-cost ratio (BCR value) at the end of the lifetime horizon defined for the project and break-even year for the bypassing solutions in the sector Figueira da Foz-Leirosa**

| | Situation A | | Situation B | |
|---|---|---|---|---|
| | BCR | *Break-even* (years) | BCR | *Break-even* (years) |
| **Solution 1** | 5.66 | 7 | 3.89 | 8 |
| **Solution 2** | 4.62 | 8 | 3.18 | 9 |
| **Solution 3** | 4.81 | 8 | 3.31 | 9 |
| **Solution 4.1** | 3.41 | 8 | 2.35 | 10 |
| **Solution 4.2** | 3.31 | 9 | 2.28 | 10 |

## CONCLUSIONS

Coastal management authorities seek solutions to plan their actions to mitigate coastal erosion downdrift of Aveiro and Figueira da Foz inlets. In this project, the feasibility of sand bypassing system to restore natural sediment transport at Aveiro and Figueira da Foz tidal inlets were studied, considering a time horizon of 30 years. Mobile, fixed and mixed solutions were discussed, supported by the analysis of past and present evolution of the coastal sectors, the characterization of the littoral drift, the preliminary design of sand bypassing solutions and correspondent cost-benefit analysis.

The results of the historical characterization of Aveiro lagoon and Figueira da Foz tidal inlets show that the sediment retention at the beaches located updrift of the jetties leads to important sedimentary imbalances, with negative impacts in the morphological evolution of the downdrift areas (shoreline retreat, beach width reduction, decrease in the morphological robustness of the frontal dune/sandy dike and washover processes). Currently, based on the estimation of the volumes that transpose the jetties, the results indicate that at Aveiro inlet the month of Aveiro constitutes a partial barrier to sediment transposition (there is no continuous bar formation in front of the inlet) while at Figueira da Foz is partial (a submerged bar is observed).

Overall, based on the results of the numerical studies performed to assess the physical impact of the sand bypassing solutions in the shoreline position evolution and in the cross-shore beach profile evolution, it is concluded that several solutions to transpose the sediments are technically viable to mitigate the coastal erosion. However, the economic viability of the solution was only achieved in the coastal sector Figueira da Foz-Leirosa. One of the reasons pointed for this result can be partly attributed to the higher benefits at Figueira da Foz. In one hand, the solutions induce a better performance at Figueira da Foz, where the potential sediment transport capacity is estimated lower. In the scope of the present study, in Aveiro the longshore sediment transport was estimated to be around $9.96 \times 10^5$ $m^3$/year and in Figueira da Foz is approximately $7.46 \times 10^5$ $m^3$/year in Figueira da Foz. In the other hand, in the coastal sector Figueira da Foz-Leirosa the physical impact in terms of areas maintained or gained are located in the territories with the highest monetary values, increasing the benefits of the bypassing system.

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