OPTIMAL LAYOUT OF LIMESTONE SUBSTRATES FOR OYSTER BEDS AS NATURE-BASED SOLUTIONS FOR COASTAL MANAGEMENT

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This paper presents a preliminary design for beach restoration using nature-based solutions (NBS) in the northern Adriatic Sea, specifically between the Bevano and Fiumi Uniti rivers in Ravenna, Italy. The project leverages the high potential of sabellariid worm and oyster reefs, supported by numerical modeling results. The area, characterized by existing populations of native sabellariid worms, is ideal for species settlement. The proposed intervention involves constructing a submerged Basal Limestone Reef (BLR) offshore, which aims to stabilize sand, mitigate flooding from storm surges, and enhance biodiversity. The BLR will be created using limestone boulders retained in metallic cages and will be strategically placed to create optimal initial conditions for oysters and sabellariid worms settlement. The hydrodynamic characteristics of the BLR, particularly its wave transmission performance, were assessed through numerical simulations, indicating minimal diffractive phenomena due to its submerged nature. The findings contribute to understanding the effectiveness of artificial reefs in coastal habitat protection and resilience.

Keywords: Nature Base Solution, Oysters, CELERIS, Wave transmission

INTRODUCTION

Worldwide coastal areas are threatened by increasing erosion, flood risks, and habitat loss due to the loss of natural defense and climate change. These risks are more evident along non-rocky coasts, where coastal erosion has increased due to the reduction of the sediment load from rivers, natural and anthropogenic subsidence phenomena, sea-level rise, and increased storm frequencies and intensities due to global climate change.

Several natural defenses can play a significant role in coastal protection by providing natural defense against erosion, storm surges, and other coastal hazards. Their function, presence, and value have sometimes been diminished by anthropogenic interventions.

Some types of ecosystems in coastal environments (Wiberg et al., 2019, Gravina et al., 2018) can act as natural defenses. Incorporating and preserving these biogenic reefs is essential for sustainable coastal protection. Human activities, such as overfishing, habitat destruction, and climate change, can threaten the health of these ecosystems. Conservation and restoration efforts are crucial to maintaining the protective functions of biogenic reefs and ensuring the resilience of coastal environments.

For decades, after the natural morphodynamical coastal equilibrium was altered, attempts have been made to protect the coastlines in the most densely populated areas, by erecting artificial walls and breakwaters reefs. Still, these have often proved ineffective in the long term and have produced severe alterations of natural coastal habitats with a high loss of biodiversity and ecosystem goods and services, including the loss of natural barrier reefs able to provide coastal protection. (Ranasinghe et al. 2010, Lamberti et al., 2005).

Hence in the context of sustainable coastal protection there is a great interest in adapting nature-based solutions (NBSs) to analyze the advantages of ecosystem services and thereby impart more economic/social benefits (Sutton-Grier et al., 2015; Schoonees et al., 2019).

NBSs seek to use local natural elements and processes in coastal ecosystems, as much as possible, to harness the forces of nature for society's benefit. These solutions are gaining popularity not only for addressing coastal erosion but also for remediating marine sediments in decommissioned industrial areas (LIFE-Sedremed.eu.; Buccino et al, 2021). We focus on soft sedimentary coasts, like beaches and dunes, salt marshes, seagrass beds and mangroves. By shifting coastal management from conventional 'Building in Nature' to 'Building with Nature', NBS can be seen as a valuable alternative to the traditional approach, which is based on hydraulic, civil engineered designs. NBS can be applied in diverse situations and at various scales, from small-scale (ecosystem elements, a small pond) to large-scale (entire coastal stretches). The practice of NBS is also valuable for adaptation of climate change, when forces of nature will increase. NBS requires a governance setting that makes use of an integrated approach with

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disciplines of ecology, economy and society working together. But integration is not yet a frequent practice in many countries. We conclude that NBS are a promising alternative to the traditional approach. Because the practice is relatively young, more field and laboratory projects should be executed, particularly under extreme weather conditions. The future challenge is to build up more stakeholder acceptance and (local) trust in the concept.

All over the world, NBSs have been thoroughly studied to mitigate coastal risks. More specifically, NBSs aim to use nature to provide the maintenance, development, and restoration of biodiversity and ecosystems to address multiple concerns simultaneously (Unguendoli et al. 2023). An exhaustive overview on NBS for coastal protection is given in Perricone et al. (2023).

Among the various forms of ecosystems in coastal environments (Kirwan and Megonigal, 2013) such as seagrass meadows, salt marshes, dunes; biogenic reefs (https://www.sciencedirect.com/topics/earth-and-planetary-sciences/biogenic-reef), have a high capacity to protect the coasts against flooding and eroding. In natural coastal marine ecosystems, some marine organisms can build natural biogenic reefs and other biogenic habitats able to provide coastal defenses. Biogenic reefs are secondary marine substrates, also referred to as bioconstructions or bioherms, made by autogenic ecosystem engineers (see Jones et al., 2010) that provide habitats for various species. Their ecological role goes far beyond simple physical effects because they can modulate many resources and interactions between species inhabiting the reefs. Marine bioconstructions involve a variety of fragile three-dimensional habitats, from shallow water coral reefs to mesophotic coralligenous concretions, hosting rich and diverse benthic assemblages (Cocito, 2004, Ingrosso et al., 2018, Cerrano et al., 2019). Biogenic reefs can be found from the intertidal to the deep sea; some are ephemeral and last a few years, while others remain active for millennia. The main framework builders can form bioconstructions at different latitudes, from tropical to polar regions, and include films of cyanobacteria and diatoms, calcareous rhodophytes, sponges, hermatypic symbiotic and aposymbiotic corals, polychaetes as serpulids and sabellariids, mollusks like vermetids, oysters and mussels, and bryozoans (Ponti et al., 2021).

Biogenic reefs have an inestimable value for the biodiversity they host and for the countless ecosystem goods and services they provide, which are only partially quantifiable in their economic values. As for the time required for their formation, their destruction can often be considered almost irreversible, so bioconstruction requires the utmost attention in any conservation measure. Indeed, tropical, and temperate biogenic reefs are increasingly threatened by multiple stressors resulting in the decline of reef communities worldwide (e.g., Ellis et al., 2019). Natural and anthropogenic stressors include the decline in water quality, overexploitation of resources, habitat destruction and global climate change among others, which have all been linked in tropical and temperate areas with the occurrence of mass coral bleaching and a variety of diseases and mass mortality events (Ponti et al., 2016, Carpenter et al., 2008).

In temperate coastal environments, like the Mediterranean Sea and northern Europe, this role is fulfilled by seagrass meadows, oyster and sabellariid reefs providing a “living shoreline” (Ysebaert et al., 2019). These ecosystem engineers create three-dimensional structures that retain sediments, dissipate wave energy, and create many ecological niches that allow for high biodiversity and provide nursery habitats. Native oysters can build barrier reefs within a few hundred meters from the coast, whose ecosystem services are summarized in Figure 1, and include:

- biodiversity enhancements, forming a complex structure that provides shelter and food for a diversity of species
- stabilization of sediments, reducing the resuspension of fine sediment
- improvement of water clarity, which can be beneficial for seagrass and other coastal aquatic plants
- increment of fish production, providing a suitable feeding and nursery grounds for fish
- increase of oyster populations, providing a spill over to local oyster fisheries
- enhancement of cultural values, previously formed the heart of coastal communities
- improvement of water quality by removing pollutants from the water column
- removal of excess nutrients through the denitrification.

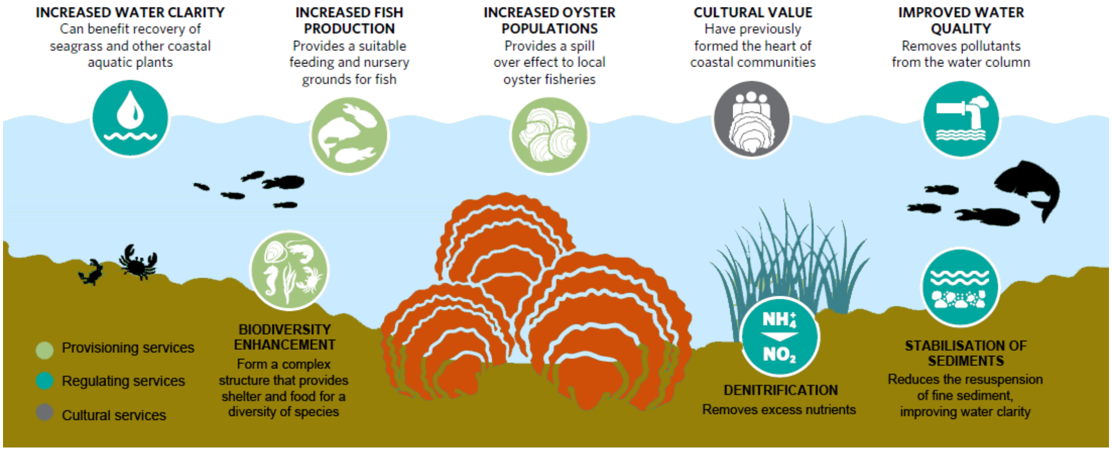

Figure 1 Ecosystem services provided by native European oysters (adapted from Preston et al. 2020).

Erosion control and shoreline stabilization provided by oyster reefs are no less important than the direct ecological effects and go far beyond, through well-known ecological facilitation cascade effects (Figure 2).

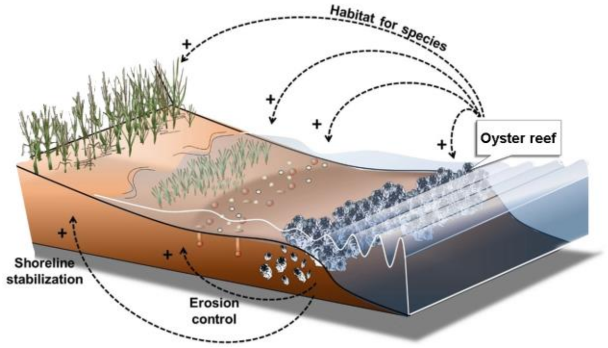

Figure 2 Biological and sedimentary facilitation services provided by oyster reefs. Such kind of reefs may provide coastal protection through erosion control and shoreline stabilization, and modify the physical landscape by ecosystem engineering, thereby providing habitat for species by facilitative interactions with other habitats such as tidal flat benthic communities, sea grasses and marshes (adapted from Ysebaert et al., 2019).

Sabellariid worm reefs, although less renowned, provide ecological services, including biodiversity enhancement and coastal protection, very similar to those of oyster reefs, as described by Pearce et al. (2011) and summarized in Figure 3.

Unfortunately, native oyster and sabellariid reefs are among the most threatened marine habitats in Europe, including the Mediterranean Sea.

Based on the high potential of sabellaria and oyster reef, the aim of this paper is to present the preliminary design of a beach restauration with a NBS in the northern Adriatic Sea based on results of numerical modelling.

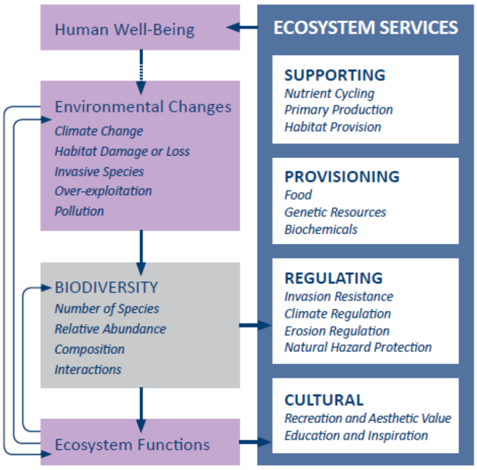

Figure 3. Schematic diagram illustrating the interactions between biodiversity, ecosystem functions and services, human well-being, and environmental change provided by sabellariid worm reefs (adapted from Pearce et al. 2011).

Figure 4 Study site location.

THE PROJECT DESCRIPTION

The project area is located between the estuaries of the Bevano river and Fiumi Uniti, in the municipality of Ravenna (Emilia-Romagna Region, Italy), NE of the Adriatic Sea (Figure 4); the area includes a system of brackish lagoons, and behind the coastal dunes a historical pine forest (Pinus pinaster). Almost all types of northern Adriatic halophilous vegetation are present in this area.

The estuary of the Bevano river includes one of the rare stretches of coast in the region that are still not urbanized and devoid of intense tourist development (Figure 5). It is the only river mouth in the region free to evolve following the natural dynamics of coastal sedimentary systems. The area represents a naturalistic oasis characterized by transitional ecotones between fresh, brackish, and marine waters and between wooded, dune, and beach systems. Its terrestrial and aquatic habitats play an important

ecological role as breeding and nursery areas. For these reasons, the entire area, which is an Italian state-owned area, was totally dedicated to nature conservation (100%) and designated as NATURA 2000 site (code IT4070009, named "Ortazzo, Ortazzino, Foce del Torrente Bevano").
The site has a total surface area of 12.55 km2, without any urbanization, and extends seaward from the coastline for about 300 m, on average. It has 0.64 km2 of coastal area including submerged dunes, emerged dunes, and areas behind the dunes.

Figure 5. Northward aerial photograph of the Bevano river estuary, lagoons and coastal areas. In the background an offshore gas platform.

Unfortunately, the area is seriously threatened by coastal erosion, saline intrusion and flooding due to the lack of natural nourishment of the beaches, subsidence, sea level rise and increase in frequency and intensity of storm surges (Archetti 2009, Armaroli and Duo, 2018; Romagnoli et al., 2021), Subsidence is a widespread phenomenon in the Emilia-Romagna, particularly important along the coast because the coastal system consists of sandy beaches and coastal wetlands (Taramelli et al., 2015). The coasts are affected by a marked natural subsidence, because of tectonic processes and recent sediment consolidation. Since the second half of the last century, the subsidence of this area has increased significantly due to intense gas extraction and groundwater exploitation (Bonaldo et al., 2019).
The area is particularly suitable for the settlement and growth of these species, as witnessed by the already existing populations of *Sabellaria spinulosa* at the base of the nearby breakwater barriers. Moreover, historical documentation testifies the presence of native oyster (*Ostrea edulis*) beds along the northern Adriatic coasts, of which today there is no trace (Thurstan et al., 2024 a,b). The project will consist of a submerged consolidated Basal Limestone Reef (hereafter BLR), a few hundred meters from the coast. The summit part of the limestone stone bed, if properly prepared, can host oysters and sabellariid worms that may stabilize the reef and retain the sand, and grow naturally, adapting to the rise in sea level. These are gregarious species that require a proper initial substrate for the first settlement but in good environmental conditions can create the ideal habitat for continuous settlement over time.
For these reasons, by exploiting the knowledge acquired especially in northern Europe, the initial conditions suitable for the settlement of these species will be created, and the bioconstruction process will be triggered by a pre-seeding with farmed native oysters (*Ostrea edulis*) and transplanting of live *Sabellaria* reef potrions from neighboring areas.

The project idea

The reef of oysters and sabellariids will be implemented on a rocky structural base, the "Basal Limestone Reef" (BLR;), it will be made of small/medium natural limestone 8-15 cm stones from quarries, retained by metallic cages (i.e. gabions or mattresses), which represent reef modules. The modules will be placed on the bottom at a depth equal or greater of -1.7 m, with respect to the mean Sea Water Level (SWL), this value allows the craig to operate in shallow waters and gives a permanent submersion of the benthic organisms. The area of intervention will extend parallel to the coast to resemble a natural reef.

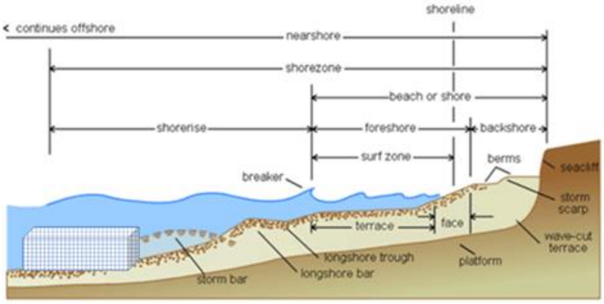

Figure 6. Scheme of native oyster restoration LBR (adapted from Preston et al. 2020).

The realization of the BLR is being preceded by an accurate study of the oceanographic, geological, and ecological features of the entire intervention and monitoring area, including the coastal habitats to be defended, which will provide the necessary baseline to design the BLR reef and its biogenic reefs cover, and monitor their success. The reef, besides contributing to give a support of high biodiversity, will contribute to protecting the coastal habitats from sediment erosion and mitigate the flooding due to storm surges and salt intrusion risks.

Observations on the impact of artificial reefs are rare (i.e., Buccino et al., 2013, Huang et al., 2024), and data and information on low crested structures can be adapted as references. When the incident waves reach the structure, a process of energy transformation occurs. One part of this energy is dissipated by wave breaking and by friction with the structure, while another part is transmitted above the crest and through its interior in the case of permeable submerged breakwaters and the remaining energy is reflected seaward.

The hydrodynamic performance of the BLR is a key point in the design. Several studies have investigated the roles of geometry, the porosity of the mound and the materials (Pilarczyk, 2003, Marini et al., 2020, Marini et al., 2022). The transmission coefficient, Kt, defined as the ratio of the height directly shoreward of the breakwater to the height directly seaward of the breakwater, has the range $0<Kt<1$, for which a value of 0 implies no transmission, and a value of 1 implies complete transmission (no breakwater). Factors that control wave transmission include crest height and width, structure slope, core and amour material (permeability and roughness), tidal and design level, wave height and period. As wave transmission increases, diffraction effects decrease, thus decreasing the size of a salient through direct attack by the transmitted waves and weakening the diffraction-current moving sediment into the shadow zone. It is obvious that the design rules for submerged structures should include a transmission coefficient as an essential governing parameter (Zuo et al., 2011).

The wave evolution over the BLR can be attributed to the changes in the interplay of sum and difference interactions (Sancho et al., 2001). Waves propagating on the BLR will break on it, dissipating a great quantity of their energy. A small part of the incident wave is reflected, a part dissipated, and the rest will be transmitted and refracted across the structures. An extended review of transmission coefficient empirical formulae is provided in Brancasi et al. (2022) where existing formulae are applied to existing dataset of wave transmission. Formulae considering the berm width are seldom, and where existing the berm width range tested is limited.

Numerical simulations were performed to estimate some preliminary indications on wave transmission, diffraction and impact on the coast.

NUMERICAL MODELLING

To assess the effect of the BLR on the wave field and in general the impact of the BLR on the shoreline, the following simulations (Gaeta et al. 2016) were performed:

- Wave propagation through a spectral model (MIKE21 SW).
- Hydrodynamic and morphodynamic studies through MIKE 21 HD and ST.
- Shoreline modelling through MIKE21 SM.

- Bousinnesq modelling through CELERIS

A preliminary layout of the BLR, made by mattresses, is shown in Figure 7. The layer is supposed to be 0.60 m high. Clusters of mattresses are spaced each other providing room for the lateral growth of the bioconstructions.

The total dimension of the designed BLR is approx. 56 m width per 200 m length for a total gross extension of 11’000 m^2. The BLR will be placed at a depth ranging from 1.70 m to 3.00 m as represented in Figure 7.

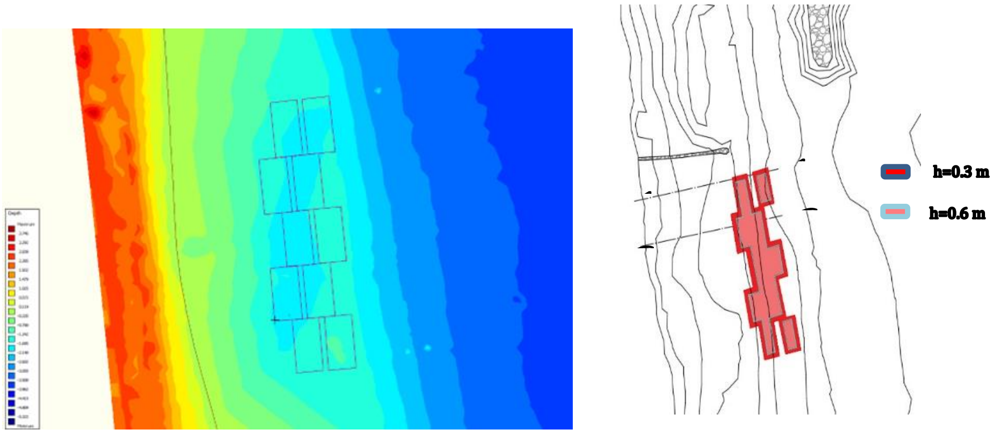

Figure 7. Sketch of the BLR

Wave Hydro and Morphodynamics modelling

The impact of the BLR on the wave field and hydrodynamics are assessed by comparing the configuration 0 (absence of the breakwater) with the field view in the presence of the BLR.

The mesh is presented in Figure 8, its dimension is reduced in proximity to the BLR as shown in Figure 8.

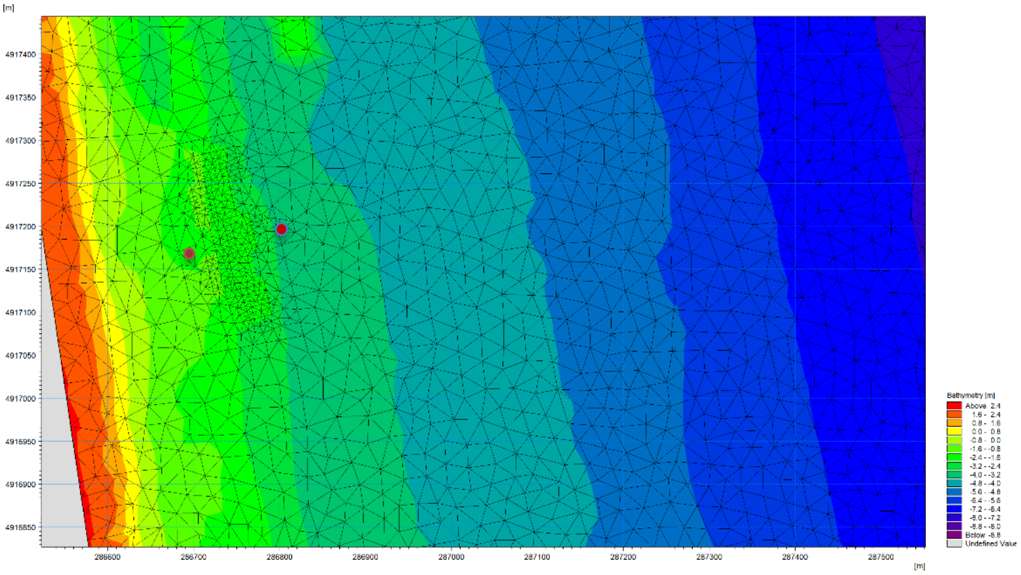

Figure 8 Mesh used for the Mike21 SW simulation

The structure has a height of 0.60 m and the depth ranges between 1.70 to 3.00 m. The BLR is represented with a high roughness (Gauckler-Strickler = 30 m$^{1/3}$/s).

We have investigated two wave conditions representing the peaks of two different storms. Specifically, we have tested two sea states characterized by H_{m0} = 1.4 m, T_p = 5.5 s, MWD = 90 °N and H_{m0} = 3.8 m, T_p = 7s, MWD = 60 °N, respectively, whose data were recorded by the wave buoy Nausicaa, located on a depth of -10 m, 30 NM south of the study site.

The results of the wave field during the peak of the second storm are presented in Figure 9. Extracted wave data (Hm0) at two positions, onshore and offshore the BLR and represented with red bullets in Figure 8, allowed to have data on the wave transmission and to calibrate the Kt coefficient through the Buccino et al. (2013) empirical formula.

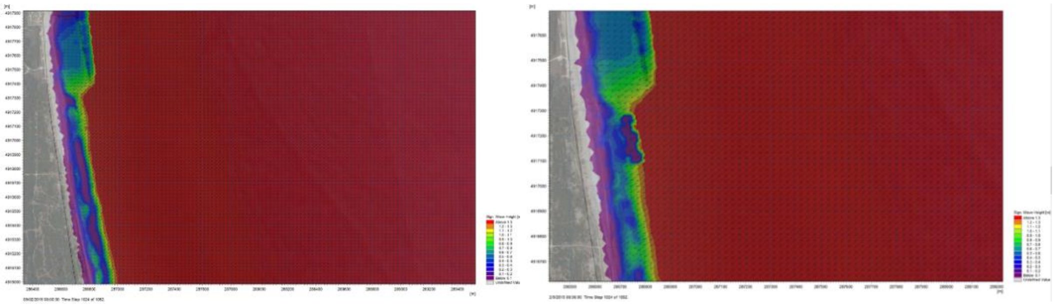

Figure 9 Map of the significant wave height, without (left panel) and with (right panel) the presence of BLR, respectively. The simulation refers to the offshore wave condition characterized by Hm0 = 3.8 m, Tp = 7 s, MWD = 60 °N.

The BLR presents a high capacity in wave energy dissipation. During the storms considered, for Hs>1.2 m, the Kt ranges between 0.25 to 0.55.

Celeris

The open-source Boussinesq-type model (BTM) aims to assess the potential diffractive effects of the BLR. Among the different BTMs, we adopted the open-source software CELERIS, which has been developed by the Coastal Engineering Group and the Tsunami Research Center of University of Southern California (Tavakkol and Lynett, 2017).

The phase-resolving model CELERIS integrates the extended Boussinesq equations – formulated in conservative form – derived by Madsen and Sørensen (1992):

$$\begin{bmatrix} h \\ P \\ Q \end{bmatrix}_t + \begin{bmatrix} P \\ \frac{P^2}{h} + \frac{gh^2}{2} \\ \frac{PQ}{h} \end{bmatrix}_x + \begin{bmatrix} Q \\ \frac{PQ}{h} \\ \frac{Q^2}{h} + \frac{gh^2}{2} \end{bmatrix}_y + \begin{bmatrix} 0 \\ ghz_x + \psi_1 + f_1 \\ ghz_y + \psi_2 + f_2 \end{bmatrix} = 0 \quad (1)$$

where the unknown variables are the total water depth, h, and the depth-integrated mass fluxes along the directions x and y, P and Q, respectively; g is the gravitational acceleration, f_1 and f_2 are the bottom friction terms, which can be determined through the Manning roughness coefficient. Moreover, the terms ψ_1 and ψ_2 in Eq. (1) account for the dispersive properties of the model. Finally, it is worth specifying that CELERIS handles the physical dissipation related to the breaking mechanism via the numerical dissipation; thus, unlike other existing BTMs, the governing equations do not contain any additional term representing breaking models (e.g. eddy viscosity model, Kennedy et al., 2000).

To evaluate if the BLR might generate wave diffraction, we have investigated the same two wave conditions already defined in previous section, representing the peaks of two different storms. (H_{m0} = 1.4 m, T_p = 5.5 s, MWD = 90 °N and H_{m0} = 3.8 m, T_p = 7 s, MWD = 60 °N).

Since the storms' characteristics have been measured at the water depth of 10m, which means about 4000m seaward the structure, the sea states have been propagated up to h = 4.5m via 1D simulations to reduce the computational time. Such propagation tests have been performed using the non-hydrostatic model SWASH (Zijlema et al., 2011). The sea states – driven by mean JONSWAP spectra – have been propagated within a numerical flume characterised by horizontal and vertical resolutions of 3m and two layers, respectively. Then, the sea surface and velocity time series obtained by SWASH at h = 4.5m have been used as wave generation boundary conditions in CELERIS.

Concerning CELERIS's numerical setup, we have adopted two different grids according to the mean wave direction tested, i.e. the latter is perpendicular to the offshore boundary of the grid. Along the other edges of the numerical tanks, the wave absorption condition avoids any undesired reflective effect. Figure 10 shows the boundary conditions adopted along the numerical tank. For both the grids, the square cells had 1m of grid spacing; the time step was set to 0.1s to guarantee a proper value of the Courant number. The Manning coefficient adopted was 0.012 $m^{-1/3}/s$. Each test has run for 200 waves.

To better evaluate the reef's effect in terms of diffraction, we have performed the simulations with and without the structure (i.e., two tests for each wave condition). It is worth specifying that the BLR has been modelled as part of the bathymetry.

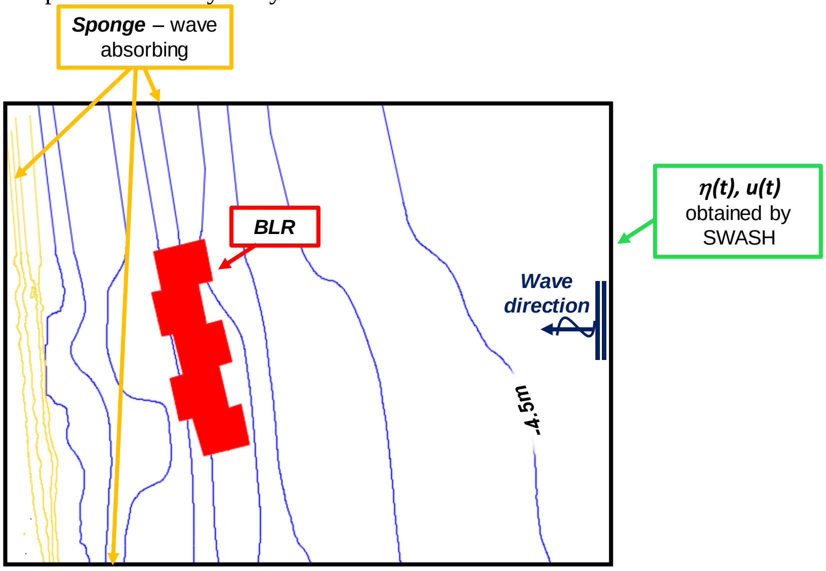

Figure 10. Boundary conditions adopted during CELERIS numerical experiments. Grid orientation refers to the wave condition characterized by H_{m0} = 1.4m, T_p = 5.5s, MWD = 90°N.

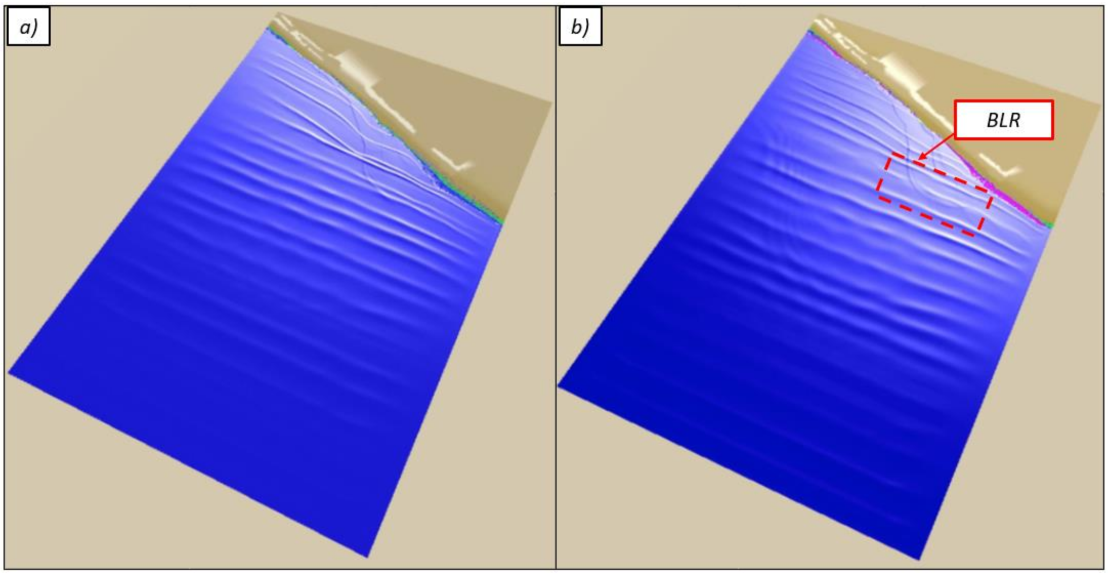

Figure 11. Panels a) and b) show numerical experiments without and with the presence of BLR, respectively. The experiment refers to the wave condition characterized by H_{m0} = 3.8 m, T_p = 7 s, MWD = 60 °N.

Qualitative analysis of the numerical results reveals that the presence of BLR does not generate diffractive phenomena, as can be appreciated in the comparison shown in Figure 11. However, this result is somehow expected as the BLR is a submerged reef, which usually does not activate the diffraction phenomenon.

Shoreline Morphology

MIKE 21 Shoreline Morphology (SM) is a multiline model which offers best-in-class functionality for modelling the morphological evolution of coastal areas and shorelines. It enables users to simulate changes in coastline profiles, and shoreline dynamics over time due to natural processes or human interventions. The structures can be inserted in the model by their location and their hydrodynamic characteristics; therefore, we have inserted the existing low crested structures, which is present northward the BLR (red line in figure 10) and the BLR to be designed.
The BLR k_t resulting from the simulations was implemented in the shoreline modelling, to reproduce the effect of the barrier on the shoreline.

The model was run for an entire year, we selected 2015 for the high percentage of valid data collected by the wave buoy Nausicaa, and because during this year two significant storms were recorded. The results of shoreline modelling after one year of waves are presented in Figure 12. We can observe the shoreline (blue) on the first day of the year and in the last day of the year (orange), on the left side with the existing breakwater and the BLR, and on the right only with the BLR. The presence of the BLR produces a small increase of the beach width.

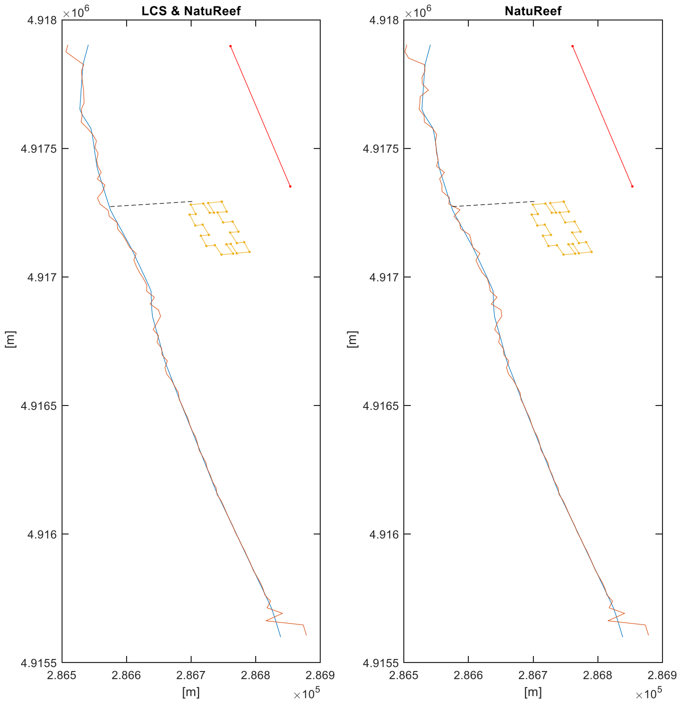

Figure 12 Result of the shoreline modelling: shoreline on Jan 1st, 2015 (blu) and on Dec 31st (orange line), with both the BLR natureef and the existing breakwater (left) and only the BLR natureef (right)

CONCLUSIONS

Nature Based Solutions are becoming increasingly the most convenient approach for coastal protection from flooding and erosion. In temperate coastal environments, like the Mediterranean Sea and northern Europe, seagrass meadows, oyster and sabellariid reefs can create three-dimensional structures that retain sediments, dissipate wave energy, and create many ecological niches that allow for high biodiversity and provide nursery habitats. Native oysters can build shallow-water barrier reefs. The paper has investigated the hydraulic performances of NBS made as basal limestone reef to be placed on a depth ranging between -1.70m to -3.0 m, parallel to the coast 200 m long, extending for approximately 50 m. The BLR is the habitat for the European oysters.

Due to the relative freeboard (submergence/incident wave) of the BLR, which depends on the sea water level and on the incoming waves, we expect a resulting range of transmitted waves between 0.25 to 0.6. The model results show that the BLR will cause a limited wave diffraction and can reduce coastal erosion.

The implementation and growth of biogenic reefs above the BLR will, over time, consolidate the substrate and increase its physical and hydrodynamic effects.

Acknowledgments

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