Article

A Stepwise Approach to Beach Restoration at Calabaia Beach

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Abstract: Sea hazards are increasingly threatening worldwide coastal areas, which are among the most strategic resources of the Earth in supporting human population, economy and the environment. These hazards enhance erosion processes and flooding events, producing severe socio-economic impacts and posing a challenge to ocean engineers and stakeholders in finding the optimal strategy to protect both the coastal communities and the health of the environment. The impact of coastal hazards is actually worsened not only by an enhancing rate of relative sea level rise and storminess driven by climate changes, but also by increasing urban pressure related to the development of the sea economy. With regard to larger environmental awareness and climate change adaptation needs, the present study focuses on a stepwise approach that supports the actions for coastal protection at Calabaia Beach, which is located in the Marine Experimental Station of Capo Tirone (Cosenza, Italy). These actions first aim to protect humans and coastal assets, then to restore the environment and the local habitat, overcoming the need for the emergency interventions carried out in the last decades and pointing out that healthy ecosystems are more productive and support a sustainable marine economy (“Blue Growth”).

Keywords: coastal erosion; coastal engineering; coastal management; nature-based solutions; boulders in bulk; beach nourishment; *Posidonia oceanica*

1. Introduction

Coastal areas sustain the Mediterranean human population [1]. These areas are complex socio-ecological systems, based on a strong relationship between human activities and natural processes [2], where human activities when using the coastal resources should conserve their resilience and the services they can provide to local communities [3–6]. The increasing demand for the use of the sea, such as facilities for energy production, extraction of materials from submarine quarries for building and beach nourishment, shipping and fishing activities, tourism, aquaculture, marine cultural heritage, and ecosystem and biodiversity conservation, along with the multiple pressures threatening the coastal resources, requires an integrated planning and management approach (see Directive 2014/89/EU). The Mediterranean region should pursue a long-term strategy to support a sustainable development of the economy based on the use of the sea for innovative and sustainable purposes (Blue Growth) [7,8]. Despite the great opportunities that Blue Growth offers, coastal areas regularly face several geopolitical, economic and environmental challenges which are worsened by climate change, subjecting the vulnerable areas of the Mediterranean Sea to large economic and environmental loss and damage [9–16]. In particular, flooding and coastal erosion processes are enhanced by climate changes, which can produce additional hazards than those attributable to sea level rise alone [17–24]. Moreover, since increasing urban pressure will further exacerbate these hazards, there is a clear need

for a joint initiative to promote integrated economic actions aimed to preserve the ecosystems and the biodiversity of the Mediterranean Sea [25–27].

In recent decades, coastal protection interventions have been planned following major sea calamities, but only focusing on the safety and protection of humans and economic resources, without taking into account the environmental needs of the land [28,29]. Nowadays, several maritime policies aim to protect coastal habitats and natural resources, promoting a sustainable use of land [30–32], following the guidelines of the sustainable development goals of Agenda 2030, the United Nations Environment Assembly (UNEA-4, 2019, Nairobi, Kenya) and the Intergovernmental Conference (New York, 2019) concerning the law of the sea. The European Union promotes Blue Growth following the Treaty 2002/413/CE ICZM (Integrated Coastal Zone Management), the Directive 2008/56/CE (Marine Strategy Framework Directive, MSFD), the Commission Decision 2010/477/UE and the Directive 2014/89/UE, supporting an integrated and cross-sectorial sustainable management of coastal areas to promote the restoration of the environment and the ecosystem (i.e., nature based solutions, NBS) [33]. In this context, it is of paramount importance to address the effects of local human action on the environment [34,35], supporting the evaluation of the vulnerability of the area [36,37].

Despite recent policies, environmental degradation still threatens coastal communities, mostly due to the impact of the rigid structures built in the last decades [38,39], which affect landscape, ecosystems, biodiversity and biological interactions [40–42]. Therefore, shifting from hard structures towards environmentally-friendly interventions and NBS is crucial in the development of a sustainable sea economy [43–48]. Although NBS are certainly an improvement with respect to previous approaches that did not consider the multiple needs of the environment, certain interventions aiming to restore coastal ecosystems failed in their purpose, since bio-geomorphic feedbacks inherent to ecosystems were not analysed sufficiently. Moreover, NBS are often expensive, making any possible failures a huge issue to deal with for stakeholders. Thus, any restoration measure has to be evaluated on the basis of the specific nature of the area.

The coastal area of Belvedere Marittimo provides a significant example concerning sea-defence structures designed in turn to protect the Calabaia Beach, located in the Marine Experimental Station of Capo Tirone (Belvedere Marittimo, Cosenza, Italy, 39°36′13″ N, 15°51′24″ E). This area is crucial in planning scientific activities concerning the Blue Growth, with particular reference to the study of local hydrodynamics, coastal protection measures, dispersion of pollutants and marine biology. Since Calabaia Beach has been affected by erosion processes for decades [49–51], several hard structures were designed in the late 20th century, subsequently converted into submerged breakwaters fixing a nourishment cell. Actual plans promote NBS through the use of *Posidonia oceanica*, a native seagrass which reduces wave power and restores coastal areas [52–56], following policies of good environmental management and sustaining the development of Blue Growth [57–59].

Here we illustrate the stepwise approach adopted at Calabaia Beach, which aimed to restore the environment while protecting maritime and coastal assets, shifting from hard interventions to NBS. The case study of Calabaia Beach is a representative example of how sea hazard and environmental protection can be pursued together. The paper first describes the sea defence structures widely used in coastal protection, with particular reference to Calabaia Beach. A brief characterization of the area and of the approach is provided in Section 2. Section 3 describes the effectiveness of the interventions carried out at Calabaia Beach in recent decades, moving from measures that aim to mitigate sea hazards but only protecting humans and goods to measures that also pursue the restoration of the environment, with particular reference to innovative environmentally-friendly solutions. A set of conclusions closes the paper.

2. Materials and Methods

2.1. Coastal Erosion Management: A Time Dependent Approach

Beaches are complex systems requiring a multidisciplinary design and management approach. Actions aimed at challenging the erosion process have to be designed on the basis of the specific characteristics of the land. Morphological features, together with the economic and environmental needs of the area and the climate change scenario, are fundamental in choosing a coastal protection strategy, as stated in the EUROSION report [31]. Five adaptation strategies could be pursued:

- do nothing: no changes with respect to the existing situation;
- managed realignment: land-use planning, recovering areas from sea flooding;
- hold the line: sea defence measures supporting the former defence line;
- move seaward: sea defence measures promoting an advancement toward the sea of the defence line;
- limited intervention: non-invasive measures to support natural processes in reducing flood hazards and erosion processes.

Action planning is strictly related to the time scale of the hazard and to the priority of the needs of the area [8,35,60]. Floods, erosion processes and damage to the assets of coastal settlements that occur with a single storm surge can be counteracted only by means of hard structures, which are, on the one hand, effective in facing sea hazards but, on the other, inadequate for the environmental needs of the land. Conversely, sea hazards driven by climate change show a long-term evolution and can be counteracted by means of environmental-friendly measures that restore the coastal environment. Figure 1 summarizes measures widely used in coastal defence.

Coastal Protection Function				Nourishment	Submerged Breakwater	Emerged Breakwater	Submerged Isles	Emerged Island	Partially submerged groyne	Emerged Short Groyne	Emerged Long Groyne	Submerged T-shape Groyne	Emerged T-Shape Groyne
Reduction of incident waves due to wave-breaking	Direct					●		○					●
	Indirect				○		○					○	
Beach Enlargement	Positive Contribution			●									
	Reduction of Erosion	Cross-Shore			●	○						○	○
		Long-Shore	Emerged Beach						●				
			Submerged Beach				●	●		●		●	●
			Whole Beach			○					●		

Figure 1. Example of coastal defence measures and their main effects. Black dots stand for direct effects; white dots for indirect effects.

Coastal protection arises from the need to identify the optimum time-dependent approach to sea hazard management. Although erosion processes occur gradually, at a certain time shoreline buildings are suddenly threatened due to the lack of adequate sea defence measures (i.e., the do nothing option). In such a threat, it is not possible to plan long term actions since the intervention must be aimed at protecting assets within the shortest time. On the other hand, when the erosion process has been contained, the stakeholders have enough time to promote long-term planning, evaluating the sustainability and the durability of different solutions and taking into account all the needs of the land (Figure 2).

When the progression of the erosion process threatens humans and goods, stakeholders have no time to plan an intervention that satisfies all the needs of the coastal area, limiting the action to containment measures (i.e., the hold the line option). In this condition, hard defences (e.g., seawall and

bulk boulder breakwaters, Figure 3a) provide a rapid solution in protecting the shoreline but affect the landscape, triggering the erosion process and requiring high maintenance costs [28,61,62].

Soft defences (i.e., the move seaward option) are usually less efficient than hard structures in flood protection, but they are increasingly supported by international standards due to their low costs and impacts on landscape, local habitat and the marine ecosystem. Perched nourishments are the most popular example of soft defences (Figure 3b), which aim to nourish and fix the shoreline by reproducing the original slope of the seabed and achieving the natural equilibrium profile of the beach after each storm [63–73].

Figure 2. Summary of the stepwise approach in coastal defence.

Figure 3. Examples of coastal defence interventions. (a) longitudinal view of a breakwater made of bulk-boulders; (b) transversal section of a submerged breakwater; (c) interaction between natural elements of the shoreline and waves; (d) *Posidonia oceanica* meadows located at the Experimental Marine Station of Capo Tirone. Photographer F. Sesso.

The evolution of soft defences is represented by NBS, usually classified as a limited intervention option and largely used to counteract the erosive processes produced by former rigid measures [72–76]. NBS consist of a wide range of interventions (e.g., cobble berm, dunes, mangroves), depending on the features of the local environment [72]. Wave height reduction produced by NBS is comparable to wave height reduction achieved by artificial breakwaters [71] but NBS are usually cheaper [72]. The strength of NBS is to achieve the goals of the limited intervention option, by enhancing the resilience of the coastal marine environment. First, NBS are supported by anthropic action, further becoming an ecosystem capable of developing and becoming self-supportive (Figure 3c). A good example in the Mediterranean area is provided by the *Posidonia oceanica* meadows (Figure 3d) [77–82]. *Posidonia oceanica* meadows can serve multiple purposes, by offering an additional resistance to the hydrodynamic action, promoting biodiversity and environmental resilience [57,58] and increasing the self-purification of the sea [80,83]. In addition, *Posidonia oceanica* reduces the need for further coastal interventions [59] and supports Blue Growth.

As a footnote, we stress that the number of measures in the stepwise approach depend on the beach conditions (e.g., NBS only for well-preserved beaches; more interventions for degraded shorelines).

2.2. Calabaia Beach

Here we focus on Calabaia Beach, located in the southern Tyrrhenian Sea (Figure 4). The morphology of the southern Tyrrhenian coast is mostly characterized by metamorphic and sedimentary rocks directly extending to the sea and narrow coastal plains.

Figure 4. Location of Calabaia in the Tyrrhenian coast.

2.2.1. Bathymetric and Topographic Surveys

Since the 1960s, the Southern Tyrrhenian shoreline has been intensively developed, enhancing erosion processes (Figure 5) and requiring the building of many sea defence structures [48,84,85]. Watercourses formerly conveyed fine-grain material to the coast, balancing the erosion process. However, the urbanization of the coast, with particular reference to the Salerno–Reggio Calabria railway, reduced sediment supply from the rivers to the coast, demanding a continuous maintenance effort against erosion.

Figure 5. Evolution of Tyrrhenian coastline, from Nocera Terinese to Gizzeria: (a) Royal Air Force (RAF) image taken in August 1943. Pink line shows the railway. (b) Satellite image taken in June 2008. Yellow line represents the railway.

Based on studies performed by the U.S. Coastal & Hydraulics Laboratory (CHL), the Army Corps of Engineers and the Pavia Environmental Engineering Study Center (CSDIA), the southern Tyrrhenian coast can be divided into 11 coastal cells (Figure 6). Calabaia Beach, which belongs to cell D, had eroded considerably until the mid-1970s (Figure 6a). The hard defences built during the 1980s stopped the retreat of the shoreline (Figure 6b).

Further bathymetric surveys were carried out from 2005–2008, based on World Geodetic System 1984 data and two cornerstones (Figure 7), the CS1 ($39^{\circ}35'58.9871''$ N, $15^{\circ}51'37.6292''$ E) and the CS2 ($39^{\circ}37'00.8050''$ N, $15^{\circ}51'06.6870''$ E). In some sections, the surveys were performed perpendicular to the shoreline, from the railway to 10 m sea depth. The collected data have been further compared to address the effects of the sea defence works on the evolution of the shoreline (Figure 7) [86].

Figure 6. Historical sediment balance along the southern Tyrrhenian coast from Tortora (located in the northern boundary of the Calabria region) to Lamezia Terme, performed by CHL and CSDIA. The panels show the eroded volume in each cell of the shoreline in two different periods: 1954–1978 (a) and 1978–1987 (b). Calabaia Beach belongs to the cell D.

Figure 7. Location of the cross-sections used in the bathymetric and granulometric surveys.

2.2.2. Granulometric Surveys

Granulometric analyses have been carried out from 2005–2008 following the American Society for Testing Materials 200 procedure (ASTM International-Standards Worldwide, 2006). Table 1 provides the characteristics of the soil samples taken in section 29 (see the location in Figure 7). The shoreline evolves rapidly due to the predominance of fine material, which is affected by ordinary wave action. The sharp slope at the bottom (almost 15%), causes the loss of most of the material, triggering an erosion process that cannot be counteracted by the river sediment supply.

Table 1. Survey of 30.05.2005 at section 29.

Sample (N°)	Depth [m]	Ys [kN/m ³]	Gravel [%]	Sand [%]	Silt [%]	Clay [%]	d50 [mm]
2	+1	25.70	52	48	0	0	3
4	0	25.69	23	77	0	0	1.1
6	−2	25.59	58	42	0	0	7.4
8	−4	25.65	0	100	0	0	0.48

2.2.3. Wave Climate

A hindcast analysis of the wave climate has been performed on the Tyrrhenian coast by using the coupled ECMWF-WAM wave model [87] validated by the data of the Ponza buoy, collected from 1 July 1989–31 December 1999, and by the Cetraro buoy, collected in 1999, (see EUROWAVES project, [88,89]). The Ponza buoy is a Wavac MKI directional wave meter located at 40°52′00″ N, 12°57′00″ E; the Cetraro buoy is a Waverider directional wave meter located at 39°27′01″ N, 15°55′01″ E (Figure 4). Both the buoys are anchored at a depth of 100 m. Figure 8 illustrates the offshore wave climate at Calabaia Beach.

Figure 8. Offshore wave climate at Calabaia Beach, based on the EUROWAVES project hindcast.

3. Coastal Management at Calabaia Beach: Experiences and Planning

3.1. Emergency Measures

From the 1980s to the early 2000s several hard structures were built at Calabaia Beach after major storms, trying to limit flood risk for the population by using concrete blocks set a few meters seaward (Figure 9), affecting the landscape and the environment.

Figure 9. Calabaia Beach in 2002: (a) seaward view; (b) landward view; (c) an overview.

The rapid progression of the erosion process required a large use of hard defences, which, on the one hand, achieved the stabilization of the coastline, but, on the other hand, affected the environment, the landscape and the social value of the areas, since seawalls and breakwaters enhanced the erosion process beyond the structures and triggered a transversal sediment accretion, interfering with the natural growth of the beach [61,62,77].

An example of the effect of the former interventions is provided by Figure 10, which refers to section 29 (see Figure 7) during the survey of 2005. The section, located near the urban settlement of Calabaia, shows a steep slope of the bottom. The sea defences protected only the coastal buildings, leaving the beach, located ahead, defenceless.

In this context, NBS would not have brought any benefit, constrained by the depth of the bottom.

Figure 10. Survey of section 29 performed in May 2005. The red dot represents the location of the seafront buildings.

3.2. Perched Nourishment

Once the threat to the assets had been counteracted, the awareness of the need for an environmental restoration arose, strongly supported by the needs of the local sea-economy (e.g., the move seaward option). Since the shoreline historically suffered erosion (Figure 6a), the optimum solution has been identified as a durable nourishment intervention supported by a submerged breakwater located at the toe of the refilling, allowing the dissipation of a large fraction of the wave energy.

In order to identify the optimum characteristics of the work, i.e., its location and the depth of the ridge, several simulations have been carried out supported by hydrodynamic [86] and physical models [86] evaluating the efficiency of the defence structure in a scaled-basin.

The hydrodynamic FLOW-3D model integrates the RANS (Reynolds Averaged Navier-Stokes equations) on a spatial grid through a Eulerian approach using the VOF (Volume of Fluid) technique to track the liquid surface [90]. The simulations were performed on a two-dimensional domain, to be aligned to the physical model, with and without the barrier and for different wave climates, focusing on changes in wave energy, wave setup and bottom friction produced by the submerged breakwater. Results show that the barrier increases the wave setup at the back (Figure 11a) and decreases bottom friction (Figure 11b).

Figure 11. Effect of the submerged breakwater for different wave heights and periods: (a) wave setup; (b) bottom friction. Different lines represent the different incoming waves (thick lines with the breakwater; dashed lines without the breakwater). The effect of the breakwater is proportional to wave height [91].

A further set of scaled replicas were set up in a basin 18 m long, 3.6 m wide and 1.2 m deep (Figure 12), on the basis on the wave climate computed by means of the FLOW-3D model [91]. The basin is equipped with a wave generator, resistive probes, an acoustic Doppler profiler and a 3D laser scanner. The physical model allowed testing of the materials of the breakwater and of the nourishment by simulating the wave action. Results indicate that the submerged breakwater is stable, showing a wave reflection coefficient of 0.3.

At the beginning of the 2000s, the large deterioration of the shoreline led the Calabria Region and the Province of Cosenza, supported by the CHL, to characterize the area in order to identify guidelines to protect urban settlements and to restore the environment [48,85]. These guidelines were drawn up into the Executive project for the defence and requalification of the coast in the Municipalities of Bonifati, Sangineto and Belvedere M.-Section from the north of Capo Bonifati to north of Capo Tirone, which includes the restoration of the Calabaia Beach by means of:

- a submerged breakwater located 250 m seaward, 2.5 m below the mean sea level and 700 m long. The structure consists of natural boulders and re-used concrete boulders taken from former emerged breakwaters;
- semi-submerged groynes made of natural boulders and re-used concrete boulders taken from former emerged breakwaters, connecting the heads of the submerged breakwater to the shoreline;

- a beach nourishment using 600,000 m³ of quarried quartz sand with $d_{50} = 3$ mm, which is a material showing similar characteristics to the in-situ soil (Figure 13).

Figure 12. Basin used for the scaled-replicas: (a) 3D rendering of the laboratory channel; (b) foreground of the wave generator; (c) location of the coarse material before the experiment; (d) coarse material at the end of the experiment [91].

Figure 13. Materials used for the intervention: (a) quarry in the municipality of Cetraro (natural boulders); (b) quarry in the municipality of Orsomarso (nourishment sand); (c,d) fine material quarried from the Lao river.

Figure 14 represents some stages of the works performed at Calabaia Beach in the early 2000s.

Figure 14. Works at Calabaia Beach: (a) construction of the emerged part of the groyne; (b) construction of the submerged breakwater using a pontoon; (c) construction of the submerged part of the groyne (the right shows the concrete boulders re-used from the former submerged breakwaters) and first nourishment of the beach; (d) view of the submerged part of the groyne after the removal of the track.

In the year 2006, the works were completed, allowing the adoption of further measures to restore the whole coastal area. (Figure 15).

Figure 15. Calabaia Beach, works achieved (December 2006): (a) longitudinal view of the groyne; (b) boulders of the submerged breakwater; (c) plan view of the overall works.

The intervention partly restored the environment and the landscape at Calabaia Beach (Figure 16).

Figure 16. Calabaia Beach: effects of the intervention. Yellow line represents the original shoreline; blue line the current shoreline; red line the location of breakwaters in 2002. The white dotted line shows the boundary of the cell of the protected nourishment.

A further monitoring campaign [86,90] proved the efficiency of the works in retaining the material in the cell, even if several significant storms occurred [91] (Figure 17).

The effectiveness of the perched nourishment has been evaluated by comparing satellite images taken in different periods (Figure 18). (a) illustrates the Calabaia Beach in September 2004, when the shoreline was close to the buildings. (b) shows the effect of the intervention ten years after the achievement of the works, estimating an increasing of the area of the beach of about 46,000 m². Six years after (c) the beach has not changed, proving the achievement of the equilibrium profile of the beach.

Figure 17. Bathymetric surveys of the cross-shore at Calabaia Beach from 2005 (before the end of the works) to 2008 [91].

Figure 18. Calabaia Beach. (a) NASA satellite Aster L1T, res. 33 m, 14-09-2004; (b) ESRI Wayback Archive, res. 5 m, 20-02-2014; (c) ESRI Wayback Archive, res. 5 m, 29-04-2020. In red is the shoreline before the nourishment.

The protected nourishment proved to be an effective measure to protect the shoreline. Figure 19 illustrates the bed profile of section 29 (see Figure 7) three years after the nourishment, clearly highlighting a wide beach located between the shoreline and the seafront buildings, and an underwater mildly decreasing depth.

The solution of a perched beach supports both the protection of the shoreline and the use of the sea. As a footnote, we stress that the quality of the cliff-beach ecosystem can be further improved by means of NBS (e.g., *Posidonia oceanica*).

Figure 19. Survey of section 29 performed in May 2008. The slope of the bed is mild, with an almost linear deepening. Red point illustrates the location of the seafront buildings.

3.3. NBS Example: The Further Use of *Posidonia Oceanica* at Calabaia Beach

The restoration of Calabaia Beach began with the construction of a perched beach by removing the former rigid defence, aiming to increase the resilience of the environment by moving from a move seaward to a limited intervention option, on the basis that a rich and complex ecosystem

faces ecological threats more successfully [92,93]. The actual target is to support the growth of *Posidonia oceanica*, a seagrass which is threatened worldwide by climate change and sea pollution. In particular, *Posidonia oceanica* meadows have been significantly reduced along the whole Southern Tyrrhenian coast [92,93], enhancing the local erosion process [94–97].

Studies focused on the rooting and the growth of the seagrass [98,99], showed that *Posidonia oceanica* thrives better in stable environments with coarse sands [100,101] and is sensitive to seasonal variations of nutrients, with particular reference to nitrogen and phosphorus [102–105]. *Posidonia oceanica* reproduces through cuttings that can be easily transplanted into fertile environments [106]. The NBS proposed at Calabaia Beach consists of a *Posidonia oceanica* nourishment achieved by grafting seeds and cuttings on biodegradable films anchored to the seabed (Figure 3d), containing all the nutrients.

3.3.1. Laboratory Experiments

At the Chemical and Environmental Engineering Laboratory of the University of Calabria, the optimum bed-layer material for the growth of the *Posidonia oceanica* was investigated, which must be biodegradable and environmentally friendly, and capable of resisting wave action and being extruded in order to be anchored on the bottom to hold seeds and cuttings. The aggregating base of the film consists of poly-hydroxy-butyrate polymer in a percentage of between 10 and 50%, which is biodegradable in about a year, ensuring good mechanical resistance until the plants have taken root. This is combined with 10–30% of lignin, which provides excellent mechanical properties [107]. The nutrients are provided through a glutinous substance, which is an excellent plasticizer with good mechanical properties. The compound is finally enriched with other salts fundamental for the development of the plants.

Laboratory findings show good mechanical strength of the compound. Further tests will be carried out to identify the proportion of the components and the thickness of the film that entail the best mechanical properties.

3.3.2. Sea Bottom Installation

In recent years, several studies have evaluated the effect of the *Posidonia oceanica* on the inshore hydrodynamics of the area, addressing the wave attenuation on plant density and on submergence. *Posidonia oceanica* meadows reduce the inshore wave climate by means of the leaves and the leaf systems and retain the fraction of sediments covered by the vegetation [108–110].

The installation of the film on the seabed at Calabaia Beach will be performed at different depths by the divers of the Capo Tirone Marine Experimental Station, who are in charge of anchoring the film to the seabed by means of sand screws, designed in order to guarantee the adhesion of the film on the sandy substrate. The operation will be supported by a boat equipped with a reel system which locates the film as the boat advances along the barrier. Since currents and waves could interfere with the laying and anchoring operations and could affect the substrate, the season in which to begin the work has to be chosen accordingly. The planting of the cuttings and seeds will be performed by using both the native *Posidonia oceanica* meadows of Belvedere Marittimo and cuttings made in the laboratory.

Close to the protected site of Capo Tirone, *Posidonia oceanica* meadows actually reach a leaf height of about 60 cm, with an approximate density of 400 to 500 stem/m². Based on the bathymetry of the area, the target is to plant four strips of *Posidonia oceanica* located parallel to the shoreline, 20 m wide each. In order to reduce the wave energy from 2.5 m sea depth, the optimum solution is a high-density strip of seeds and cuttings within the nourishment area located close to the barrier. The submergence ratio between the depth of the seabed and the height of the leaf should improve the damping of waves of a significant height >2 m [108,109].

Seaward of the breakwater, planting will start at 6.5 m sea depth and ends at about 8 m sea depth, covering an area of about 60 × 700 m² through four strips of *Posidonia oceanica* characterized by different densities, ranging from 400 stem/m² close to the barrier to lower values seaward (Figures 20 and 21). The second high-density area located close to the breakwater does not significantly support wave

reduction, because the submergence ratio is too small. The purpose of this layer is to increase the durability of the work, by reducing the effects of waves and currents, with particular reference to the scouring effect at the toe. The two low density layers do not have a specific hydrodynamic purpose, mainly supporting the local habitat and the monitoring of the plants.

Figure 20. Location of the four strips of *Posidonia oceanica* proposed in the area of Calabaia Beach.

Figure 21. Example of implantation of *Posidonia oceanica* in section 29.

3.3.3. Monitoring Campaigns

The intervention requires a monitoring campaign performed every fifteen days of the first quarter, aiming to evaluate the percentage of germination of the seeds, the foliar and radical development of the cuttings, the presence of benthic macroinvertebrates in the *matte substrate*, and the anomalies of the film.

The growth of the *Posidonia oceanica* will be further supervised through photographic inspections carried out by means of the AUV Tirone I (Figure 22a), which can also monitor the chemical status of the water by means of a multiparameter scope, evaluating the health of the ecosystem. In particular, the data will be compared to the database belonging to the protected area of Capo Tirone (Figure 22b,c), in order to identify possible threats to the plants and to monitor the proliferation of competitor species, such as the allochthonous algae of the *Caulerpa* family, which have invaded the ecological niche of *Posidonia* in many areas of the Mediterranean Sea [111,112].

In addition, the sedimentological budget of the beach will be monitored in order to address the presence of *Posidonia oceanica* and its effects on the retention of the sediments on the bottom. Periodic bathymetric surveys will be performed by means of a MultiBeam sonar to detect any changes in beach

morphology. Finally, a set of simulations will be carried out by means of a mathematical model with the aim of quantifying the effects of the *Posidonia oceanica* on wave damping and on sediment budget.

Figure 22. (a) Autonomous Underwater Vehicle (AUV) Tirone I in ROV navigation mode; (b) monitored area by means of the AUV. Green line delimits the protected area of Capo Tirone; red line indicates the location of the submerged breakwater; white line the track prescribed to the AUV for autonomous navigation. (c) illustrates an example based on the data collected by the AUV in the monitoring area (b), showing the concentration of dissolved oxygen. Darker colours represent higher values of dissolved oxygen.

4. Discussion and Conclusions

Erosion process produces long-term effects on coastal environments, threatening urban settlements and leading to the building of emergency structures that often affect the landscape and the ecosystem, which requires to be further restored by means of more expensive measures. In this context, recent maritime policies promote environmentally friendly and sustainable measures aimed at protecting both buildings and natural resources. Nature based solutions are often preferred to former approaches that did not consider the needs of the environment and the ecosystem. However, certain nature-based interventions aimed at restoring the coastal ecosystems failed in their purposes, mainly due to an incorrect estimation of the bio-geomorphic feedbacks that characterize the ecosystem.

This document illustrates the time-dependent approach performed at Calabaia Beach, an area that has been subjected to several sea-defence interventions, shifting from a hold the line method toward the move seaward and limited intervention measures, since the do nothing solution has proved to be ineffective due to the erosion processes that affect the area. In the past century, many hard structures

successfully protected the seafront buildings located at Calabaia Beach from the damages produced by major swells, allowing the touristic use of the sea, but affecting the environment. At the beginning of the present century, the coast has been partly restored through beach nourishment supported by submerged breakwaters and groynes, built using the material taken from the former structures. The intervention proved to be effective, protecting the coastal settlements by reducing wave energy, keeping sand in the erosion cells and restoring the whole ecosystem. Further measures consist in planting *Posidonia oceanica* meadows beyond the groynes, which serve as lung, larder, nursery of the sea and as a shelter where several marine species can thrive.

The case study of Calabaia Beach is a worthwhile example of the implementation of a time-dependent strategy in counteracting coastal erosion and in restoring the environment, in accord with the most recent EU directives. We speculate that this methodology could be successfully applied to other case studies when it is required to balance flooding protection with economic interests and the safeguarding of the coastal ecosystem. However, any restoration measure has to be evaluated on the basis of the specific nature of the area, promoting, if possible, long-term planning that first focuses on the natural action of the beach on the retaining of the material, and then on the restoration of the environment and the ecosystem.

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