# DOES COASTAL WETLAND RESTORATION WORK AS A CLIMATE CHANGE ADAPTATION STRATEGY? THE CASE OF THE SOUTH-EAST OF SICILY COAST

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The South-East of Sicily hosts a complex system of coastal lagoons and wetlands of great naturalistic value. The area is under significant anthropogenic pressure due to intensive agriculture and tourism activities, resulting in a decline in biodiversity, ecosystem services, and an increase in coastal erosion and flooding risks, which are further exacerbated by the impact of climate change. The present study investigates the effectiveness of a set of restoration activities to mitigate coastal risks in the region. Specifically, the effects of revegetation interventions in the estuary and in the dune strip are investigated. This was carried out through a numerical modeling developed to simulate coastal flooding under present and climate change scenarios (IPCC AR5). The model consists of a coupled SWAN model for nearshore wave processes and Xbeach for flood modelling. Wave forcing were obtained by means of extreme event analysis associated with 100 years return time. Effects of sea level rise are also included. The results show that the proposed restoration measures reduce the risk of coastal flooding from extreme wave events up to 18% of the flooded volume.

*Keywords: coastal restoration; climate change; numerical modelling; XBeach; SWAN*

## INTRODUCTION

The coastal transition zone between the sea and inland is a valuable region where significant socio-economic assets, biodiversity and cultural heritage are located. These are concentrated in a narrow strip that is characterized by delicate hydraulic, geomorphological, and ecological processes (Day and Rybczyk, 2019; Nicholls et al., 2019). Risks associated with climatic and anthropic pressures are increasing in these regions (Amores et al., 2020; Reguero et al., 2020; Foti et al., 2020), inducing a loss of natural capital and provided ecosystem services (Cohen-Shacham et al., 2019; Baustian et al., 2018; Bayraktarov et al., 2020).

The dynamic and increasingly unpredictable impacts of climate change on coastal regions worldwide ask for paradigm shift in coastal defense strategies (Cavallaro et al., 2018; Stagnitti et al., 2022). In this context, nature-based environmental restoration interventions can be a sustainable strategy for risk mitigation (Ruangpan et al., 2020). Coastal environmental restoration can be a more effective strategy than conservation alone to recover ecosystem functionality of coastal wetlands. While conservation aim to protect existing ecosystems, environmental restoration interventions involve passively or actively restoring degraded or damaged ecosystems to their original state. By restoring the natural ecological processes and functions of wetlands, restoration interventions can enhance their capacity to provide valuable ecosystem services and enhance their resilience to climate change and other stressors. Restoration actions can often have co-benefits, such as improving water quality, enhancing biodiversity, and providing recreational opportunities for local communities. Therefore, a combination of conservation and restoration efforts can be an effective approach to ensure the long-term health and sustainability of coastal wetlands (Jacob et al., 2018; Oppenheimer et al., 2019; Sánchez-Arcilla et al., 2022).

The present work investigates the effectiveness of restoration activities in reducing coastal risks under present and climate change scenarios. Specifically, the efficacy of estuarine and dune revegetation actions as Nature-Based Solutions to reduce marine flooding was investigated. The case study is the Cuba-Longarini lagoon system (Sicily), a partly urbanized coastal saline lagoon complex. The effectiveness of the investigated measures were evaluated using numerical modelling and analysis of the flooded area caused by extreme wave events combined with sea-level rise projections. To this aim, a numerical modeling chain, with the aim of simulating hydraulic processes that characterize the wetland area and the associated coastal zone, was developed. The work is organized as follows: Section  describes the environmental characteristics of the case study area, next Section  describes the materials and methods employed for the modelling activity and data analysis, then the main results of the flooding analysis are given, finally some conclusions are drawn.

## CASE STUDY

The "Pantani della Sicilia Sud-Orientale" (South-East of Sicily lagoons) area of is a saline lagoon system with intermittent hydrological functioning, archetypal for Mediterranean coastal lagoons. This region is characterized by numerous lagoons in close connection to the nearby coastal environment. The hydrographic network is characterized by low slopes from the Iblei mountains to the coast, with limited and

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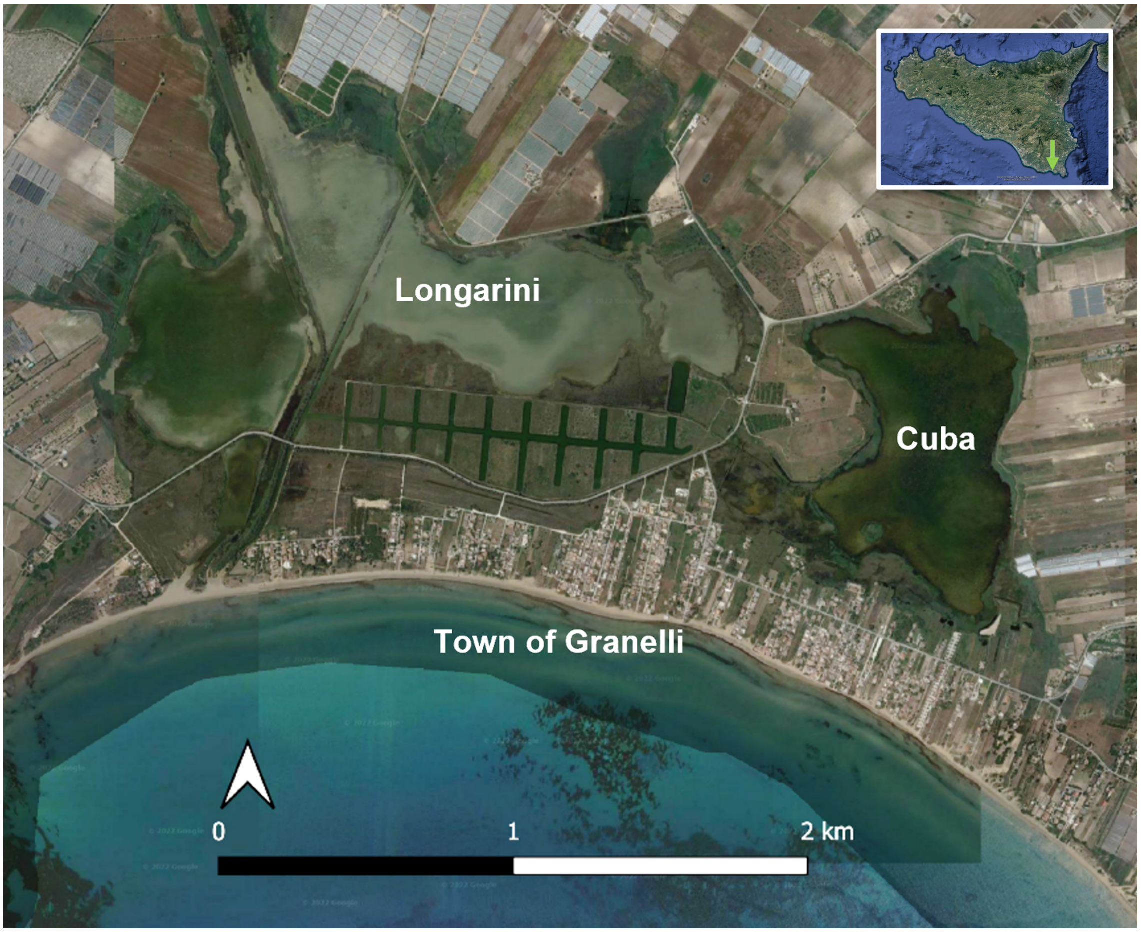



**Figure 1: Aerial view of Cuba-Longarini lagoon system and the town of Granelli.**

intermittent annual flows, and small mouths that interact with sandy beaches, interspersed with numerous promontories and small rocky islands. The area hosts important breeding populations of rare and endangered species, representing a crucial migration hot-spot for bird species along the central Mediterranean migration flyway. The wetlands of the Pantani zones are included in international environmental protection frameworks (RAMSAR, Natura 2000), Special Protection Areas and some regional nature reserves.

Historically, the Pantani zones have been partially reclaimed since the 19$^{th}$ century to promote local industrial, agricultural and commercial production, which exploits these areas through water withdrawal from the lagoons for irrigation. Some of these lagoons were partially transformed, in the last century, into now abandoned artificial salines. The progressive growth of the population and intensive agricultural exploitation, as well as the construction of numerous tourist facilities, has led to a reduction in hydraulic connectivity between the lagoons and between the lagoons and the sea, impacting also on the existing dune belt.

The Cuba-Longarini lagoons is the largest complex of lagoons in the area (Figure 1). The lagoons cover an area of about 240 ha (water bodies only). They are separated from the sea by a narrow coastal fringe and are intermittently connected to the sea by a small estuary channel. The lagoons are characterized by shallow waters, with depth of less than one meter. The surronding area is surrounded by marshy areas and reed beds.

The town of Granelli in the narrow fringe between the sea and the Cuba-Longarini lagoons. The development of residential and tourism infrastructure within this region has led to anthropogenic pressures and subsequent environmental degradation in the area. Specifically, construction activities have resulted in a reduction in the hydraulic connectivity between the lagoons and the sea, as well as within the lagoonal system itself, thereby impacting the existing dune strip. The area is also subject to flooding due to intense rainfalls, upward seepage when groundwater levels increase and wave storm conditions.

From a biodiversity standpoint, the hydraulic connectivity between the lagoons and the sea played a crucial role in the natural circulation of water, nutrients, and biota within this ecosystem. The construction of housing and tourist facilities within the region has led to the obstruction of the natural fluxes between land and sea. Moreover, the use of the lagoons as an agricultural waste dump has facilitated the introduction of invasive alien species into the ecosystem, further exacerbating the decline in biodiversity. These non-native species often outcompete the native flora and fauna for resources and habitat, thereby altering the ecosystem functional characteristics. Additionally, the anthropogenic pressure has resulted in the depletion of water resources, leading to a decrease in the water surface and, consequently, impacting the hydrological balance of the whole system.

## MATERIALS AND METHODS

### Marine climate data

The wave climate near Granelli beach was characterized using the MEDSEA MULTIYEAR WAV 006 012 reanalysis dataset provided by the Copernicus Marine Environment Monitoring Service (CMEMS data) to determine the present wave characteristics. This dataset provided time series of significant wave height, peak wave period, and mean wave direction for the period 1993-2021, with a time resolution of one hour and a spatial resolution of 4 km along the W-E direction and 5 km along the N-S direction.

For the future wave climate, projected wave data timeseries under RCP4.5 and RCP8.5 scenarios were employed. The wave dataset included hourly time series of significant wave height, peak wave period, mean wave period, mean wave direction, and spectral directional wave width for the European coast along the 20 m bathymetric contour with a spatial resolution of 30 km. In addition, sea level change projections were generated using the Deltares Global Tide and Surge Model and made available by the Copernicus Climate Change Service.

Based on the geographical and territorial limits of the studied area, the directional sector from which the waves propagate extends from 150°N to 270°N, for a total width of 120°. the latter was then divided into eight 15°-wide sub-sectors, which are presented in Figure 1, in order to analyse only the significant datasets for the site of interest and to facilitate subsequent analysis.

Present extreme wave climate was characterized for each directional sub-sector through a traditional extreme value analysis based on the peak over threshold method for the detection of the peaks of the significant wave height timeseries. In particular, a threshold equal to 1.50 m and a minimum temporal distance between independent events equal to 12 hours were employed (Boccotti, 2000). The analysis was performed for each directional sub-sector, and the best-fitting probability distribution function of extreme significant wave height was presented as a function of the return period for each sub-sector. Then, $H_s$ associated with a return period of 100 years is chosen. Given that the CMEMS data interval (1993-2021) currently spans 29 years, it has been chosen to divide and analyze the datasets obtained from projection models for the RCP4.5 and RCP8.5 scenarios, using rolling windows of the same width of 29 years.

### Numerical modelling

The modeling chain consists of a coupled SWAN model for the nearshore wave processes (Booij et al., 1996) and Xbeach for the flooding and vegetation modelling (Van Rooijen et al., 2015). SWAN is a third generation wave model capable of computing random, short-crested wind-generated waves in coastal regions and inland waters, having the ability to simulate several coastal processes, including but not limited to wave breaking, wave shoaling, nearshore currents, and wave-current interaction (Faraci et al., 2021). XBeach is an open-source numerical model for simulating hydromorphodynamic processes in the coastal zone, able to simulate flooding and morphological changes. The SWAN model domain was built to cover a coastline length of approximately 90 km and extended offshore for a distance of over 20 km. The grid elements obtained through interpolation are triangular in shape and their dimensions vary based on depth. For depths greater than 100 m, the elements have a side of 1 km. For depths between 100 m and 30 m, the size gradually changes from 1 km to 400 m. For depths less than 30 m, the elements maintain a size of 400 m. A higher resolution (100 m) was adopted in the area under consideration. The Xbeach domain covers an area of 1340 ha that encloses the Granelli area and the Cuba and Longarini lagoons. Morphology variations and sediment transport are not included in the model.

The effects of vegetation are implemented through the Xbeach vegetation module. Spatial distribution of vegetation was obtained from EUNIS maps (Chytrỳ et al., 2020). For each habitat in the area an autoc-

| Species | $n_{sec}$ | $a_h$ | $C_d$ | $b_v$ | $N$ |
|---|---|---|---|---|---|
| *Phragmites Australis* | 2 | 0.25/2 | 0.86/0.86 | 0.006/0.026 | 110/110 |
| *Ammophila Arenaria* | 1 | 1 | 0.7 | 0.0025 | 260 |
| *Spartina Alterniflora* | 1 | 0.62 | 1 | 0.003 | 400 |

**Table 1: Characteristics of vegetation**

| Simulation | Vegetation | Scenario | Window | $\theta$ [°] | $H_s$ [m] | $T_p$ [s] | SLR [m] |
|---|---|---|---|---|---|---|---|
| 1 | Current state | Present | 1993-2021 | 157.5 | 3.42 | 9.12 | 0.00 |
| 2 | Current state | Present | 1993-2021 | 262.5 | 6.01 | 10.55 | 0.00 |
| 3 | Current state | RCP4.5 | 2056-2084 | 157.5 | 7.32 | 11.28 | 0.41 |
| 4 | Current state | RCP4.5 | 2072-2100 | 157.5 | 6.78 | 11.03 | 0.51 |
| 5 | Current state | RCP4.5 | 2056-2084 | 262.5 | 7.66 | 11.42 | 0.41 |
| 6 | Current state | RCP4.5 | 2072-2100 | 262.5 | 10.19 | 12.41 | 0.51 |
| 7 | Current state | RCP8.5 | 2056-2084 | 157.5 | 5.85 | 9.50 | 0.51 |
| 8 | Current state | RCP8.5 | 2072-2100 | 157.5 | 5.16 | 9.23 | 0.63 |
| 9 | Current state | RCP8.5 | 2056-2084 | 262.5 | 8.02 | 10.06 | 0.51 |
| 10 | Current state | RCP8.5 | 2072-2100 | 262.5 | 7.74 | 9.98 | 0.63 |
| 11 | Revegetation | Present | 1993-2021 | 157.5 | 3.42 | 9.12 | 0.00 |
| 12 | Revegetation | Present | 1993-2021 | 262.5 | 6.01 | 10.55 | 0.00 |
| 13 | Revegetation | RCP4.5 | 2056-2084 | 157.5 | 7.32 | 11.28 | 0.41 |
| 14 | Revegetation | RCP4.5 | 2072-2100 | 157.5 | 6.78 | 11.03 | 0.51 |
| 15 | Revegetation | RCP4.5 | 2056-2084 | 262.5 | 7.66 | 11.42 | 0.41 |
| 16 | Revegetation | RCP4.5 | 2072-2100 | 262.5 | 10.19 | 12.41 | 0.51 |
| 17 | Revegetation | RCP8.5 | 2056-2084 | 157.5 | 5.85 | 9.50 | 0.51 |
| 18 | Revegetation | RCP8.5 | 2072-2100 | 157.5 | 5.16 | 9.23 | 0.63 |
| 19 | Revegetation | RCP8.5 | 2056-2084 | 262.5 | 8.02 | 10.06 | 0.51 |
| 20 | Revegetation | RCP8.5 | 2072-2100 | 262.5 | 7.74 | 9.98 | 0.63 |

**Table 2: Table of simulations.**

tone vegetation is associated and characteristics of vegetation, i.e. number of vertical section $n_{sec}$, vertical section height $ah$, drag coefficient $C_d$, stem diameter $b_v$, vegetation density $N$, were obtained from literature (Knutson et al., 1982; Garzon et al., 2019; Fernández-Montblanc et al., 2020; van Loon-Steensma et al., 2016). The employed values are shown in Table 1.

A restoration intervention was modeled for both present and future scenarios, including a plantation of Phragmites Australis in the estuary area and an extension of the vegetated dune strip for the entire coastline of Granelli. Figures 2a and 2b show the spatial distribution of vegetation for current state and revegetation action respectively. A total of 20 simulations were carried out, 10 considering the current state of vegetation distribution and 10 considering the revegetation actions (Table 2), including both present state and future scenarios.

## RESULTS

To evaluate the effectiveness of the intervention, Table 3 shows in percentage terms the increase or reduction in the flooded volumes compared to the existing state $\Delta V_f$, computed as the ratio between the flooded volume of the current state simulation and the corresponding vegetation restoration scenarios.

Figure 3a and Figure 3b show simulation 4 and 14 respectively, both with $H_s$ = 6.78 m, $\theta$ = 157.5 °N, $T_p$ = 11.28 s, SLR = 0.41 m but the former with the current state of vegetation and the latter with revegetation intervention. The presence of the revegetated dune strip reduce the flooded volumes by 11.54%. Still the urbanized area is threatened by the lagoon level rise on the back of the Granelli village.

The results indicate a slight increase in the percentage of flooded volumes for present scenarios in the case of revegetation, showing a worsening of flooding conditions compared to the case without revegetation intervention, with a significant increase of flooded volumes. This is due to the presence of Phragmites, which, although featuring larger stem diameter and height, have a lower drag coefficient than the Spartina

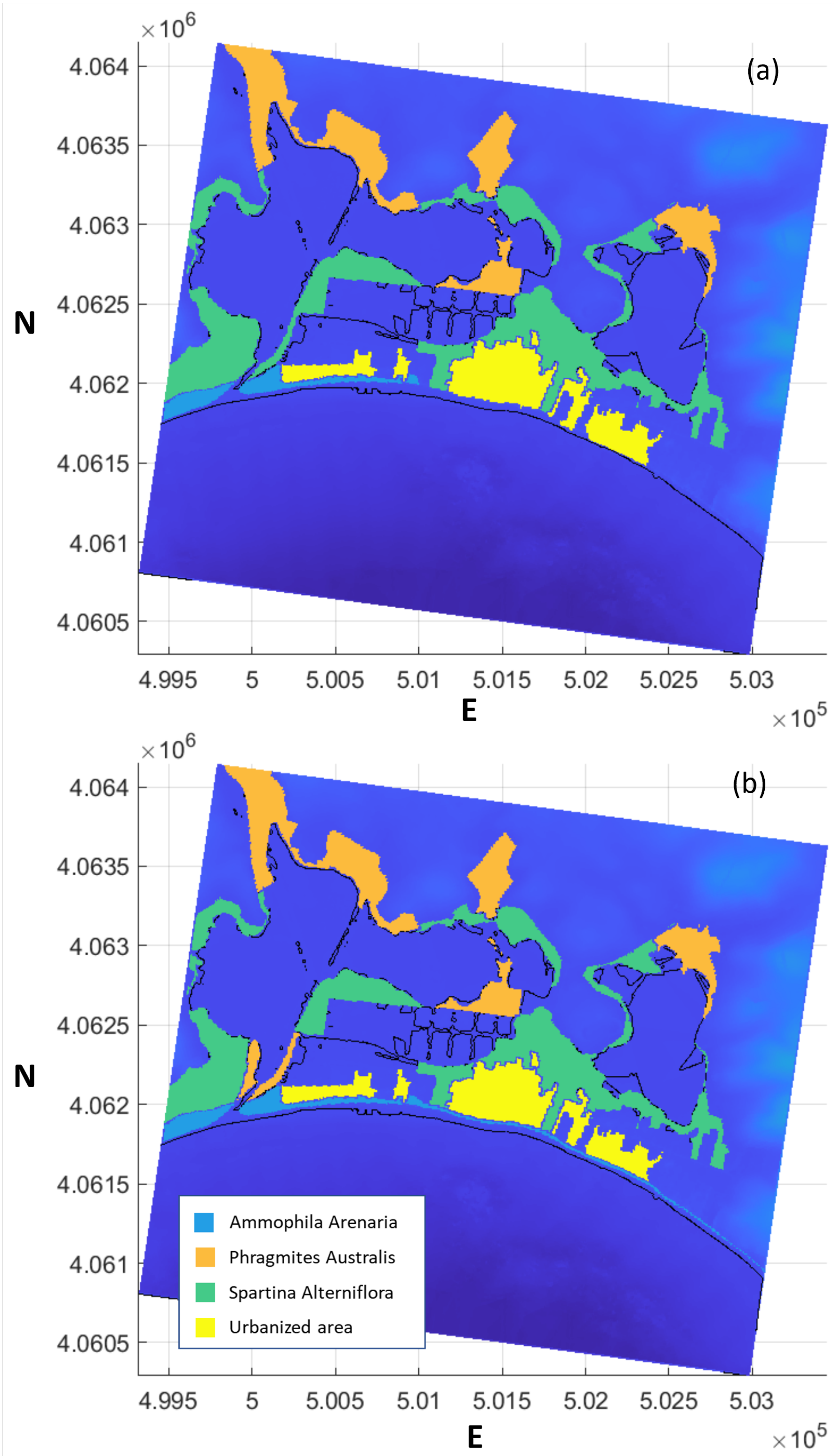



**Figure 2: Spatial distribution of vegetation for current state (a) and restoring actions through revegetation (b).**

| Scenario | Window | $\theta$ [°] | $H_s$ [m] | $T_p$ [s] | SLR [m] | $\Delta V_f$ [%] |
|---|---|---|---|---|---|---|
| Present | 1993-2021 | 157.5 | 3.42 | 9.12 | 0.00 | +1.54 |
| Present | 1993-2021 | 262.5 | 6.01 | 10.55 | 0.00 | +2.86 |
| RCP4.5 | 2056-2084 | 157.5 | 7.32 | 11.28 | 0.41 | -13.34 |
| RCP4.5 | 2072-2100 | 157.5 | 6.78 | 11.03 | 0.51 | -11.54 |
| RCP4.5 | 2056-2084 | 262.5 | 7.66 | 11.42 | 0.41 | -16.00 |
| RCP4.5 | 2072-2100 | 262.5 | 10.19 | 12.41 | 0.51 | -14.06 |
| RCP8.5 | 2056-2084 | 157.5 | 5.85 | 9.50 | 0.51 | -12.04 |
| RCP8.5 | 2072-2100 | 157.5 | 5.16 | 9.23 | 0.63 | -8.04 |
| RCP8.5 | 2056-2084 | 262.5 | 8.02 | 10.06 | 0.51 | -18.72 |
| RCP8.5 | 2072-2100 | 262.5 | 7.74 | 9.98 | 0.63 | -8.68 |

**Table 3: Flooded volumes differences $\Delta V_f$ between current state and revegetation actions.**

alterniflora currently present in the estuary. Such an occurrence suggests that that the presence of Phragmites determines a more marked effect of alteration of the flooded volume. It should also be noted that, in the present scenarios cases, the area that is flooded is limited to the estuary, not affecting the area behind the dune strip, as wave heights do not exceed the dune zone. On the contrary, the remaining simulations show a reduction in the flooded volumes, mainly due to the presence of revegetation of the dune area.

## CONCLUSION

In this study, an investigation was conducted to investigate the effects of vegetation to mitigating coastal flooding under present and climate change scenarios. The study area was the Cuba-Longarini coasta lagoon and wetlands area.

Ten hydrodynamic scenarios were obtained for the site: two present scenarios, four future scenarios based on RCP 4.5 predictions, and four future scenarios based on RCP 8.5 predictions. The characteristics of the wave motion obtained through extreme wave analysis were used as input, along with the characterization of the calculation domain, into a SWAN+XBeach numerical model.

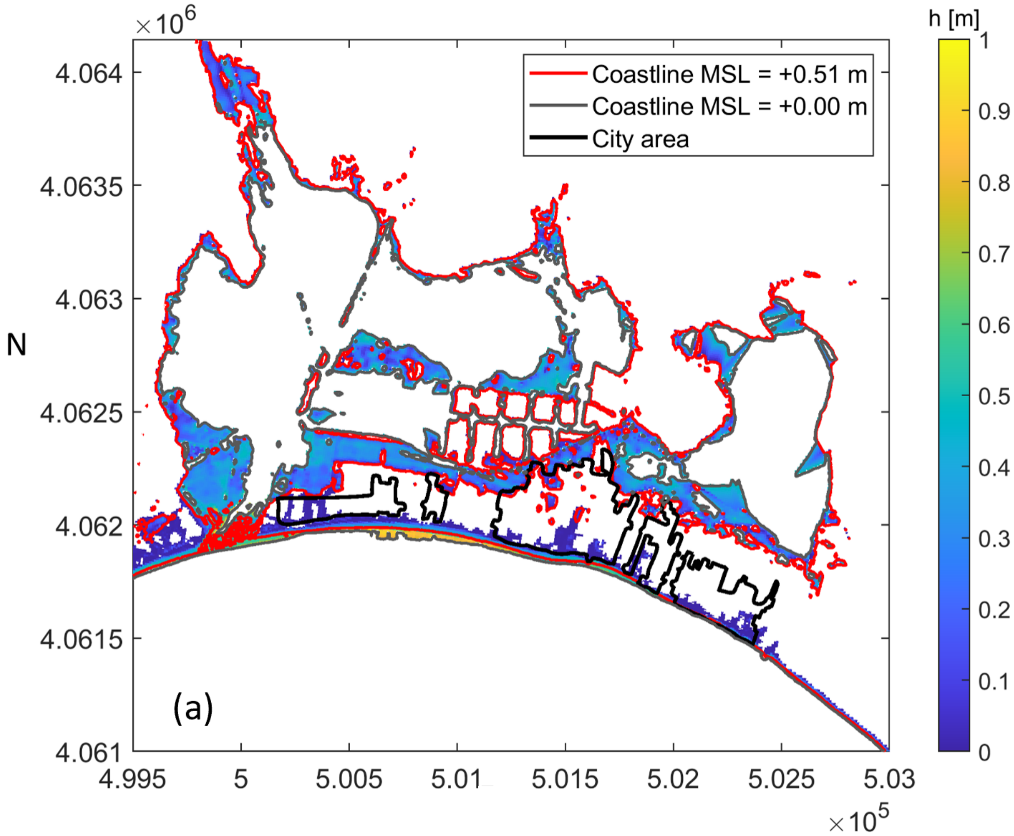
The energy spectra obtained from the SWAN model were used as hydrodynamic forcing in the XBeach model to obtain flooded areas. Based on the EUNIS map of vegetation, the habitats present in the site were defined, thus obtaining the positioning and typology of the plant communities. For each community, a representative species was chosen, and homogeneous distribution of vegetation was hypothesized. The species considered were Phragmites australis, Spartina alterniflora, and Ammophila arenaria. Through an in-depth literature search, the necessary characteristics for the modeling of each species were determined.

In addition to the vegetation map adopted for the current state, a second map was created assuming an intervention consisting of extending the dune strip to the entire coast considered and changing the vegetation present on the sides of the Longarini marsh estuary to Phragmites Australis. Simulations were run for each situation (current state and revegetation intervention) and for each hydrodynamic scenario, for a total of 20 simulations.

From the results, the following conclusions were reached:

- The presence of revegetation contributes to the reduction of flooded volumes up to 18%;
- the vegetation modification intervention on the sides of the estuary with the Phragmites seems to worsen the situation slightly increasing flooded volumes, at least for present scenarios;
- the extension of the dune strip intervention contributes positively, reducing the flooding in the proximity of the urban center.

Despite some approximations introduced in this study (non-erodible substrate, homogeneously distributed vegetation, non-flexible vegetation), it has emerged that the presence of vegetation can offer a valid contribution to the mitigation of coastal flooding in the area for both present scenarios and climate change predictions. Further studies can strengthen the idea that Nature-Based Solutions, applied on a large scale, represent a sustainable tool for reducing the risk of coastal flooding, offering at the same time a series of benefits (ecosystem services, carbon sequestration, etc.) to the community. It is imperative to investigate



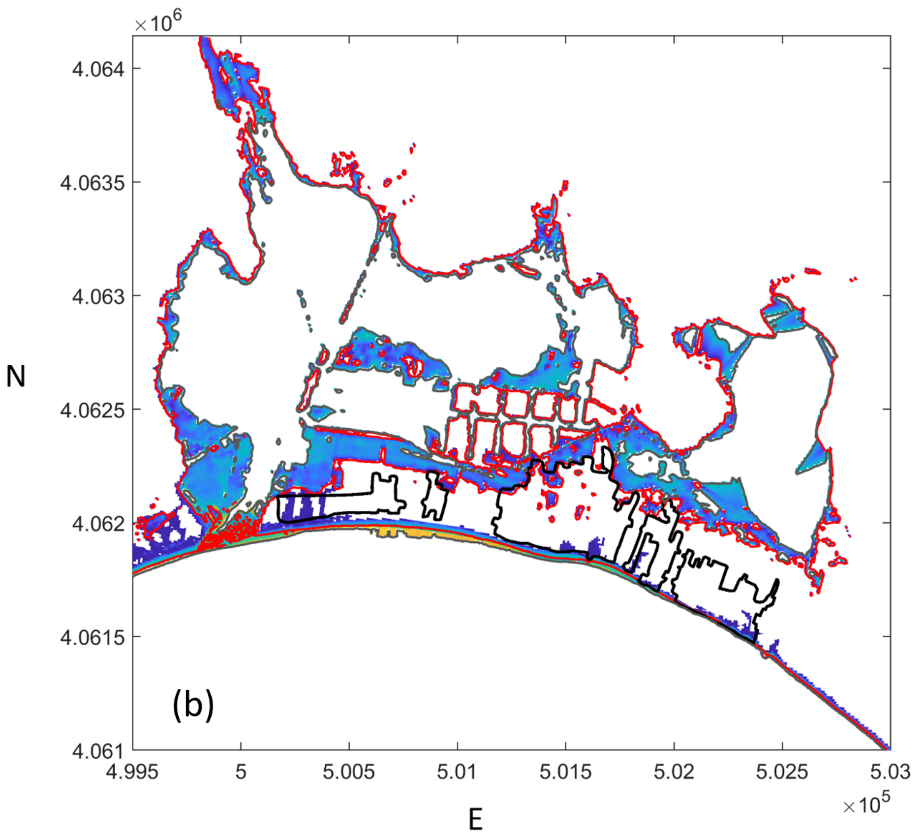




**Figure 3: Flooding maps for simulation 4 (a) and 14 (b).**

the effectiveness of other Nature-based solutions and consider additional factors such as sediment transport to gain a comprehensive understanding of the overall efficacy of vegetated dune strips as a coastal protection measure. Additionally, the sustainability of the dune strip in the long term, including its maintenance and potential impacts on the surrounding ecosystem, must be carefully assessed.

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