# High-Resolution Coastal Vulnerability Assessment: Integrating Ecosystem Services Mapping for Sustainable Urban Management in the Naples Coastline

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**Abstract.** Environmental stresses of coastal zones becoming more intense due to natural processes and anthropogenic pressures are increasing. Now more than ever, the need for robust environmental management is crucial in urban areas where critical interplay of economic development, infrastructure growth, and environmental protection have to be struck at the right balance. Also using low-resolution data in a great many coastal vulnerability assessment models impairs their skill to identify fine-scale risk hotspots within high-density regions. This study presents a methodology supported by *InVEST* model for identifying high-risk and highly vulnerable coastal areas by integrating spatial analysis with ecosystem services mapping. The approach is applied to the city of Naples as a case study, utilizing high-resolution data to assess the protective role of coastal ecosystems, particularly *Posidonia oceanica,* in mitigating flood risks and stabilizing the shoreline. The findings indicate that highly urbanized areas exhibit the greatest vulnerability, whereas regions with well-preserved natural features provide enhanced coastal protection. By using this approach the decision makers will set a priority list of recommended management strategies that will both inform tradeoffs in regional planning between urbanization and environmental sustainability. Given the continued magnification of coastal fringe risks with climate change, advanced analysis tools play an even greater role. The method described here is a reusable framework that can be applied to other urban coastal areas to implement data-driven decision-making and resilience planning. Additionally, the peri-urban urban area on and around the central region is already fulfilling an ecological function thus highlighting the necessity of balancing and including nature-based solutions in coastal management.

**Keywords:** Ecosystem Services mapping · Regulating Services · Coastal Vulnerability Assessment · INVEST

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## 1 Introduction

Coastal cities worldwide are increasingly exposed to both natural and anthropogenic stressors, necessitating structured approaches for vulnerability assessment, planning and management. According to IPCC, vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

Vulnerability in the context of coastal systems refers to the degree to which a system (e.g., a community, an ecosystem, or infrastructure) is likely to experience harm due to exposure, sensitivity, and limited adaptive capacity to coastal hazards. More formally, vulnerability can be broken down into three key components:

- Exposure: The extent and magnitude to which a system is in the path of potential threats like coastal flood or erosion.
- Sensitivity: The degree to which a system is affected by those threats, such as structural fragility or ecological health.
- Adaptive Capacity: The system's ability to respond, cope, or reorganize in ways that mitigate damage and capitalize on new opportunities.

In coastal urban areas, vulnerability manifests through high population density, infrastructure at or near sea level, and the complexity of balancing economic growth with environmental protection [1].

Ecosystem Services (ES) concept refers to the direct and indirect benefits that ecosystems provide to humans, encompassing provisioning, regulating, supporting, and cultural services [2, 3]. These services are vital for human well-being and sustainability, and their evaluation and management are critical for effective policy and conservation efforts to reduce vulnerability of socio-ecological systems [4]. The regulating function of ecosystem services can be described as the capacity of natural and semi-natural ecosystems to regulate essential ecological processes and life support systems through biogeochemical cycles and other biospheric processes [5]. In addition to maintaining ecosystem health, these regulation functions provide many services that have direct and indirect benefits to humans [6]. Coastal vulnerability-related ecosystem services, in particular, perform the function of disturbance prevention, i.e. the influence of ecosystem structure on dampening environmental disturbances [7, 8].

The assessment of coastal vulnerability has become essential for effective planning and management of coastal zones, especially in light of climate change and increasing coastal hazards [9–11]. Scientific community has been relying for long years on different methods to assess vulnerability and develop effective adaptation strategies.

Nevertheless, some gaps recur in scientific literature on current assessment approaches. First, they rely on physical and social data, simple models, and expert judgment. This suggests that existing methods may not be comprehensive or robust enough to address the complexities of coastal vulnerabilities [12]. Another gap points out that there is currently no universal method for accurately assessing coastal vulnerability, which can lead to inconsistencies across different regions [13]. At least, data lacking emerges as one of the most recurring gaps which prevents decision-makers in some countries from

obtaining consistent information about coastal risks and, thus, to address comprehensive climate plans [14].

From this research perspective, Spatial Decision Support Systems (SDSS) are positioned as an advanced category of Decision Support Systems (DSS) [15], integrating Geographic Information Systems (GIS) technologies to collect, analyse, and organise spatial data in support of territory-related decision-making [16]. The SDSS has proven to be useful tool not only to solve resource allocation problem but also in other different fields, such as environmental management, urban planning, emergency response, and infrastructure optimization [18]. In particular, the integration of GIS capabilities into the DSS enables the collection, processing, and visualisation of geospatial data through maps, three-dimensional models [23], and scenario simulation by allowing Decision Makers to understand the impacts of specific decisions on a territory [17].

Recently, SDSS has evolved through the use of advanced spatial analysis capabilities, which include simulations, AI support, and predictive algorithms. As an example, an SDSS can integrate historical rainfall data with hydrological model to predict flood risks, while enhanced visualisation allowing users to explore several scenarios and DMs to make informed decisions for risk reduction [19].

In this study, an SDSS for scenario simulation of natural disasters, such as floods, was suggested to provide critical insights for preventing damage and avoiding costs through the preservation and valorisation of Ecosystem Services.

In conclusion, the effectiveness of SDSS depends not only on the quality and regular updating of spatial data, but also on their capacity to integrate other methodologies and tools used for assessing urban dynamics. In this context, the study presents an integrated Spatial Decision Support System (SDSS) developed to evaluate coastal vulnerability by combining ecosystem services mapping with high-resolution data analysis. This methodology provides a foundation for advancing an SDSS that offers more refined support to policymakers, proposing alternative strategies to help adapt to and reduce risks affecting the built heritage of urban areas and their communities.

## 2 State-of-Art on Coastal Vulnerability Assessment Methods

A short survey of coastal vulnerability assessment approaches has highlighted that spatial assessments through GIS and Ecosystem Services mapping are the most recurring approaches to detect the vulnerability levels of coastal zones [20, 21]. Indeed, essential tools in coastal vulnerability assessment are Geographic Information Systems (GIS) since they allow users to visualize which areas are most at risk from rising sea levels, coastal erosion, and habitat loss [9, 11]. Through spatial analysis and mapping functions, GIS not only helps identify vulnerable locations but also supports planners and policymakers in making informed decisions [16, 23] about conservation efforts, disaster risk reduction, and development of Nature-Based Solutions [7, 23, 25].

Another broad and integrated approach relates to the Integrated Assessment Models (IAMs) [27], which bring together multidimensional factors to assess the cumulative effects of different stressors by identifying their intercations in a cross-cutting perspective [28]. In a nutshell, IAMs help decision-makers explore long-term effects and assess the most effective adaptation strategies [29]. A particularly fitting form of IAM relates to ES

mapping approach, which is a good practice for identifying, assessing, and managing the direct and indirect benefits provided by ecosystems. By employing empirical models, remote sensing, and GIS mapping, IAMs allows specialists to classify specific typology of services and their spatial distribution to inform decision-making towards integrated sustainability strategies [30].

On the other hand, DMs can recur to risk assessment framework to evaluate the probability of adverse events impacts by combining qualitative and quantitative data to prioritize intervention areas. These models can be integrated with Multi-Criteria Decision Analysis (MCDA) to produce composite vulnerability indices to benchmark the susceptibility of different regions [20, 31]. Composite indices can aggregate factors like exposure to hazards, sensitivity to environmental changes, and the ability to adapt. In this way, the vulnerability indices can provide a standardized way to identify the most at-risk regions while prioritising mitigation efforts and fundings [24]. Moreover, involving local communities in the vulnerability assessment process is essential for developing effective, place-based solutions that respect and reflect territorial values [32]. Coastal residents possess firsthand experience of environmental changes and previous climate-related events. Their knowledge can enrich scientific findings, contributing to more practical and locally tailored strategies. Such engagement also nurtures a sense of ownership and motivates communities to take an active role in coastal protection initiatives [33].

Additionally, scenario analysis supports decision-makers in exploring a variety of strategic options. By simulating different future scenarios—including variations in climate change, human activity, and policy interventions—experts can better anticipate the outcomes of potential decisions. This approach promotes flexible and adaptive planning, helping ensure that coastal management strategies remain responsive to emerging challenges [26].

The integration of above-mentioned methods can promote a deeper understanding of coastal risks by sparking proactive strategies to preserve and manage the socio-ecological landscape system.

## 3 The Case Study: Naples Coastal Areas and Marine Ecosystem Services

Naples exemplifies coastal vulnerability due to its convergence of high urban density, extensive economic infrastructure, and exposure to extreme weather events. Population data from the Italian Statistical Institute shows Naples as the most densely populated area in Italy. This coastal city include a variety of infrastructures such as commercial and tourist ports, urban waterfronts, and areas of ecological importance. With the combination of these elements and the rising climate-induced threats such as storm surges and sea-level rise, there is a need for a systematic coastal risk assessment and resilience planning.

The Gulf of Naples, located in the Tyrrhenian Sea, is a semi-enclosed basin characterized by a unique coastal landscape that includes sandy beaches, rocky cliffs, and densely urbanized shorelines. Equally worth mentioning are the marine protected areas existing in the region such as the Parco Sommerso di Gaiola where high maritime traffic

can be observed, as well as the Port of Naples, the Port of Pozzuoli, and other touristic harbors. The continuous transformation of the coastal area mainly due to urban and port development negatively affects the ecosystems, making them more vulnerable to climate change.

Severe weather incidents recorded in history serve as a reminder of the vulnerability of the Naples coastline to natural extreme events. The storm surge that occurred on December 28, 2020, combined with several infrastructural problems, severe urban flooding, and economic disruptions, showed how much these events have increased their frequency and apprehensiveness. Similar incidents from past decades justify the need for a comprehensive risk assessment approach based on physical infrastructure and ecosystem functions of both types. Posidonia oceanica (hereafter *P. oceanica*) meadows are among the natural protections created by the plants that are not robotic. They are wave attenuators, sediment stabilizers, and shoreline preservatives. However, these critical ecosystems are increasingly impacted by excessive human activities like boat anchoring, coastal development, and habitat degradation, which calls for the implementation of biodiversity conservation plans.

The highly urbanized Naples coastline, which is becoming more prone to coastal risks, needs an integrated spatial decision-support system (SDSS) to plan and manage coastal risks. The use of GIS-based modeling tools, like the InVEST Coastal Vulnerability Model, allows the quantification of numerous risk factors, leading to a data-driven approach to urban planning and policymaking for coastal management. These frameworks can also be used to promote the introduction of nature-based adaptation strategies taking advantage of *P. oceanica* as a coastal defense biological asset. The disappearance of these meadows means that not only the coastal protection is undermined but also the ecosystem services like habitat provision and water quality maintenance are compromised. The incorporation of an SDSS into the decision-making process within the regional planning framework would promote the adaptive, informed management, thus leading to a more resilient Naples' coastal areas.

*P. oceanica* is a vital seagrass species existing in the Mediterranean marine environment mainly due to its ecological significance. It is well-known for its part in sediment stabilization, water quality regulation, and biodiversity support, as proved by numerous studies made by science practitioners. Found mainly in the shallow coastal zone, this species of seagrass forms dense meadows that are an essential part of the ecosystem and increase its function.

### 3.1 Posidonia Oceanica as an Ecosystem Service

In the Gulf of Naples, *P. oceanica* colonizes a variety of locations along the coastal ecosystem. As reported by ISPRA, this seagrass generally colonizes depths between 1 and 40 m, depending on the water's transparency and the substrate's characteristics. These meadows are sensitive to multiple environmental variables, including anchoring, discharges, and coastal modifications, exerting their pressure on them. This study seeks to determine the particular contribution of *P. oceanica* to wave propagation reduction and resilience in the Gulf of Naples coastal area. Previous studies have demonstrated the species' capacity to mitigate hydrodynamic forces and lower the rate of erosion but the real impact of the species in the study area still has to be established. With

the coming together of geographical research and ecological studies, it is intended to discover how much *P. oceanica* forester class meadows are equally a part of the adaptive ecological features and thus create a new knowledge base for the development of coastal conservation policies and their implementation. The high urban density and extensive reliance on coastal infrastructure in Naples necessitate a data-driven approach to risk mitigation. Integrating spatial data analytics, long-term monitoring, and conservation strategies within an SDSS framework provides a comprehensive method for managing vulnerability.

## 4 Material and Methods

A structured methodological framework, built on the foundational research questions, was established to guide the development of the SDSS, setting a clear objective and organizing the process into three distinct phases: intelligence, design, and choice (Fig. 1).

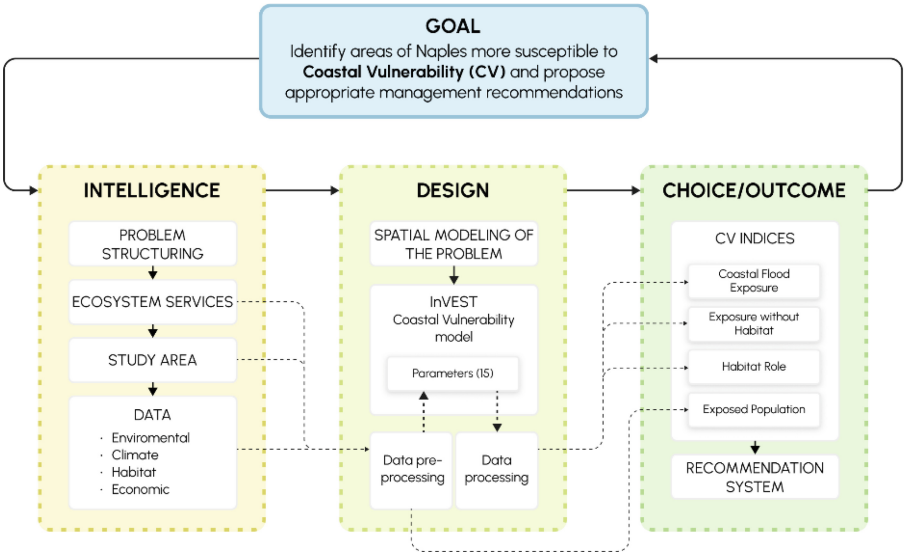


**Fig. 1.** Methodological framework of the SDSS

In the intelligence phase, the decision problem is defined, and the necessary data are compiled—encompassing local ecosystem services and key parameters for the InVEST© model. The design phase centers on spatial modeling through the Coastal Vulnerability tool, supported by meticulous data preprocessing and analysis of model outputs. During the choice phase, the computed indices are compared, and a preliminary recommendation system is outlined, equipping decision-makers with evidence-based strategies for coastal management interventions.

### 4.1 Intelligence Phase

To implement the InVEST Coastal Vulnerability model, a diverse set of spatial and numerical parameters was prepared (Table 1), often requiring non-trivial data acquisition and processing.

**Table 1.** Datasets description and sources.

| Category | Dataset | Source | Content | Spatial resolution | Spatial extension | Timeframe |
|---|---|---|---|---|---|---|
| Economy | POIs | Overture Maps Foundation | Commercial activities location | n/a | Global | 2025 |
| Climate | Wind speed & direction | Rete Mareografica Nazionale | Wind speed and direction measured every 10 min | Single point | Port of Naples | 2010–2025 |
| Environmental | DTM | Campania Region Geoportal | Digital Terrain Model | 86 cm | Campania region | 2008–2013 |
| | MaGIC | Protezione Civile | Bathymetry | 10 to 50 m | Several Italian coastal areas | 2007–2012 |
| | Continental Shelf Contour | Marine Regions | Shallow submerged continental margin | n/a | Global | 2009 |
| Habitat | Seabed habitats | EMODnet | Marine habitats | n/a | Europe | 2021 |

First, all raster and vector datasets were projected to the same coordinate system (WGS84/UTM zone 33N) to ensure proper overlay and distance measurement.

High-resolution bathymetric data from the MaGIC project allowed for a detailed representation of the seafloor, addressing one of the common challenges in coastal modeling—the lack of adequate bathymetric resolution.

The digital terrain model (DTM) used for emerged land underwent quality checks to ensure consistency with the study area and correct any small-scale inaccuracies.

Marine habitats, particularly the Mediterranean seagrass *P. Oceanica,* were sourced from EMODnet's Seagrass Cover in European Waters and assigned a protective rank informed by research demonstrating its relevance in shallow-water coastal defense.

Wind and wave data were adapted to reflect NOAA's WaveWatchIII outputs, using a 90th-percentile threshold derived from historical observations at the port of Naples (ISPRA) to capture high-energy storm events.

Furthermore, InVEST's "Human Population" field was repurposed to reflect economic exposure by converting Overture Maps Foundation POI datasets into a 50-m raster showing commercial activity density within 50 m inland from the coastline.

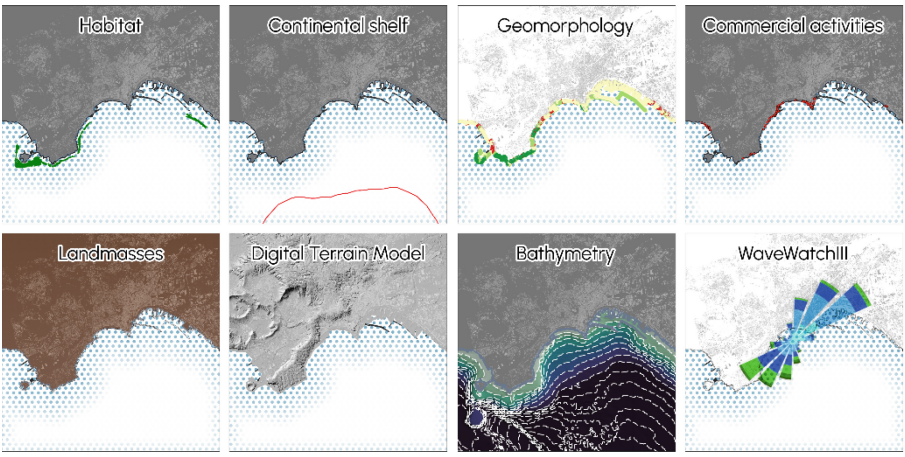


**Fig. 2.** Pre-processed geographical datasets to suit the InVEST model

These processes (Fig. 2) ensured that all inputs were harmonized, georeferenced, and calibrated to local conditions, in so doing enhancing the model's reliability for coastal vulnerability assessment and scenario testing.

### 4.2 Design Phase

The InVEST Coastal Vulnerability model quantifies the relative exposure of coastal areas to wave energy, coastal erosion, and flooding by integrating multiple spatial datasets—such as shoreline geometry, bathymetry, wave exposure, and habitat distribution—to generate a coastal vulnerability index that highlights the regulating function of coastal habitats. In this study, the focus is on *P. oceanica* for two main reasons: it is recognized as a key seagrass species in the Mediterranean (forming extensive meadows along much of the Gulf of Naples) and broader Mediterranean research indicates that its meadows significantly mitigate wave impact, particularly in shallow waters. Mechanistically, *P. oceanica* rhizomes and leaves slow water flow, causing sediment to settle and reducing wave energy before it reaches the shoreline. Information on the distribution of these meadows was obtained from a high-resolution European dataset and refined with local depth measurements; the meadows in the study area predominantly occupy depths between −5 m and −15 m (though *P. oceanica* can thrive as deep as −40 m). The high resolution of the bathymetric data used enabled accurate delineation of shallow-water meadows, which are especially relevant for wave attenuation. By default, the InVEST

model assigns a protective rank of 4 to marine habitats, indicating low protective capacity, but Mediterranean-wide studies [1, 34] suggest a stronger protective effect for *P. oceanica* compared to that baseline. Indeed, Infantes et. al. (2012) have highlighted that: "*Root mean squared wave height (Hrms) is reduced by around 50% for incident waves of 1.1 m propagating over ~ 1,000 m of a meadow of P. oceanica with shoot density of ~ 600 shoots m − 2*.". At the same time, rank 1 is typically reserved for habitats like mangroves, whose protective impact is exceptionally high; for this reason, assigning rank 1 to *P. oceanica* would have been unrealistically high for this context.

Consequently, two intermediate scenarios (rank 2 and rank 3) were explored to capture a plausible range of protection offered by *P. oceanica* in shallow Mediterranean waters, accounting for ecological attributes and studies reporting its influence on nearshore hydrodynamics.

- In Scenario 1, the meadows receive rank 2, reflecting evidence that dense and shallow *P. oceanica* meadows can dissipate a significant portion of wave energy.
- In Scenario 2, the meadows are assigned rank 3, indicating a moderate protective effect above the default assumption but below the maximum protection.

The model was run using these two rankings, incorporating the high-resolution input layers (shoreline segments, wave exposure indices, localized fetch distances) and adhering to InVEST Coastal Vulnerability guidelines with adjustments for the Gulf of Naples' hydro-geomorphological features. Advanced hydrodynamic modeling and detailed biological analyses were outside the scope, and the approach relies on existing Mediterranean-wide literature rather than direct local measurements. Nonetheless, employing both ranks 3 and 2 provides a bounded exploration of how parameter variations might affect coastal vulnerability outputs, making this method suitable for informing preliminary urban and territorial planning considerations related to coastal exposure and climate resilience.

## 5 Choice/Outcome Phase

### 5.1 Coastal Vulnerability Index Maps

The model autonomously computes four outputs: the Coastal Exposure Index with and without the presence of *P. oceanica*, an evaluation of the ecosystem's role in mitigating vulnerability, and an estimate of the exposed commercial activities. These results derive directly from the model's spatial analysis and computational framework, ensuring an objective and data-driven assessment of coastal hazards.

**Coastal Vulnerability Index**
The Coastal Vulnerability Index, is shown with two variants (Fig. 3) reflecting different classifications for the *P. oceanica* habitat. Differences between the scenarios are minimal, mainly noticeable along the coastal stretch of San Giovanni a Teduccio. Notably, the areas with the highest vulnerability values coincide with zones historically affected by flooding events.

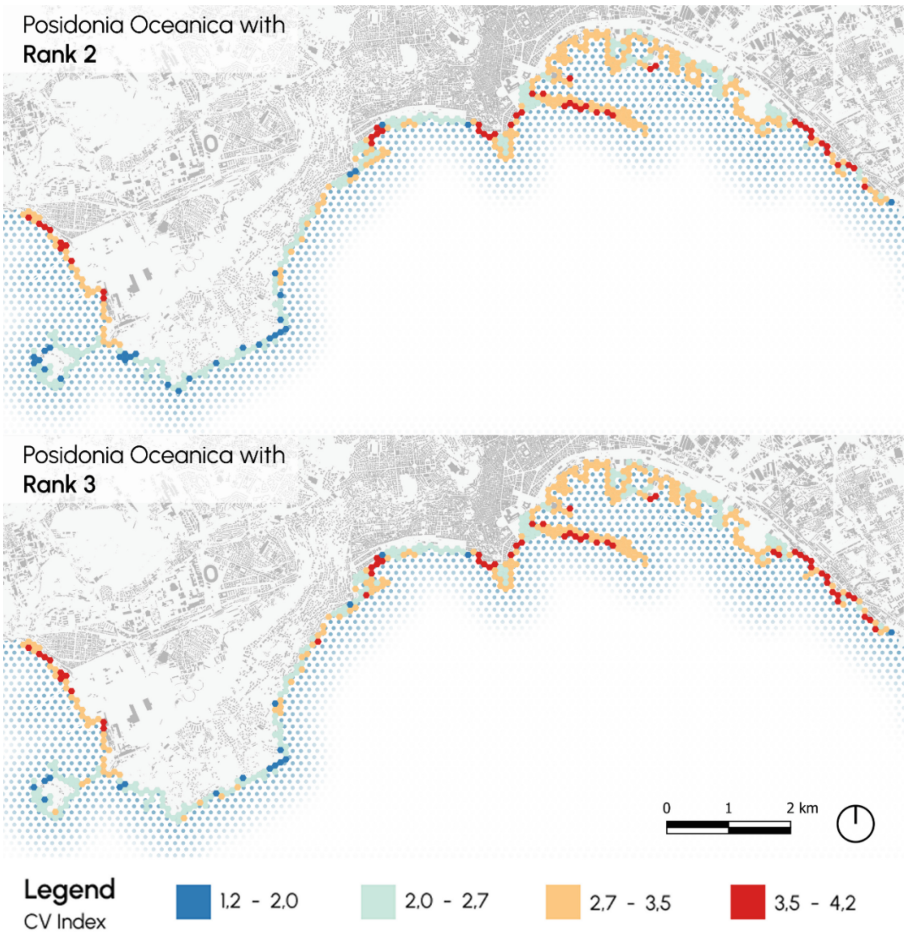


**Fig. 3.** Coastal Vulnerability Index in the two scenarios of coastal protection provided by *P. oceanica.*

**Coastal Vulnerability Index Without Habitat**

Figure 4 presents the Coastal Vulnerability Index in the absence of habitat protection. This index is of particular importance to understand what would happen if the habitats of seagrasses currently present disappeared, leaving the coast without protection offered by ecosystem services.

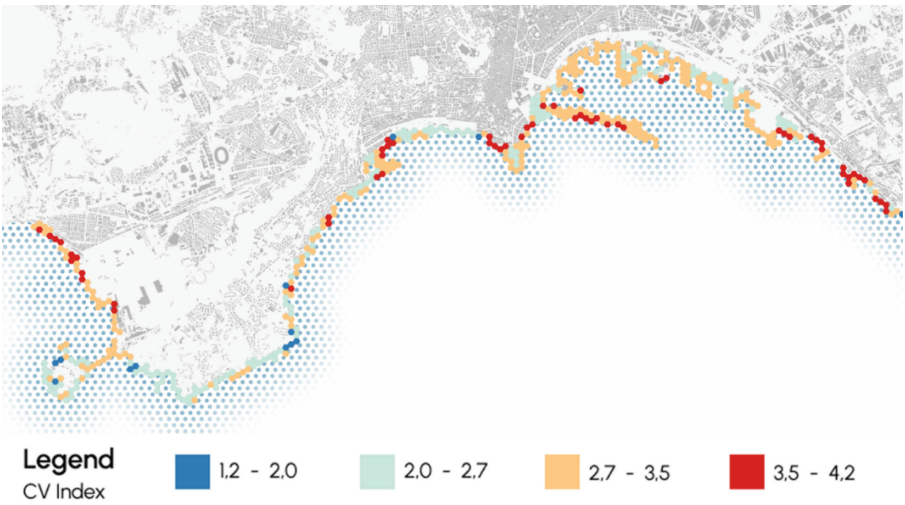


**Fig. 4.** Coastal Vulnerability Index in the scenario of absence of *P. oceanica*.

**Habitat Role in Coastal Protection**

Figure 5 quantitatively assesses the role of marine habitats, specifically *P. oceanica* meadows, in mitigating coastal vulnerability. The ecosystem contribution index is derived from the difference between CV indices calculated with and without the presence of these habitats. Although habitat effectiveness logically depends on the assigned rank across the two considered scenarios, this variation occurs uniformly across all coastal cells adjacent to existing marine habitats.

**Commercial Activities Exposed to Coastal Hazards**

Figure 6 illustrates the distribution of population exposure along the Gulf of Naples, based on the "Human Population" field that was repurposed for this study. The results indicate that densely populated urban areas, particularly those lacking natural protection, are disproportionately exposed to coastal hazards. The integration of demographic and spatial risk data allows for the identification of high-risk zones, supporting targeted adaptation and mitigation strategies.

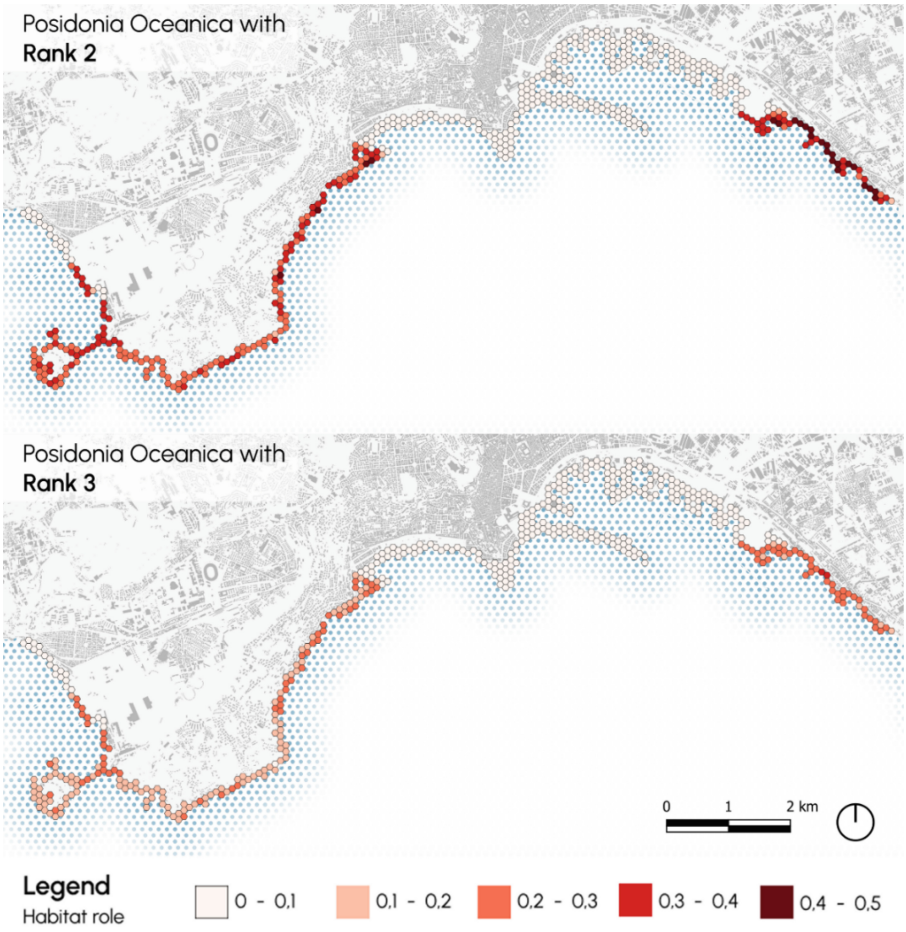


**Fig. 5.** Comparison of the Habitat Role in the two scenarios of coastal protection provided by *P. oceanica.*

### 5.2 Scenario Comparison

The graphs (Fig. 7) compare the two scenarios with the arithmetic averages of the entire distribution for the two indices of CV and Habitat Role.

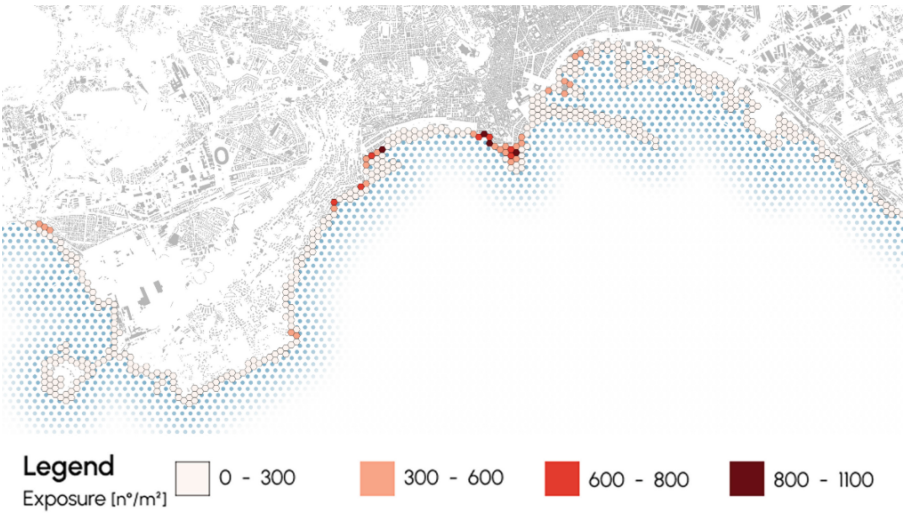


**Fig. 6.** Concentration of commercial activities in direct proximity to the shoreline.

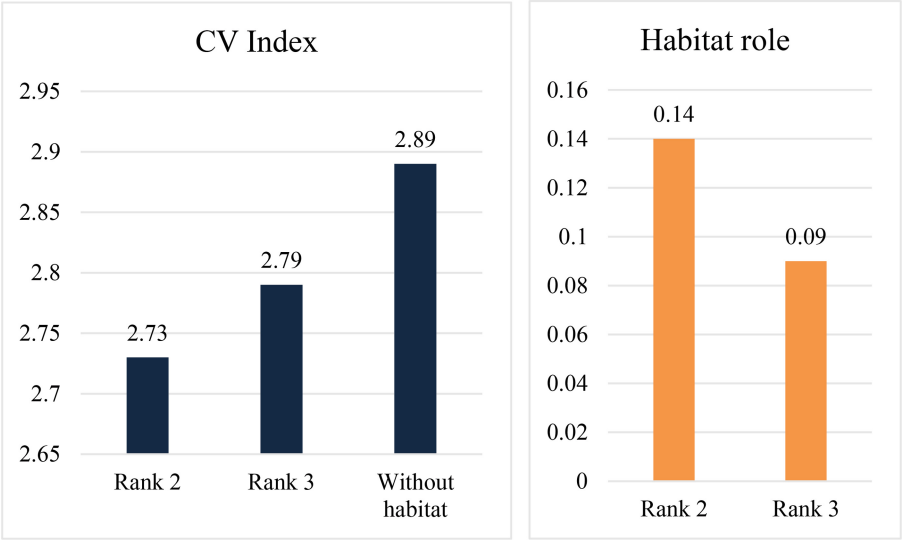


**Fig. 7.** Quantitative comparison between the different simulated scenarios.

### 5.3 Data-Driven Preliminary Recommendation System

Building on the spatial modeling outcomes and the analyses of key marine habitats, a preliminary recommendation framework was devised to lower the Coastal Vulnerability Index in the city of Naples. The distribution of *P. oceanica*, primarily observed off the Posillipo coastline and in a smaller meadow about 800 m from San Giovanni a Teduccio, underscores the importance of restoring and expanding seagrass meadows in

ecologically suitable areas. Such Nature-Based Solutions (NBS) can provide significant co-benefits by enhancing biodiversity, sequestering "blue carbon," and improving water quality through the mitigation of eutrophication processes.

Three incremental intervention scenarios were thus defined. Scenario 1 entails reinforcing existing Posidonia meadows and establishing new ones where local conditions permit. Scenario 2 enhances coastal resilience by introducing "living breakwaters" in the most vulnerable shoreline segments, effectively reducing wave impacts while preserving ecological function. Lastly, Scenario 3 adds dune systems along San Giovanni a Teduccio and Bagnoli, representing a broader-scale strategy that couples the protective effect of dunes with the ecological benefits of submerged habitats (Fig. 8).

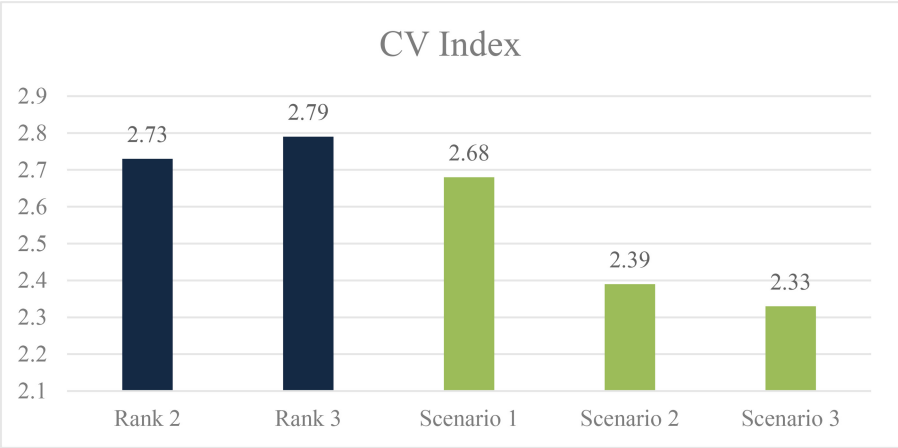


**Fig. 8.** Quantitative comparison of the CV Index between the actual and proposed state scenarios.

Although the first scenario yields a modest decrease in CVI, Scenario 2 shows a clearer reduction of coastal risk in areas previously identified as highly vulnerable. Scenario 3 further refines these improvements, principally in areas where dune systems were simulated, although the overall change is incremental rather than transformative.

In combining ecological restoration, engineered habitat structures, and soft coastal defenses, this integrated approach aims to deliver measurable benefits for urban coastal resilience, aligning essential protective functions with the co-benefits inherent in healthy marine and coastal ecosystems.

## 6 Conclusions

Traditionally, the InVEST "Coastal Vulnerability" model has been applied at large scales—with national or regional datasets and correspondingly low spatial resolution—limiting its applicability in urban settings. In contrast, our approach has adapted this model for the urban context of Naples, employing high-resolution input data to capture fine-scale variations in coastal vulnerability and the benefits of ecosystem services. Particular emphasis was placed on regulating services, such as flood mitigation and shoreline

stabilization, which are critical for the resilience of urban coastal areas. By integrating detailed ecosystem services mapping within the SDSS framework, this methodology could provide local stakeholders with robust decision-support tools to balance urban development with the preservation of vital coastal functions. The results demonstrated that high-resolution assessments enhance our understanding of coastal dynamics in urban environments, offering a replicable model for improving coastal risk management in cities facing similar challenges.

In conclusion, the conservation and restoration of *P. oceanica* meadows must be prioritized as a core component of adaptive coastal management, bridging ecosystem-based strategies with urban resilience planning. Strengthening these initiatives through multidisciplinary collaboration and policy integration will be essential to ensuring the long-term sustainability of one of Italy's most exposed coastal regions.

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