Università Ca'Foscari Venezia
Dipartimento di Scienze Ambientali, Informatica e Statistica

Master's Degree Programme in
Environmental Sciences

D.M. 270/2004

Final Thesis

GIS-based Multi-criteria Decision Analysis for the Suitability Mapping of Nature-based Solutions (NbS) in the Mediterranean Eco-region

Supervisor

Ch. Prof. Andrea Critto

Co-tutor

Dr. Elisa Furlan

Graduand

Ozan Özkiper

Matriculation Number: 887604

Academic Year

2021 / 2022

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

AHP	Analytic Hierarchy Process
CC	Climate Change
CCAM	Climate Change Adaptation and Mitigation
Chl-a	Chlorophyll A
CMCC	Cento Euro-Mediterraneo sui Cambiamenti Climatici
CMEMS	Copernicus Marine Environment Monitoring Service
DO	Dissolved Oxygen
DRR	Disaster Risk Reduction
EC	European Commission
EU	European Union
EEA	European Environment Agency
EMODnet	European Marine Observation and Data Network
EU	European Union
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GI	Green Infrastructure
GIS	Geographic Information System
ICZM	Integrated Coastal Zone Management
IUCN	International Union for Conservation of Nature
IPCC	Intergovernmental Panel on Climate Change
K_d	Light Attenuation Coefficient
MaCoBioS	Marine Coastal Ecosystems Biodiversity and Services in a Changing World
MAP	Mediterranean Action Plan
ML	Machine Learning
MCDA	Multi-criteria Decision Analysis
MCE	Marine Coastal Ecosystem
MedECC	Mediterranean Experts on Climate and Environmental Change
MPA	Marine Protected Area
MSP	Marine Spatial Planning
NbS	Nature-based Solutions
PSU	Practical Salinity Unit
RF	Random Forest

SOS	Safe Operating Space
SPM	Suspended Particulate Matter
SST	Sea Surface Temperature
TSS	Total Suspended Solids
UNEP	United Nations Environment Programme
WQ	Water Quality

SUMMARY

The growing environmental risks induced by interacting climate-related and human-induced pressures threaten the survival and growth of different terrestrial and marine coastal ecosystems (MCEs). Climate adaptation and mitigation measures are required against this complex interplay to cope with resulting impacts jeopardizing the health and resilience of ecosystems and the services they provide. Nature-based solutions (NbS), consisting of ecosystem-based approaches, have gained increased attention as a tool for climate adaptation and mitigation that can increase biodiversity and benefit people. Even though there is broader knowledge of NbS in the terrestrial environment in the state-of-the-art, experience in their design and implementation in MCEs is limited. In the specific context of the marine coastal environment, restoration measures and transplantation of MCEs, such as seagrass meadows and mangroves, are the most applied NbS. They contribute to climate regulation by sequestering carbon while improving water quality thanks to their denitrification and sediment trapping potential and contributing to disaster risk reduction by providing services such as coastal protection and flood control.

Identifying suitable environmental conditions for implementing NbS in marine coastal areas is a key priority to drive more robust and cost-effective nature-based adaptation pathways. Drawing on this need, this thesis aims to develop a GIS-based NbS suitability model to identify proper areas for NbS mainstreaming, with a specific focus on seagrass meadows in the Mediterranean Sea. Analytic Hierarchy Process (AHP), a widely used multi-criteria decision analysis (MCDA) method, is applied for data integration and variable prioritization. Different environmental variables are combined, including geomorphological (e.g., bathymetry, substrate type), water quality (e.g., salinity, nutrient concentration), and climatic (e.g., sea surface temperature, thermal stress) ones. Moreover, suitability classes are identified for the selected environmental indicators based on an in-depth statistical approach leveraging multiple open-source web-data portals available for the Mediterranean basin (e.g., Copernicus Marine Environment Monitoring Service). By using weights derived from pairwise comparison matrices based on expert judgement, suitability maps, and related statistics, for geomorphology, water quality, and climate are obtained for the Mediterranean shallow waters.

In terms of geomorphology, western Liguria and eastern Cote d'Azur, western Corsica, and southwestern Mediterranean (i.e., Morocco and Algeria) show small and patchy suitable surfaces due to deeper water and relatively steep slope. Moreover, a large less suitable area

was identified in the northern Adriatic Sea as a consequence of a reduced water quality score. On the other hand, the coasts of Egypt and southeastern Tunisia reported lower scores regarding climate suitability.

This thesis represents the first attempt to evaluate eco-regional scale NbS suitability for seagrasses in the Mediterranean Sea, using geomorphologic, water quality, and climate parameters. Socio-economic and governance-related indicators should be integrated as well within the obtained environmental suitability, thus paving the way for a more complex multi-tier and multi-scale approach supporting detailed analysis and targeted interventions in MCEs.

MOTIVATION AND OBJECTIVES

Marine and coastal areas are one of the most vulnerable regions to climate change (CC) impacts and anthropogenic activities (IPCC 2022), requiring protection and restoration actions, as well as the transplantation of marine coastal ecosystems (MCEs), such as seagrass meadows, mangroves, and salt marshes, to adapt and mitigate CC. Indeed, climate-related impacts and human-made pressures (e.g., rising sea surface temperature, sea level rise, light attenuation, etc.) reduce the ability of ecosystems to survive, grow and provide their services both in the terrestrial and marine coastal environment (IPBES, 2019; IPCC, 2019). However, MCEs are crucial as they can provide many ecosystem services and functions, such as reducing water quality degradation and absorbing carbon (E. Cohen-Shacham et al., 2016a; EEA, 2021; UNEP-WCMC, 2011). Nature-based Solutions (NbS), including ecosystem-based approaches, are innovative, integrated, and sustainable solutions that protect and manage nature while providing wide societal benefits. However, although NbS implementations have been performed in different contexts (e.g., mangrove restoration) for a while, the integration of this concept to larger scale interventions (i.e., upscaling processes) has been on the rise in the last two decades (E. Cohen-Shacham et al. 2019).

According to the International Union for Conservation of Nature (IUCN), the implementation of NbS must respond to the societal challenges identified in: i) climate change adaptation and mitigation (CCAM), ii) disaster risk reduction (DRR), iii) socio-economic development, iv) food security, v-) water security, vi) human health, and vii) environmental degradation and biodiversity loss (E. Cohen-Shacham et al., 2016b). NbS can improve environmental resilience and mitigate environmental degradation with many co-benefits by delivering multifaceted ecosystem services (Gómez Martín et al., 2020). They represent more flexible and adaptive solutions to changing environmental conditions compared to traditional/grey infrastructures, able to face the aforementioned societal challenges (EC, 2015; EEA, 2021). Nevertheless, there is still limited knowledge on NbS suitability, especially in marine coastal environments. NbS suitability analysis is essential for identifying the proper and effective solutions to implement, considering environmental, socio-economic, and governmental conditions at different scales and locations. To this aim, the first step is understanding the areas presenting suitable environmental conditions for NbS design and implementation and, in particular, identifying the optimum and threshold values of environmental variables supporting the survival and growth of different ecosystems, considering their spatio-temporal changes. Subsequently, a complete analysis can be performed to integrate the effects of socio-economic and governmental settings supporting proper implementation at local scale.

With the main aim of filling this gap, this Thesis aims to develop a Geographic Information System (GIS) based methodology, integrating Multi-criteria Decision Analysis (MCDA) and Analytic Hierarchy Process (AHP) to identify proper areas for NbS implementation, with a specific case study focus on seagrass meadows in the Mediterranean eco-region. From an operative perspective, this bold objective breaks down into 4 consecutive steps underpinning the analytical process and research of this Thesis.

1) Review of the state-of-the-art literature concerning NbS suitability mapping in MCEs, with a specific focus on the integration of water quality variables into modeling processes;

2) Characterization of the case study area (Mediterranean eco-region), as well as collection and pre-processing of GIS-based environmental data (e.g., sea surface temperature and nutrient concentrations);

3) Design of the MCDA-based methodology, allowing the scoring and weighting of the selected environmental variables to evaluate the environmental NbS suitability (i.e., *Posidonia oceanica* in this Thesis) in the investigated area;

4) Development of GIS-based suitability maps and final suitability metrics supporting the design of NbS implementation using ecosystem-based approaches at the case study level.

This thesis was carried out in the frame of the H2020 MaCoBioS project (https://macobios.eu) in collaboration with the Euro-Mediterranean Center on Climate Change (www.cmcc.it). The project aims to propose cost-effective NbSs for mitigation and adaptation to deal with the effects of climate change on biodiversity and ecosystem services in MCEs.

THESIS STRUCTURE

This thesis consists of three main sections: **Section A** provides the theoretical background on the NbS concept with a specific focus on water quality and suitability assessments in marine coastal environments; **Section B** describes the data and methodology underpinning the NbS suitability model; **Section C** presents the results obtained after the application of the developed model for *Posidonia oceanica* to the Mediterranean eco-region case study area.

In more detail:

Section A briefly introduces the NbS concept and NbS types, reviews the connection between NbS measures and water quality degradation, and finally presents the state-of-the-art NbS suitability assessment models/approaches already applied by the research community in marine coastal areas.

Section B describes the selected study area, the Mediterranean eco-region, and produces a framework for NbS suitability assessment by focusing on significant environmental indicators for the survival and growth of MCEs (i.e., *Posidonia oceanica* in this Thesis). Moreover, this section presents the data collection and pre-processing, as well as the steps developed for the model application to the case study area.

Section C presents and critically analyses the results obtained from the application of the developed model for *P. oceanica* in the Mediterranean eco-region in terms of NbS suitability maps and statistics for different sub-indices (i.e., geomorphological, water quality, and climate). The results should drive decision-makers in implementing NbS and developing future ecosystem-based management strategies in marine-coastal areas.

The conclusion section summarizes the methodology applied and the main findings obtained, highlighting its strengths and limitations with some recommendations for future investigation.

SECTION A: THEORETICAL BACKGROUND

1. Review of NbS Concept, Mitigating Water Quality Degradation, and NbS Suitability

1.1. NbS Concept and Classification

The definitional framework of NbS evolves since it is an emergent concept in scientific literature. Three different definitions of NbS can be identified in the literature. The first of these was proposed by the IUCN as "*Actions to protect, sustainably manage and restore natural or modified ecosystems that address social challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits*" (E. Cohen-Shacham et al., 2016b). A further definition is provided by the European Commission (EC) as *"Solutions inspired by, supported by or copied from nature and which aim to help societies address a variety of environmental, social and economic challenges in sustainable ways"* (EC, 2015). The most recent definition is made by the United Nations Environment Programme (UNEP), which states *"Actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems, which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, and resilience and biodiversity benefits"* (UNEP, 2022).

In previous studies to define and classify NbS, Eggermont et al. (2015) characterized NbS along two gradients which are "level and type of engineering of biodiversity/ecosystems" and "targeted number of services/stakeholder groups". Eggermont et al. (2015) categorized the typology of NbS interventions into three main classes according to the level of ecosystem services delivery and the level of engineering applied. Type 1 class includes the protection of ecosystems by applying minimal intervention to ecosystems, such as the creation of marine protected areas (MPAs). Type 2 class includes ecosystem management and restoration activities to improve species resilience. Finally, Type 3 class categorizes concepts such as blue-green infrastructure that support the creation of new ecosystems (Eggermont et al. 2015; Cohen-Shacham et al. 2016; Think Nature 2019).

Within the IUCN framework, NbS can be considered an umbrella concept that includes different ecosystem-based approaches (also known as ecosystem approaches) that contribute to increasing human well-being and protecting biodiversity (E. Cohen-Shacham et al., 2016a; EEA, 2021). More specifically, the NbS approaches have been classified in five broad categories by the IUCN, which are; ecosystem restoration approaches (e.g., ecological restoration), ecosystem protection approaches (e.g., area-based conservation approaches including protected area management), issue-specific ecosystem-related approaches (e.g., ecosystem-based adaptation, ecosystem-based mitigation, and ecosystem-based disaster risk reduction), ecosystem-based management approaches (e.g., integrated coastal zone management (ICZM), MPAs) and infrastructure-related approaches (e.g., green infrastructure (GI) including hybrid solutions with hard infrastructure) (E. Cohen-Shacham et al., 2016a). Common management strategies for the conservation of MCEs, such as seagrass meadows, mangroves, and coral reefs, are MPAs, ICZM, and marine spatial planning (MSP). While these strategies conserve the ecosystems and ensure their sustainability for ecosystem services, they provide an opportunity for coastal development. On the other hand, when ecosystem degradation is prevalent, traditional ecosystem conservation measures may not be sufficient, and restoration and transplantation activities are considered in areas with highly degraded MCEs (Lester et al., 2020; Wilson & Forsyth, 2018). In order to implement successful MCE restoration projects, site-specific conditions such as abiotic factors (e.g., temperature, salinity) and threats (e.g., pollution) need to be analyzed, and a suitable site selection should be made for the proper ecosystem. In addition, the selection of specific species to transplant or restore is important as well. For instance, *Cymodocea nodosa* and *Zostera marina* may be more suitable for transplanting thanks to their high growth rate (Marbà et al. 1996; 2004; Lester et al. 2020; Wilson and Forsyth 2018). Since the outcomes of the various management and restoration actions on specific types of MCEs will be different, implementing the suitable ecosystem approach for the appropriate species according to the targeted ecosystem services can be useful in deciding the optimum NbS alternative (Lester et al., 2020).

1.2. Mitigating Water Quality Degradation

Water quality (WQ) degradation is one of the key challenges of the 21st century affecting both ecosystem sustainability and functioning and socioeconomic systems (EEA, 2019; Zhou, 2019). Therefore, understanding the processes underpinning WQ can benefit integrated water resource management and human activities while protecting ecosystems, as required by Agenda 2030 and the EU 2030 Biodiversity Strategy.

Although the reduction of physical impacts of climate change (e.g., floods, erosion) is considered the primary benefit of NbS measures in marine coastal areas, improvement of WQ, degraded by human pressures and climate change impacts, is a very valuable co-benefit of NbS implementation (CNRD & UNEP, 2019). For instance, mangroves provide a barrier to physical events such as storm surges and tsunamis and support sediment stabilization thanks to the complex root system and improve WQ by depositing suspended solids due to runoffs and by filtering chemical compounds (e.g., heavy metals, nutrients). Mangroves can also regulate the sediment's chemical properties, such as acidity and redox potential, and improve WQ by contributing to heavy metal accumulation in sediments (Wang et al., 2019).

Overall, MCEs contribute to WQ through two main ecosystem services: uptaking nutrients (i.e., nitrogen and phosphorus compounds) as supporting services and sediment trapping and carbon sequestration as regulating services. Indeed, nutrients in the water column and sediments can accumulate in tissues of marine ecosystems, such as seagrass meadows, both in leaves and roots (Terrados & Williams, 1997), contributing to reducing excessive nutrient concentrations in the water column. Different ecosystems and plant organs differ in the uptake rate of nutrients. For example, the accumulation of ammonium and nitrate by adsorption and absorption in the leaves of seagrasses has a higher uptake rate than in roots. However, if the nutrient concentration in the sediment is relatively higher than in the water column, nitrogen and phosphorus uptake by seagrass roots can be the major source of seagrass growth but decrease their contribution to water purification (Koch et al., 2010; Short & Mcroy, 1984).

Marine ecosystems also contribute to trapping suspended particulate matter (SPM) in both above-ground biomass (e.g., leaves) and at the sediment bottom in below-ground biomass (e.g., rhizomes and roots) (de los Santos et al., 2020; Gamble et al., 2021). Since sediment load is directly related to turbidity and light attenuation, some studies (Ruiz & Romero, 2003; Vermaat et al., 1997) analyze data on turbidity and/or irradiance parameters instead of SPM. The increased SPM concentration in seawater increases the turbidity and negatively affects the rate of photosynthetic activities as it reduces the sunlight that can penetrate deep water.

Moreover, increasing acidification resulting from the absorption of approximately 33-50% of atmospheric CO_2 emissions by the oceans harms especially shell-forming species such as oysters and corals. Plant communities in marine ecosystems with high photosynthesis capacity increase the organic carbon sink concentration in the sediments thanks to the carbon sequestration service. In this way, they improve the quality of marine life by moderating seawater's pH (Camp et al., 2016). Furthermore, there is a correlation between pH and dissolved oxygen (DO) and chlorophyll-a (Chl-a) as they depend on primary production. DO concentration and pH increase with the photosynthetic activity, while Chl-a, representing the concentration of algae in the water body, decreases.

Additionally, combining different MCEs can effectively improve WQ and provide co-benefits to the ecosystems. For example, seagrass meadows sink organic carbon in sediments, regulating the seawater pH and hence facilitating the calcification of reef systems, such as corals and oysters, which, in turn, increase their resilience. On the other hand, reefs can provide sheltered conditions for seagrass meadows, as the reefs have a high capacity to mitigate hydrodynamic effects such as high-energy waves that can damage seagrass meadows. In this way, they help ecosystem services such as the blue carbon sink provided by seagrass meadows to become more efficient (Guerra-Vargas et al., 2020; Unsworth et al., 2012).

Although MCEs in good health status can improve WQ, ecosystems already in poor WQ conditions are not expected to grow healthy and contribute to improving WQ and providing ecosystem services. In addition, the environmental conditions that each MCE can grow and tolerate are different. For example, mangroves grow better in warm and humid environments, while saltmarshes are more resistant to colder conditions and can grow in tide and wave-dominated areas. On the other hand, seagrasses are adapted to warm, temperate, and cold climate conditions; however, they are sensitive to high nutrient concentrations and turbidity since they highly depend on light availability. Therefore, MCEs need good environmental conditions to grow and positively affect the WQ (Moffett et al., 2015; Simpson et al., 2021). This requires evaluating the status of baseline WQ conditions and identifying the multiple stressors for setting up effective management and restoration strategies in marine coastal areas.

1.3. NbS Suitability Modelling

The state-of-the-art methodological approaches for suitability assessment of the ecosystem-based strategies, already applied by the research community, were summarized in this section to develop a proper model for NbS suitability mapping in the Mediterranean eco-region.

NbS suitability assessment is necessary for the decision-making of NbS measures according to the spatial and temporal characteristics with various dimensions (i.e., environmental, socio-economic, and governmental) to contribute to sustainable development. However, suitability is a gradual concept without a universal definition, thus evolving into a complex decision-making process. Beyond the large-scale spatial characteristics, local conditions should also be evaluated for the necessary NbS implementation (e.g., management and restoration) to obtain more robust results.

The suitability assessments have been developed mainly in the terrestrial environment, while it still lacks a comprehensive assessment and a clear definition of the concept in marine coastal areas. In the terrestrial environment, ecosystem-based solutions proposed for climate change and human-related pressures are more complex with the contributions of landscape modifications. For example, while solutions with wide networks such as urban GI are in NbS measures in the terrestrial environment (Bellamy et al., 2017), NbS in marine and coastal environments are ecosystems (e.g., seagrasses, corals, mangroves, oysters, and algae). Therefore, suitability analysis in the terrestrial environment provides social benefits by identifying areas requiring rehabilitation and restoration actions, understanding species' habitat requirements, modeling the impacts such as climate change, and planning urban land use. Furthermore, the suitability analysis is performed at local scale in urban and rural areas, considering the relationship between human and nature with environmental, socio-economic, and governance dimensions (Antognelli & Vizzari, 2021; Bellamy et al., 2017; Saha & Paul, 2021). On the other hand, most studies on MCEs consider only environmental criteria, while socio-economic and governance indicators are rarely assessed due to the complexity of interactions and lack of knowledge.

In marine coastal areas, the concept of suitability is used mainly to evaluate the status of a specific ecosystem. Values of selected indicators should be within the limited ranges defined for each parameter and as close to the optimum value as possible. However, it is a complex task to determine the optimum range and thresholds of the parameters necessary for each species's growth and survival because the species can adapt to different conditions. Accordingly, it is not sufficient to evaluate stressors independently because of synergetic effects. This issue coincides with the 'safe operating space (SOS)' concept mentioned by Rockström et al. (2009), related to anthropogenic impacts on ecosystems. It proposes not exceeding the limits of nine planetary boundaries to provide life-support systems for sustainable human development. Therefore, Earth systems should process at a safe distance by avoiding tipping points. Identifying and quantifying the threshold of each boundary is necessary for the systems to remain resilient, but the uncertainty in nature complicates this. The concept of creating an SOS for ecosystems has been studied by Scheffer et al. (2015) to investigate the responses and adaptive capacity of ecosystems to changing environmental conditions. While most ecosystems do not show a high response to environmental changes until the tipping point is reached, they show a sudden break after exceeding the threshold (i.e., non-linear response). While adapting the SOS concept to wetlands, the idea is based on local stressor management, but the effect of climate change on undesirable states is also included. For example, by reducing local stressors such as water extraction and nutrient loading for wetlands, it can be ensured that wetlands remain in an SOS despite the pressure of climate change. The high level of local stressors reduces the resilience against climate change. It limits the range of variables where the ecosystem can survive and grow safely, i.e., a significant decrease in tolerance (Green et al., 2017). However, defining stressors' thresholds is difficult due to uncertainty, including non-linear responses, interactions, and feedback (Rockström et al. 2009; Scheffer et al. 2015; Green et al. 2017). As an example of interactions, the cyanobacterial dominance resulting from 1 °C increase can be balanced by a 33% decrease in nitrogen concentration. As a synergetic effect, water extraction increases the concentration of nutrients and contaminants in the water, which affects the suitability of MCEs (Green et al., 2017; Scheffer et al., 2015).

More specifically, four publications representing the most updated and relevant research for NbS suitability mapping in marine coastal areas are selected as "key papers". The publications are summarized in Table 1.1., detailing the objectives, approaches, study area, NbS measures, and indicators used for suitability modeling.

Table 1.1. Summary of the key papers

Reference	Objective	Study Area	Methodology	Indicators	NbS (MCE or physical intervention)
Bakirman and Gumusay, 2020	Developing a habitat suitability model based on environmental variables and expert judgements for seagrass distribution. Identification of suitable habitats for seagrasses	Gulluk Bay, Turkey	AHP method to weight different criteria to build up habitat suitability model for seagrasses by applying GIS-MCDA and remote sensing techniques	Depth, slope, sediment yield, topographic position index, sheltered area of water	Seagrasses *(P. Oceanica)*
Syahid et al. 2020	Assessing the amount of suitable land for mangrove restoration today and in the future, according to the different climate change scenarios	Coastal areas in Southeastern Asia	GIS-based AHP method with remote sensing, model, and statistical data is used for the suitability analysis of mangroves by integrating scenario analysis for 2050 and 2070	Elevation, slope, tidal inundation, air temperature, precipitation, land cover, population, gross domestic product (GDP), night light	Mangroves
Catucci and Scardi, 2020	Assessing the vulnerability of *Posidonia Oceanica* using Machine Learning	Italian Sea	Random Forest to estimate the occurrence of *P. Oceanica*, i.e., presence and absence	35 environmental variables (Table 1 in Catucci and Scardi (2020)	Seagrasses *(P. Oceanica)*
Mubeen et al. 2021	Developing a methodology and tool for the spatial suitability assessment of NbS for river basins using a GIS approach	Tamnava river basin in Serbia	GIS-MCA approach to developing a toolbox for selection and allocation of large-scale NbS	Slope, soil type/class, distance from the stream, land use type/zone, and road buffer	- Floodplain restoration, - Detention basins, - Retention ponds, - River widening

The suitability concept in marine coastal areas has been defined by the four authors in different ways: Bakirman and Gumusay (2020) developed a suitability model to investigate the ideal habitat of seagrass species (i.e., *Posidonia oceanica*), for their restoration and transplantation. They considered environmental (i.e., geomorphological) indicators and developed a suitability model using GIS-MCDA and remote sensing techniques to determine the reference habitat conditions required for the growth of *P. oceanica* in Gulluk Bay in the southeast Mediterranean region of Turkey. The model includes five criteria: depth, slope, sediment yield, topographic position index (TPI), and sheltered area. According to expert surveys, variables were clustered and normalized with scores between 0-100. Their weights were decided using the AHP, a common method for various suitability assessments (e.g., land suitability). Pairwise comparisons scored by seagrass experts are used to integrate the relative importance of environmental indicators. Finally, normalized scores were multiplied by their weights obtained from AHP to obtain the final scores, and mapping was done as in Figure 1.1. Overall, it has been a novel approach for *P. Oceanica* to integrate spatial environmental data and expert judgement with GIS-MCDA techniques while assessing habitat suitability.

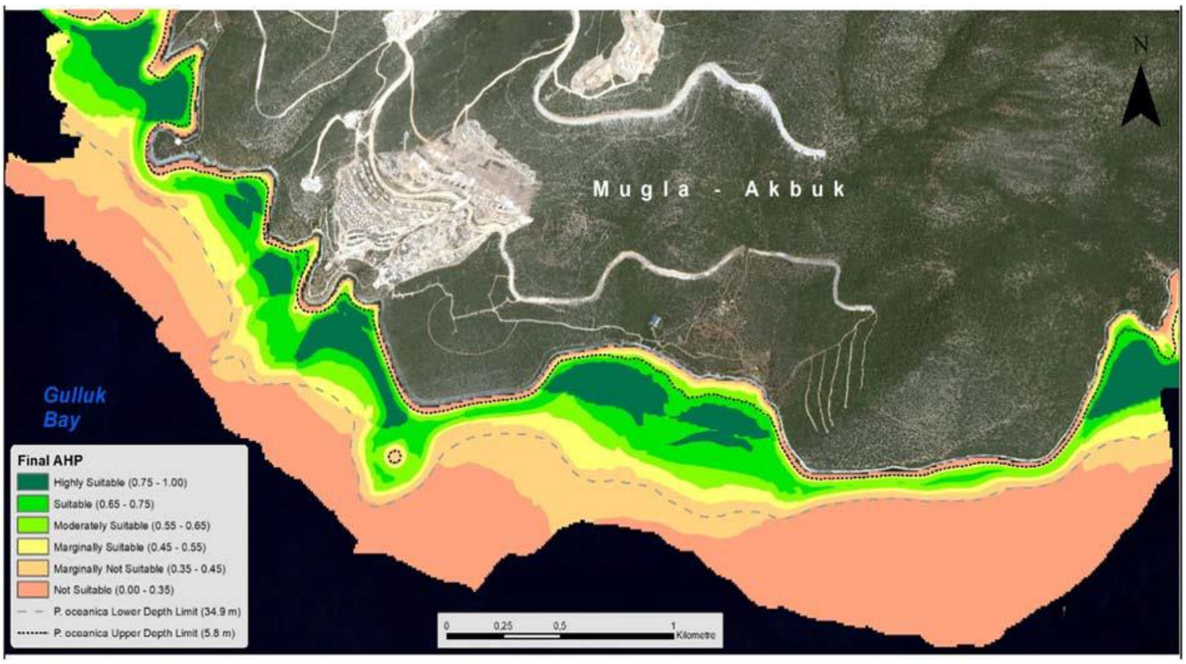

Figure 1.1. Final suitability mapping in Bakirman and Gumusay (2020).

A similar study was performed by Syahid et al. (2020) that identified suitable locations for mangrove planting in Southeast Asia. Suitability concept is defined in a more complex way by including both temporal dimension (i.e., future scenarios) and socio-economic conditions linked to human-based pressures (e.g., land cover). As in Bakirman and Gumusay (2020), potential land suitability for mangroves is evaluated using the AHP method with expert judgement for the weighting of parameters by forming a pairwise comparison matrix. The novelty of this study is the inclusion of both environmental criteria, including climate, hydrodynamic, and geomorphological indicators with sub-parameters, such as tidal inundation, elevation, and average air temperature, and socio-economic indicators related to human pressures such as GDP per capita and population. Moreover, the climatic parameters (e.g., average air temperature and precipitation) were considered both for baseline analysis and future scenarios using representative concentration pathways (RCP 2.6, 4.5, and 8.5). Future scenario analysis is essential in NbS design for selecting the proper intervention in suitable areas. Priority areas for intervention (e.g., restoration and management) can be identified by analyzing potential vulnerable or suitable areas in the future and by comparing them with the current situation.

This study analyzed mangrove land suitability in five different ways, as illustrated in Figure 1.2: i) using AHP without considering human pressures; ii) using AHP and considering human pressures; iii) without considering AHP (equal importance for each parameter) and human pressures; iv) without using AHP but considering human pressures; v) using AHP and considering human pressures for 2050 and 2070 with data from two models (CNRM-CM5.1 and MIROC5). While the first four scenarios are for baseline land suitability, the fifth is applied for future land suitability of mangroves. In addition, while the influence of human pressure parameters can be investigated by comparing the scenarios in which they are included and those that are not (e.g., i and ii), the accuracy of the weights given are tested by comparing the scenarios with and without AHP (e.g., ii and iv).

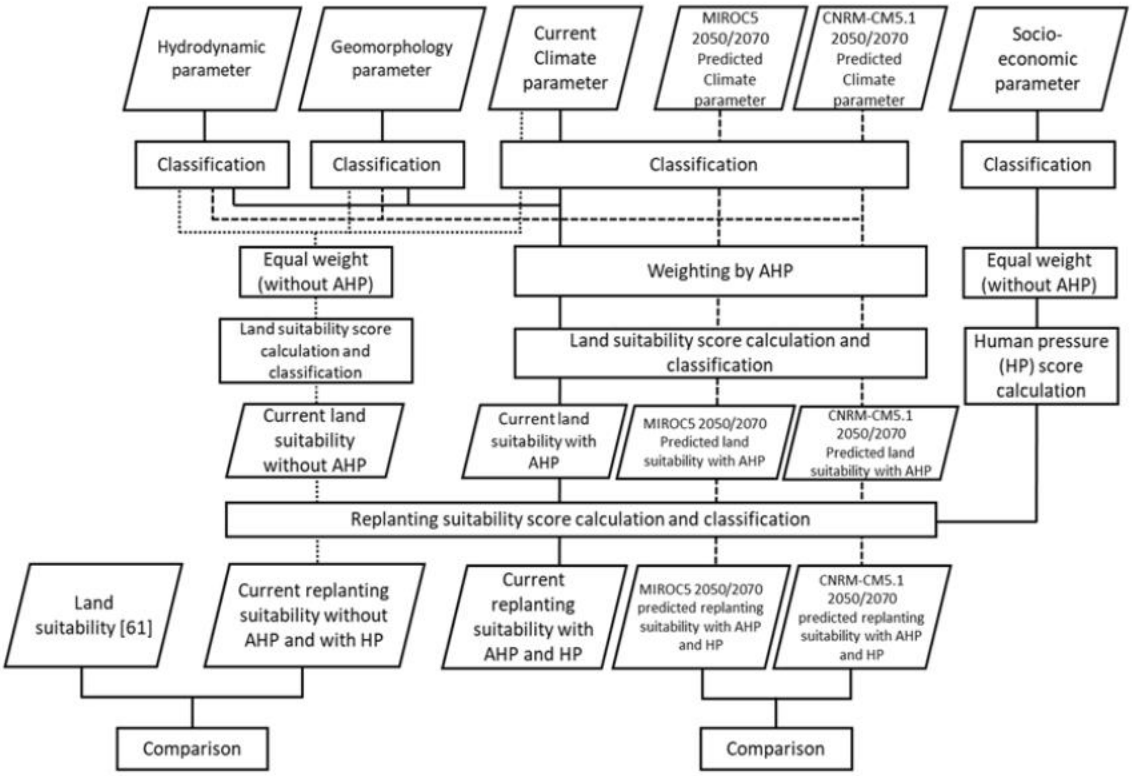

Figure 1.2. Data processing scheme in Syahid et al. (2020).

After identifying and classifying the indicators based on a literature review, scoring was completed in the 0-4 range. Finally, mapping was performed for five scenarios illustrated in Figure 1.2. According to the results, a significant reduction in suitable mangrove land area was obtained with human pressure indicators. On the other hand, when weighting is not considered, very suitable and suitable areas for mangrove planting are smaller. The inclusion of human pressure factors and the relative importance of the parameters influence the selection of potentially suitable land for mangroves. Interestingly, scenario analysis for 2050 and 2070, including climate model projections, show an increase in suitable areas for mangroves in the future as increasing greenhouse gas (GHG) concentration (i.e., from RCP2.6 to RCP8.5).

Catucci and Scardi (2020) defined the suitability concept with spatial distribution (i.e., linked to presence-absence of *P. oceanica*) and conditions of meadows (i.e., living, regressed, or mixed conditions) by assessing the vulnerability of *P. Oceanica* meadows as outputs with reproducible distributions. Catucci and Scardi (2020) developed a habitat suitability model for *P. oceanica* in the Italian seas by using Random Forest (RF), a Machine Learning (ML) technique, as a classification tool rather than a predictive tool. ML methods have become more frequently used tools because they can effectively model complex relationships between species and environmental parameters with non-linear and high-order interactions. The novelty of Catucci and Scardi (2020) is performing the vulnerability assessment of *P. Oceanica* using 35 environmental variables based on in situ measurements, such as depth and salinity, as well as modeled anthropogenic variables, such as population and human impact on marine ecosystems, by considering a temporal dimension using historical and current occurrence data.

Relative importance is evaluated for environmental variables by normalizing the results based on the largest relative importance criteria using permutation measure. Moreover, while depth shows the largest relative importance as 1, the other predictors have relative importance only between 0.02-0.33, which is much lower than the importance of depth. However, Catucci and Scardi (2020) stated that the relative importance of other indicators is not fully reflected, as the RF technique yields results by looking at correlations between predictors rather than complex causal relationships. The RF provides presence predictions in the [0, 1] interval, and the optimal threshold for a predicted presence was obtained using Receiver Operating Characteristic (ROC) curve. Since low RF value also means low predicted habitat suitability, vulnerability and the potential regression risk are higher in such areas. Potential regression-risk areas should be identified to contribute to the environmental impact assessment and to prioritize the seagrass populations for interventions. Accordingly, conservation actions are necessary to control the regression risk of highly vulnerable meadows. On the other hand, mitigation measures and monitoring programs can be adequate for less vulnerable ones to maintain their present level of habitat suitability.

Mubeen et al. (2021) is the only key paper that used the term ‘NbS suitability mapping’ and focuses on NbS other MCEs. Suitability mapping was carried out to assist in selecting and allocating four NbS interventions (i.e., floodplain restoration, detention basins, retention ponds, and river widening) that could face increased flood risk with climate projections. Although it is relevant to the urban and rural context as performed for the Tamnava River basin, the authors conduct a comprehensive NbS suitability assessment that supports suitability models in marine coastal environments. The GIS-MCA approach (with ESRI ArcMap) is used to develop toolboxes for the spatial allocation of large-scale NbS, considering local contexts and both environmental and socio-economic parameters. For the spatial suitability assessment of NbS, Mubeen et al. (2021) formed a conceptual model as in Figure 1.3 involving the most used criteria in the previous tools (i.e., slope, soil type/class, distance from the stream, land use type/zone, and road buffer) to avoid using similar input data/criteria. Thanks to the flood maps and suitability maps, the amount of floodwater that needs to be stored can be decided. This study is a decision-support tool that facilitates the selection of suitable NbS with enough potential for storage and its allocation by estimating the volume of floodwater and available storage capacity of NbS.

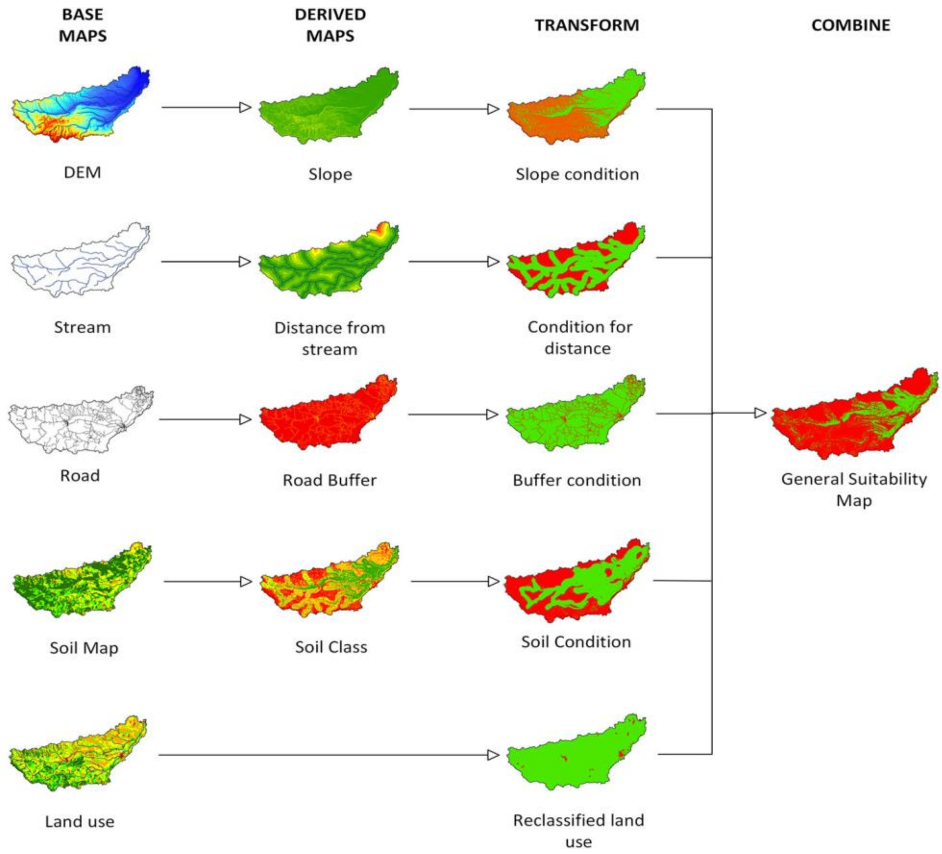

Figure 1.3. The conceptual model for mapping for NbS in Mubeen et al. (2021).

SECTION B: METHODOLOGICAL DEVELOPMENT

2. Description and characterization of the case study area

2.1. The MaCoBioS Project

The H2020 MaCoBioS (Marine Coastal Ecosystems Biodiversity and Services in a Changing World)[1] is an EU-funded project aiming to provide efficient and integrated management and conservation strategies for MCEs (e.g., seagrass meadows, coral reefs, mangroves, saltmarshes, kelp forests, maerl beds) in Europe to face the impacts of climate change considering the inter-relations between climate change, biodiversity, and ecosystem services. For this purpose, it contributes to climate change mitigation and adaptation actions by improving knowledge of the spatio-temporal dynamics of MCEs in the context of NbS and by proposing suitable creation, conservation, restoration, and management strategies involving multidisciplinary approaches.

In this direction, the potential ecosystem services and benefits MCEs can provide for societal challenges depend on their biological and ecological conditions. Changes in environmental conditions and degradation or disturbance of ecosystems due to climate change impacts and anthropogenic factors reduce the quantity and quality of ecosystem services and biodiversity. Ecosystems vulnerable to environmental drivers or anthropogenic stressors become unable to provide services such as nutrient uptake, and the vulnerability of the socio-ecological system increases subsequently. However, the evaluation of the complex relationship between MCE degradation and ecosystem services, as well as a comprehensive analysis for implementation/transplantation or protection of ecosystems with ecosystem-based approaches in a robust manner, remain limited due to knowledge gaps such as insufficient data. MaCoBioS leads to filling the knowledge gap for implementing effective and integrated NbS measures by establishing a bridge between climate change and MCE using multiple indicators and providing guidance for decision-makers. For this purpose, MaCoBioS pursues four main targets based on scientific work packages (WPs) and activities, as follows: i) Providing empirical models for the relationship between climate change, biodiversity, functions and services of MCEs (WP1), ii) Assessing the vulnerability of marine socio-ecological systems to climate conditions under multiple *'what-if'* scenarios (WP2), iii) Evaluation of the effectiveness and suitability of NbS measures by improving the resilience capacity of MCEs (WP3), iv) Developing evidence-based guidance for marine policy and innovative research (WP4).

[1] https://macobios.eu/

This thesis was developed in collaboration with the Euro-Mediterranean Center on Climate Change (CMCC)[2] and contributes to Task 3.3 of WP3 on 'Nature-based solutions suitability mapping' by supporting information on the optimum environmental conditions for appropriate NbS implementations considering the main environmental drivers of the suitability of seagrass meadows in marine and coastal areas of the Mediterranean Sea and using MCDA techniques.

2.2.Mediterranean Eco-region

The Mediterranean Sea, which is the largest (2.5 million km^2) and deepest (average 1460 m, maximum 5267 m) enclosed sea (Coll et al. 2010, 2012), is located between 30° 15' – 45° 47' N and 6° 1' W – 36° 13' E (IHO, 1953) and connects to the Atlantic Ocean in the west, to the Red Sea in the southeast and to the Sea of Marmara and the Black Sea in the northeast. The Mediterranean Sea is surrounded by 22 countries from Western and Southern Europe, Anatolia, North Africa, and the Levant, with a total coastline length of 46,000 km (Giorgi, 2006). The Mediterranean Sea is divided into four sub-regions according to its biogeographic and oceanographic features, namely the Adriatic Sea, the Western Mediterranean, the Ionian and Central Mediterranean, and the Aegean-Levantine region (Figure 2.1). Since the characteristics of these sub-regions are slightly different, their ecosystem tolerance and exposed pressures can be evaluated by considering site-specific conditions.

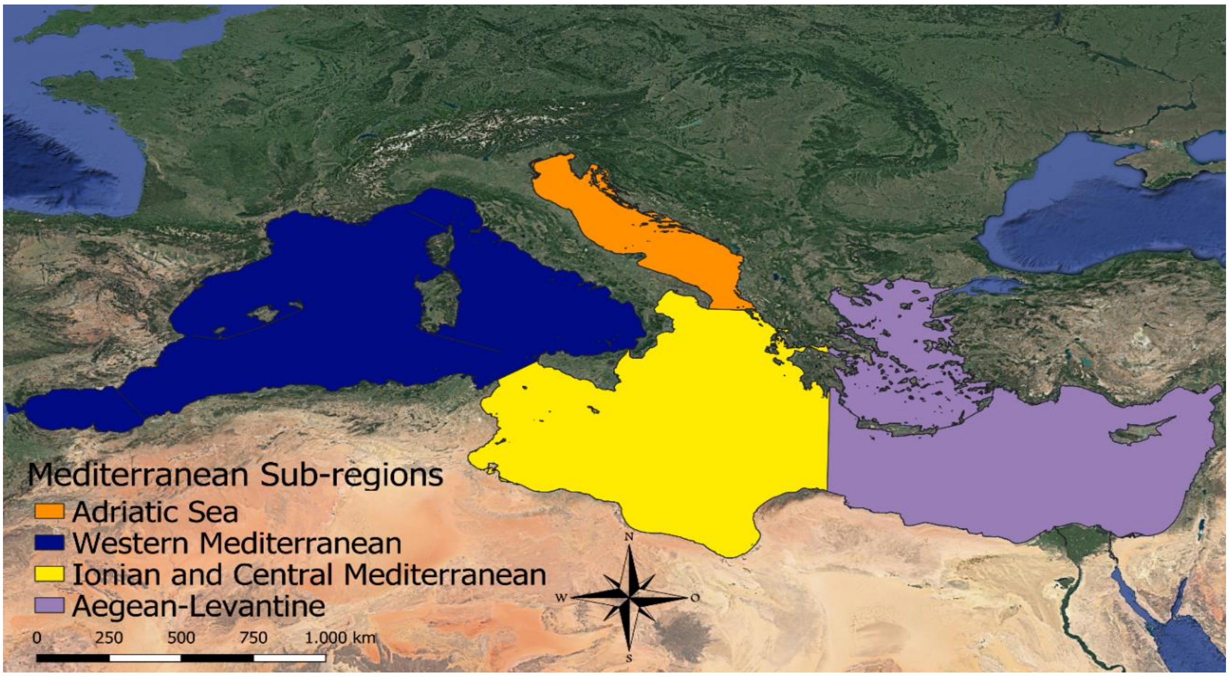

Figure 2.1. Sub-regions of the Mediterranean Sea.

[2] www.cmcc.it

Regarding the physicochemical characteristics of the water, the Mediterranean Sea is one of the most oligotrophic oceanic systems, with some exceptions in coastal areas where high river discharges, vertical mixing, and upwelling phenomena occur (e.g., Gulf of Lion). A large part of the Mediterranean is deep sea, having unusual features such as temperature variations from 12.8-13.5°C in the western basin to 13.5-15.5°C in the eastern basin. Moreover, there is an eastward increase in salinity (average 37.5-39.5 PSU) and a decrease in sea surface height due to higher evaporation and less runoff on the east side. In contrast to temperature and salinity, biological productivity increases from east to west and from south to north (UNEP/MAP 2017; Piroddi et al. 2015). In terms of climate conditions, precipitation in the Mediterranean, which has hot, dry summers and mild, windy, humid winters, has an increasing gradient from south to north. While the annual precipitation does not exceed 250 mm on the North African coasts, the northern Mediterranean countries receive annual precipitation up to 2500 mm, with a maximum in mountainous coastal areas (UNEP/MAP, 2017).

The Mediterranean, which covers only 0.82% of the global ocean surface, has high oceanic productivity and hosts more than 17,000 different marine species (7% of global marine biodiversity and 18% of the global macroscopic marine biodiversity) (Bianchi & Morri, 2000) and about 25% of the global marine primary production (Coll et al., 2010). Given its richness, the Mediterranean is considered one of the world's 25 hotspot areas for biodiversity loss since it contains valuable and endangered key shallow (e.g., seagrasses) and deep-water ecosystems (e.g., submarine canyons and deep-sea structures), which increase from southeast to northwest (EEA, 1999). The Atlantic Ocean is the primary source of marine biodiversity in the Mediterranean. New species were introduced to the Mediterranean Sea from the Red Sea through the Suez Canal and the Atlantic Ocean due to the intensification of anthropogenic activities (e.g., shipping activities) (Coll et al., 2010).

Different direct drivers (e.g., climate change, degradation of habitats, invasive alien species (IAS)) and indirect drivers (e.g., demographic, economic, and social) affect MCEs and ecosystem processes in the Mediterranean Sea. Specifically, the Mediterranean Experts on Climate and Environmental Change network (MedECC) classified the direct drivers of change into four macro-categories: i) climate change, ii) pollution, iii) land and sea use changes, and iv) non-native species.

The IPCC 6th assessment report estimated that the current conditions in the world will exacerbate the threats to both nature and human well-being by considering the most impactful climate drivers, such as temperature increases. Specifically, the key pressures affecting the

Mediterranean Sea are sea surface temperature, sea level rise, precipitation, ocean acidification, salinity change, and extreme events, such as marine heatwaves, storm surges, and flood events. It has been reported that the species at risk of extinction will be 5%, and 16% at 2°C, and 4.3°C warmings, respectively (UNEP/MAP, 2017). The Mediterranean is more sensitive to climate change impacts than other seas due to its characteristics, such as being enclosed (i.e., limited water exchange with oceans) and having sensitive ecosystems (Coll et al., 2012). Additionally, human-induced pressures, such as fishing and shipping, accelerate the adverse impacts on this eco-region.

On the other hand, water pollution includes marine litter introduced by maritime activities (e.g., dredging) and chemical compounds discharged from land (e.g., nutrients, persistent organic pollutants, heavy metals, and oxygen-depleting substances). These factors degrade WQ by changing water's chemical and biological properties and disturbing the growing conditions of ecosystems (UNEP/MAP, 2009).

The changes in land and sea use, especially after the second half of the 20th century, have caused habitat degradation and biodiversity loss by both increasing pollution and overexploitation of natural resources through coastal development, agriculture, aquaculture, mining, and energy production (IPBES, 2019).

Finally, non-indigenous species (NIS) enter the eastern side of the Mediterranean through the Suez Canal (more than 50%) through the ballast waters of the ships and can drastically alter the Mediterranean biota by damaging native species (UNEP/ MAP and Plan Bleu, 2020). Increasing trade networks accelerate the pressure of NIS in the Mediterranean Sea. In addition, non-native species introduced from the south can survive northward expansion by the temperature rise in seawater, i.e., meridionalisation, and can be seen in different parts of the Mediterranean (Tsiamis et al., 2018).

Overall, the direct drivers create cumulative pressure on MCEs with the support of indirect impacts by disrupting the environmental conditions of ecosystems and causing severe reductions in ecosystem services flow. Among photosynthetic MCEs, endemic seagrasses will deserve special attention within this thesis. In the following sections, distribution trends of seagrass species in the Mediterranean, the pressures on them, and the required environmental conditions to grow healthy and to provide ecosystem services will be described, with a particular focus on *Posidonia oceanica*.

2.2.1. Seagrass meadows

Seven seagrass species characterize the Mediterranean Sea, of which *Posidonia oceanica* is the most frequent and endemic species and covers the largest area (12,247 km^2 despite the lack of data). Specifically, *P. oceanica* extends for 11,907 km along the Mediterranean coastline, while no information is available for 21,471 km for *P. oceanica* presence/absence (Telesca et al., 2015). Therefore, it is estimated that *P. oceanica* covers approximately 25,000-50,000 km^2 in the Mediterranean Sea (Pasqualini et al., 1998). In addition, other seagrass species, such as *Cymodocea nodosa*, *Zostera marina*, and *Zostera noltii*, are widespread native species in temperate coastal areas of the Mediterranean, while *Ruppia maritima* prefers salt marshes and brackish water environments. Finally, *Halophila stipulacea* and *Halophila decipiens* are invasive seagrass species introduced through the Suez Canal and ballast water (Boudouresque et al., 2021).

The distribution of seagrass species depends on multiple environmental features which vary over time. According to the analysis of seagrass area gains and losses between 1869 and 2016, an overall 21% decline was reported for the seagrass coverage on the Mediterranean coasts. More specifically, available estimations indicated that *P. oceanica* had lost 13-50% of its extent after 1960 (Marbà et al., 2014). Nevertheless, some seagrass species have gained area in some Mediterranean sites during the 2000s (de los Santos et al., 2019). For instance, the areal extent of *C. nodosa* meadows are increasing with seawater warming and replacing the decreasing *P. oceanica* (Boudouresque et al., 2021).

Increased coastal development activities, such as land reclamation, dredging and constructions, runoffs, anchoring, and trawling, are the main pressures on seagrass meadows (Otero, M.M and Pergent-Martini 2016; Pergent-Martini, Otero, and Numa 2016). These threats may cause direct mechanical damage to seagrasses, pollution, eutrophication, and turbidity in seawater. Moreover, introducing invasive species, such as marine green seaweed *Caulerpa taxifolia* and epiphytic *Lophocladia lamellandii*, may reduce seagrass coverage since they can invade seagrasses by affecting the density and complexity of meadow assemblages (Otero, M.M and Pergent-Martini 2016; Pergent-Martini, Otero, and Numa 2016).

According to the European Red List of Habitat assessment, *P. oceanica* is considered as "Vulnerable" status in the Mediterranean since there has been a significant decline in the extent of this habitat. Moreover, other seagrass species are categorized as "Least Concern" since the trend in quantity is not very well known, and their habitat is widely distributed and relatively undegraded (Micu et al., 2016). For the conservation and management of seagrass meadows in the Mediterranean, *P. oceanica* is protected by EU legislation (1992) and the Bern (1996) and Barcelona (1976) conventions, while *Zostera* species and *C. nodosa* are protected by Barcelona conventions and some national legislations and MPAs.

2.2.2. Posidonia Oceanica

This thesis focuses on analyzing environmental conditions suitable for *P. oceanica* growth. Thus, a pioneering methodology for suitability analysis will be developed for *P. oceanica* and to be applied to other species and ecosystems in the future. This section summarizes the environmental characteristics necessary for the survival and growth of *P. oceanica* scanned in the literature.

P. oceanica meadows prefer transparent, oligotrophic, and oxygenated waters to live, grow, and manage photosynthetic activity. The most important factor affecting the growth rate of *P. oceanica* meadows is temperature. It can grow well between 10-28 ℃ while sudden high temperatures and prolonged marine heatwaves reduce shoot growth and increase shoot mortality (Marbà & Duarte, 2010). The threshold value of this change is about 28-29 ℃ (Lee et al., 2007; Olsen et al., 2012). Another feature affecting the growth of *P. oceanica* is water depth, which is linked to light availability. Meadow density is highest in shallow waters (more than 1000 shoots m^{-2}), while shoot density decreases exponentially as depth increases (70-80 shoots m^{-2} at 30 m depth). It has been stated that the maximum depth for *P. oceanica* survival is around 40 meters (Hemminga, M., & Duarte, 2000). Furthermore, seagrasses grow more efficiently on protected and gently sloping marine coastal areas. However, the rising sea-level may have a regression effect on the lower limit of *P. oceanica* meadows grown on very gentle slopes (Pergent et al., 2015).

Considering light availability, the minimum threshold required for *P. oceanica* growth is 0.1-2.8 mol PAR (i.e., photosynthetically active radiation) photons $day^{-1}m^{-2}$ (Hemminga, M., & Duarte, 2000), but different factors that contribute to turbidity, such as suspended particulate matter (SPM), colored dissolved organic matter (CDOM) and phytoplankton pigment (chlorophyll), can reduce sunlight penetration in the water column (Abdelrhman, 2017b). SPM contains both inorganic and organic materials (e.g., particulate organic carbon and particulate organic nitrogen) (Fitzsimons et al. 2012) and is a significant anthropogenic pressure that originates from both land-based transportation activities, and direct interventions to the sedimentary structure (e.g., bottom trawling) that determine the resuspension of particulate matter.

Regarding the living condition related to the seabed type, *P. oceanica* prefers soft bottom substrates such as sand. It can also grow on rocky and other hard substrate types. However, on substrates with high mud content, *P. oceanica* may not sufficiently attach to the ground, requiring a higher irradiance due to the turbidity from mud. On the other hand, the dead matte of *P. oceanica* meadows is considered a very effective substrate type, especially for transplantation and regeneration (Alagna et al., 2015; Calvo et al., 2021). Moreover, the threshold of sediment accumulation rate for *P. oceanica* is 4-5 cm yr^{-1} since it is sensitive to very high sedimentation rates (i.e., erosion) that can cover and suffocate the rhizomes. However, some dynamic sediments and water systems can positively affect meadow development instead of a very low sedimentation rate (D'Angelo & Fiorentino, 2012; Manzanera et al., 2011).

A further environmental feature affecting *P. oceanica* growth is salinity. According to the literature, the optimum salinity range is between 33 and 39 PSU, while higher values increase the mortality trends. *P. oceanica* is more sensitive to salinity increment while having more tolerance for salinity reductions. This feature may be due to the terrestrial origin of seagrass ecosystems (Fernández-Torquemada & Sánchez-Lizaso, 2005).

In addition, the increased concentration of organic matter loaded into the sediment increases the oxygen consumption rate due to microbial activities through increased sulfate reduction rates in the sediment. Hence, hydrogen sulfide can increase mortality by reacting with oxygen while penetrating *P. oceanica* tissues (Pérez et al., 2007).

2.3. Data Sources and Collection for the Case Study Area

The implementation of multi-criteria approaches for suitability mapping requires integrating a huge amount of heterogeneous data from different fields. Therefore, various environmental, climatic, geomorphological, and water quality data were retrieved to spatially characterize the main drivers contributing to the suitability of *P. oceanica*. The environmental data were collected as GIS-based and NetCDF datasets to understand the suitable conditions in which seagrasses live in the Mediterranean eco-region, trying to achieve homogeneous coverage by paying attention to spatial resolutions. Publicly available data portals were used to obtain these datasets. Specifically, Copernicus Marine Environment Monitoring Service (CMEMS)[3] portal was used to retrieve climate (e.g., sea surface temperature) and hydrologic (e.g., dissolved oxygen, light attenuation coefficient) variables for the historical period (1987-

[3] http://marine.copernicus.eu/

2018). Geomorphological variables, such as bathymetry and substrate type, and seagrass distribution data in the Mediterranean were collected from EMODnet data portals (EMODnet seabed habitats[4], EMODnet bathymetry[5], and EMODnet geology[6]). Table 2.1 reports the metadata of the data collected for the suitability assessment of *P. oceanica* in the Mediterranean eco-region. Specifically, the metadata includes i) spatial domain, ii) unit of measure, iii) spatial resolution and time frame, iv) data format and data sources/web-reference.

Table 2.1. Metadata of the data collected and calculated for the implementation of NbS suitability mapping in the Mediterranean eco-region

Data type	Spatial Domain	Unit of measure	Spatial resolution	Time-frame	Data format	Reference
Environmental Parameters						
Climate						
Sea Surface Temperature (SST)	Mediterranean	[Kelvin]	0.05° × 0.05°	2008-2022	NetCDF	CMEMS (https://resources.marine.copernicus.eu/product-detail/SST_MED_SST_L4_NRT_OBSERVATIONS_010_004/INFORMATION)
Thermal Stress Duration	Mediterranean	[Day]	0.05° × 0.05°	2008-2022	NetCDF	(Calculated from sea surface temperature data)
Thermal Stress Intensity	Mediterranean	[Kelvin]	0.05° × 0.05°	2008-2022	NetCDF	(Calculated from sea surface temperature data)
Geomorphology						
Bathymetry	Global	[m]	0.001° × 0.001°	/	Raster file	EMODnet bathymetry (https:// www.emodnet -bathymetry.eu/)
Seabed Slope	Global	[%]	0.001° × 0.001°	/	Raster file	(Calculated from bathymetry data)
Substrate Type	Europe	/	/	/	Shapefile	EMODnet geology (https://www.emodnet-geology.eu/data-products/seabed-substrates/)
Hydrologic						
Nutrients (NO_3)	Mediterranean	[mmol m^{-3}]	0.042° × 0.042°	1999-2022	NetCDF	CMEMS (https://resources.marine.copernicus.eu/product-detail/MEDSEA_MULTIYEAR_BGC_006_008/INFORMATION)

[4] https://www.emodnet-seabedhabitats.eu/
[5] https://www.emodnet-geology.eu/
[6] https://www.emodnet-bathymetry.eu/

Table 2.1. Metadata of the data collected for the implementation of NbS suitability mapping in the Mediterranean eco-region case study (cont'd)

Light attenuation coefficient (K_d)	Global	[m^{-1}]	0.042° × 0.042°	1997-2022	NetCDF	CMEMS (https://resources.marine.copernicus.eu/product-detail/OCEANCOLOUR_GLO_OPTICS_L4_REP_OBSERVATIONS_009_081)
Dissolved Oxygen (DO)	Mediterranean	[mmol m^{-3}]	0.042° × 0.042°	1999-2022	NetCDF	CMEMS (https://resources.marine.copernicus.eu/product-detail/MEDSEA_MULTIYEAR_BGC_006_008/INFORMATION)
Salinity	Mediterranean	[PSU]	0.042° × 0.042°	1987-2022	NetCDF	CMEMS (https://resources.marine.copernicus.eu/product-detail/MEDSEA_MULTIYEAR_PHY_006_004/INFORMATION)
Nature-based Solutions Distributions						
Seagrass meadows	Europe	/	/		Shapefile	EMODnet Seabed Habitats (https://www.emodnet-seabedhabitats.eu/)

2.4. Data Pre-processing and Analysis

Data preparation and pre-processing were performed to represent and homogenize all input data for NbS suitability model development. This phase aims to prepare raster layers to be imported into GIS applications for mapping by homogenizing data with different spatial resolutions collected from various open-source data platforms. Moreover, this stage supports the determination of threshold values of environmental variables for *P. oceanica* survival and growth by performing a statistical analysis. Since most of the seagrass meadows in the Mediterranean are recorded and reported in the 2016-2018 timeframe, the suitability model is trained using environmental data monitored during this reference period. Then, 3-year-based metrics (i.e., mean, maximum, and minimum) were calculated and mapped, as detailed in the following paragraphs. As emerged in the literature, seagrass meadows generally live at a maximum of 45-50 meters depth (Hemminga, M., & Duarte, 2000) with some exceptions in deeper water with high water clarity (e.g., Malta), the case study area was framed up to 60 meters depth in the bathymetry layer as in Figure 2.2. Then, other environmental parameters (e.g., SST, salinity) were preprocessed according to this threshold.

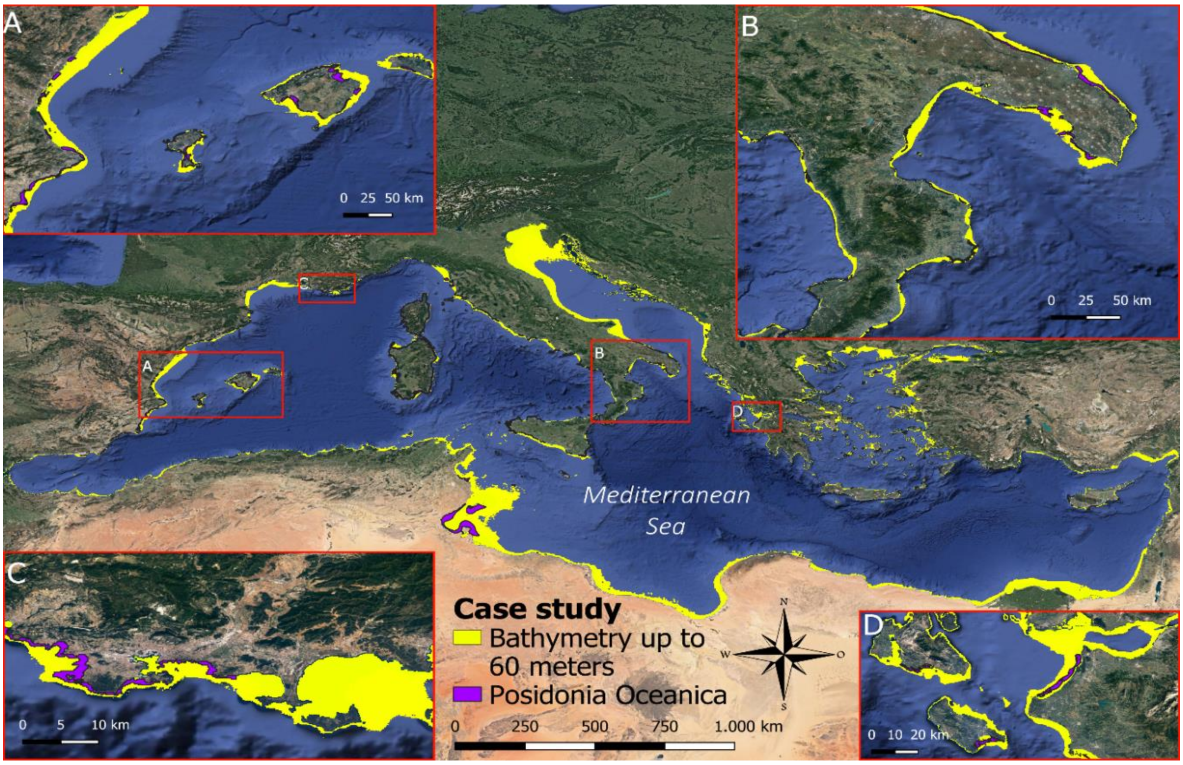

Figure 2.2. Case study area.

Climate and WQ data in the daily-mean temporal resolution were downloaded from the Copernicus Marine Environment Monitoring Service (CMEMS) using Python's *motuclient* library. It was processed with the *xarray* library, manipulating the raw data in NetCDF format. Mean, maximum, and minimum values were obtained for 2016-2018 using daily data grouped according to latitude and longitude. Data frames of environmental variables were converted to raster using the *rioxarray* library and then interpolated using the nearest method in Python, in order to include the values of environmental parameters for each pixel of seagrass meadows in the analysis.

Since this model was developed specifically for the *P. oceanica* seagrass species, seagrass polygons with EUNIS code 'A5.535' were selected and extracted from the seagrass dataset retrieved from the EMODnet Seabed Habitat data portal (for years 2016, 2017, 2018) using the GIS-tool. Accordingly, the shapefile for *P. oceanica* distribution was imported in Python using the *geopandas* library to clip environmental variables data according to the locations (latitude-longitude) where *P. oceanica* exists. An example of the resulting output from this process for salinity is displayed in Figure 2.3d. In the statistical graphs (Figure 2.3a-c), the x-axis represents the range of environmental variable values, while the y-axis represents the number of *P. oceanica* pixels (frequency) at those values of environmental variables. This gave as output three histogram graphs for mean, maximum, and minimum values, and a map of *P. oceanica* in which salinity values overlapped with the mean level of salinity for three years in the Mediterranean (lower right corner in Figure 2.3).

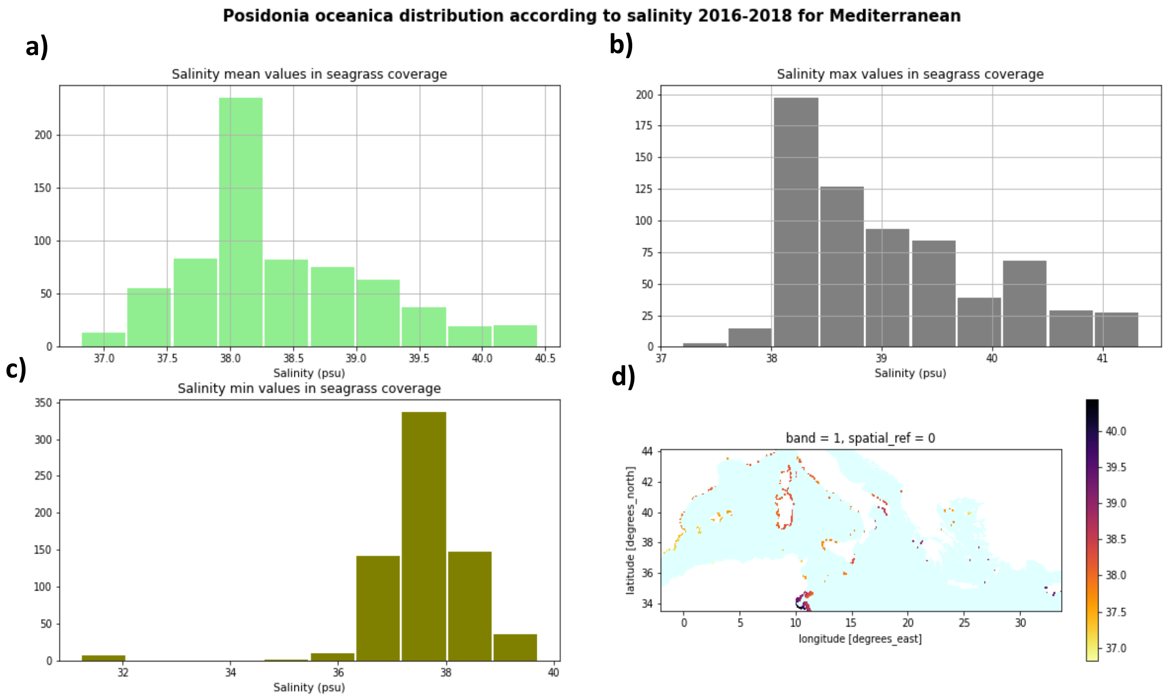

Figure 2.3. Salinity values for the P. oceanica in Eastern Mediterranean with a) average of daily mean; b) daily maximum; c) daily minimum values for three years (2016-2018); d) Map of average daily mean values in graph a.

Furthermore, the annual range of environmental variables (i.e., minimum-maximum values) in the regions with *P. oceanica* was analyzed separately for each pixel and plotted as a percentage according to the number of *P. oceanica* found. For example, the largest percentage of *P. oceanica* in the Mediterranean are exposed to SST between 13-28 °C in the annual range as graphed in Figure 2.4. The same analysis is performed for SST and WQ parameters.

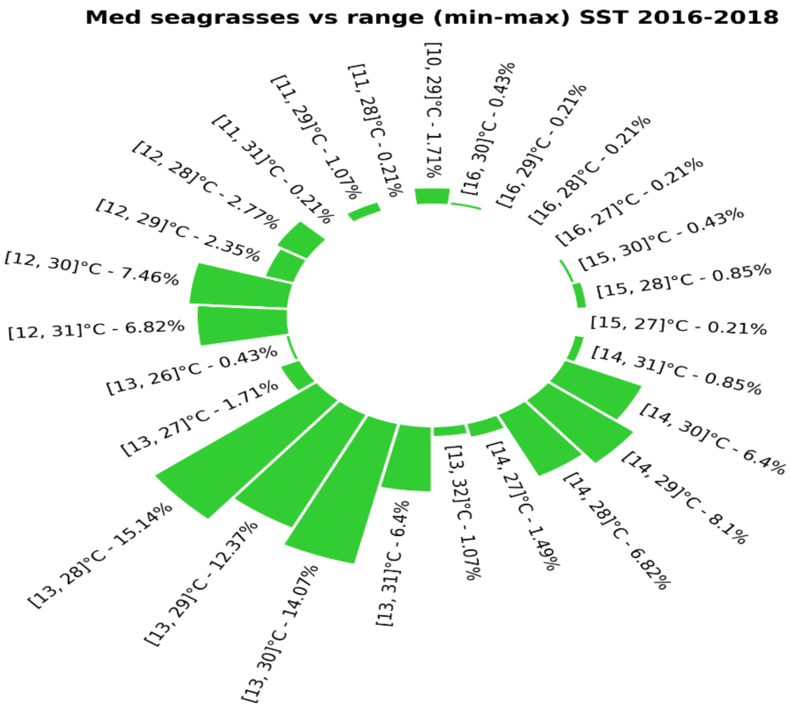

Figure 2.4. Minimum and maximum values of SST for P. oceanica in the Mediterranean.

In addition, according to literature and expert judgment, 28 °C is a critical threshold for *P. oceanica* mortality (Bennett, Alcoverro, et al., 2022). Thus, an analysis was performed for the duration and intensity of exposure above 28 °C (i.e., thermal stress on seagrass meadows). When forming datasets for thermal stress duration and intensity, the number of consecutive days that each grid was exposed to temperature values higher than 28 °C was counted, and the maximum exposure period between 2016-2018 was stored using Python. The maximum temperature value during the selected period was then extracted for each grid. In Figure 2.5, the histogram on the left represents the maximum duration, while the one on the right represents the temperature values higher than 28 °C during the maximum duration.

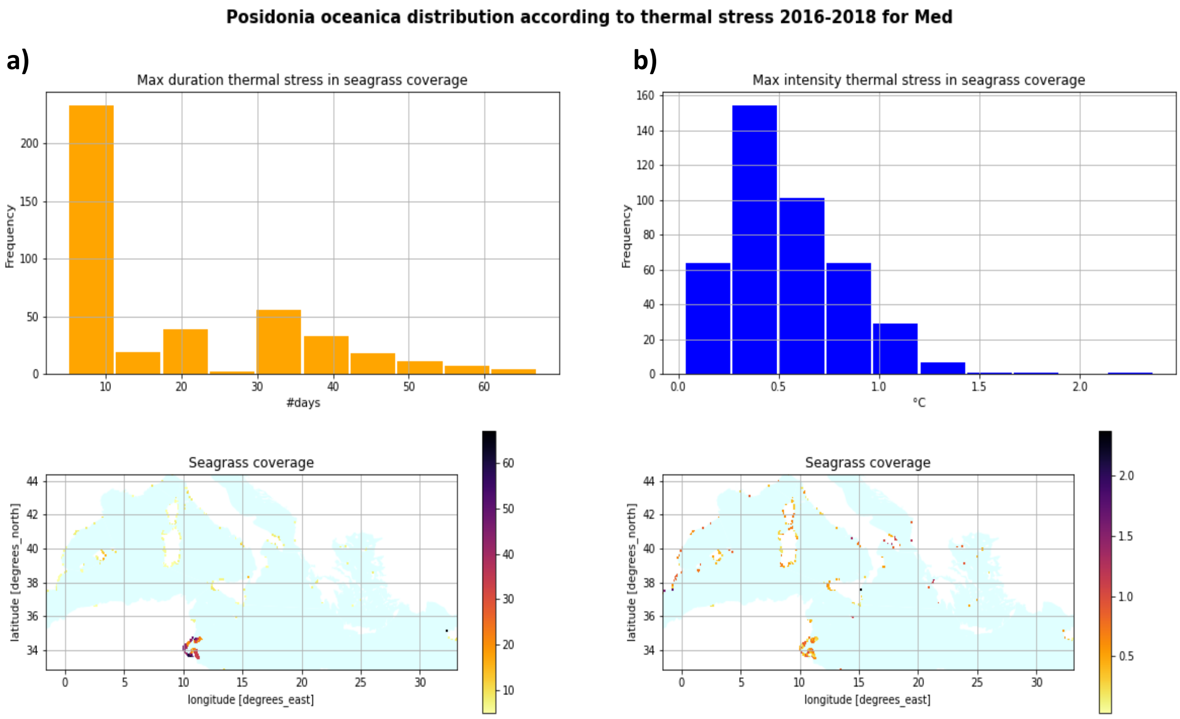

Figure 2.5. Thermal stress duration and intensity. a) Maximum consecutive days of exposure to temperature higher than 28 °C (i.e., duration); b) Maximum temperature value higher than 28 °C during the maximum duration (i.e., intensity).

Geomorphologic data were downloaded from different EMODnet data portals. The substrate type shapefile retrieved from EMODnet Geology was imported into QGIS, and a new vector layer representing the overlapping substrate polygons with *P. oceanica* polygons was created using GIS geoprocessing tools. Figure 2.6 shows the number of polygons overlapped with the substrate type.

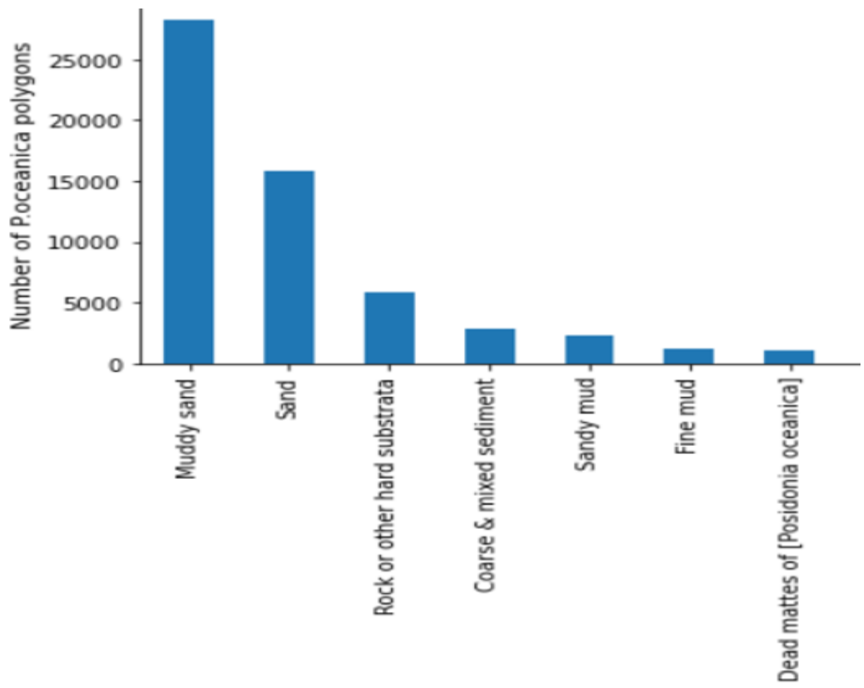

Figure 2.6. Substrate types of P. oceanica in the Mediterranean.

The bathymetry data downloaded from EMODnet was converted from the *ascii* format to *tif* and merged with the GIS tools. After importing the raster into Python, it was extracted for the areas up to 60 meters. Then, it was cropped according to the *P. oceanica* shapefile using the *rioxarray* library, and the statistical analysis of the output is reported in Figure 2.7 using the *rasterio* library. In addition, from bathymetry data, the slope layer was calculated with the GRASS tools in QGIS and imported to Python as new datasets.

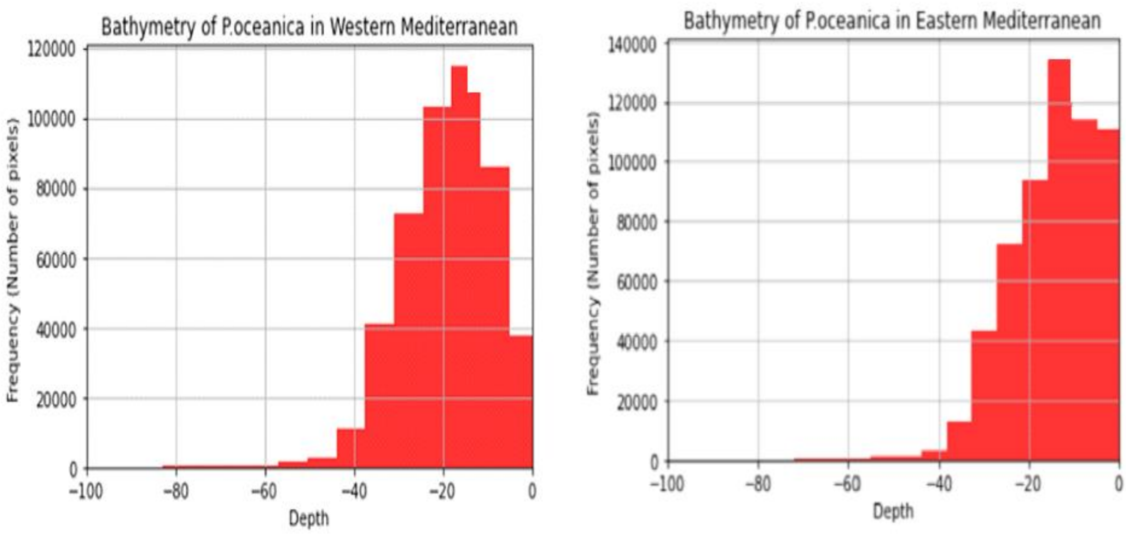

Figure 2.7. Bathymetry values of P. oceanica in Western and Eastern Mediterranean.

3. GIS-based MCDA for NbS suitability mapping

3.1. Conceptual Framework for NbS Suitability

The suitability assessment of NbS alternatives should be performed by considering and integrating environmental, socio-economic, and governmental parameters to decide on the most effective and feasible NbS implementation. The suitability assessment can be managed for different MCEs, such as saltmarshes, mangroves, and coral reefs, considering different types of parameters since the effects and importance of the parameters are not the same for the survival, growth, and effectiveness of each MCE. For NbS suitability analysis, a multi-tiers approach illustrated in Figure 3.1 is proposed. In Tier 1, NbS suitability is analyzed by considering environmental factors and setting up the SOS of these indicators for the different MCEs at eco-regional scale. The outputs of the environmental suitability of Tier 1 can be overlapped with the risk analysis and maps of ecosystems at eco-regional scale (Tier 2). Finally, NbS suitability assessment can be completed with a local scale analysis using socio-economic and governmental indicators for the effectiveness analysis of NbS implementation in Tier 3.

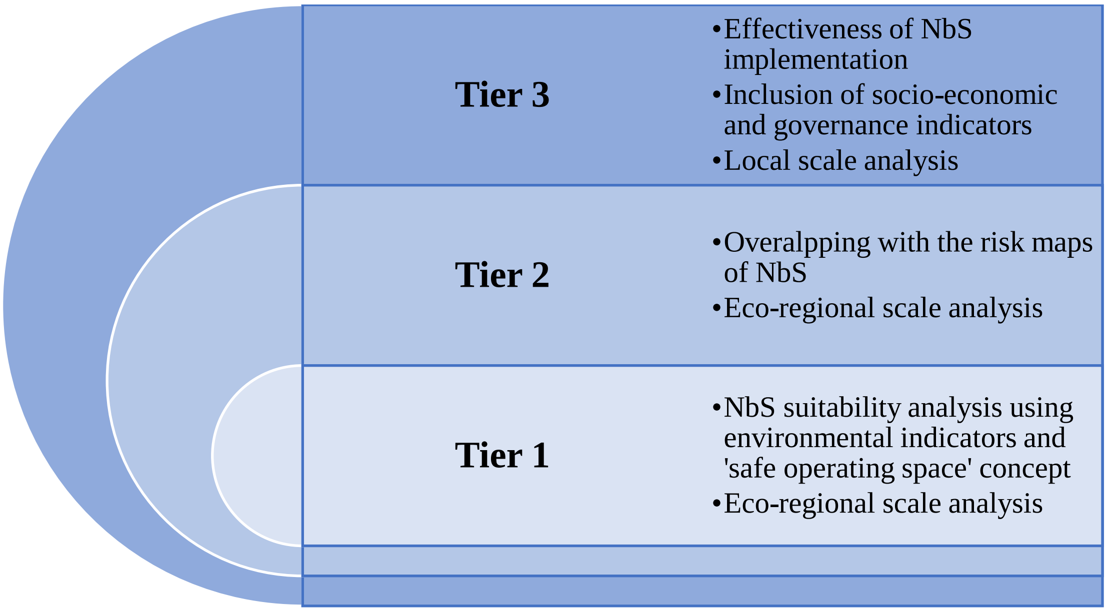

Figure 3.1. Multi-tier approach for NbS suitability assessment.

As mentioned above, Tier 1 of the multi-tier approach will be applied to seagrass meadows as training in this thesis. However, in future studies, the suitability analysis for various ecosystems with the integration of Tier 2 and Tier 3 may be effective in making a complete NbS suitability evaluation for the decision-making of the ecosystem-based approach.

This thesis is framed within Tier 1 of the NbS suitability framework, and the workflow includes (i) selecting and preparing the variables that are important for the survival and growth *of P. oceanica* using as input the environmental data, (ii) classifying and scoring the variables according to the literature review, expert opinions, and statistical distributions obtained in data pre-processing, (iii) deriving the overall suitability score for each segment of the Mediterranean coasts by combining the normalized suitability scores and the weights obtained using the AHP method performed by expert judgement.

3.2. Multi-Criteria Decision Analysis (MCDA) for NbS Suitability Model Development on Posidonia Oceanica

The assessment of suitable environmental conditions for *P. oceanica* growth is evaluated by developing a suitability model using the GIS-based MCDA method. GIS systems are effective tools for the analysis of spatial decision problems, and their integration with MCDA techniques can provide powerful models to frame complex decision-making problems involving multiple criteria by aggregating different variables into a single index. GIS-MCDA is a valuable tool for identifying and evaluating criteria and enabling ranking and/or choice among alternatives. Various MCDA approaches have different requirements, strengths, and weaknesses, but the steps followed according to the generalized MCDA process are common. GIS-based MCDA is a multi-step process that involves setting up criteria, weighting, aggregation, and geoprocessing tasks (Greene et al., 2011). In the MCDA process, the decision context is first established by structuring the problem and identifying the criteria. Secondly, the analysis step is applied by making criteria assessment, weighting, and aggregation. The raw information that shows the effect of each selected parameter is classified. Then, assigned values are converted to a dimensionless form (i.e., normalization). Weighting is applied using a proper method (e.g., random weighting, AHP, etc.) to express the relative importance of criteria on the final scores. Finally, results are obtained by combining the normalized values and weights via aggregation methods (e.g., weighted linear combination) (Adem Esmail & Geneletti, 2018).

In this study GIS-based Analytic Hierarchy Process (AHP), one of the most extended MCDA methods has been applied. Python script language was used to obtain the raster files for each environmental variable, and GIS tools (e.g., reclassification, mask creation) were used to calculate the final NbS suitability scores and maps. The workflow used for Tier 1 includes the selection of the main parameters (i.e., climate, WQ, geomorphology) and the indicators for each selected variable (e.g., SST for climate), reclassification, AHP for weighting, and GIS analysis for mapping, as illustrated in Figure 3.2.

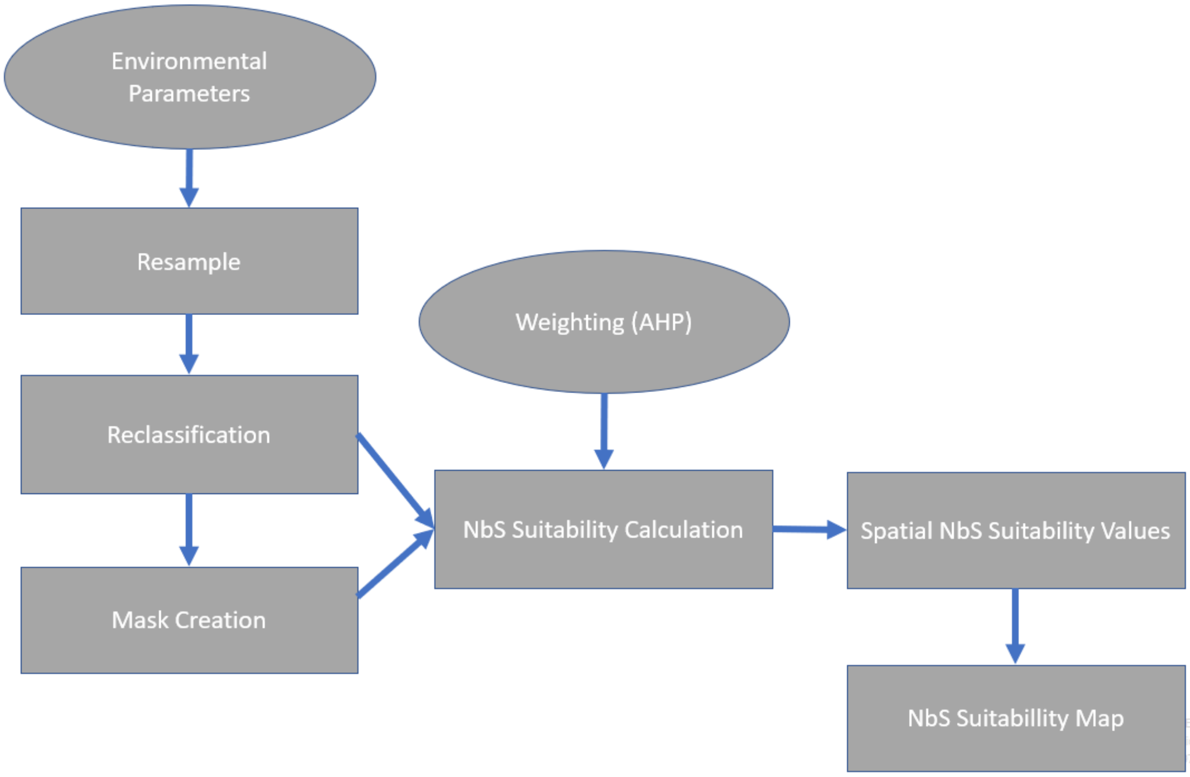

Figure 3.2. The workflow of the application.

3.2.1. Selection and Normalization of Environmental Indicators

One of the crucial steps of the GIS-based MCDA approach is the selection of variables to describe the spatial problem and provide quantifiable results. While the variables were selected based on literature review and expert opinions, ten environmental indicators were grouped into three main categories: climate, geomorphology, and WQ (Table 3.1).

SOS and thresholds were assigned for each variable based on the distribution of environmental variables in data pre-processing, non-structured discussions with the seagrass experts, and the literature review. The identified indicators need to be normalized in a standard scoring system to aggregate them, stating the contribution of each variable to the suitability. In this study, the 0-100 range was adopted for the scoring, with 100 representing the *very suitable* class. 80 and 60 were assigned for *suitable* and *moderately suitable*, respectively. As the values of indicators approach the threshold, small changes may have a large impact on the ecosystem and the state. Therefore, 30 was assigned for the *less suitable* instead of making an equal range. Lastly, since the threshold values are not very precise for each variable in literature, 10 is given instead of 0 for the *not suitable* class.

Table 3.1. Designation of suitability scores based on the range of values for each input

Variable	Classes	Suitability class	Scores
Climate			
Sea Surface Temperature (°C)	<10	Not suitable	10
	10-15	Moderately suitable	60
	15-19	Suitable	80
	19-21.5	Very suitable	100
	21.5-25.5	Suitable	80
	25.5-28	Moderately suitable	60
	>28	Not suitable	10
Thermal Stress duration (days)	<5 days	Very suitable	100
	5-10 days	Suitable	80
	10-35 days	Moderately suitable	60
	35-60 days	Less suitable	30
	>60 days	Not suitable	10
Thermal Stress intensity (°C)	0 °C	Very suitable	100
	0-0.5 °C	Suitable	80
	0.5-1 °C	Moderately suitable	60
	1-2 °C	Less suitable	30
	> 2°C	Not suitable	10
Geomorphology			
Bathymetry (m)	0-0.5	Less suitable	30
	0.5-2	Moderately suitable	60
	2-10	Suitable	80
	10-20	Very suitable	100
	20-25	Suitable	80
	25-30	Moderately suitable	60
	30-45	Less suitable	30
	>45	Not suitable	10
Seabed Slope (%)	0-0.5	Very suitable	100
	0.5-1.5	Suitable	80
	1.5-3	Moderately suitable	60
	3-5	Less suitable	30
	>5	Not suitable	10
Substrate Type	Sand or Dead matte	Very suitable	100
	Muddy sand	Suitable	80
	Rock and hard substrate	Moderately suitable	60
	Others	Less suitable	30
Water Quality			
Light attenuation coefficient (m^{-1})	<0.07	Very suitable	100
	0.07-0.11	Suitable	80
	0.11-0.2	Moderately suitable	60
	0.2-0.3	Less suitable	30
	>0.3	Not suitable	10
Dissolved Oxygen ($mmol/m^3$)	>220	Very suitable	100
	200-220	Suitable	80
	190-200	Less suitable	30
	<190	Not suitable	10
Salinity (PSU)	<33	Not suitable	10
	33-36	Less suitable	30
	36-37	Moderately suitable	60
	37-37.5	Suitable	80

Table 3.1. Designation of suitability scores based on the range of values for each input (cont'd)

	37.5-39	Very suitable	100
	39-39.5	Suitable	80
	39.5-40	Moderately suitable	60
	40-40.5	Less suitable	30
	>40.5	Not suitable	10
NO_3^- (mg/L)	<0.25	Very suitable	100
	>0.25	Not suitable	10

3.2.1.1. Geomorphology

Bathymetry, seabed slope, and substrate type were selected as key geomorphological parameters for *P. oceanica* growth. **Bathymetry** plays a crucial role since light penetration into the seafloor decreases exponentially as depth increases. Most *P. oceanica* populations in the Mediterranean Sea are found in the first 20 meters (Infantes et al. 2009). However, the shallowest parts may not be suitable for *P. oceanica* growth due to stressors (e.g., waves and temperature) (Infantes et al. 2009; Bakirman and Gumusay, 2020). High energy waves may directly disturb shallow *P. oceanica* populations or cause their burial by resuspending the sediment. Moreover, shallow populations are affected by sudden temperature elevations and variations during daytime. Therefore, 0-0.5 meters from the sea surface were assigned as not suitable. Most seagrass meadows have been found between 10 to 20 meters depth, for which higher scores and the very suitable class were assigned. Lower scores, hence suitability classes, were assigned for values above 20 meters depth due to light limitation. Values above 45 meters were considered not suitable because it is unlikely to observe extensive *P. oceanica* meadows unless water is very clear (Hemminga and Duarte, 2000).

Seabed slope is the proxy representing past and present hydrodynamic effects since geomorphology and sediment properties, especially soft sediments, depend on hydrodynamic effects (e.g., subtidal currents, wave forces) (Folmer et al., 2016). In this study, seabed slope was derived from the bathymetry layer using the GRASS tool in QGIS and expressed in percentage. Seagrass meadows require gentle slopes for their regular and continuous expansion/distribution (Tonielli et al., 2016), hence higher suitability scores were assigned to this type of slopes (<5%), while values higher than 5% were considered not suitable for *P. oceanica* growth in the Mediterranean region.

P. oceanica can grow on different **substrate type**, which is fundamental for the anchorage of plants' roots and the availability of nutrients (e.g., minerals). Substrate type is also relevant to turbidity caused by resuspension. Sand and dead matte are the most suitable substrate for *P. oceanica* growth thanks to their contribution to anchorage and nutrients (Di Maida et al., 2013). Muddy sand is considered a suitable substrate for *P. oceanica*, but sandy mud was assigned as less suitable, considering that increasing mud content contributes to turbidity (Díaz-Almela & Duarte, 2008). Moreover, although soft soils are more suitable for the growth of *P. oceanica*, rock/hard substrates were considered moderately suitable (even sometimes higher resilience to hydrodynamic impacts) (Zenone et al. 2022). *P. oceanica* can grow on seabed types other than sand and rock substrates (e.g., clay). However, since the growth performance of *P. oceanica* decreases, other seabed types were considered less suitable, and there was no substrate type assigned as not suitable.

3.2.1.2. Water Quality

P. oceanica needs transparent, oligotrophic, and oxygenated water, therefore water quality parameters have been chosen considering the main factors affecting seagrass survival and growth, as reported in Section 1.2. Accordingly, salinity, dissolved oxygen (DO), nutrient concentration (i.e., NO_3), and light attenuation coefficient (K_d) were selected as key WQ parameters.

The light availability is one of the most important parameters affecting growth and the lower limit of seagrass meadows. Many factors contribute to light attenuation in the water column, such as total suspended solids (TSS), colored dissolved organic matter (CDOM), phytoplankton pigment, absorption by pure water, backscattering by TSS and pure water (Abdelrhman, 2017a). In this study, the light attenuation coefficient (K_d) is considered the proxy representing turbidity/light availability. *P. oceanica* grown in turbid waters (K_d>0.2 m^{-1}) have a higher light requirement, while it could grow more easily in very clear waters (K_d<0.07 m^{-1}) (Duarte et al., 2013; Saulquin et al., 2013). Therefore, 0.07 m^{-1} and lower K_d values are considered very suitable, while lower scores were assigned for higher K_d values.

Nutrient concentration is linked to water transparency and clearly shows the effect of wastewater discharges on nitrogen and phosphorus dynamics. Although seagrasses need nutrients from sediment to grow efficiently, the increased dissolved nutrient concentration in water column will accelerate the growth of epiphytic algae, which may cause eutrophication and deteriorate the *Posidonia* beds. Plants and epiphytes are able to absorb and directly use nitrogen when in **NO_3** state, which was selected to represent nutrients for *P. oceanica* suitability in this study. Indeed, the increase in NO_3 concentration in the water column may also cause direct physiological responses in seagrass meadows independent of algal light attenuation (Lee et al., 2007; Leoni et al., 2007). Considering the threshold shared by Italy and Greece, 0.25 mg/L is selected as the threshold for NO_3 concentration, which is usually low in the Mediterranean water column (< 0.25 mg/L), except for high river input areas, hence lower scores are assigned higher than 0.25 mg/L (Poikane et al., 2019; Lee et al., 2007).

Even though seagrass meadows can regulate **dissolved oxygen (DO) concentration,** low oxygen availability significantly affects species' distribution and health status. Compounds with high carbon content favor higher oxygen consumption rates, deoxygenation, and anoxic conditions, which in turn reduce biodiversity, degrade the habitat assemblages, and threaten species that rely on seagrass beds for shelter and food purposes (Altieri et al., 2019; Stramma & Schmidtko, 2019). In addition, at low oxygen availability, hypoxia can cause sulfide invasion on seagrasses and affect their growth and photosynthesis, and the oxygen required to face toxic sulfide may not be supplied due to deoxygenation.

DO saturation is a dependent variable on temperature and salinity, and a minimum value of 80% is required for marine life to be healthy (CWT, 2004). The lower levels of DO concentration in the water column were set up by considering the minimum levels needed by marine life in the Mediterranean Sea. The water temperature and salinity of the Mediterranean Sea were assumed as constant over the reference period, 19 °C and 38.5 PSU, respectively. The threshold value for DO was assigned at 190 mmol/m^3, below which were considered not suitable, while higher scores were assigned as very suitable as DO concentration increases.

P. oceanica species are sensitive to changes in **salinity** levels in seawater, and values above 39-40 PSU accelerate its mortality rate. Hence, discharge of brine water with salinity content higher than 40 PSU threatens the survival of *P. oceanica* meadows (Ruíz et al., 2009). A salinity gradient exists between western and eastern Mediterranean Sea, with slightly higher values in the eastern part of the Mediterranean basin. *P. oceanica* meadows can have different salinity tolerance thresholds by adapting to natural conditions of the area where they grow. (Sánchez-Lizaso et al., 2008). *P. oceanica* populations in the western Mediterranean are located in areas with salinity values (38-38.5 PSU) similar to the eastern Mediterranean (e.g., Tyrrhenian, Ligurian, and Balearic seas). Thus, in this thesis, an overall suitability classification was performed for the whole Mediterranean Sea. Since the mortality of *P. oceanica* populations increases at salinity values over 40-40.5 PSU, higher suitability scores were assigned to the values below this threshold (e.g., 37.5-39 PSU as very suitable). On the other hand, the lower threshold for *P. oceanica* tolerance is identified as 33 PSU, and lower suitability scores were assigned as salinity decreases below 37.5 PSU. (Ruíz et al., 2009; Sánchez-Lizaso et al., 2008).

3.2.1.3. Climate

Sea surface temperature (SST), thermal stress duration and intensity were selected as key variables for the climatic group. *P. oceanica* tolerates a wide range of **SST** (10-28 °C) (Chefaoui et al., 2017). Within the tolerance range, the 19-21.5 °C range was classified as very suitable for *P. oceanica* growth and photosynthetic activity (Tudela et al. 2010; Bennett, Vaquer-Sunyer, et al. 2022; Lee, Park, and Kim 2007), while lower scores were assigned for values above or below the optimal range. SST values higher than 28 °C were considered not suitable since 28 °C is a threshold. When exceeding this value, *P. oceanica* is in a thermal stress condition that inhibits its growth and functioning (Chefaoui et al., 2017; Marbà & Duarte, 2010).

Prolonged **thermal stress** negatively affects *P. oceanica* growth, increasing shoot mortality, especially at temperatures over 28 °C (Bennett, Alcoverro, et al., 2022). Therefore, the maximum time of exposure to temperature values higher than 28 °C was extracted for each grid between 2016-2018 to classify the **thermal stress duration** and **intensity**. While setting up suitability classes for the maximum thermal stress duration, five consecutive days were selected as the threshold according to the marine heatwaves (MHW) definition by Hobday et al. (2016). Regions exposed to 28 °C for less than five consecutive days were considered as very suitable for *P. oceanica* growth. Lower scores were designated as the maximum exposure duration to temperatures higher than 28 °C increases (i.e., greater than five consecutive days).

On the other hand, the maximum temperature value during the selected maximum duration is used for thermal stress intensity. Regions without exposure to temperatures higher than 28 °C have been assigned as very suitable for the growth of *P. oceanica*. As the exposed maximum temperature value increases, lower scores were assigned (i.e., lowest scores at temperatures higher than 30 °C).

3.2.2. Analytic Hierarchy Process

The method for NbS suitability scores is developed by integrating AHP, which is one of the most preferred MCDA methods in land suitability analysis to solve complex decision-making problems. AHP, developed in the 1970s, is one of the widely used weighting methods for multi-variables using pairwise comparisons (T. L. Saaty, 1980). The relative importance of criteria determined according to expert scoring can be derived via AHP to assign the final weights to variables. It is essential to integrate relative importance when calculating the suitability scores for more robust decision-making, but final weights should be reliable to incorporate into the calculations.

Pairwise comparison matrices are used in AHP to decide the relative significance of variables by comparing all the variables one-to-one. The values are selected for the pairwise comparison matrices by experts with scores between 1-9, according to the standard scale introduced by Saaty (1980). The intensity of importance represented by the values is in Table 3.2. Since the rows and columns of pairwise comparison matrices are symmetrical and created from variables in the same order, all the values in the diagonal part of the matrix have a value of 1 (i.e., equal importance) because the row and column have the same variable. However, if the variable A in the row has extreme importance compared to the variable B in the column, the value 9 is assigned to raw A column B. Accordingly, the reciprocal value of 1/9 is given when the variable B in the row is compared to the variable A in the column.

Table 3.2. Intensity of importance on an absolute scale (R. W. Saaty, 1987)

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement moderately favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Very strong importance	Activity is strongly favored, and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgements	When compromise is needed

This matrix is normalized to compute the priority vector, which is the normalized eigenvector of the matrix. Normalization is performed by dividing each value into columns by the total value of that column. The final weights of variables are obtained by calculating the arithmetic mean of the normalized values.

One of the most significant features of AHP is to measure the consistency of the results from pairwise matrices (i.e., final weights). This is calculated through the consistency ratio (CR), which indicates the likelihood that the comparison matrix judgments were assigned randomly through Equation 1.

$$CR = \frac{CI}{RI} \quad \text{Eq.1}$$

CI: Consistency index (expressed as Equation 2)

RI: Random index (the average of the resulting CI values of comparison matrices with various matrix sizes using a sample size of 500, expressed in Table 3.3. (R. W. Saaty, 1987))

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad \text{Eq.2}$$

λ_{max}: the largest principal eigenvalue of the matrix (maximum eigenvalue)

n: the order of matrix (the number of criteria or sub-criteria)

Table 3.3. Random index values according to the size of the matrix (R. W. Saaty, 1987)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The magnitude of the CR should have a value of 0.1 or less for the weights derived to provide a reasonable level of consistency (R. W. Saaty, 1987).

In this study, climate, WQ, and geomorphology will be calculated separately using the simple weighted sum approach with the following equations as follows:

$$\sum_{1}^{n} Climate\ suitability == w_1x_1 + w_2x_2 + \ \dots\dots\dots + w_nx_n \quad \text{Eq.3}$$

$$\sum_{1}^{m} Water\ quality\ suitability == w_1x_1 + w_2x_2 + \ \dots\dots\dots + w_mx_m \quad \text{Eq.4}$$

$$\sum_{1}^{l} Geomorphology\ suitability == w_1x_1 + w_2x_2 + \ \dots\dots\dots + w_lx_l \quad \text{Eq.5}$$

x, y, z: climate, WQ, and geomorphology parameters, respectively

n, m, l: Number of indicators in a sub-group for climate, WQ, and geomorphology, respectively

w: Weighting coefficient factors defined for each indicator

SECTION C: APPLICATION TO THE CASE STUDY AREA

4. Results and Discussion: Suitability Mapping using GIS-based AHP in the Mediterranean Eco-region

4.1. Analytic Hierarchy Process

The AHP method was applied to the Mediterranean case study following the process described in Section 3.2.2. Specifically, the weights of the parameters were derived, and CRs were calculated using pairwise comparison matrices scored by the expert from MaCoBioS project. The scores were assigned separately for climate, WQ, and geomorphology sub-groups. While the CR for geomorphology was 0.047, the weights of bathymetry, seabed slope, and substrate type parameters were 0.66, 0.21, and 0.13, respectively. The CR for WQ was 0.036, while the weights of salinity, DO, K_d, and NO_3 variables were 0.09, 0.09, 0.54, and 0.29, respectively. Lastly, the CR for climate was 0, and the weights of SST, thermal stress duration, and thermal stress intensity variables were obtained as 0.14, 0.43, and 0.43, respectively. As a result, since the weightings show satisfactory CR values below 0.1, the weights can be used to calculate the suitability scores. Expert scores and CI, RI, and CR values for climate, WQ, and geomorphology parameters are in Table 4.1- 4.3.

Table 4.1. Pairwise comparison matrix to determine the weights of the geomorphology indicators

Parameter	Bathymetry	Slope	Substrate Type
Bathymetry	1	4	4
Seabed Slope	0.25	1	2
Substrate Type	0.25	0.5	1
n =3, λ = 3.05, CI=0.03, RI=0.58, CR=0.047			

Table 4.2. Pairwise comparison matrix to determine the weights of the WQ indicators

Parameter	Light attenuation coefficient (K_d)	Salinity	DO	Nutrients (NO_3)
Light attenuation coefficient (K_d)	1	5	5	3
Salinity	0.2	1	1	0.25
Dissolved Oxygen (DO)	0.2	1	1	0.25
Nutrients (NO_3)	0.33	4	4	1
n =4, λ = 4.10, CI=0.03, RI=0.90, CR=0.036				

Table 4.3. Pairwise comparison matrix to determine the weights of the climate indicators

Parameters	SST	Thermal Stress Duration	Thermal Stress Intensity
SST	1	0.33	0.33
Thermal Stress Duration	3	1	1
Thermal Stress Intensity	3	1	1
n =3, λ = 3, CI=3, RI=0.58, CR=0			

4.2. Suitability Scores and Maps for *P. oceanica* in the Mediterranean Eco-region

Once implemented the methodological steps for the suitability calculation, the resulting outputs of the suitability assessment for *P. oceanica* in the case study area have been reported in this section. After having normalized the variables as reported in Table 3.1, suitability scores for geomorphology, water quality, and climate were obtained by multiplying the normalized variables by the derived weights using the simple weighted sum approach (see Section 3.2.2) for each grid. This allowed to create the suitability maps and to identify the total area of each suitability class for climate, water quality, and geomorphology.

Final suitability scores were partitioned into five classes between 0-100 according to the lowest and highest suitability. Values up to 30 were assigned as *not suitable* because if the final score is below 30, at least one variable is in the *not suitable* class. 30-50 was identified as *less suitable*, 50-70 as *moderately suitable*, 70-90 as *suitable*, and 90-100 as *very suitable*. Based on this classification, the suitability of the Mediterranean eco-region for *P. oceanica* was ranked using aggregated scores for geomorphology, water quality, and climate, as reported in sections 4.2.1 – 4.2.3. Suitability maps for each sub-group were obtained in 0.001^{o} x 0.001^{o} grids. Final map was formed for *P. oceanica* by intersecting the suitable and very suitable areas in each sub-group, as reported in section 4.2.4. Maps and statistics developed through the GIS-based AHP in the case study are presented and discussed in the following sections.

4.2.1. Geomorphology

The resulting geomorphologic suitability scores and maps are shown in Table 4.4 and Figure 4.1. A great heterogeneity is highlighted in suitability scores and classes from not suitable to very suitable, 37.5% of the areas are very suitable and suitable, although 37.8% are defined as less suitable (Table 4.4.).

Table 4.4. Percentage and total area of geomorphology suitability classes for P. oceanica in Mediterranean marine coastal areas

Suitability	**Percentage (%)**	**Area (km^2)**
Not suitable [0,30)	7.8	14,869
Less suitable [30,50)	37.8	72,009
Moderately suitable [50,70)	16.9	32,216
Suitable [70,90)	23.6	44,951
Very suitable [90,100]	13.9	26,522

Geomorphologic suitability mainly decreases according to bathymetry, which has the highest weight compared to the seabed slope and substrate type. In this study, marine coastal areas of the Mediterranean Sea were mapped up to 60 meters depth since seagrass populations (even if very few) can be found at a depth of around 50-55 meters if conditions of clear seawater and rare thermal stress events are met. However, areas between 45-60 meters were unsuitable for efficient growth of seagrasses due to light limitations. In Figure 4.1, a large areal extent for geomorphologic suitability can be seen in the Northern Adriatic and the southeast of Tunisia (i.e., Gulf of Gabès) since they have a large shallow water. The Gulf of Lion, the northern part of Spain and Greece, and the eastern part of Egypt also have significant suitable areas.

In addition to shallow waters, seagrass meadows prefer gentle slope areas in which the hydrodynamic effects (e.g., waves, currents) are reduced, but rather lower wave energy and stable sediment with high matte accumulation favorite seagrass growth. Seabed slope usually has low percentage values on most of the Mediterranean coasts, hence it contributes with high scores to the geomorphologic suitability for most of the case study area. On the other hand, relatively steep slopes cause irregular coastlines, limiting the seagrass beds' expansion. Therefore, geomorphologic suitability is more patchy on the northern Mediterranean coasts of western Liguria and eastern Cote d’Azur (from Genoa to Nice), western Corsica, and Elba island due to deep water and relatively steep slope conditions. Similarly, Western Algeria and Morocco coasts in the southern Mediterranean have small suitable areas due to steeper slopes. Hence, seagrass undercover would be lower compared to the length of the shoreline in these areas. In order to make a more precise evaluation of the hydrodynamic effects on seagrass meadows, a proper wave model can be integrated.

Considering only the substrate type, the large area of sandy mud and fine mud on the Italian coastline (from Venice to Apulia) reduces the geomorphological suitability due to the contribution of the high mud ratio to turbidity. However, since the relative importance of substrate type is less than bathymetry and seabed slope, the overall geomorphological score is high on this coastline.

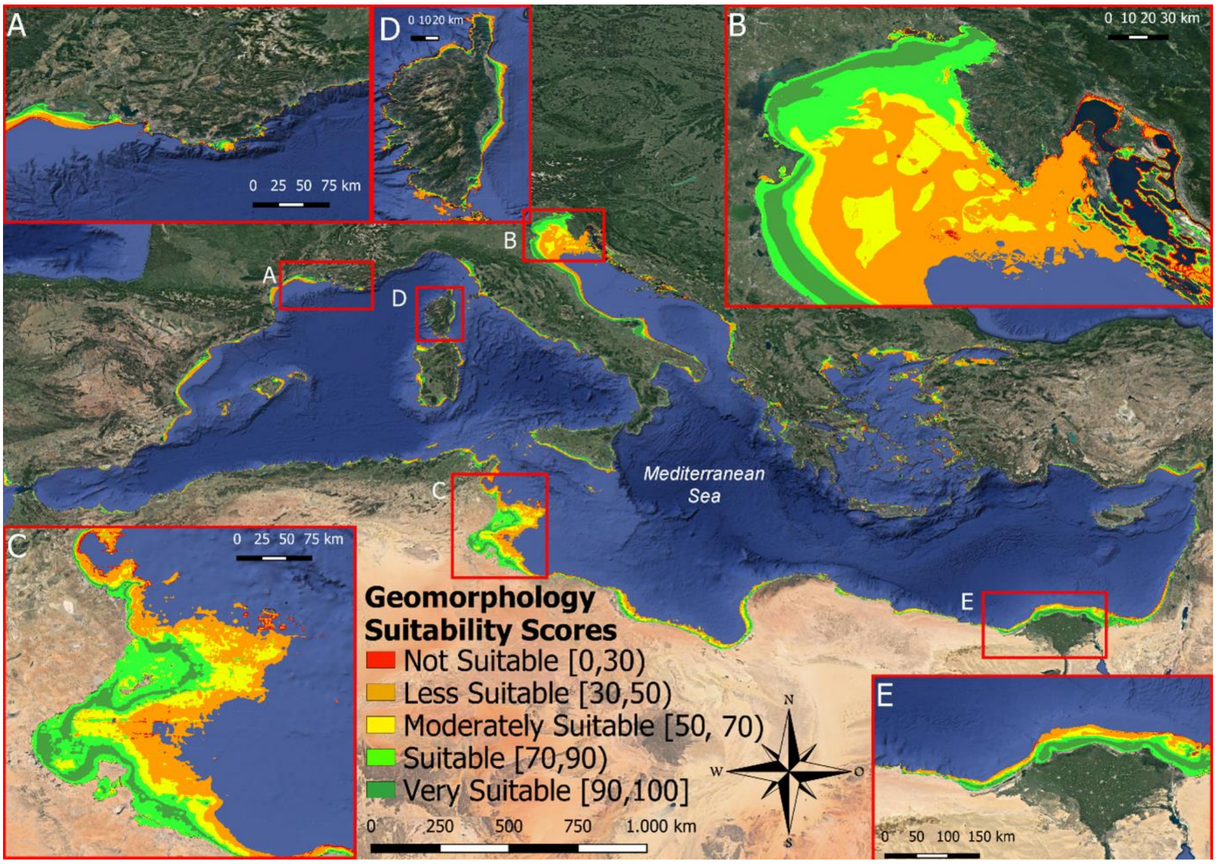

Figure 4.1. Suitability map of P. oceanica for geomorphology (A: western Mediterranean; B: Northern Adriatic; C: Gulf of Gabès; D: western Corsica; E: Egyptian coasts).

4.2.2. Water Quality

The final scores of WQ show that 84.75% of the total area is very suitable and suitable classes for *P. oceanica*. This result is highly relevant to the oxygenated, oligotrophic, and transparent water characteristics of the Mediterranean Sea. The distribution of the total area for each suitability class and suitability map for WQ can be seen in Table 4.5 and Figure 4.2. Although the total area of the not suitable and less suitable classes is very small (i.e., 1.9%), attention should be paid to moderately suitable areas (i.e., 13.4 %) as the WQ may affect *P. oceanica* meadows growth.

Table 4.5. Percentage and total area of WQ suitability classes for P. oceanica in Mediterranean marine coastal areas

Suitability	Percentage (%)	Area (km^2)
Not suitable [0,30)	0.14	271
Less suitable [30,50)	1.73	3,290
Moderately suitable [50,70)	13.38	25,472
Suitable [70,90)	15.19	28,922
Very suitable [90,100]	69.56	132,410

The areas of less suitable and moderately suitable regions are primarily located in the Northern Adriatic and south/southeast Mediterranean (i.e., Egypt, Tunisia). The main reason for lower WQ scores in the Northern Adriatic (i.e., Veneto region) is the excessively high NO_3 concentration compared to the Mediterranean coasts (Figure 4.2, box B), which registered many pixels with values around 1 mg/L of NO_3. Moreover, light attenuation coefficient values decreased the WQ score in this area. Similarly, the WQ in the area where the Rhone River flows into the Mediterranean Sea on the coast of France has the lowest values in the western Mediterranean (Figure 4.2, box A). Even if the values are reported in the moderately suitable class, WQ may threaten the *P. oceanica* around the west and east side of the Rhone River. In addition to the high NO_3 concentration for Egyptian coasts (Figure 4.2, box E), high light attenuation coefficient values indicate that light penetration is low in seawater. In southeastern Tunisia, high turbidity (i.e., light attenuation coefficient) and salinity values made the WQ moderately suitable in the innermost parts of the Gulf of Gabès (Figure 4.2, box C). In particular, increases in salinity with increased temperature and evaporation can significantly affect the suitability of *P. oceanica* in this region.

While WQ suitability scores increase as moving away from the coasts, geomorphologic suitability decreases. On the other hand, seagrass meadows can grow in clear seawater even if the geomorphological characteristics have low suitability. For example, western Corsica presents moderately suitable geomorphological conditions and high WQ scores which allow *P. oceanica* populations to survive (Figure 4.2, box D).

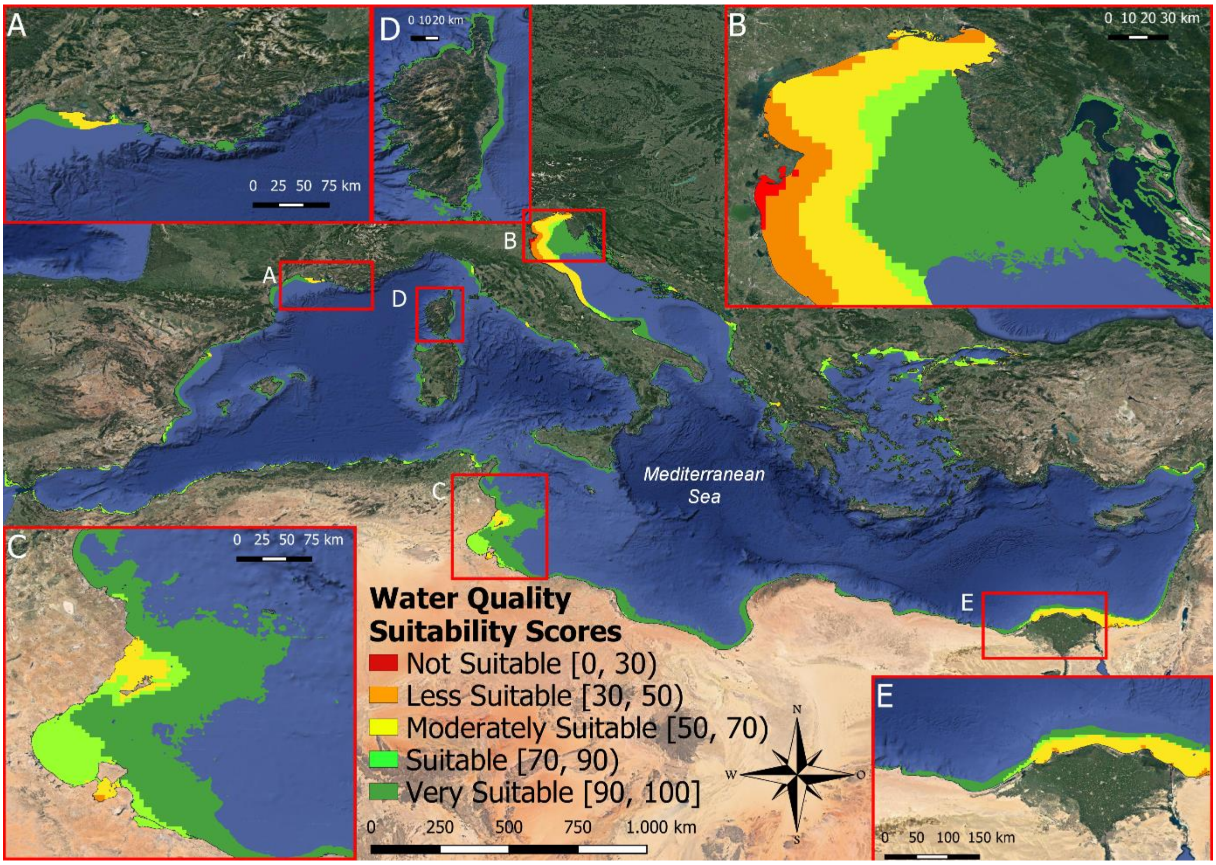

Figure 4.2. Suitability map of P. oceanica for WQ (A: western Mediterranean; B: Northern Adriatic; C: Gulf of Gabès; D: western Corsica; E: Egyptian coasts).

Overall, the Mediterranean Sea presents high WQ scores, but the influence of WQ parameters on suitability can be different in terms of scales and causes. Local-scale analysis can provide more precise outputs and show the effects of anthropogenic pressures, supporting an understanding of the specific WQ issue and possible measures. For example, aquaculture systems and wastewater inlets have a high level of particulate matter, which has a significant environmental impact at small scale. While high particulate matter concentration can cause over sedimentation on shallow seagrasses, it limits the light availability of deep seagrass populations.

Moreover, seagrass meadows can increase their tolerance according to the parameter values in the environment where they are grown. For example, seagrass meadows in the eastern Mediterranean can grow efficiently at slightly higher salinities than in the western Mediterranean. Typically, around 39 PSU appears as a threshold for *P. oceanica*, while they can resist up to 40 PSU in the eastern Mediterranean. For that reason, local scale analysis can give more robust results. In addition to the spatial scale, the temporal scale is essential in WQ evaluation. Although the case study area shows high WQ values on average, meaning good environmental status, prolonged exposure to poor WQ values that exceed the threshold values affects seagrass meadows' growth and survival.

4.2.3. Climate

The climate parameters present very suitable and suitable conditions for *P. oceanica* growth, reaching an overall score of 72.3%. These results are in line with the favorable conditions of the Mediterranean Sea, with mild temperatures over the year. However, moderately suitable and less suitable classes cover substantial areas (Table 4.6).

Table 4.6. Percentage and total area of climate suitability classes for P. oceanica in Mediterranean marine coastal areas

Suitability	Percentage (%)	Area (km^2)
Not suitable [0,30)	1.94	3,698
Less suitable [30,50)	8.00	15,254
Moderately suitable [50,70)	17.75	33,827
Suitable [70,90)	22.74	43,326
Very suitable [90,100]	49.57	94,458

Considering the lower climate suitability scores, the Northern Adriatic and the coasts of the western Calabria are the areas with lower suitability scores for *P. oceanica* growth, compared to the rest of the western-northern Mediterranean. As well, the south (i.e., Tunisia and Libya) and especially east/southeast (i.e., Egypt, Lebanon, south Turkey) Mediterranean are less suitable for *P. oceanica*. Although the average SST of the Mediterranean is generally favorable for *P. oceanica*, thermal stress duration and intensity have a large impact on the overall weights that make such areas less suitable to seagrasses.

More specifically, the areas on the eastern coasts of Egypt (Figure 4.3, box E) have temperature values higher than 30 °C for about 2 months, which reduce the climate suitability of this area. On the other hand, southeastern Tunisia (Figure 4.3, box C) has long-term exposure to SST above 28 °C, but the maximum temperature reaches around 28.5-29 °C, which overlap with increasing salinity values that limit the growth of *Posidonia* meadows. Conversely, even though high SST values last only for few days in the Northern Adriatic (Figure 4.3, box B), temperature can reach 30 °C under thermal stress conditions. Exposure to thermal stress is higher in the southern Mediterranean, thus triggering a reduction in the shoot density of meadows.

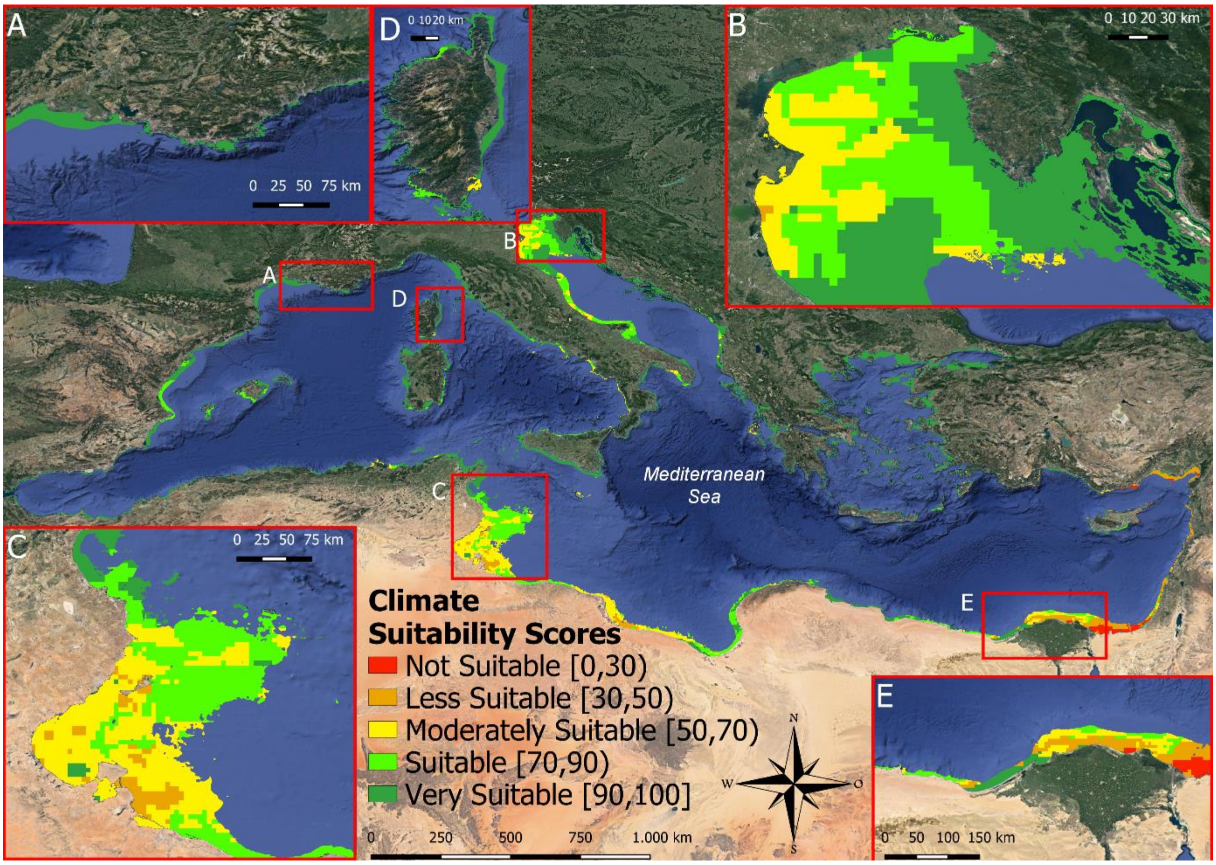

Figure 4.3. Suitability map of P. oceanica for climate (A: western Mediterranean; B: Northern Adriatic; C: Gulf of Gabès; D: western Corsica; E: Egyptian coasts).

The results of this study are obtained based on the thermal stress event having the maximum duration in 2016-2018 and the maximum SST recorded during the maximum duration. However, higher number of thermal stress/heatwave events with different intensity can impact the survival and growth of seagrass meadows over the baseline period. Therefore, integrating the effects of each thermal stress/heatwave in the analysis can provide a more robust model.

4.2.4. Final Suitability Map and NbS measures

The final suitability map is created by extracting the intersecting/overlapping suitable and very suitable areas of all sub-groups (i.e., geomorphology, water quality, and climate) to explore the most suitable areas for the growth of *P. oceanica.* After selecting suitable and very suitable areas in the geomorphological assessment (Figure A.1 in Appendix A), WQ classes were overlaid in the selected areas (Figure A.2 in Appendix A), and suitable and very suitable WQ areas were extracted. Finally, climate classes were overlaid (Figure A.3 in Appendix A), and suitable and very suitable areas were extracted to obtain the final suitability map, as illustrated in Figure 4.4. Climate factors, although crucial for seagrass growth, were considered the tertiary suitability stage since growing *P. oceanica* in areas unsuitable in terms of geomorphology and WQ can be very challenging independently of climate criteria. Therefore, step-by-step evaluation may give better results to support the decision-making of suitable areas and the definition of proper management and restoration actions.

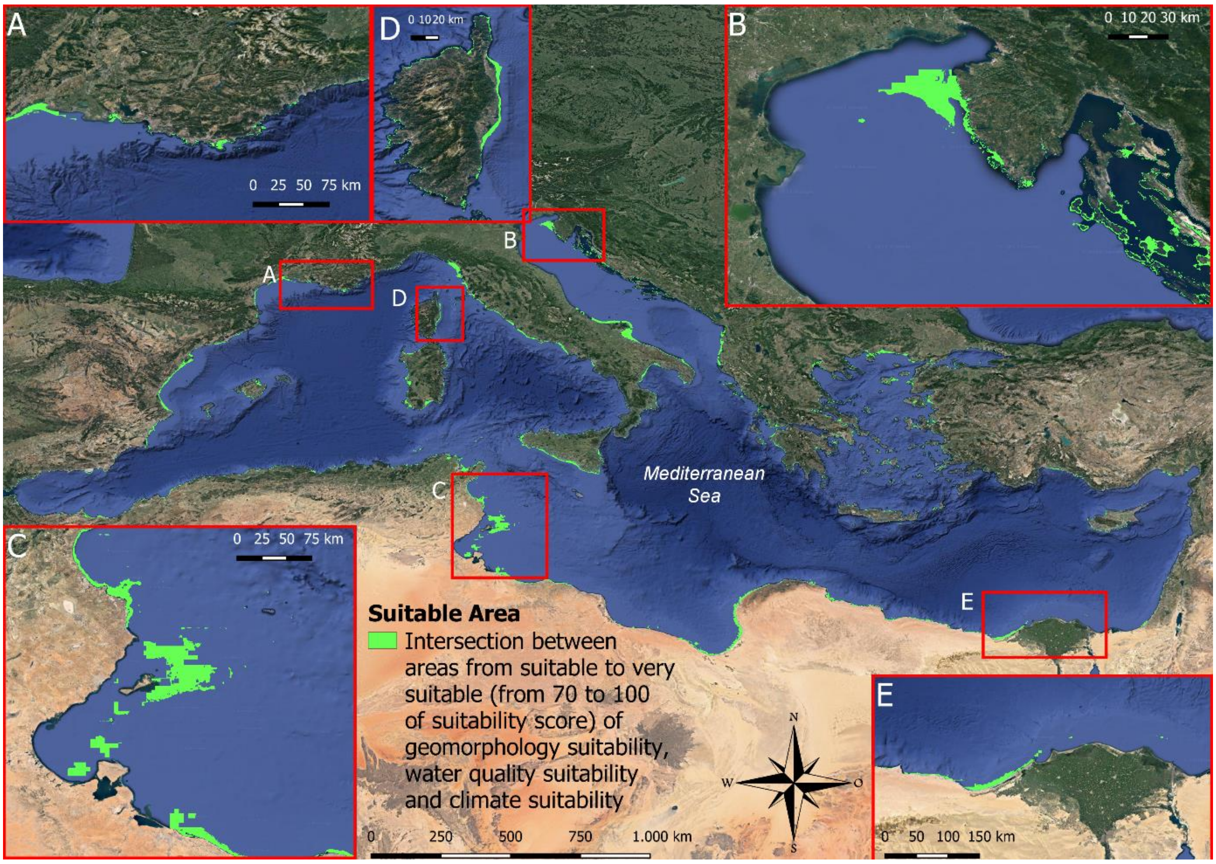

Figure 4.4. Suitable and very suitable areas overlapped for geomorphology, WQ, and climate (A: western Mediterranean; B: Northern Adriatic; C: Gulf of Gabès; D: western Corsica; E: Egyptian coasts).

Overall, a total area of 17,780 km^2 was obtained as the intersection of suitable and very suitable areas of geomorphology, WQ, and climate assessment. Western Italian coasts (Tuscany, Lazio), Apulia, southern Sicily, and Sardinia have large suitable areas. Although most of the Northern Adriatic is not included due to less suitable WQ scores, northern Croatian coasts have suitable areas as well (Figure 4.4, box B). Moreover, the coastline of Spain (from Valencia to Barcelona), Gulf of Lion, and eastern Corsica (Figure 4.4, box A and D) have a valuable extent of suitable areas in the Western Mediterranean.

The extent of suitable areas for *Posidonia* is high on the coasts of Libya and Tunisia in the Southern Mediterranean. However, the inner parts of the Gulf of Gabès are not included in this map due to the moderate climate (i.e., thermal stress) and WQ scores (i.e., salinity and light attenuation), as mentioned in the previous sections. In the Eastern Mediterranean, a large suitable area for *P. oceanica* is available on the coasts and islands of Greece.

In the environmentally suitable and very suitable areas represented in Figure 4.4, transplantation/restoration of *P. oceanica* can be considered an NbS measure for seagrass expansion in regions where the current seagrass population is absent or low. Restoration activities can also be a measure in these areas if the seagrass populations are degraded. However, transplantation/restoration may need to be applied with conservation and management measures since *P. oceanica* is a slower-growing species than other seagrass species (e.g., *Zostera marina*, *Cymodocea nodosa*) (E. Díaz-Almela, 2008; Marbà, Duarte, et al., 1996). Human-induced pressures should not be intense for the planted seagrass shoots to be colonized and recover in good health status. Construction activities, local impacts (e.g., dredging actions), or natural causes of disturbance (e.g., storms, erosion) can reduce the success of transplantation/restoration activities. Moreover, transplanting projects require analysis of transplanting techniques (i.e., anchorage), transplanting costs, estimation of *P. oceanica* growth rate for the expected colonization, regression reasons (e.g., economic activities), and investment in reducing pressures (e.g., water treatments) (Díaz-Almela & Duarte, 2008).

For existing *P. oceanica* populations outside the suitable layers identified in Figure 4.4, management and protection actions (e.g., MPAs) can be considered instead of restoration since the environmental conditions may not support *P. oceanica* growth efficiently. The first aim of the management and conservation activities should be to provide proper water and sediment conditions and prevent siltation and erosion. In order to identify proper protection levels, seagrass meadows' vulnerability and ecological conditions need to be analyzed at local scale. Complementary management actions supporting MPAs (e.g., seagrass-friendly moorings, management of stranded seagrass litter, control of invasive species, and dredging recovery) can be implemented to integrate coastal zone management and marine spatial plans and reduce pressures on the land-sea interface.

CONCLUSION

This thesis provided NbS suitability assessment and mapping in the Mediterranean eco-region using a GIS-based MCDA method integrating multiple environmental indicators. To this aim, the state-of-the-art approaches for suitability modeling in marine coastal environments were analyzed, and GIS-based monitoring data for the investigated region were collected and pre-processed.

Building on the review, the NbS suitability model was developed for seagrass meadows using GIS-based AHP, tailoring environmental variables' classes and scores to the Mediterranean Sea case study. Suitability scores and maps were obtained against its application for the baseline scenario (i.e., 2016-2018, the years showing a more complete seagrass record). In particular, a set of geomorphologic, water quality, and climate parameters were preliminarily selected based on the performed literature review and expert judgement, as well as by considering data availability at the Mediterranean scale. Bathymetry, seabed slope, and substrate type were chosen to fit with the geomorphology group; salinity, DO, NO_3 concentration, and K_d were then considered in the WQ group; finally, SST and thermal stress duration and intensity were integrated into the climate group. GIS-based environmental data useful to feature these variables were retrieved from open-source data portals (e.g., CMEMS, EMODnet) for three years (2016-2018).

In addition to the review and expert judgement, the statistical distributions of environmental variables under the existing seagrass meadows were analyzed to identify the optimum conditions (safe operating space) and the thresholds for seagrass meadows' proper growth and survival. Based on this statistical analysis to allow for heterogeneous data integration, all variables' values were categorized into 5 classes, i.e., from *not suitable* to *very suitable* class, and then scored between 0-100 range. Then, AHP was applied for geomorphology, WQ, and climate sub-groups using pairwise comparison matrices scored by the involved experts, and the final weights were derived for each variable. Finally, the weighted sum approach was used by multiplying each variable's normalized score and weight to obtain suitability scores and maps for each sub-group. A final suitability map was obtained by overlaying suitable and very suitable areas in geomorphology, WQ, and climate maps.

The resulting suitability maps and metrics showed that while the suitable and very suitable areal extent in terms of climate and WQ is large in the case study area, the geomorphological assessment is a more decisive and limiting environmental sub-group for suitable areas. Bathymetry can be considered the most dominant indicator in the geomorphological seagrass suitability evaluation, with a weight of 0.66. Specifically, while the sum of suitable and very suitable areas in geomorphological assessment for the growth of *P. oceanica* is 37.5% of the case study area, it is 84.8% and 72.3% in terms of WQ and climate suitability, respectively. Large suitable areas under WQ and climate conditions can be expected, considering that *P. oceanica* is an endemic species in the Mediterranean. However, the Northern Adriatic and some parts of the southern Mediterranean coasts show less suitable areas. The main reason for the Northern Adriatic is the low WQ suitability (especially due to light attenuation coefficient and NO_3 concentration, linked to the presence in the area of the Po Delta River), while the southern Mediterranean regions have lower suitability scores in climate evaluation due to thermal stress.

The variables chosen and methodology developed for this study are practical and replicable at different locations and scales. On the one hand, a reliable and feasible model was aimed at including 10 variables instead of using fewer variables to obtain a simple index. In contrast, more than 10 variables could be used to make the model more complex, but the number of parameters representing similar processes would also increase with redundancy (e.g., SPM and K_d both represent turbidity). On the other hand, one of the method's strengths lies in the integration of statistical analysis and expert opinion for the identification and classification of optimum and threshold values representing different suitability classes for the survival and growth of seagrass meadows. AHP also allowed experts' qualitative assessments of variables to be converted into quantitative information by defining their weights in the MCDA. In this setting, the proposed weighted method provides more consistent outcomes for potentially suitable areas compared to an unweighted approach.

One of the limitations of the developed method is that the possible interactions/relationships between the criteria could not be integrated since each parameter is included in the model individually. Furthermore, considering that ecosystems can adapt to the environmental conditions of the site they grow (i.e., seagrass populations with different thresholds), suitability analysis in smaller sub-regions (e.g., Western Mediterranean) may give more robust results. In addition to the mean values of variables, analysis of the exposure time to the threshold value of each variable (e.g., as with the thermal stress classification) could improve the model. However, for this target, it would be necessary to classify the exposure duration against the identified threshold values for each variable by analyzing the increased mortality of seagrass populations with respect to time.

This study attempted to manage the first phase of the proposed multi-tier NbS suitability framework by including multiple environmental factors for NbS suitability modeling. For a complete NbS suitability assessment, integration of future climate projections and inclusion of socio-economic and governance-related parameters (e.g., population, fishing activities) at local scale is crucial to prioritize the areas for appropriate NbS implementation with more robust decision-making. Drawing on this, future investigations and widening of this methodological approach will include the integration of other factors embracing socio-economic and governance dimension of climate adaptation, also applying more sophisticated spatio-temporal modeling analysis tools allowing to support marine managers and policymakers in implementing effective NbS measures.

REFERENCES

Abdelrhman, M. A. (2017a). Quantifying Contributions to Light Attenuation in Estuaries and Coastal Embayments: Application to Narragansett Bay, Rhode Island. In *Estuaries and Coasts* (Vol. 40, Issue 4, pp. 994–1012). https://doi.org/10.1007/s12237-016-0206-x

Abdelrhman, M. A. (2017b). Quantifying contributions to light attenuation in estuaries andcoastal embayments: Application to Narragansett Bay, RhodeIsland. *Estuaries and Coasts : Journal of the Estuarine Research Federation*, *40*(4), 994. https://doi.org/10.1007/S12237-016-0206-X

Adem Esmail, B., & Geneletti, D. (2018). Multi-criteria decision analysis for nature conservation: A review of 20 years of applications. In *Methods in Ecology and Evolution* (Vol. 9, Issue 1, pp. 42–53). https://doi.org/10.1111/2041-210X.12899

Alagna, A., Fernández, T. V., D’Anna, G., Magliola, C., Mazzola, S., & Badalamenti, F. (2015). Assessing Posidonia oceanica Seedling Substrate Preference: An Experimental Determination of Seedling Anchorage Success in Rocky vs. Sandy Substrates. *PLoS ONE*, *10*(4). https://doi.org/10.1371/JOURNAL.PONE.0125321

Altieri, A. H., Nelson, H. R., & Gedan, K. B. (2019). The significance of ocean deoxygenation for tropical ecosystems – corals, seagrasses and mangroves. *Ocean Deoxygenation: Everyone’s Problem. Causes, Impacts, Consequences and Solutions*, 401–429.

Antognelli, S., & Vizzari, M. (2021). Assessing ecosystem and urban services for landscape suitability mapping. In *Applied Sciences (Switzerland)* (Vol. 11, Issue 17). https://doi.org/10.3390/app11178232

Bakirman, T., & Gumusay, M. U. (2020). A novel GIS-MCDA-based spatial habitat suitability model for Posidonia oceanica in the Mediterranean. *Environmental Monitoring and Assessment*, *192*(4). https://doi.org/10.1007/s10661-020-8198-1

Bellamy, C. C., van der Jagt, A. P. N., Barbour, S., Smith, M., & Moseley, D. (2017). A spatial framework for targeting urban planning for pollinators and people with local stakeholders: A route to healthy, blossoming communities? In *Environmental Research* (Vol. 158, pp. 255–268). https://doi.org/10.1016/j.envres.2017.06.023

Bennett, S., Alcoverro, T., Kletou, D., Antoniou, C., Boada, J., Buñuel, X., Cucala, L., Jorda, G., Kleitou, P., Roca, G., Santana-Garcon, J., Savva, I., Vergés, A., & Marbà, N. (2022).

Resilience of seagrass populations to thermal stress does not reflect regional differences in ocean climate. *New Phytologist*, *233*(4), 1657–1666. https://doi.org/10.1111/nph.17885

Bennett, S., Vaquer-Sunyer, R., Jordá, G., Forteza, M., Roca, G., & Marbà, N. (2022). Thermal Performance of Seaweeds and Seagrasses Across a Regional Climate Gradient. *Frontiers in Marine Science*, *9*(February), 1–11. https://doi.org/10.3389/fmars.2022.733315

Bianchi, C. N., & Morri, C. (2000). Marine biodiversity of the Mediterranean Sea: Situation, problems and prospects for future research. *Marine Pollution Bulletin*, *40*(5), 367–376. https://doi.org/10.1016/S0025-326X(00)00027-8

Boudouresque, C. F., Blanfuné, A., Pergent, G., & Thibaut, T. (2021). Restoration of seagrass meadows in the mediterranean sea: A critical review of effectiveness and ethical issues. *Water (Switzerland)*, *13*(8), 1–34. https://doi.org/10.3390/w13081034

Calvo, S., Calvo, R., Luzzu, F., Raimondi, V., Assenzo, M., Cassetti, F. P., & Tomasello, A. (2021). Performance assessment of posidonia oceanica (L.) delile restoration experiment on dead matte twelve years after planting—structural and functional meadow features. *Water (Switzerland)*, *13*(5). https://doi.org/10.3390/w13050724

Camp, E. F., Suggett, D. J., Gendron, G., Jompa, J., Manfrino, C., & Smith, D. J. (2016). Mangrove and seagrass beds provide different biogeochemical services for corals threatened by climate change. In *Frontiers in Marine Science* (Vol. 3, Issue APR). https://doi.org/10.3389/fmars.2016.00052

Catucci, E., & Scardi, M. (2020). A Machine Learning approach to the assessment of the vulnerability of Posidonia oceanica meadows. *Ecological Indicators*, *108*(June 2019). https://doi.org/10.1016/j.ecolind.2019.105744

Chefaoui, R. M., Duarte, C. M., & Serrão, E. A. (2017). Palaeoclimatic conditions in the Mediterranean explain genetic diversity of Posidonia oceanica seagrass meadows. *Scientific Reports*, *7*(1), 1–8. https://doi.org/10.1038/s41598-017-03006-2

Clean Water Team (CWT). (2004). Dissolved Oxygen Fact Sheet, FS-3.1.1.0(DO). *The Clean Water Team Guidance Compendium for Watershed Monitoring and Assessment*, *2*, 1–5.

CNRD, & UNEP. (2019). *Disasters and Ecosystems: Resilience in a Changing Climate*

Convention on Biological Diversity Sendai Framework for Disaster Risk Reduction United Nations Economic Commission for Europe World Business Council for Sustainable Development.

Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (2016a). Nature-based solutions to address global societal challenges. Gland, Switzerland: IUCN. xiii + 97pp. In *Nature-based solutions to address global societal challenges*.

Cohen-Shacham, E., Walters, G., Janzen, C., & Maginnis, S. (2016b). Nature-based solutions to address global societal challenges. In *Nature-based solutions to address global societal challenges*. https://doi.org/10.2305/iucn.ch.2016.13.en

Cohen-Shacham, Emmanuelle, Andrade, A., Dalton, J., Dudley, N., Jones, M., Kumar, C., Maginnis, S., Maynard, S., Nelson, C. R., Renaud, F. G., Welling, R., & Walters, G. (2019). Core principles for successfully implementing and upscaling Nature-based Solutions. *Environmental Science and Policy*, *98*(February), 20–29. https://doi.org/10.1016/j.envsci.2019.04.014

Coll, M., Piroddi, C., Albouy, C., Ben Rais Lasram, F., Cheung, W. W. L., Christensen, V., Karpouzi, V. S., Guilhaumon, F., Mouillot, D., Paleczny, M., Palomares, M. L., Steenbeek, J., Trujillo, P., Watson, R., & Pauly, D. (2012). The Mediterranean Sea under siege: Spatial overlap between marine biodiversity, cumulative threats and marine reserves. *Global Ecology and Biogeography*, *21*(4), 465–480. https://doi.org/10.1111/j.1466-8238.2011.00697.x

Coll, M., Piroddi, C., Steenbeek, J., Kaschner, K., Lasram, F. B. R., Aguzzi, J., Ballesteros, E., Bianchi, C. N., Corbera, J., Dailianis, T., Danovaro, R., Estrada, M., Froglia, C., Galil, B. S., Gasol, J. M., Gertwage, R., Gil, J., Guilhaumon, F., Kesner-Reyes, K., … Voultsiadou, E. (2010). The biodiversity of the Mediterranean Sea: Estimates, patterns, and threats. *PLoS ONE*, *5*(8). https://doi.org/10.1371/journal.pone.0011842

D'Angelo, S., & Fiorentino, A. (2012). Phanerogam meadows: a characteristic habitat of the mediterranean shelf-examples from the tyrrhenian sea. *Seafloor Geomorphology as Benthic Habitat*, 159–168. https://doi.org/10.1016/B978-0-12-385140-6.00007-4

de los Santos, C. B., Krause-Jensen, D., Alcoverro, T., Marbà, N., Duarte, C. M., van Katwijk, M. M., Pérez, M., Romero, J., Sánchez-Lizaso, J. L., Roca, G., Jankowska, E., Pérez-Lloréns, J. L., Fournier, J., Montefalcone, M., Pergent, G., Ruiz, J. M., Cabaço, S., Cook, K., Wilkes, R. J., … Santos, R. (2019). Recent trend reversal for declining European seagrass meadows. *Nature Communications*, *10*(1), 1–8. https://doi.org/10.1038/s41467-019-11340-4

de los Santos, C. B., Olivé, I., Moreira, M., Silva, A., Freitas, C., Araújo Luna, R., Quental-Ferreira, H., Martins, M., Costa, M. M., Silva, J., Cunha, M. E., Soares, F., Pousão-Ferreira, P., & Santos, R. (2020). Seagrass meadows improve inflowing water quality in aquaculture ponds. *Aquaculture*, *528*(May), 735502. https://doi.org/10.1016/j.aquaculture.2020.735502

Di Maida, G., Tomasello, A., Sciandra, M., Pirrotta, M., Milazzo, M., & Calvo, S. (2013). Effect of different substrata on rhizome growth, leaf biometry and shoot density of Posidonia oceanica. *Marine Environmental Research*, *87–88*, 96–102. https://doi.org/10.1016/j.marenvres.2013.04.001

Díaz-Almela, E., & Duarte, C. M. (2008). MANAGEMENT of Natura 2000 habitats_Posidonia beds (Posidonion oceanicae) 1120. In *Ecosystems*.

Duarte, C. M., Marbà, N., Dorte, K.-J., & Maria, S.-C. (2013). Testing the Predictive Power of Seagrass Depth Limit Models Testing. *Estuaries and Coasts*, *30*(4), 652–656.

E. Díaz-Almela, C. M. D. (2008). *Management of Natura 2000 habitats. 1120 *Posidonia beds (Posidonion oceanicae)*. European Commision.

EC. (2015). *Towards an EU Research and Innovation policy agenda for Nature-Based Solutions & Re-Naturing Cities: Vol. III* (Issue February).

EEA. (1999). State and pressures of the marine and coastal Mediterranean environment. In *European Environment Agency* (Issue 5). http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:State+and+pressures+of+the+marine+and+coastal+Mediterranean+environment#1

EEA. (2019). The European Environment-State and Outlook 2020. Knowledge for Transition to a Sustainable Europe. In *Teruleti Statisztika* (Vol. 60, Issue 3). https://doi.org/10.15196/TS600305

EEA. (2021). *Nature-based solutions in Europe* (Issue 01). https://www.eea.europa.eu/publications/nature-based-solutions-in-europe

Eggermont, H., Balian, E., Azevedo, J. M. N., Beumer, V., Brodin, T., Claudet, J., Fady, B., Grube, M., Keune, H., Lamarque, P., Reuter, K., Smith, M., Van Ham, C., Weisser, W. W., & Le Roux, X. (2015). Nature-based solutions: New influence for environmental management and research in Europe. *Gaia*, *24*(4), 243–248. https://doi.org/10.14512/gaia.24.4.9

Fernández-Torquemada, Y., & Sánchez-Lizaso, J. L. (2005). Effects of salinity on leaf growth and survival of the Mediterranean seagrass Posidonia oceanica (L.) Delile. *Journal of Experimental Marine Biology and Ecology*, *320*(1), 57–63. https://doi.org/10.1016/j.jembe.2004.12.019

Folmer, E. O., van Beusekom, J. E. E., Dolch, T., Gräwe, U., van Katwijk, M. M., Kolbe, K., & Philippart, C. J. M. (2016). Consensus forecasting of intertidal seagrass habitat in the Wadden Sea. *Journal of Applied Ecology*, *53*(6), 1800–1813. https://doi.org/10.1111/1365-2664.12681

Gamble, E. C., Debney, A., Glover, A., Bertelli, C., Green, B., Hendy, I., Lilley, R., Nuuttila, H., Potouroglou, M., Ragazzola, F., Rees, S., Unsworth, R., & Preston, J. (2021). *RESTORATION HANDBOOK* (Issue November).

Giorgi, F. (2006). Climate change hot-spots. *Geophysical Research Letters*, *33*(8). https://doi.org/10.1029/2006GL025734/

Gómez Martín, E., Máñez Costa, M., & Schwerdtner Máñez, K. (2020). An operationalized classification of Nature Based Solutions for water-related hazards: From theory to practice. *Ecological Economics*, *167*(October 2018), 106460. https://doi.org/10.1016/j.ecolecon.2019.106460

Green, A. J., Alcorlo, P., Peeters, E. T. H. M., Morris, E. P., Espinar, J. L., Bravo-Utrera, M. A., Bustamante, J., Díaz-Delgado, R., Koelmans, A. A., Mateo, R., Mooij, W. M., Rodríguez-Rodríguez, M., van Nes, E. H., & Scheffer, M. (2017). Creating a safe operating space for wetlands in a changing climate. *Frontiers in Ecology and the Environment*, *15*(2), 99–107. https://doi.org/10.1002/fee.1459

Greene, R., Devillers, R., Luther, J. E., & Eddy, B. G. (2011). GIS-Based Multiple-Criteria Decision Analysis. *Geography Compass*, *5*(6), 412–432. https://doi.org/10.1111/j.1749-8198.2011.00431.x

Guerra-Vargas, L. A., Gillis, L. G., & Mancera-Pineda, J. E. (2020). Stronger Together: Do Coral Reefs Enhance Seagrass Meadows "Blue Carbon" Potential? In *Frontiers in*

Marine Science (Vol. 7). https://doi.org/10.3389/fmars.2020.00628

Hemminga, M., & Duarte, C. (2000). Seagrass Ecology. *Cambridge: Cambridge University Press.*, *250*(1–2), 117–131. https://doi.org/10.1017/CBO9780511525551

IHO. (1953). *Limits of oceans and seas. 3rd edition. IHO Special Publication, 23. International Hydrographic Organization (IHO): Monaco. 38 pp.*

Infantes, E., Terrados, J., Orfila, A., Cañellas, B., & Álvarez-Ellacuria, A. (2009). Wave energy and the upper depth limit distribution of Posidonia oceanica. *Botanica Marina*, *52*(5), 419–427. https://doi.org/10.1515/BOT.2009.050

IPBES. (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services. In *Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (Vol. 45, Issue 3). https://zenodo.org/record/3553579#.YfmYTerMI2w

IPCC. (2019). Summary for policymakers. In *Climate change 2007: Impacts, adaptation and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel of Climate Change (IPCC)* (Vol. 9781107025). https://doi.org/10.1017/CBO9781139177245.003

Koch, E., Stevenson, C., & DeWitt, T. H. (2010). *Nutrient uptake by marshes and seagrasses: Ecosystem functions and spatial variability in the provision of this ecosystem servoce | Science Inventory | US EPA*. https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NHEERL&dirEntryId=231275

Lee, K. S., Park, S. R., & Kim, Y. K. (2007). Effects of irradiance, temperature, and nutrients on growth dynamics of seagrasses: A review. *Journal of Experimental Marine Biology and Ecology*, *350*(1–2), 144–175. https://doi.org/10.1016/j.jembe.2007.06.016

Leoni, V., Pasqualini, V., Pergent-Martini, C., Vela, A., & Pergent, G. (2007). Physiological responses of Posidonia oceanica to experimental nutrient enrichment of the canopy water. *Journal of Experimental Marine Biology and Ecology*, *349*(1), 73–83. https://doi.org/10.1016/j.jembe.2007.05.006

Lester, S. E., Dubel, A. K., Hernán, G., McHenry, J., & Rassweiler, A. (2020). Spatial Planning Principles for Marine Ecosystem Restoration. *Frontiers in Marine Science*, *7*(May), 1–15. https://doi.org/10.3389/fmars.2020.00328

Manzanera, M., Alcoverro, T., Tomas, F., & Romero, J. (2011). Response of Posidonia oceanica to burial dynamics. *Marine Ecology Progress Series*, *423*(February), 47–56. https://doi.org/10.3354/meps08970

Marbà, N., Cebrián, J., Enríquez, S., & Duarte, C. M. (1996). Growth patterns of western Mediterranean seagrasses: Species- specific responses to seasonal forcing. *Marine Ecology Progress Series*, *133*(1–3), 203–215. https://doi.org/10.3354/meps133203

Marbà, N., Díaz-Almela, E., & Duarte, C. M. (2014). Mediterranean seagrass (Posidonia oceanica) loss between 1842 and 2009. *Biological Conservation*, *176*, 183–190. https://doi.org/10.1016/j.biocon.2014.05.024

Marbà, N., & Duarte, C. M. (2010). Mediterranean warming triggers seagrass (Posidonia oceanica) shoot mortality. *Global Change Biology*, *16*(8), 2366–2375. https://doi.org/10.1111/j.1365-2486.2009.02130.x

Marbà, N., Duarte, C. M., Alexandre, A., & Cabaço, S. (2004). How do seagrasses grow and spread ? *European Seagrasses: An Introduction to Monitoring and Management*, *September*, 11–18. www.seagrasses.org

Marbà, N., Duarte, C. M., Cebrian, J., Gallegos, M. E., Olesen, B., & Sand-Jensen, K. (1996). Growth and population dynamics of Posidonia oceanica on the Spanish Mediterranean Coast: Elucidating seagrass decline. *Marine Ecology Progress Series*, *137*(1–3), 203–213. https://doi.org/10.3354/meps137203

Micu, D., Sinop, L. B., Palmas, L., Canaria, G., Palmas, L., & Canaria, G. (2016). *European Red List of Habitats* (Issue September 2017). https://doi.org/10.2779/032638

Moffett, K. B., Nardin, W., Silvestri, S., Wang, C., & Temmerman, S. (2015). Multiple stable states and catastrophic shifts in coastal wetlands: Progress, challenges, and opportunities in validating theory using remote sensing and other methods. *Remote Sensing*, *7*(8), 10184–10226. https://doi.org/10.3390/rs70810184

Mubeen, A., & Ruangpan, L. (2021). *Planning and Suitability Assessment of Large-scale Nature-based Solutions for Flood-risk Reduction Content courtesy of Springer Nature , terms of use apply . Rights reserved . Content courtesy of Springer Nature , terms of use apply . Rights reserved* . 3063–3081.

Olsen, Y. S., Sánchez-Camacho, M., Marbà, N., & Duarte, C. M. (2012). Mediterranean Seagrass Growth and Demography Responses to Experimental Warming. *Estuaries and Coasts*, *35*(5), 1205–1213. https://doi.org/10.1007/s12237-012-9521-z

Otero, M.M and Pergent-Martini, C. (2016). *A5 . 53 Seagrass beds (other than Posidonia) on Mediterranean infralittoral sand*. 1–11.

Pasqualini, V., Pergent-Martini, C., Clabaut, P., & Pergent, G. (1998). Mapping of Posidonia oceanica using aerial photographs and side scan sonar: Application off the Island of Corsica (France). *Estuarine, Coastal and Shelf Science*, *47*(3), 359–367. https://doi.org/10.1006/ecss.1998.0361

Pérez, M., Invers, O., Ruiz, J. M., Frederiksen, M. S., & Holmer, M. (2007). Physiological responses of the seagrass Posidonia oceanica to elevated organic matter content in sediments: An experimental assessment. *Journal of Experimental Marine Biology and Ecology*, *344*(2), 149–160. https://doi.org/10.1016/j.jembe.2006.12.020

Pergent-Martini, C., Otero, M. M., & Numa, C. (2016). A5.535 Posidonia beds in the Mediterranean infralittoral zone. *European Red List of Habitats.*, 1–11.

Pergent, G., Pergent-Martini, C., Bein, A., Dedeken, M., Oberti, P., Orsini, A., Santucci, J. F., & Short, F. (2015). Dynamic of Posidonia oceanica seagrass meadows in the northwestern Mediterranean: Could climate change be to blame? *Comptes Rendus - Biologies*, *338*(7), 484–493. https://doi.org/10.1016/j.crvi.2015.04.011

Piroddi, C., Coll, M., Steenbeek, J., Moy, D. M., & Christensen, V. (2015). Modelling the Mediterranean marine ecosystem as a whole: Addressing the challenge of complexity. *Marine Ecology Progress Series*, *533*(August), 47–65. https://doi.org/10.3354/meps11387

Poikane, S., Kelly, M. G., Salas Herrero, F., Pitt, J. A., Jarvie, H. P., Claussen, U., Leujak, W., Lyche Solheim, A., Teixeira, H., & Phillips, G. (2019). Nutrient criteria for surface waters under the European Water Framework Directive: Current state-of-the-art, challenges and future outlook. *Science of the Total Environment*, *695*, 133888. https://doi.org/10.1016/j.scitotenv.2019.133888

Ruíz, J. M., Marín-Guirao, L., & Sandoval-Gil, J. M. (2009). Responses of the Mediterranean seagrass Posidonia oceanica to in situ simulated salinity increase. *Botanica Marina*, *52*(5), 459–470. https://doi.org/10.1515/BOT.2009.051

Ruiz, J. M., & Romero, J. (2003). Effects of disturbances caused by coastal constructions on spatial structure, growth dynamics and photosynthesis of the seagrass Posidonia oceanica. *Marine Pollution Bulletin*, *46*(12), 1523–1533. https://doi.org/10.1016/j.marpolbul.2003.08.021

Saaty, R. W. (1987). The analytic hierarchy process-what it is and how it is used. *Mathematical Modelling*, *9*(3–5), 161–176. https://doi.org/10.1016/0270-0255(87)90473-8

Saaty, T. L. (1980). The analytic hierarchy process: planning. *Priority Setting. Resource Allocation, McGraw-Hill, New York International Book Company*, 287.

Saha, J., & Paul, S. (2021). An insight on land use and land cover change due to tourism growth in coastal area and its environmental consequences from West Bengal, India. *Spatial Information Research*, *29*(4), 577–592. https://doi.org/10.1007/s41324-020-00368-0

Sánchez-Lizaso, J. L., Romero, J., Ruiz, J., Gacia, E., Buceta, J. L., Invers, O., Fernández Torquemada, Y., Mas, J., Ruiz-Mateo, A., & Manzanera, M. (2008). Salinity tolerance of the Mediterranean seagrass Posidonia oceanica: recommendations to minimize the impact of brine discharges from desalination plants. *Desalination*, *221*(1–3), 602–607. https://doi.org/10.1016/j.desal.2007.01.119

Saulquin, B., Hamdi, A., Gohin, F., Populus, J., Mangin, A., & d'Andon, O. F. (2013). Estimation of the diffuse attenuation coefficient KdPAR using MERIS and application to seabed habitat mapping. *Remote Sensing of Environment*, *128*, 224–233. https://doi.org/10.1016/j.rse.2012.10.002

Scheffer, M., Barrett, S., Carpenter, S. R., Folke, C., Green, A. J., Holmgren, M., Hughes, T. P., Kosten, S., van de Leemput, I. A., Nepstad, D. C., van Nes, E. H., Peeters, E. T. H. M., & Walker, B. (2015). Creating a safe operating space for iconic ecosystems. *Science*, *347*(6228), 1317–1319. https://doi.org/10.1126/science.aaa3769

Short, F. T., & Mcroy, C. P. (1984). *Zostera azote.pdf*. *XXVII*, 547–555.

Simpson, L. T., Cherry, J. A., Smith, R. S., & Feller, I. C. (2021). Mangrove Encroachment Alters Decomposition Rate in Saltmarsh Through Changes in Litter Quality. *Ecosystems*, *24*(4), 840–854. https://doi.org/10.1007/S10021-020-00554-Z

Stramma, L., & Schmidtko, S. (2019). Global evidence of ocean deoxygenation. *Ocean Deoxygenation: Everyone's Problem*, 25–36.

Stramska, M., & Anisliewicz, P. (2019). Recent Large Scale Environmental Changes in the Mediterranean Sea and Their Potential Impacts on Posidonia Oceanica. In *Nature*.

Syahid, L. N., Sakti, A. D., Virtriana, R., Wikantika, K., Windupranata, W., Tsuyuki, S., Caraka, R. E., & Pribadi, R. (2020). Determining optimal location for mangrove planting using remote sensing and climate model projection in southeast asia. *Remote Sensing*, *12*(22), 1–29. https://doi.org/10.3390/rs12223734

Telesca, L., Belluscio, A., Criscoli, A., Ardizzone, G., Apostolaki, E. T., Fraschetti, S., Gristina, M., Knittweis, L., Martin, C. S., Pergent, G., Alagna, A., Badalamenti, F., Garofalo, G., Gerakaris, V., Louise Pace, M., Pergent-Martini, C., & Salomidi, M. (2015). Seagrass meadows (Posidonia oceanica) distribution and trajectories of change. *Scientific Reports*, *5*, 1–14. https://doi.org/10.1038/srep12505

Terrados, J., & Williams, S. L. (1997). Leaf versus root nitrogen uptake by the surfgrass Phyllospadix torreyi. *Marine Ecology Progress Series*, *149*(1–3), 267–277. https://doi.org/10.3354/meps149267

Think Nature. (2019). Nature Based Solutions Handbook. *ThinkNature Project Funded by the EU Horizon 2020 Research and Innovation Programme*, *730338*, 1–226. https://platform.think-nature.eu/system/files/thinknature_handbook_final_print_0.pdf

Tonielli, R., Innangi, S., Budillon, F., Di Martino, G., Felsani, M., Giardina, F., Innangi, M., & Filiciotto, F. (2016). Distribution of Posidonia oceanica (L.) Delile meadows around Lampedusa Island (Strait of Sicily, Italy). *Journal of Maps*, *12*, 249–260. https://doi.org/10.1080/17445647.2016.1195298

Tsiamis, K., Zenetos, A., Deriu, I., Gervasini, E., & Cardoso, A. C. (2018). The native distribution range of the European marine non-indigenous species. *Aquatic Invasions*, *13*(2), 187–198. https://doi.org/10.3391/ai.2018.13.2.01

UNEP-WCMC. (2011). Marine and coastal ecosystem services: Valuation methods and their application. In *PNCIMA, Suzuki Foundation* (Issue 33).

UNEP/ MAP and Plan Bleu. (2020). Summary for decision makers. In *Assessment of Climate Change in the Southwest United States: A Report Prepared for the National Climate*

Assessment. https://doi.org/10.5822/978-1-61091-484-0_1

UNEP/MAP. (2009). State of the Mediterranean Marine and Coastal Environment. *Ecological Applications*, *10*(4), 1047–1056. http://www.jstor.org/stable/2641016

UNEP/MAP. (2017). *UNITED UNITED NATIONS ENVIRONMENT PROGRAMME Quality Status Report (QSR) Cross-cutting and horizontal issues (Plan Bleu , Version 10 / 07 / 2017). September*.

UNEP. (2022). Nature-based solutions for supporting sustainable development. *United Nations*, 3–5.

Unsworth, R. K. F., Collier, C. J., Henderson, G. M., & McKenzie, L. J. (2012). Tropical seagrass meadows modify seawater carbon chemistry: Implications for coral reefs impacted by ocean acidification. In *Environmental Research Letters* (Vol. 7, Issue 2). https://doi.org/10.1088/1748-9326/7/2/024026

Vermaat, J. E., Agawin, N. S. R., Fortes, M. D., & Uri, J. S. (1997). The capacity of seagrasses to survive increased turbidity and siltation: The significance of growth form and light use. *Ambio*, *26*(8), 499–504.

Wang, Q., Mei, D., Chen, J., Lin, Y., Liu, J., Lu, H., & Yan, C. (2019). Sequestration of heavy metal by glomalin-related soil protein: Implication for water quality improvement in mangrove wetlands. *Water Research*, *148*, 142–152. https://doi.org/10.1016/J.WATRES.2018.10.043

Wilson, A. M. W., & Forsyth, C. (2018). Restoring near-shore marine ecosystems to enhance climate security for island ocean states: Aligning international processes and local practices. *Marine Policy*, *93*(February), 284–294. https://doi.org/10.1016/j.marpol.2018.01.018

Zenone, A., Badalamenti, F., Gorb, S. N., & Infantes, E. (2022). Assessing Tolerance to the Hydrodynamic Exposure of Posidonia oceanica Seedlings Anchored to Rocky Substrates. In *Nature*. https://doi.org/https://doi.org/10.3389/fmars.2021.788448

Zhou, X. Y. (2019). Spatial explicit management for the water sustainability of coupled human and natural systems. *Environmental Pollution*, *251*, 292–301. https://doi.org/10.1016/j.envpol.2019.05.020

APPENDIX A: Intermediate maps obtained while creating the final map

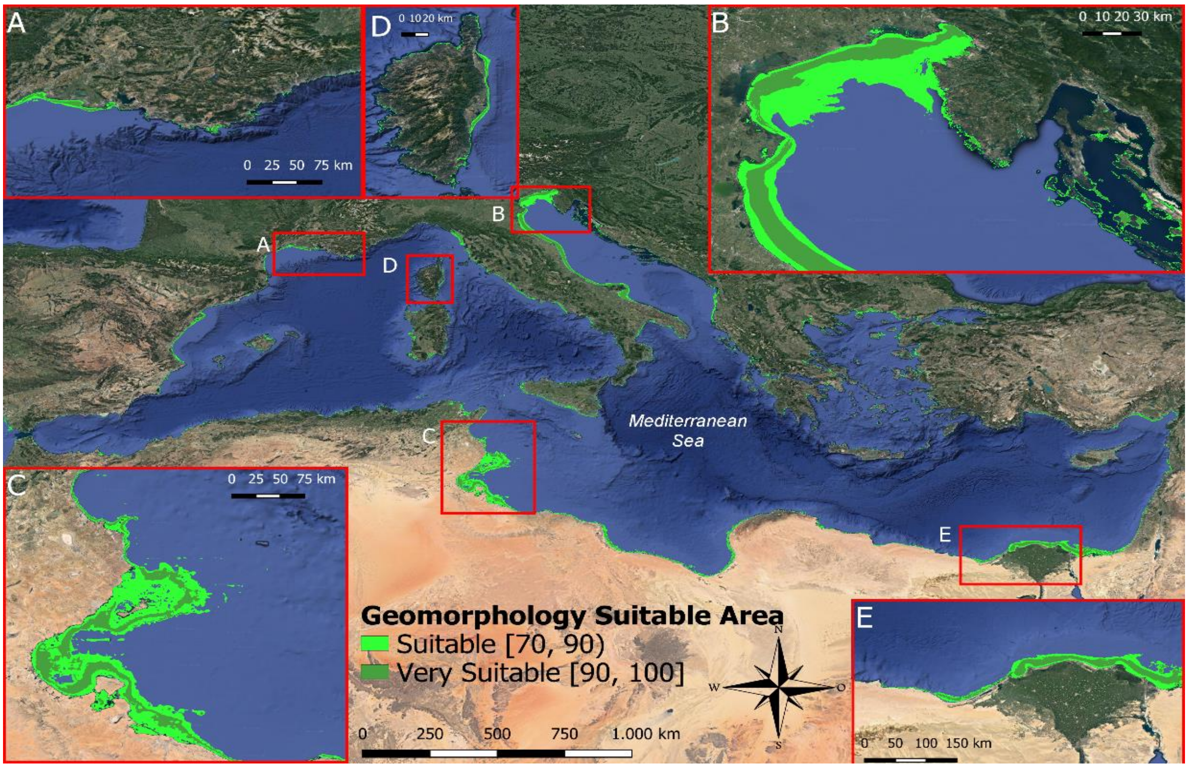

Figure A.1. Suitable and very suitable areas in geomorphologic assessment.

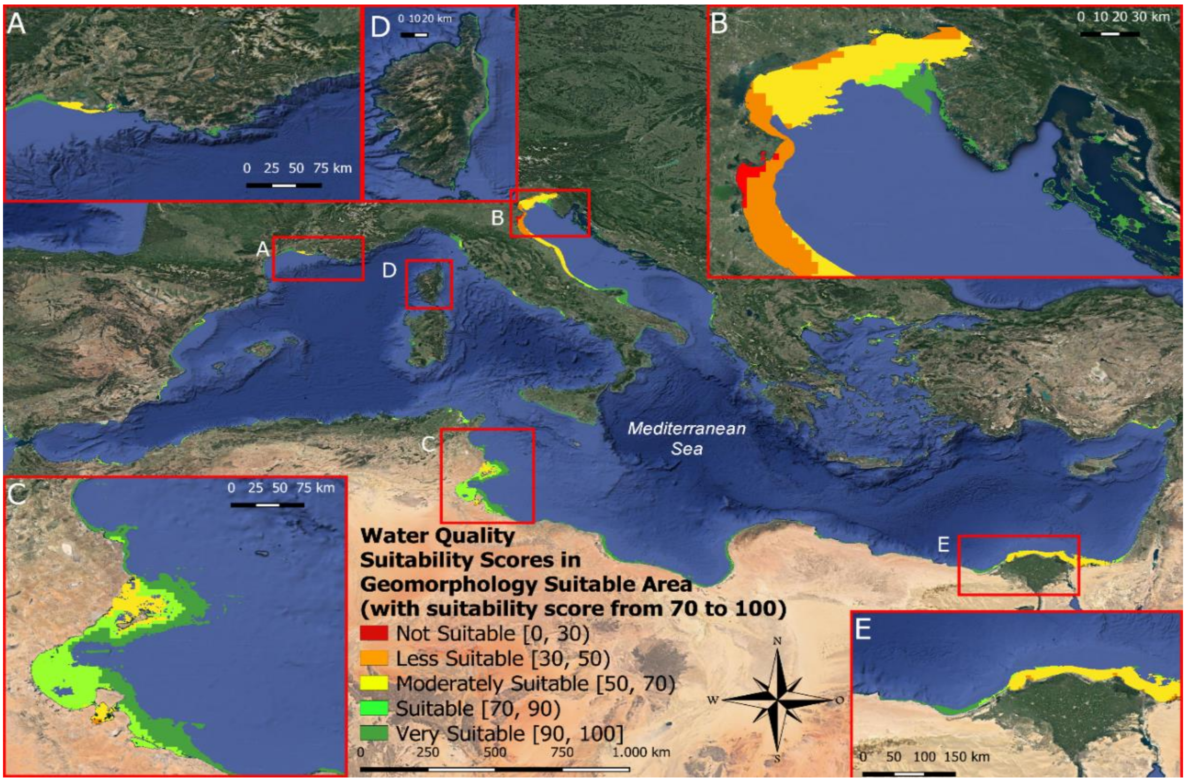

Figure A.2. WQ suitability classes in the selected areas (suitable and very suitable geomorphologic areas in Figure A.1.).

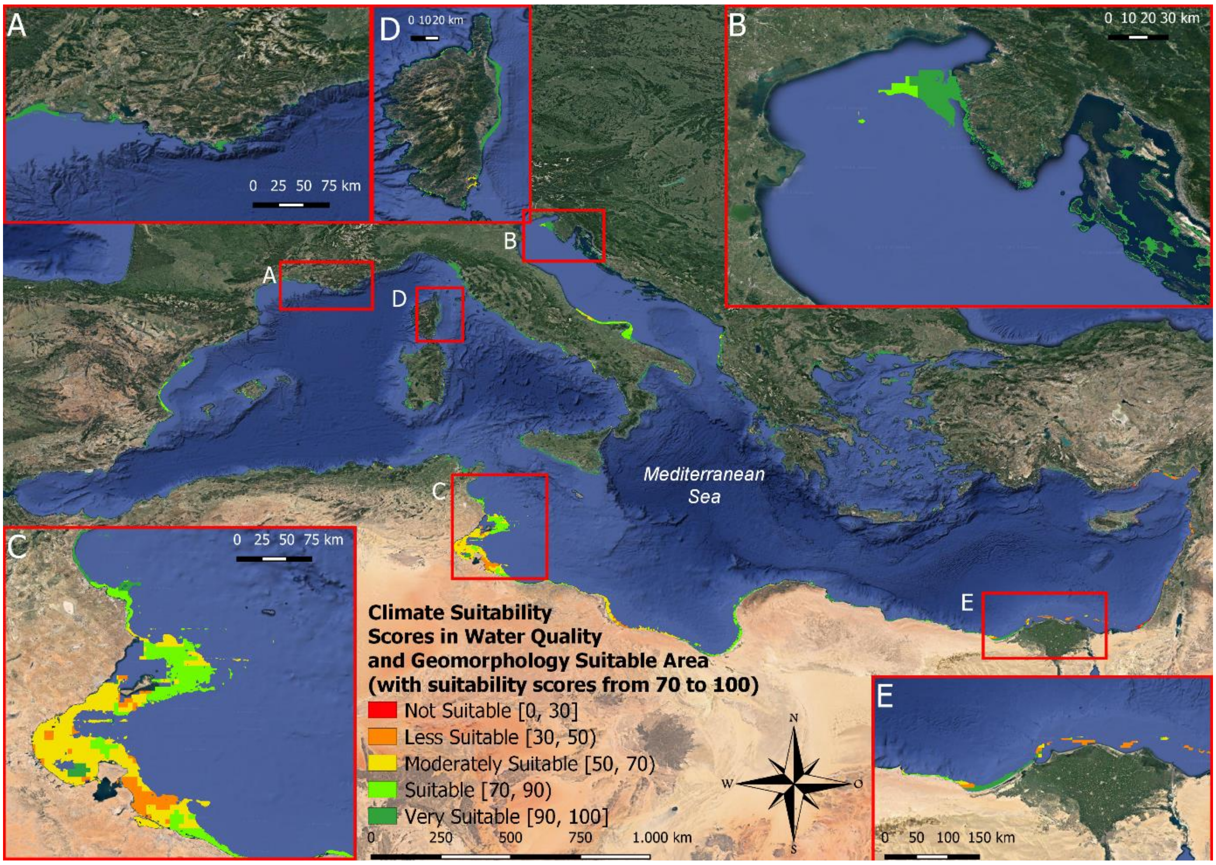

Figure A.3. Climate suitability classes in the selected areas (suitable and very suitable geomorphologic and WQ areas in Figure A.2.).