



**MASTER'S DEGREE IN CONSTRUCTION ENGINEERING
AMBIT OF THE DOUBLE DEGREE PROGRAMME
MARIA LUIZA CARVALHO MONTEIRO**

**GREENING THE GREY: APPLICATION OF ECO-
ENGINEERING TO COASTAL AND HARBOUR
INFRASTRUCTURES**

**BRAGANÇA
JULY 2025**

MARIA LUIZA CARVALHO MONTEIRO

**GREENING THE GREY: APPLICATION OF ECO-ENGINEERING TO COASTAL AND
HARBOUR INFRASTRUCTURES**

Dissertation submitted to the Polytechnic Institute of Bragança as part of the requirements of the Double Degree Programme in Construction Engineering with Federal University of Lavras, for the award of Master's Degree.

Approved on 10 of July of 2025.

Profa. Dra. Débora Rodrigues de Sousa Macanjo Ferreira IPB

Prof. Dr. Saulo Rocha Ferreira UFLA

Profa. Dra. Flora Cristina Meireles Silva IPB

Prof. Dr. Manuel Teixeira Braz César

Prof. Dr. Saulo Rocha Ferreira

Advisors

Eng. Diogo Filipe da Silva Fonseca, MSc

Prof. Dr. Diogo Silva Mendes

Co-supervisors

**BRAGANÇA
JULY 2025**

ACKNOWLEDGEMENTS

Firstly, I would like to thank my parents, Renata and Célio, for funding and supporting my studies right from the start. Without their love, encouragement and trust, I wouldn't have got this far. To my sister, Ana Carolina, I thank you for always supporting my decisions with generosity and affection, even when it meant facing distance.

My deepest thanks go to my supervisors, Professors Saulo Ferreira (UFLA) and Manuel Braz César (IPB) for the academic guidance. I would also like to thank Diogo Mendes, a professor at IST Lisboa, and Diogo Fonseca, a port engineer at HAEDDES, partners in this research, whose technical support and constant encouragement were essential to the development of this work.

I am grateful to the universities involved for the opportunity to take part in the double degree programme, which allowed me to realise my dream of studying for a master's degree. I would like to thank all the teachers who have contributed to my education throughout my academic career, especially Professor Andrea Corrêa, for whom I have enormous admiration and affection.

To my fellow students, thank you for your friendship, companionship and the lessons you have learnt over the years. To the Nucleus for Studies in Non-Conventional Materials and Techniques in Civil Construction (NEMATENC), thank you for fuelling my passion for sustainability and for giving me unforgettable experiences. To the members and friends who have passed through it, my sincere gratitude for becoming a true family within the university.

Finally, I would like to thank all the friends who have been part of my life during this journey and who, in different ways, have helped me to move forward. And to my partner, who has always been my inspiration and encouragement to follow my dreams.

ABSTRACT

This research explores the application of nature-based solutions in port infrastructures as a strategy to promote environmental sustainability in traditionally artificialized coastal environments. In a scenario of global warming, rising sea levels and increased frequency of extreme weather events, especially in urbanised coastal areas, the applicability of these solutions in Portugal's commercial ports was analysed. These approaches are in line with European and global goals for sustainable development and biodiversity conservation, as they help to mitigate the impacts of dredging, restore degraded habitats, favour marine biodiversity and protect coastal areas from overtopping and flooding. The research is based on the concept of greening the grey, derived from eco-engineering, which proposes the incorporation of ecological principles into the hard environment of urban infrastructures. The methodology consisted of selecting six techniques applicable to ports, identified through a review of the Scopus database and the EcoShape website, followed by an analysis of 26 commercial ports in mainland Portugal and the autonomous regions, based on physical, operational and environmental parameters. The results indicate that three of the techniques, including two aimed at promoting biodiversity and one at coastal protection, have demonstrated applicability in at least 19 ports, due to their technical and economic viability. The other techniques, with more specific requirements, were considered viable in a smaller number of ports. Even so, all the ports analysed showed potential for adopting at least two solutions. The research contributes to future studies aimed at the implementation of these techniques by port authorities and encourages the integration of nature-based solutions into rigid port infrastructures.

Keywords: Greening the grey; Nature-based Solutions; Ecoengineering; Harbour Infrastructures.

RESUMO

Esta pesquisa explora a aplicação de soluções baseadas na natureza em infraestruturas portuárias como estratégia para promover a sustentabilidade ambiental em ambientes costeiros tradicionalmente artificializados. Num cenário de aquecimento global, elevação do nível do mar e aumento da frequência de fenómenos climáticos extremos, especialmente em áreas costeiras urbanizadas, analisou-se a aplicabilidade dessas soluções nos portos comerciais de Portugal. Tais abordagens alinham-se às metas europeias e globais de desenvolvimento sustentável e conservação da biodiversidade, pois contribuem para mitigar impactos de dragagens, recuperar habitats degradados, favorecer a biodiversidade marinha e proteger zonas costeiras contra galgamentos e inundações. A pesquisa fundamenta-se no conceito *greening the grey*, oriundo da ecoengenharia, que propõe a incorporação de princípios ecológicos ao ambiente duro das infraestruturas urbanas. A metodologia consistiu na seleção de seis técnicas aplicáveis a portos, identificadas por meio de revisão na base Scopus e no site da EcoShape, seguida da análise de 26 portos comerciais em Portugal continental e nas regiões autónomas, com base em parâmetros físicos, operacionais e ambientais. Os resultados indicam que três das técnicas, incluindo duas voltadas à promoção da biodiversidade e uma à proteção costeira, demonstraram aplicabilidade em pelo menos 19 portos, devido à sua viabilidade técnica e econômica. As demais técnicas, com exigências mais específicas, foram consideradas viáveis em um número mais restrito de portos. Ainda assim, todos os portos analisados apresentaram potencial para a adoção de pelo menos duas soluções. A pesquisa contribui com subsídios para estudos futuros voltados à implementação dessas técnicas pelas autoridades portuárias e fomenta a integração de soluções baseadas na natureza em infraestruturas portuárias rígidas.

Palavras-chave: *Greening the grey*; Soluções Baseadas na Natureza; Ecoengenharia; Infraestruturas portuárias.

LIST OF FIGURES

Figure 1 – Definition of coastal terms.	4
Figure 2 – A classification of coastlines and a presentation of morphological features.....	5
Figure 3 – Impression of polehulas.	7
Figure 4 – Impression pontoonhulas.	7
Figure 5 – Installation of polehulas.	8
Figure 6 – Mussels attached to the ropes of a pontoonhula.....	9
Figure 7 – Design of the bird island.	10
Figure 8 – Eco-friendly surfaces, roughened with various texture.....	11
Figure 9 – Eco-concrete breakwater structures.	11
Figure 10 – Construction of the ecobasins.	12
Figure 11 – Monitoring results indicated an increase in the amount of species with respect to the reference.	13
Figure 12 – Selection funnelling system.	14
Figure 13 – Keyword substrings for methodology.	15
Figure 14 – Illustration of the wave channel and vertical seawalls.....	25
Figure 15 – Design inspirations and related models.....	26
Figure 16 – Schematic view of the wave flume and experimental equipment.....	27
Figure 17 – Map of the ports of mainland Portugal.	28
Figure 18 – Map of the jurisdiction area of the Viana do Castelo port.	29
Figure 19 – Map of the jurisdiction area of the Leixões port.....	30
Figure 20 – Map of the jurisdiction area of the Aveiro port.....	30
Figure 21 – Map of the jurisdiction area of the Figueira da Foz port.....	31
Figure 22 – Map of the jurisdiction area of the Lisbon port.	32
Figure 23 – Map of the jurisdiction area of the Setúbal port.....	32
Figure 24 – Map of the jurisdiction area of the Sines port.....	33
Figure 25 – Map of the jurisdiction area of the Portimão port.....	34
Figure 26 – Map of the jurisdiction area of the Faro port.	34
Figure 27 – Map of the ports of Madeira Archipelago.....	35
Figure 28 – Map of the jurisdiction area of the Funchal port.....	36
Figure 29 – Map of the jurisdiction area of the Caniçal port.	36
Figure 30 – Map of the jurisdiction area of the Porto Santo port.....	37
Figure 31 – Map of the ports of Azores archipelago.....	37
Figure 32 – Map of the jurisdiction area of the Corvo port.....	38
Figure 33 – Map of the jurisdiction area of the Santa Cruz das Flores port.....	39
Figure 34 – Map of the jurisdiction area of the Lajes das Flores port.....	39
Figure 35 – Map of the jurisdiction area of the Graciosa port.	40
Figure 36 – Map of the jurisdiction area of the Horta port.	40
Figure 37 – Map of the jurisdiction area of the São Roque do Pico port.	41
Figure 38 – Map of the jurisdiction area of the Lajes do Pico port.....	41
Figure 39 – Map of the jurisdiction area of the Madalena port.....	42
Figure 40 – Map of the jurisdiction area of the Velas port.....	42
Figure 41 – Map of the jurisdiction area of the Calheta port.	43
Figure 42 – Map of the jurisdiction area of the Praia da Vitória port.....	43
Figure 43 – Map of the jurisdiction area of the Angra do Heroísmo port.....	44

Figure 44 – Map of the jurisdiction area of the Ponta Delgada port.	44
Figure 45 – Map of the jurisdiction area of the Vila do Porto port.	45
Figure 46 – Graph of normalized density (D') and species richness (S) by port.	46
Figure 47 – Scatter plot of area in kilometres versus species richness.....	47
Figure 48 – Graph of the average annual movement of ships and cargo in the ports.	50
Figure 49 – Annual ship movements by area in square kilometres of the ports.....	51
Figure 50 – Graphical representation of the ERP index score for the ports.....	53
Figure 51 – Types of breakwaters blocks founded in the ports.	58

LIST OF TABLES

Table 1 – Coastal flooding and overtopping susceptibility class.....	22
Table 2 – Areas threatened by the sea for Azores ports.....	22
Table 3 – Flood and overtopping risk classification for mainland ports.	23
Table 4 – Species richness (R) by ports.....	46
Table 5 – Ecosystem and artificiality of the ports.	48
Table 6 – Port depth values.....	49
Table 7 – Average Annual Cargo and Vessels Traffic of the ports.	50
Table 8 – Ecological Restoration Potential classification of the ports.	52
Table 9 – Classification of the presence of environmental protection zones located near port areas.	53
Table 10 – Flood and overtopping risk classification for the ports.	54
Table 11 – Parameters and choice of application for polehulas and pontoonhulas NbS for ports.	55
Table 12 – Parameters and choice of application for bird island NbS for the ports.	57
Table 13 – Parameters and choice of application for eco-concrete breakwater NbS for the ports.	58
Table 14 – Parameters and choice of application for eco-basins NbS for the ports.	60
Table 15 – Parameters and choice of application for seawalls with topographic complexity NbS for the ports.....	61
Table 16 – Parameters and choice of application for bioinspired underwater breakwaters NbS for the ports.....	63
Table 17 – Summary of NbS application potential choices for each port.	64
Table 18 – Selected articles from Scopus.	77
Table 19 – Article selection table.	85
Table 20 – Materials for the breakwaters in each harbour.....	96
Table 21 – Materials for the eco-basin sites in each harbour.....	97
Table 22 – Materials for the seawalls in each harbour.	98

LIST OF ABBREVIATIONS

AIA	<i>Ambientes Inovadores de Aprendizagem</i>
APA	<i>Administração do Porto de Aveiro</i>
APDL	<i>Administração dos Portos de Douro, Leixões e Viana do Castelo</i>
APFF	<i>Administração do Porto da Figueira da Foz</i>
APL	<i>Administração do Porto de Lisboa</i>
APP	<i>Associação dos Portos de Portugal</i>
APRAM	<i>Administração dos Portos da Região Autónoma da Madeira</i>
APRH	<i>Associação Portuguesa dos Recursos Hídricos</i>
APS	<i>Administração dos Portos de Sines e do Algarve</i>
APSS	<i>Administração dos Portos de Setúbal e Sessimbra</i>
COP	Conference of the Parties
DAROT	<i>Divisão de Análise de Riscos e Ordenamento do Território</i>
DROTRH	<i>Direção Regional do Ordenamento do Território e dos Recursos Hídricos</i>
ERP	Ecological Restoration Potential
EU	European Union
GBIF	Global Biodiversity Information Facility
GHG	Greenhouse Gas
GI	Green Infrastructure
ICNF	<i>Instituto da Conservação da Natureza e das Florestas</i>
IFCN	<i>Instituto das Florestas e Conservação da Natureza</i>
IODE	International Oceanographic Data and Information Exchange
IPCC	Intergovernmental Panel on Climate Change
IPTM	<i>Instituto Portuário e dos Transportes Marítimos</i>
IUCN	International Union for Conservation of Nature
MLW	Mean Low Water
NbS	Nature-based Solution
OBIS	Ocean Biodiversity Information System
PA	<i>Portos dos Açores</i>
POC	<i>Programas da Orla Costeira</i>
PVC	Polyvinyl Chloride
RAM	<i>Região Autónoma da Madeira</i>
SB	Submerged Breakwater
SDG	Sustainable Development Goals
SIC	<i>Sítios de Interesse Comunitário</i>
SiNIAmb	<i>Sistema Nacional de Informação de Ambiente</i>
SuDS	Sustainable Drainage System
TRL	Technology Readiness Level
UK	United Kingdom
UNESCO	United Nations Educational, Scientific and Cultural Organization
USACE	United States Army Corps of Engineers
ZEC	<i>Zonas Especiais de Conservação</i>
ZPE	<i>Zonas de Proteção Especial</i>

LIST OF SYMBOLS

D	Simpson's Index
d	Species Richness Density
D'	Normalized Density
H	Shannon's Diversity Index
Kd	Dissipation Coefficient
Kr	Reflection Coefficient
Kt	Transmission Coefficient
S	Species Richness

TABLE OF CONTENTS

	ACKNOWLEDGEMENTS	I
	ABSTRACT	II
	RESUMO	III
	LIST OF FIGURES	IV
	LIST OF TABLES	VI
	LIST OF ABBREVIATIONS	VII
	LIST OF SYMBOLS	VIII
1	INTRODUCTION	1
2	LITERATURE REVIEW	3
2.1	Habitat opportunities in harbours – Port of Rotterdam	6
2.2	Bird Island construction – expansion of Port 2000 Le Havre	9
2.3	Eco-concrete breakwater structures – IJmuiden	10
2.4	Rich Revetment for coastal protection – Eastern Scheldt	12
3	METHODOLOGY	14
3.1	Selection of the articles in the Scopus database	14
3.2	Selection of the Ecoshape case studies	17
3.3	Delimitation of the study area	18
3.4	Parameterisation of NbS application potential in ports	19
3.4.1	Biodiversity	19
3.4.2	Ecosystem and artificiality	20
3.4.3	Depth	20
3.4.4	Vessel traffic	21
3.4.5	Ecological Restoration Potential	21
3.4.6	Presence of environmental protection zones	21
3.4.7	Risk of overtopping	22
3.4.8	Other specific parameters	23
4	RESULTS AND DISCUSSION	24
4.1	Selected articles from Scopus	24
4.1.1	Seawalls with Topographic Complexity	24
4.1.2	Bioinspired Underwater Breakwaters	25
4.2	Characterisation of commercial Ports	28
4.2.1	Viana do Castelo and Leixões ports	28
4.2.2	Aveiro port	30

4.2.3	Figueira da Foz port.....	31
4.2.4	Lisbon port.....	31
4.2.5	Setúbal port.....	32
4.2.6	Sines and Algarve ports	33
4.2.7	Madeira ports	35
4.2.8	Azores ports	37
4.2.8.1	Flores ports	38
4.2.8.2	Graciosa port	40
4.2.8.3	Faial port.....	40
4.2.8.4	Pico ports.....	41
4.2.8.5	São Jorge ports	42
4.2.8.6	Terceira ports.....	43
4.2.8.7	São Miguel port	44
4.2.8.8	Santa Maria port	45
4.3	Port characterisation parameters and results	45
4.3.1	Biodiversity	45
4.3.2	Ecosystem and Artificiality.....	48
4.3.3	Depth.....	49
4.3.4	Vessel traffic	49
4.3.5	Ecological Restoration Potential	51
4.3.6	Presence of environmental protection zones	53
4.3.7	Risk of overtopping	54
4.4	Assessment framework for NbS application in the port context	55
4.4.1	Polehulas and pontoonhulas	55
4.4.2	Bird island	56
4.4.3	Eco-concrete breakwater	57
4.4.4	Eco-basins.....	59
4.4.5	Seawalls with topographic complexity	61
4.4.6	Bioinspired underwater breakwaters	63
4.4.7	General overview.....	64
5	FINAL CONSIDERATIONS ABOUT THE METHODOLOGY	66
6	CONCLUSIONS AND FUTURE PERSPECTIVES	67
	REFERENCES	70

APPENDIX A	
SELECTION OF ARTICLES BY THE SCOPUS DATABASE	77
APPENDIX B	
SUBSTRATE AND ITS LEVEL OF ARTIFICIALITY FOR THE NBS IMPLEMENTATION AREAS	96

1 INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC, 1992-2023) has long stated that anthropogenic emissions of greenhouse gases (GHGs) have caused global warming. The rise in emissions has been paralleled by the rapid urbanisation and expansion of large urban settlements. This is attributable to the fact that the construction of cities has, for a considerable period, involved the utilisation of energy derived from fossil fuels, the employment of hard engineering materials, deforestation, and the destruction or occupation of natural habitats.

As a result, the consequences of climate change are becoming increasingly evident in the form of extreme weather events, for which cities remain largely unprepared. Coastal cities, in particular, are vulnerable to the adverse effects of climate change, including rising sea levels, intense precipitation, high tide flooding, and severe storms (Xu et al., 2023). The vulnerability extends beyond human and infrastructural impacts, affecting sensitive coastal ecosystems such as wetlands and estuaries. In light of this, it is not sufficient to rely solely on mitigation strategies focused on reducing emissions and limiting global temperature rise; local-level adaptation measures must also be prioritised.

In response to these challenges, the concept of “greening the grey” has emerged within the field of engineering (Naylor et al., 2017). This approach promotes the integration of sustainable and resilient design principles inspired by nature into traditionally “grey infrastructures”, such as concrete walls, rockfills, and breakwaters. Historically, engineering decisions were driven predominantly by considerations of functionality, aesthetics, and cost-efficiency. However, with the advent of the greening the grey concept, engineers are now required to consider the environmental impacts of their designs, the protection of ecosystems, the increase of local biodiversity, and the adaptation of their designs to the effects of climate change.

Port infrastructures are emblematic of grey engineering, having traditionally been constructed with large-scale concrete and rock structures to withstand powerful wave action. However, these environments are also home to diverse marine life. These structures, which are predominantly smooth and simple in shape, lack the complexity and refuge required by the species that inhabit them. Given the rising sea levels and the increasing unpredictability of climate change, these approaches are becoming increasingly inadequate.

Considering the pressing necessity to adapt engineering practices to the realities of climate change and to safeguard and enhance biodiversity, this study aims to investigate innovative techniques and methodologies that align with the greening the grey concept in the context of coastal and port infrastructure.

The general objective of this dissertation is to analyse and promote the implementation of green engineering in grey coastal and port infrastructures with the purpose of enhancing the ecological sustainability and resilience of these structures in accordance with United Nations Sustainable Development Goals (SDGs), particularly SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 14 (Life Below Water) (United Nations, 2015).

In order to achieve the general objective, a series of specific objectives were defined as follows:

1. Carry out a comprehensive literature review on the greening the grey concept, including its global applications, and on the ecological principles relevant to coastal and harbour environments.

2. Inventory and categorise existing eco-engineering techniques that can be applied to coastal and port infrastructures.

3. Identify, map, and assess the feasibility of implementing eco-engineering techniques in all of Portugal's commercial ports.

Based on the established objectives and the literature review on the application of eco-engineering techniques and “nature-based solutions” (NbS) in coastal and harbour infrastructures, the following hypotheses were formulated to guide the development of this dissertation:

1. Eco-engineering techniques can be adapted and successfully applied to different types of coastal and harbour environments, taking into account their specific characteristics and functional demands.

2. Port authorities are likely to adopt eco-engineering techniques aligned with the greening the grey concept as a strategy to mitigate local biodiversity loss, enhance resilience to climate events, and contribute to global sustainability goals.

This dissertation is therefore organised into six sections. Section 1 presents the context of the study, the main concepts addressed, the general and specific objectives, as well as the hypotheses on which the research is based. Section 2 includes a literature review, covering the concepts of eco-engineering and the different types of coastal environments, as well as presenting four international case studies of nature-based solutions applied in real port contexts. Section 3 describes the methodology adopted, including the criteria for selecting the articles and case studies that make up the inventory of techniques, the delimitation of the ports considered as the study scenario and the parameters defined for the analysis. Section 4 presents the results, including the articles and ports selected, the classification of ports based on the parameters established and the definition of the nature-based solutions best suited to each context, as well as a discussion of the findings. Section 5 discusses the methodological limitations and relevant considerations for interpreting the results. Finally, Section 6 sets out the main conclusions of the research and proposes directions for future research.

2 LITERATURE REVIEW

The term nature-based solutions was first adopted by the International Union for Conservation of Nature (IUCN) and defined as “actions to protect, sustainably manage and restore natural or modified ecosystems [...] that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (Cohen-Shacham et al., 2016, p. xii). Furthermore, the concept was discussed at 26th Conference of Parties (COP26) in Glasgow, with an emphasis on the restoration of ecosystems as a means of mitigating climate change through adaptation (UN Climate Change Global Innovation Hub, 2022). According to the European Commission, NbS can be defined as actions inspired by, supported by or copied from nature. These solutions “use the features and complex system processes of nature, such as its ability to store carbon and regulate water flow, in order to achieve desired outcomes, such as reduced disaster risk, improved human well-being and socially inclusive green growth” (European Commission, 2015, p. 5).

The utilisation of these solutions in engineering techniques serves to guarantee functionality, resilience, adaptation and protection, thereby constituting an example of eco-engineering. The objective of eco-engineering is to achieve a mutually beneficial outcome for living beings, the environment and society by applying the ecological and sustainability principles, as defined by Bergen et al. (2001). Additionally, Strain et al., p. (2018, p. 12) posits that “interventions enhance the abundance and richness of ecological communities associated with urban infrastructure,” thereby underscoring the necessity for a precautionary approach that considers nature-based solutions prior to the construction of new structures.

In the context of eco-engineering, the term “green infrastructure” (GI) is defined as an infrastructure that preserves, enhances, or restores elements of a natural system, combining them with grey infrastructure to produce more resilient and lower-cost services (Browder et al., 2019). This approach recognises a wide range of environmental and economic benefits such as air and water purification, energy demand reduction, urban heat island effect, carbon sequestration, aesthetic enhancement and natural resource benefits (Pamukcu-Albers et al., 2021). It is also referred to as natural infrastructure or engineering with nature. In contrast to this, the traditional built structures and mechanical equipment are referred to as grey infrastructure, as they have been constructed with artificial materials such as concrete and steel, without consideration of nature and ecosystems (Browder et al., 2019). These structures have a greater impact on the environment due to the extraction, production and transportation of the materials used, as well as the construction techniques employed. Consequently, the term greening the grey denotes the integration or replacement of conventional structures with sustainable or nature-based techniques, with the objective of adapting cities to the effects of climate change and enhancing biodiversity.

Applications of GIs can be classified according to their specific characteristics and the environmental context in which they are deployed. In urban settings, for instance, green roofs improve indoor comfort, reduce energy consumption and improve environmental quality (Ran & Tang, 2018). Urban gardens, parks and forests, and green corridors, play an important role in the capture of carbon and enhancement of air quality. They also facilitate the regulation of runoff, cooling through evapotranspiration and provide habitats for diverse species, thus contributing to the conservation of biodiversity (Cabral et al., 2017). Regarding to water management, the implementation of bioswales, sustainable drainage system (SuDS), retention and detention basins, rain barrels, green spaces, wetlands, green roofs, permeable pavements and deep infiltration can assist in the reduction of flooding, recharge of groundwater and

improvement of water quality, recreation opportunities and the creation of diverse habitats (Prudencio & Null, 2018).

In the context of coastal environments, a variety of applications can be presented in greater detail. Prior to any further discussion, it is essential to gain an understanding of the components that comprise the coastal environment, more specifically the coast. In order to conceptualise the principal terms associated with coastal environments, the glossary of coastal terminology from the book *Coastal Engineering Manual* of the United States Army Corps of Engineers (USACE, 2003) and the *Shoreline Management Guidelines* of Mangor et al. (2017) were employed as a foundation for the following definitions.

“The coastal zone corresponds to the geographical space where air, sea and land interact, including its renewable or non-renewable resources, covering a maritime strip and a land strip” Gerling et al., p. (2016, p. 23). The coastal zone, which encompasses beaches and sandbanks, represents a vital habitat for a diverse range of marine and terrestrial life forms. In their book, Mangor et al. (2017) define the beach or shore as the area extending from the line of mean low water (MLW) to the point where there is a change in physiographic form or to the line of permanent vegetation. They further subdivide this area into the foreshore and the backshore.

There is a distinction to be made between the terms shoreline and coastline. Mangor et al. (2017) defines the term shoreline as an imaginary line that delineates the sea from the beach, which in turn delineates the foreshore from the backshore. This line is represented on maps and is regarded as representing the mean level of the high tide. The coastline is more readily discernible than the shoreline, as it demarcates the boundary between two morphologically disparate regions: the beach and the coast. For a more comprehensive understanding of these terms, please refer to Figure 1, taken from the *Shore Protection Manual* of 1984.

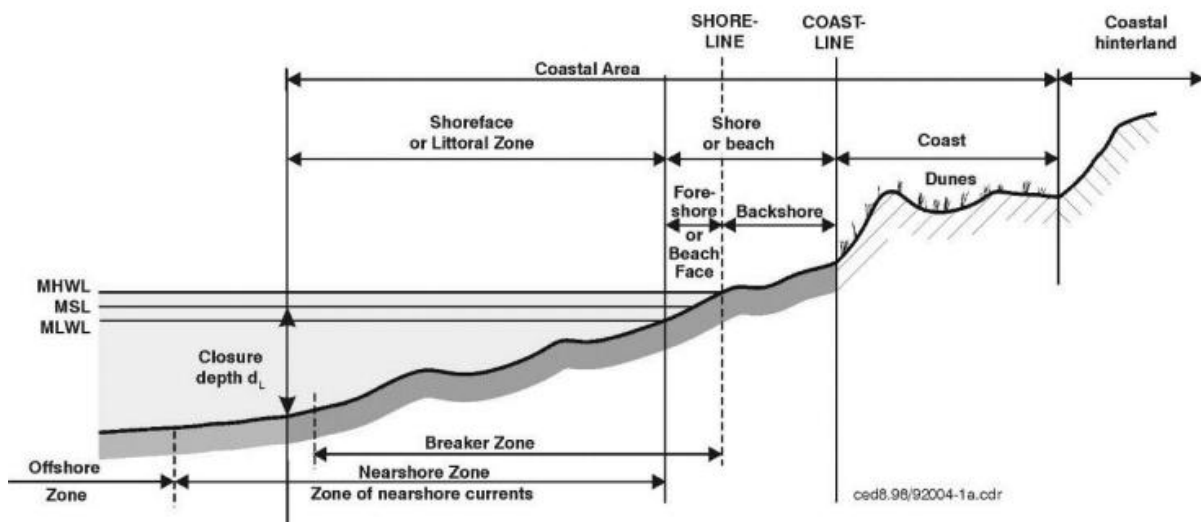


Figure 1 – Definition of coastal terms (Coastal Engineering Research Center (US), 1984).

Once the fundamental concepts of the coast have been grasped, it is possible to proceed to an examination of the various environments that can be found in this region. To facilitate a more comprehensive understanding of the anatomy and location of the terms in question, it is recommended that Figure 2 be consulted.

Tidal flats are a type of coastal habitat that are characterised by their shallow depth and muddy composition. These areas are subject to the fluctuations in sea level that occur during the tidal cycle. In the hinterland of the beaches, one may observe the presence of dunes, which are ridges of sand that have been formed with the assistance of wind action (Mangor et al.,

2017). Alternatively, one may encounter marshes, which are characterised by soft, damp soil and low-growing vegetation (USACE, 2003). Further examples of the interaction between the ocean and the continent can be observed in the form of cliffs or rock walls and lagoon formations.

In the area where the river meets the sea, an ecosystem is created with a mixture of fresh and salt water and the deposition of sediments. This ecosystem can be found in the form of an estuary, which is a bay of brackish water with mangroves, trees with intertwined roots that serve to protect the coastline and riverbanks, as well as act as nurseries for a variety of fish species (Gerling et al., 2016). Alternatively, it can be found in a branching triangular shape, which is called a delta.

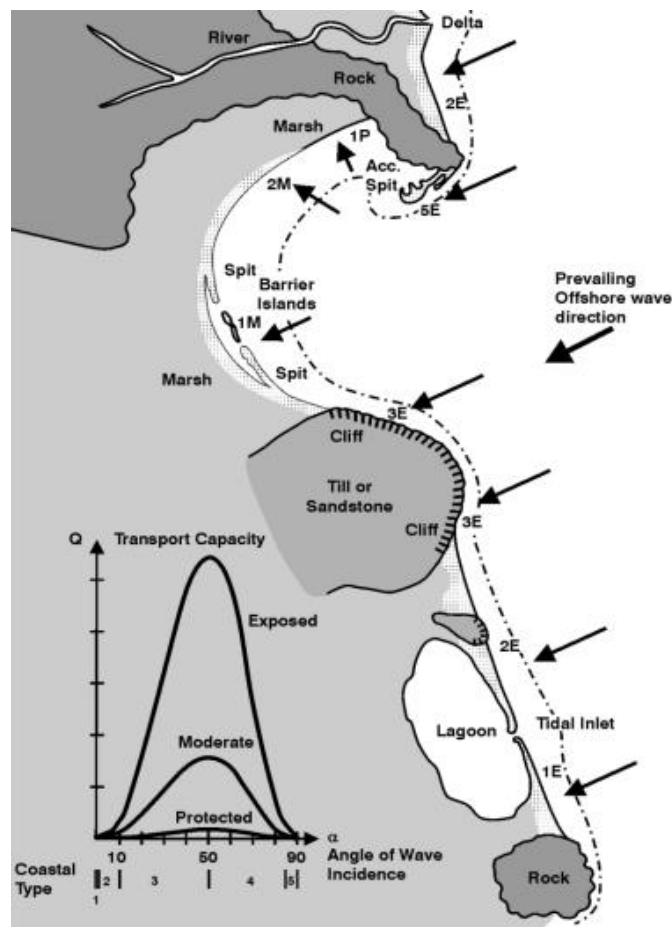


Figure 2 – A classification of coastlines and a presentation of morphological features (Pilkington, 2007).

These areas are of ecological and economic importance and warrant further investigation. They support a diverse range of animal species and provide natural resources that are crucial for the sustenance of human communities. Furthermore, they are areas of significant commercial activity, facilitating connectivity between countries and continents. A protected area with the capacity to receive vessels is referred to as a harbour, which may be either natural or artificial in origin (USACE, 2003). In these locations, the construction of ports, commercial structures, and ship and boat shelters is feasible. Such structures may include quays, wharves, cargo transfer facilities, docks, and other related infrastructure (USACE, 2003).

Furthermore, in order to safeguard a coastal zone, harbour, anchorage or wave basin from the detrimental effects of incident waves man has devised structures known as breakwaters

(USACE, 2003). There are various methods of constructing breakwaters. Breakwaters may be submerged, emergent, or floating; isolated or near-shore and connected to the coastline; rubble mound-type; constructed using caissons; constructed using revetment slopes; or constructed using composite structures. Additionally, wave attenuators of diverse configurations can be employed. Typically, breakwater materials are rigid substances such as stone or concrete. Another form of coastal protection is the seawall, which serves to safeguard urban structures in close proximity to the sea from the effects of wave action and to maintain the stability of the land on which they are situated (USACE, 2003).

These engineered structures, whether constructed for the purpose of facilitating maritime trade or for the protection of coastal areas against flooding and extreme water levels, interact directly with the ecosystems that are found in coastal and marine environments. The significant impacts of these structures include alterations to the natural habitat, changes in sedimentation patterns and currents, and a reduction in local biodiversity (Morris et al., 2017). The effects of climate change, such as accelerated sea level rise, rising temperatures, changes in the distribution of rainfall and freshwater inputs, and an increase in the frequency and intensity of storms, further intensify these impacts (Day et al., 2008). This highlights the urgent need for nature-based solutions to protect not only the integrity of human structures but also the marine habitats and species that depend on them.

In light of the aforementioned considerations, an examination of four pilot projects for nature-based solutions in port settings is warranted. These projects were identified on the EcoShape website, which serves as a network of organisations and individuals unified by the objective of fortifying and expanding nature-based initiatives within aquatic environments. This endeavour is undertaken with the intention of contributing to the SDGs, and consequently, to the advancement of nature, the economy, and society. This particular website was selected for its alignment with the objectives of this work, namely the dissemination of knowledge and the promotion of environmentally conscious development and engineering solutions. Additionally, its comprehensive range of projects and case studies, conducted in various global locations, including coastal areas, further reinforces its relevance.

2.1 Habitat opportunities in harbours – Port of Rotterdam

The first project, which was implemented between 2009 and 2010, was situated within the harbour of Rotterdam, the Netherlands' second-largest city. It was entitled Habitat Opportunities in Harbours and was a nature-based solution. Two structures designated "polehulas" and "pontoonhulas" were selected. The polehulas are ropes suspended from a band wrapped around submerged poles (Figure 3). The pontoonhulas are the same ropes hung from a nylon mesh between a rectangle of PVC pipes so that they float (Figure 4). Two types were used: in the type I, all the ropes are the same size, and in the type II, the ropes decrease in size as they approach the centre. The names ending in hula allude to the skirts of Polynesian hula dancers.

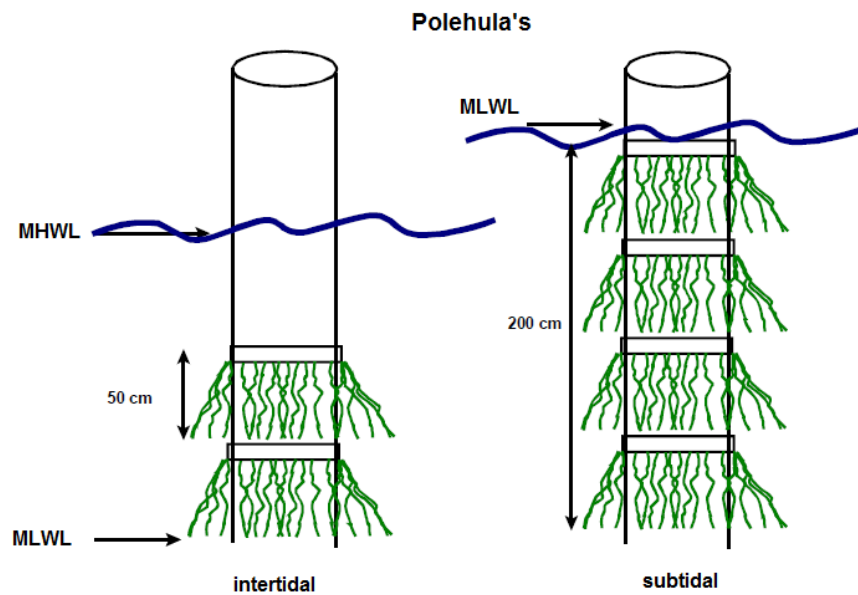


Figure 3 – Impression of polehulas (EcoShape, 2024d).

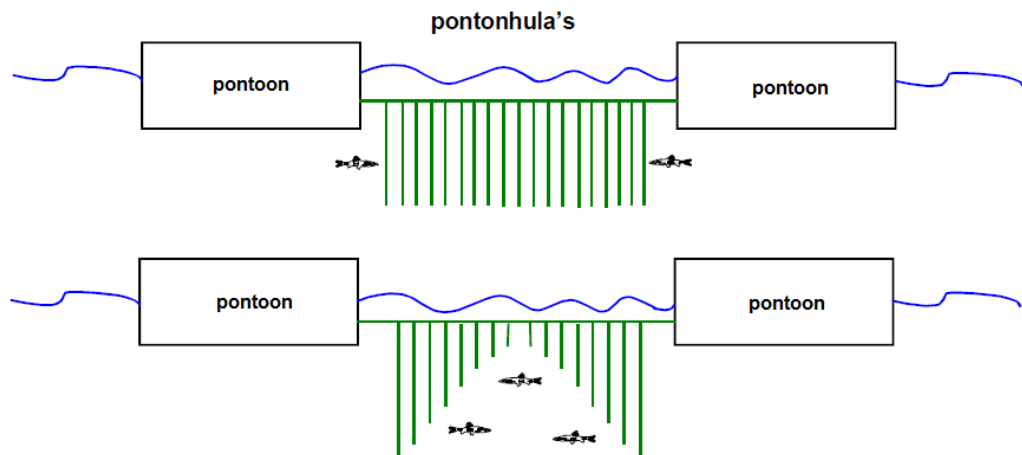


Figure 4 – Impression pontoonhulas (EcoShape, 2024d).

The objective of the project was to enhance the harbour environment to create a more hospitable habitat for marine organisms and fish. The traditional structures are characterised by a high degree of smoothness, which prevents the settlement of these organisms and provides limited opportunities for larger animals to seek refuge. The attachment of mussels offers a potential solution, as they enhance water quality by filtering out impurities and increasing light penetration. This, in turn, stimulates the growth of algae, which produce oxygen, benefiting other aerobic organisms in a mutually reinforcing cycle. Additionally, the mussels themselves create more variety and habitat complexity, and can provide refuge for fish.

At the feasibility study stage, authorisation was sought from the Dutch Ministry of Agriculture, Nature Conservation and Fisheries to remove the structures at any time, even if they had attracted protected fish species. Only then could the project commence. The study sites

were selected on the basis of salinity levels conducive to the growth of mussels. They were: Scheurhaven and Pistoohaven. In March 2009, the structures were duly positioned in the appropriate locations. In the Scheurhaven, polehulas were situated on five wooden poles and three steel poles, varying heights relative to the average water level (Figure 5). Two type I pontoonhulas and two type II pontoonhulas were additionally employed with fixed rope densities per pontoonhula. In the Pistoohaven, only three pontoonhulas were utilized, exhibiting varying densities and a density inferior to that observed in the Scheurhaven.



Figure 5 – Installation of polehulas (EcoShape, 2024d).

Fifteen weeks following the deployment of the polehulas, a notable prevalence of barnacles and mussels was observed at depths below the MLW, while two distinct species of algae were present at greater depths. A significant change in the abundance of mussels was observed thirty-four weeks later. This abundance was even higher in pontoonhulas (Figure 6), which did not attract algae, and this can be explained by the low penetration of light. The differences in biomass per centimetre of rope were also compared between the sites. In the Scheurhaven, the biomass was higher, which may be due to the lower salinity and greater turbulence, and consequently a greater supply of oxygen.



Figure 6 – Mussels attached to the ropes of a pontoonhula (EcoShape, 2024d).

In regard to water filtration, it was determined from measurements and calculations based on data from other studies, that a single pontoonhula is capable of filtering the entire volume of water in the Scheurhaven basin within 16 days. Furthermore, a separate and more specialised study conducted in another location, revealed that the pontoonhulas contributed to the reduction of wave height, effectively absorbing their energy in a manner analogous to floating breakwaters. Additionally, their porous nature and ability to penetrate deeper into the water column, may influence wave attenuation. It was therefore concluded that the use of artificial substrates represents an effective method for increasing biomass in port basins. Mussels filter water in an environmentally benign manner and warrant further investigation as potential wave attenuators.

2.2 Bird Island construction – expansion of Port 2000 Le Havre

The second project is the construction of a bird island in conjunction with the expansion of Port 2000 Le Havre in France, which was undertaken between 2001 and 2006. As in the Dominican Republic, an expansion of the port was planned, and the work included dredging the site. In response to concerns raised by the local community regarding potential environmental and economic impacts, the project proponents incorporated environmental compensation measures into the project design. These measures aimed to minimise and mitigate the adverse effects of the dredging activities while optimising the utilisation of the dredged material.

The proposed solution to the issue was the construction of a bird island, with the sand from the surrounding area removed. This solution would enhance the ecological value of the area and expand the available bird habitat. The project entailed the construction of an oval island capable of withstanding storms and following the prevailing currents, while also providing essential habitats for avifauna (Figure 7). Construction was conducted in phases to minimise adverse impacts. Initially, a bay was created, serving as a temporary storage for the dredged sand and gravel. Subsequently, the island's shape was defined, allowing the estuary to adapt, and finally, rock-lined dykes were constructed around the island to safeguard it from wave attack.



Figure 7 – Design of the bird island (EcoShape, 2024a).

The island called Banc du Ratier is situated in the middle of the main channel of the Seine and has been effective in attracting various species of birds. Initial observations suggest that the island is fulfilling its functions and ornithologists are confident of its future progress. As several measures were taken during construction to mitigate the environmental impact, the project has not only achieved this goal but has also added ecological value by combining the available resources and making intelligent use of them with a focus on sustainable development.

2.3 Eco-concrete breakwater structures – IJmuiden

Another project of particular interest, studied in the port environment, is the so-called eco-concrete breakwater structures. The present study investigates the utilisation of concrete blocks with varying textures as an eco-friendly substitute to enhance the biodiversity of marine organisms within the breakwaters at the North Sea Channel entrance in IJmuiden, the Netherlands. A further objective of the present project was to provide sustenance for a red list bird species, thereby contributing to the Natura 2000 network.

The blocks utilised in the study were identical to those that are routinely employed and replaced on the breakwater, measuring 2 m x 2 m, but with the incorporation of a 75cm x 50cm slab, featuring six distinct textures, each spanning an area of 25cm x 25cm (Figure 8). The textures of the slabs positioned in the vertical and horizontal orientations of the block were

varied, encompassing the following types: vertical grooves, horizontal grooves, fine surface, smooth surface, fine and smooth surface, medium-smooth surface, small holes, and cup (45% of the surface).

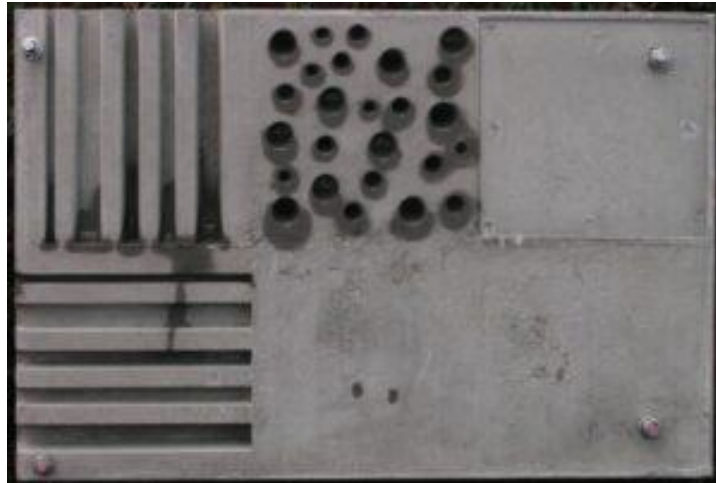


Figure 8 – Eco-friendly surfaces, roughened with various texture (EcoShape, 2024c).

In 2008, twenty slabs were constructed using a variety of concretes and bolted along the blocks, with ten positioned in an area exposed to the waves and ten in a more sheltered location (Figure 9). This study aimed to assess the optimal position in relation to the water level.



Figure 9 – Eco-concrete breakwater structures (EcoShape, 2024c).

Photographic analysis revealed that the fine and coarse surfaces attracted species of small green algae, while surfaces with cups and holes, with greater water retention, favoured the installation of larger green algae. The presence of barnacles was observed on all surfaces located at mid and high tides. Mussels were found in nine sections with grooves, holes and cups, and developed better inside the grooves. Conversely, the grooves and holes present in the low-tide zones were found to be populated by periwinkles. The total number of species of flora and fauna identified was nine and four, respectively.

At the end of the experiment, in 2009, it was concluded that the utilisation of textures had a positive impact on increasing biomass. The cost of implementing these textures directly in the mass production of blocks is 2% to 3% compared to the traditional smooth blocks already in use. Furthermore, the study enabled the identification of the optimal region for each texture, based on the species targeted for enhancement.

2.4 Rich Revetment for coastal protection – Eastern Scheldt

The final case study entitled Rich Revetment for Coastal Protection, was conducted between 2008 and 2013. It encompassed two projects: an initial experiment and the subsequent implementation of eco-basins at the base of protective dikes along the shoreline of an estuary in the Zeelandbrug region of Zierikzee, the Netherlands. The study aimed to enhance biodiversity and bio productivity among algae and animal species.

The preliminary phase involved a pre-viability assessment and a feasibility evaluation of the projects. These assessments considered various factors, including the optimal location for basin construction, risks associated with wave exposure and silting, stakeholder involvement, small-scale field trials, and the development of monitoring and maintenance plans.

The pilot project began with the construction of ten 2-metre-long pools and two 20-metre-long pools along a 1-kilometre stretch at the base of the dike, integrated into its renovation (Figure 10). In the second phase, larger pools measuring 150 metres in length, with both deep and shallow areas, were investigated.



Figure 10 – Construction of the ecobasins (EcoShape, 2024e).

Key design elements such as the shape, position, slope, and materials of the basins were carefully selected. Asphalt was used as a waterproofing material but presented challenges, particularly in forming sloping edges and sealing deeper pools. Stones were incorporated to provide shelter and hiding places for local species, while limestone and lava rock offered surfaces for organisms to attach to.

To ensure the successful establishment of species, an in-depth analysis of the local climate, surrounding ecosystem, and wave exposure was conducted. The study hypothesised that the constructed environment could be further optimised to support a wider variety of mussels, oysters, crabs, small fish, macroalgae, and other species.

Following the construction phase, the project basins underwent regular monitoring and photographic documentation over a three-year period. Species development within these basins was estimated and analysed. Results revealed that the number of taxa increased more significantly in the short basins compared to the long ones (Figure 11). This discrepancy was attributed to the higher elevation of the long basins relative to the tidal range, making them more prone to drying. Across all basins, species diversity surpassed the 2008 reference levels, showed further growth in 2009, and stabilised in 2010.



Figure 11 – Monitoring results indicated an increase in the amount of species with respect to the reference (EcoShape, 2024e).

The study concluded that introducing artificial basins within the intertidal zone of dikes effectively enhances biodiversity. It was observed that basins in low-wave-energy areas tended to accumulate silt, while those exposed to minimal wave energy supported high algal biomass. Additionally, the depth of the pools positively correlated with an increase in macrofauna species and their abundance.

Cost assessments for the project proved challenging. However, it was estimated that management costs accounted for 18% of the total expenditure. The construction costs of the eco-basins were partially integrated into the budget for the dike's reconstruction, which was a necessary expense regardless. The additional costs of the eco-basins were deemed negligible in the context of the overall project budget.

Estimating the benefits of the project presented further complexity. Based on the measurements, biodiversity within the eco-basins was found to be greater with a 3-5 factor than at the reference site, a dike section without basins. Furthermore, increased bird activity around the site was noted as a positive development for bird conservation efforts.

3 METHODOLOGY

This study aims to promote the application of ecological solutions in port environments to recover local biodiversity, which has always been neglected in design projects. It also aims to promote the sustainability and resilience of these sites to protect them from the climatic events that the world is experiencing as a result of climate change. To this end, this methodology is based on an inventory of techniques that use the principle of biomimicry and reduce the environmental impact of ports. Following this, a list of ports is categorised and used as a scenario. In conclusion, a series of parameters is analysed for each port, in order to determine the applicability of each NbS.

3.1 Selection of the articles in the Scopus database

The Scopus database, which provides extensive coverage of current scientific journals, was used to conduct a literature review on innovative nature-based solutions in port environments around the world. The type of research used is theoretical-empirical with a qualitative approach. However, to make the process more systematic, a four-stage funnelling system was used. At each stage, the number of articles decreased as they became more relevant to form part of the NbS. This scheme is summarised in Figure 12.

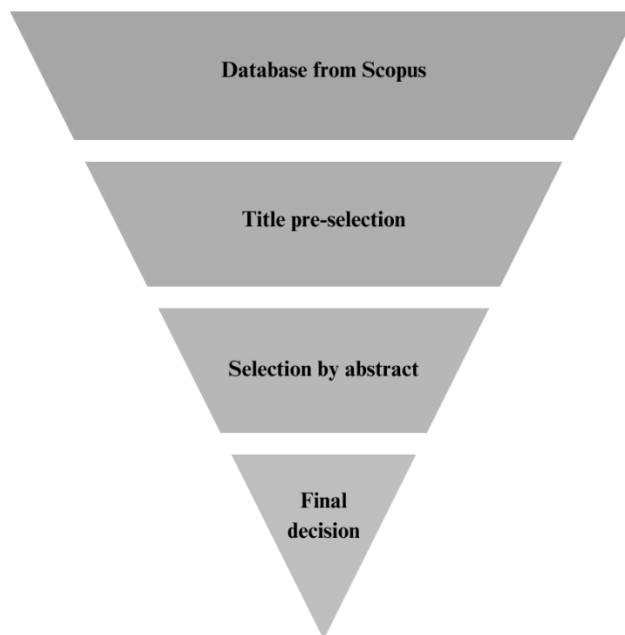


Figure 12 – Selection funnelling system.

The first phase of this process involved a system of keyword groups, based on the method used by Radfar et al. (2024). To identify relevant articles in the database, strings consisting of a combination of keywords separated by the logical operator “OR” were employed. This approach serves to restrict the database to articles containing at least one of the specified words in all the fields. The search was conducted using four distinct strings, which, when combined with the “AND” operator, represent different aspects of the main theme, constituting the intended context. The first substring looks at different port engineering solutions that are already known and used for coastal protection. The second searches for any terms that may be used in the articles that relate to nature-based solutions. The next substring imposes the port or coastal environment. Finally, the last substring incorporates the scope of

climate mitigation and resilience. The lexical choices employed can be observed in Figure 13 below.

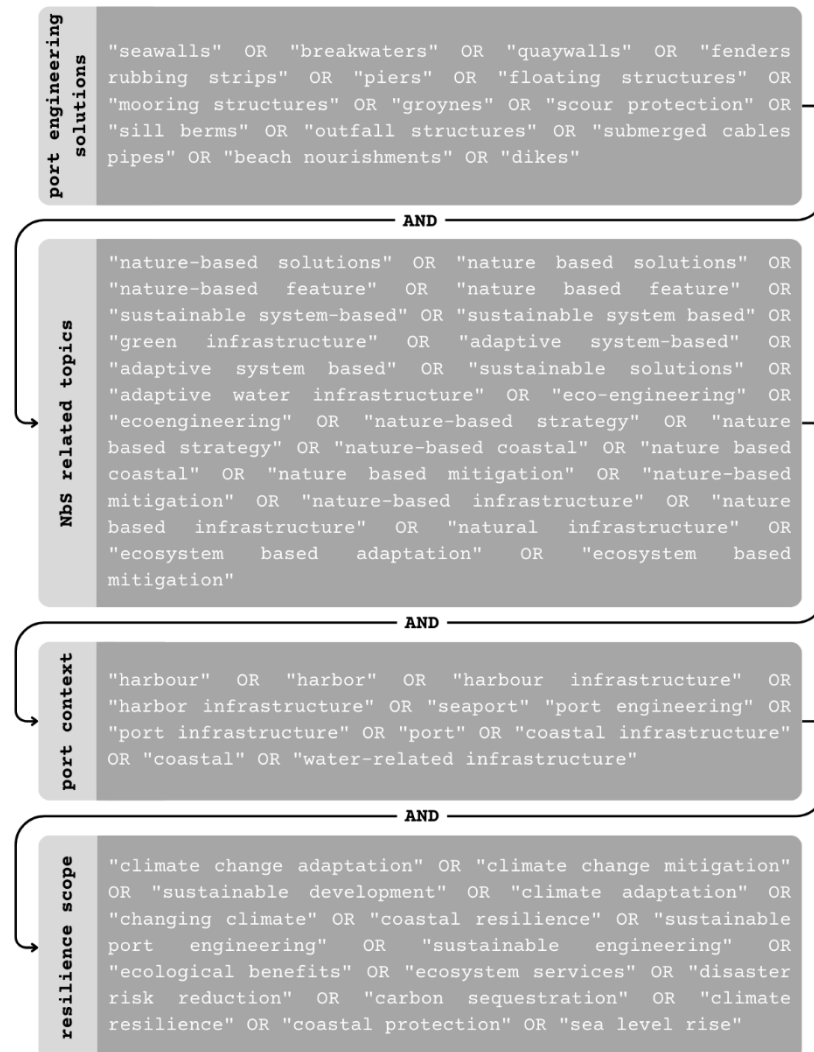


Figure 13 – Keyword substrings for methodology.

To ensure the relevance of the research, a number of filters were utilised in addition to the keywords. Firstly, a refinement by publication date was applied, selecting articles published between 2015 and 2024 (year in which this work was carried out). The justification for this choice was to limit the publication time to ten years, ensuring that the research considered was updated at the time of delivery of the present study. Subsequently, a refinement by area of knowledge was carried out, focusing on “Environmental Science”, “Engineering”, and “Earth and Planetary Sciences”. This filter was chosen to restrict the search to areas directly related to the topic, ensuring the relevance of the studies included. In addition, a refinement by document type was made, selecting only “Article”, “Review” and “Conference Paper”. The rationale behind this selection was to prioritise primary studies and systematic reviews, which provide an in-depth and comprehensive analysis of the subject matter. Finally, an article in Chinese was excluded due to limited understanding of foreign languages, ensuring that all studies considered were comprehensible. The application of the aforementioned method resulted, at the time of the search, in a database composed of 107 articles potentially relevant to the present research. For further information, please refer to the Table 18 in Appendix A.

The next phases of the selection process entailed the analysis of the articles found based on their titles and abstract. In the part designated Title pre-selection, the articles were organized in a table and classified into three distinct categories (see Table 19 in Appendix A). The first category, entitled “Relevant”, includes articles whose titles directly mention terms such as nature-based solutions, greening the grey, eco-engineering in coastal/port infrastructures, sustainability techniques or ecological resilience. The second category, “Possibly Relevant”, includes articles whose titles mention coastal infrastructures, sustainability or environmental techniques, but do not directly refer to nature-based solutions, greening the grey or eco-engineering. The third category, “Not Relevant”, encompasses articles whose titles deal with topics outside the scope of the research, such as urban infrastructures unrelated to coastal environments or purely economic aspects unrelated to ecological sustainability.

Following a thorough review of the articles, 52 were excluded as they were deemed to be “not relevant” to the study. The remaining articles, 27 of which were marked as “relevant” and 28 as “possibly relevant”, advanced to the subsequent selection phase, designated “Selection by Abstracts”. As the name suggests, an assessment was made based on reading the abstracts of the 55 articles. The assessment was based on the responses to three primary inquiries:

Question 1: *How does the article address the concept of greening the grey and its applications in coastal and port infrastructures?*

- a) *Does the article discuss specific eco-engineering techniques applied to coastal and port infrastructures?*
- b) *What examples or case studies are presented?*
- c) *Does the article analyse the effectiveness of these techniques in terms of resilience and sustainability?*

Question 2: *What are the main results presented in the article on the efficiency of nature-based solutions and their economic viability?*

- a) *Does the article provide data on the increased resilience and biodiversity of green infrastructures?*
- b) *Are there any cost-benefit analyses or discussions about reduced maintenance costs?*
- c) *Does the article mention economic, ecological and social benefits?*

Question 3: *Does the article address the perception and acceptance of eco-engineering techniques by stakeholders and their adaptation to climate change?*

- a) *Are there any surveys or data on the receptiveness of local communities?*
- b) *Does the article discuss the perceived benefits in terms of sustainability and environmental protection?*
- c) *Does the article relate its analyses to the objectives of global climate adaptation initiatives?*

The first question investigated how the article addresses the concept of greening the grey and its applications in coastal and port infrastructures. In this regard, the discussion of specific eco-engineering techniques applied to these infrastructures, the examples or case studies presented, and the analysis of the effectiveness of these techniques in terms of resilience and sustainability were considered.

The second question focused on the main results presented in the article on the efficiency of nature-based solutions and their economic viability. The analysis encompassed data on the enhanced resilience and biodiversity of GIs, along with any cost-benefit analysis or discussions on reduced maintenance costs. The economic, ecological and social benefits were also considered.

Finally, the third question addressed the perception and acceptance of eco-engineering techniques by stakeholders and their adaptation to climate change. Surveys or data on the receptiveness of local communities, discussion of perceived benefits in terms of sustainability and environmental protection, and the relationship of the article's analyses to the goals of global climate adaptation initiatives were examined.

For each set of questions, three potential responses were provided: "yes", "partially", and "no", which indicate the level of coverage of the articles in relation to the evaluated criteria. An affirmative response, is interpreted as denoting that the article addresses the established criteria in a complete and detailed manner, thereby providing comprehensive and relevant information. The answer "partially" indicates that the article addresses some aspects of the criteria, but not in a complete or detailed manner. The response of "no" indicates that the article does not address the established criteria.

The decision to include each article was finally made following consideration of the responses given to the three questions. The objective was to select a number of articles ranging from ten to twenty for progression to the subsequent phase. Consequently, the articles that were to be included were analysed once more, based on a second reading of the abstracts. Initially, priority was given to articles that answered in the affirmative to the first question, as these were deemed to be relevant to the primary theme of the present work. Although no article answered "yes" to all the questions, those who predominantly answered "yes" or "partially" were selected to ensure the acquisition of pertinent and valuable information for the dissertation. It is important to note, however, that the selection process was not characterised by meticulousness, due to the qualitative nature of the analysis and the greater emphasis placed on interpretation over the number of positive responses to the questions. Consequently, the questions served merely as a basis for support and clarification in the subsequent decisions.

At the conclusion of the analysis, 15 articles were selected for the third phase. Thereafter, the files were downloaded and printed for comprehensive review. However, due to unavailability of the journal, two files (1 and 4) could not be read. Given that this constituted the initial encounter with port engineering techniques and solutions, it was imperative to meticulously read and comprehend each article.

After this comprehensive reading process, two articles were identified as the most relevant and were retained for further analysis.

3.2 Selection of the Ecoshape case studies

Following this, a literature review was conducted for terms related to port engineering and environments, as well as the Ecoshape case studies.

The selection of case studies on the Ecoshape website, as well as on Scopus, was also subject to the implementation of filters, with the objective of narrowing down the most relevant articles. For the "Landscapes" category, the selection was restricted to articles pertaining to "Ports", with the objective of ensuring the applicability of the selected case studies to port environments. Furthermore, the technology readiness level (TRL) was filtered so that it was greater than five.

The TRL is a system that measures the maturity level of a technology and can range from 1 to 9. The TRL was originally developed by NASA (Manning, 2023) and has since been utilised by the European Union (EU) as a reference point to assess technological maturity and market acceptance (EURAXESS). It is noteworthy that TRL levels 5 and 6 ensure that the technology has been validated and demonstrated in a representative environment, which is essential to assess its viability in the port context. Levels 7 to 9 of TRL are indicative of a technology that has advanced to operational demonstration, qualification and final implementation, which allows its performance to be observed in real conditions and on a large scale (Manning, 2023).

This approach was deemed essential to mitigate risks associated with technologies still in the early development phase. The subsequent step involved the manual selection of four cases, with consideration given to their relevance for the present study. It is important to justify the selection of case studies on the EcoShape website, which did not follow the same methodical steps as the Scopus articles, due to the considerably smaller number of cases and their greater simplicity and objectivity. It is also believed that at this stage, the author had a greater understanding of the topic and therefore greater ease in selecting.

3.3 Delimitation of the study area

This topic describes the study area selected for the application of nature-based solutions: the Portuguese commercial ports. Portugal is widely regarded as a leading nation in the port sector, drawing upon its extensive maritime history dating back centuries to the Age of Discovery in the 15th century. Indeed, the nation's maritime history and legacy have left an indelible mark on its identity, with the term "port" itself becoming a part of its name. The country's strategic location in a region where 53% of European external trade passes through further reinforces its significance in the global maritime landscape (Associação dos Portos de Portugal, 2014) and justify its selection as a representative scenario for this investigation.

The study scenario includes both mainland Portugal and its two autonomous regions: the Azores and Madeira. The open-source software QGIS version 3.40.4 Bratislava (Sutton & Dassau, 2002) was used as a tool for spatially analysing each port. The first step was to demarcate and understand the area of jurisdiction of each port. The information was obtained from the websites of each port administration, as well as the Associação dos Portos de Portugal (APP) [Association of Ports of Portugal] website.

The cartographic representations depicting the locations of the ports, which are divided between the three regions, were inspired by the map Main Maritime Ports of Portugal (2012), which was presented by the Ambientes Inovadores de Aprendizagem (AIA) [Innovative Learning Environments]. Due to the geographical distance between the islands, the map of the Azores region is adjusted by approximating the three island groups in order to fit within a single visual frame.

For the Região Autónoma da Madeira (RAM) [Autonomous Region of Madeira] ports, the maps were drawn on the basis of the coordinates provided for in Articles 2, 3 and 4 of Regional Legislative Decree 25/2003/M of 23 August (Decreto Legislativo Regional n.o 25/2003/M, 2003), as no illustration of the demarcation of their area of jurisdiction could be found. In the case of the Azores, the maritime and land jurisdictions used to create the port visualisation maps were consulted on the Porto dos Açores, S.A. (PA) [Azores Ports Authority] website and in accordance with Annex II to Regional Legislative Decree 24/2011/A of 22 August (Decreto Legislativo Regional n.o 24/2011/A, 2011).

The ports were grouped by port authority for organisational purposes. The identification and spatial representation of the commercial ports, including the maps created, form the basis for the analysis presented in the Results chapter, which assesses their potential for implementing nature-based solutions.

3.4 Parameterisation of NbS application potential in ports

In order to select the green techniques, a set of qualitative parameters necessary or desirable for the application of each NbS was established. The definition of these was arrived at by taking into account the characteristics of the application environment and the available data. Following the establishment of clear criteria, a more informed decision can be made regarding the site. The subsequent section provides a comprehensive rationale for the significance of each parameter and the methodology employed for the classification of each port.

3.4.1 Biodiversity

The primary parameter, and arguably the most significant in this study, pertains to local biodiversity. It is evident that the nature-based techniques contribute to the enhancement of the habitat and the increase of substrate for growth, thereby leading to an increase in the number of organisms and animals.

Therefore, efforts were made to identify methodologies for the quantification of biodiversity within port areas. The identification of species inhabiting a given site was achieved through the utilisation of two distinct databases. The first, Global Biodiversity Information Facility (GBIF) is an intergovernmental initiative that gathers and makes available geospatial data on species occurrences around the world. The second, Ocean Biodiversity Information System (OBIS), was established as part of the Census of Marine Life programme. This programme is now associated with International Oceanographic Data and Information Exchange (IODE) of UNESCO and utilises the same principle but focuses exclusively on marine habitats.

The data was extracted directly from the websites of the respective platforms. For GBIF, specific filters were applied in order to guarantee the quality and relevance of the records: the time interval from 2015 onwards was selected; the geographical area was restricted to occurrences within the territory of Portugal; records from human observation were prioritised in order to ensure greater reliability; and only occurrences with validated presence status were considered. The same spatial and temporal filter was also used for the OBIS download.

Subsequently, Microsoft Excel and the Power Query editor were used to refine the data extracted from GBIF, restricting it to animals associated with marine habitats, such as coastal birds, algae, small fish and marine invertebrates. For this process, filters were applied by order and class, according to the desired scope for each group. For marine invertebrates, the orders selected were *Mytilida*, *Ostreida*, *Octopoda*, *Teuthida* and *Decapoda*, and the classes were *Asteroidea*, *Echinoidea* and *Holothuroidea*. In the case of fish, the orders *Perciformes* and *Clupeiformes* were considered. For marine plants and algae, the orders *Alismatales* and *Fucales* were selected. Finally, for coastal birds, records of the orders *Charadriiformes*, *Pelecaniformes* and *Procellariiformes* were included.

In conclusion, to select only those occurrences in the intended port areas, the points were entered into QGIS with the use of geographical coordinates. The selection of points was

conducted within a 2-kilometre radius of each port area. Subsequently, the data was transferred back to the Excel spreadsheet for analysis.

Biodiversity in a given area can be assessed using different metrics. Species richness (S) corresponds to the total number of distinct species recorded in a locality, with higher values indicating greater diversity. The Shannon's diversity index (H) considers both the abundance and evenness of species, reflecting diversity based on the proportion of individuals per species; the higher the H value, the greater the diversity of the community. Shannon's equitability is obtained from the ratio between H and the natural logarithm of S and expresses the degree of uniformity in the relative abundances of species, i.e. how balanced the distribution is between them. Finally, Simpson's index (D) measures the dominance of species in a community. Values close to 1 indicate strong dominance by one or a few species, while lower values suggest a more equitable distribution among the species present (Begon et al., 2006). The study initially aimed to use these metrics to quantify biodiversity. However, due to data limitations this parameter was disregarded in the analysis. The results and discussion of this parameter are presented in the following section.

In order to obtain a more equitable and representative classification of the biodiversity, the concept of Ecological Restoration Potential (ERP) was created as an alternative indicator. This new index was developed based on a set of parameters relevant to the assessment of the vulnerability and environmental degradation of ports. Among the criteria considered, the degree of artificiality of the port environment stands out, since more artificialized structures indicate a greater need for ecological restoration. In addition, the presence of sensitive ecosystems, such as estuaries and river deltas, was considered due to their greater ecological fragility. The lack of data on biodiversity was also interpreted as a potential for ecological underrepresentation, attributing, in these cases, a high priority for restoration. Another factor incorporated was the intensity of vessel traffic in relation to the port area, since higher densities of use are associated with greater anthropic pressure. Finally, the depth of the port was included as an indirect indicator of the degree of disturbance of the marine environment, considering that deeper ports may be the result of more intensive and recurrent dredging operations. Before presenting the method for calculating the proposed index, it is necessary to describe the process for obtaining the data relating to the parameters considered in this analysis.

3.4.2 Ecosystem and artificiality

A classification of the degree of artificiality in low, medium and high of each port was performed through visual analysis of satellite images made available by Google Earth, considering the level of anthropogenic transformation observed in the port infrastructure and its surroundings. Additionally, the environmental context of each port — that is, whether it is located in a naturally sensitive environment, such as estuaries or deltas, or directly in an open ocean area — was also assessed based on the same visual methodology.

3.4.3 Depth

Information on the depth of mainland ports was obtained from a study analysing the evolution of dredging quotas over time. For the ports located in the RAM, the data was available on the port administrations' websites, along with the other technical characteristics of each port. Similarly, the ports in the Azores also presented this information on their respective institutional platforms.

Based on the data collected, port depth was classified into three categories: deep (depth of more than 15 metres), medium (between 10 and 15 metres) and shallow (less than 10 metres). This categorisation was based on the draught values typical of different types of vessels: large draught vessels, such as oil tankers, bulk carriers and large container ships, generally require depths of more than 15 metres; on the other hand, small draught vessels, such as fishing, recreational and coastal transport vessels, operate at depths of less than 10 metres.

3.4.4 Vessel traffic

Data on annual ship and cargo movements was obtained from the official websites of the respective port administrations. However, the information available was not uniform between the different sources. For the ports located on the Portuguese mainland, the most recent data refers to 2024. For the ports in the RAM, the data extends to 2023, while the Azores ports only have information up to 2018. Given this inconsistency in time, it was decided to calculate an arithmetic average of the annual movement of cargo and vessels, considering the interval from 2015 to the last year available for each port. The only exception was the port of Setúbal, whose records only begin in 2020.

3.4.5 Ecological restoration potential

To construct the ecological restoration potential index, a scoring system was adopted for each of the parameters considered, assigning higher scores to the categories that indicate a greater need for ecological intervention. In the artificiality parameter, 1 point was given to environments with a low degree of artificiality, 2 points for medium and 3 points for high. In the ecosystem parameter, ports located in marine areas received 1 point, while those in more sensitive ecosystems, such as estuaries and rivers, received 2 points. Ports that had no records of species in the databases analysed received an additional 1 point, considering the absence of information as a possible indication of under-representation of local biodiversity.

For the ship traffic per area parameter, the average annual ship movement per square kilometre of port area was calculated and the score was assigned as follows: 1 point for values below 200 ships/km², 2 points for values between 200 and 600 ships/km², and 3 points for values above 600 ships/km². As for depth, 1 point was awarded for shallow harbours or those with no data available, 2 points for medium-depth harbours and 3 points for deep harbours.

The final score corresponds to the sum of the scores assigned to each port, ranging from a minimum of 4 to a maximum of 12 points. Based on this total score, the ecological restoration potential was classified into three categories: low (4 to 6 points), medium (7 to 9 points) and high (10 to 12 points).

3.4.6 Presence of environmental protection zones

In addition to the ecological restoration needs index, it was decided to also consider the presence of environmental protection zones located in or near areas of port jurisdiction. Three categories of protected areas were included in the analysis: Zonas de Proteção Especial (ZPE) [Special Protection Areas], established under the Birds Directive (Directive 2009/147/EC on the Conservation of Wild Birds, 2009), with the aim of ensuring the conservation of wild birds and their habitats; Sítios de Interesse Comunitário (SIC) [Sites of Community Importance] and Zonas Especiais de Conservação (ZEC) [Special Areas of Conservation], both provided for in the Habitats Directive (Council Directive 92/43/EEC on the Conservation of Natural Habitats and of Wild Fauna and Flora, 1992), aimed at preserving biodiversity by protecting natural habitats and species of flora and fauna considered threatened in the territory of the EU.

The presence of these protected areas was verified visually by analysing the maps available on the following official portals: the Instituto da Conservação da Natureza e das Florestas (ICNF) [Institute for the Conservation of Nature and Forests] for mainland Portugal, Instituto das Florestas e Conservação da Natureza (IFCN) [Institute of Forests and Nature Conservation] for the Madeira archipelago, and the Azores Government Portal for the Azores region (Portal do Governo dos Açores, n.d.).

3.4.7 Risk of overtopping

With regard to the risk of overtopping in the ports analysed, a diversity of data sources and formats was observed, requiring different approaches to standardisation and classification. For the ports in the Madeira region, a map of susceptibility and occurrence of coastal overtopping was used, produced by the Divisão de Análise de Riscos e Ordenamento do Território (DAROT, 2023) [Risk Analysis and Land Use Planning Division], in which the coastal strips are classified into three categories: high, moderate and low (Table 1). The classification of port risk was based on the highest risk category observed within each port's area of jurisdiction.

Table 1 – Coastal flooding and overtopping susceptibility class according to DAROT (2023).

Sites	Coastal flooding and overtopping susceptibility class
Funchal	High
Canical	High
Porto Santo	Moderate

On the Azores islands, the available data consisted of a table by Direção Regional do Ordenamento do Território e dos Recursos Hídricos (DROTRH) [Regional Directorate for Land Use Planning and Water Resources] showing the proportion of the area of the municipalities threatened by the advance of the sea, with values ranging from 0.30 per cent to 5 per cent (Table 2). Based on these percentages, the following risk classification was established: low (up to 1%), medium (between 1% and 3%) and high (above 3%). The table includes all the municipalities with ports, except Praia da Graciosa. To fill this gap, the data for the neighbouring municipality of Santa Cruz da Graciosa, located on the same island, was used as a reference, although it is recognised that this extrapolation may not accurately reflect the local reality.

Table 2 – Areas threatened by the sea for Azores ports, adapted from DROTRH (n.d.).

Council	Areas threatened by the sea in relation to the total area of the council
Corvo	1.74%
Santa Cruz das Flores	0.46%
Lajes das Flores	1.34%
Horta	1.44%
Santa Cruz da Graciosa	4.93%
São Roque do Pico	1.88%
Lajes do Pico	1.54%
Madalena	2.60%
Velas	1.61%

Table 2 – Areas threatened by the sea for Azores ports, adapted from DROTRH (n.d.).

Council	Areas threatened by the sea in relation to the total area of the council
Calheta	1.69%
Praia da Vitória	2.88%
Angra do Heroísmo	0.81%
Vila do Porto	0.31%
Ponta Delgada	1.33%

For mainland ports, two main sources obtained from the Sistema Nacional de Informação de Ambiente (SiNIAmb) [National Environmental Information System] georeferenced information visualiser were used: i) maps of coastal flood protection strip of the Programas da Orla Costeira (POC) [Coastline Programmes], which made it possible to check whether these zones were contained within the area of port jurisdiction; and ii) maps of flooding area for rivers and estuaries from the Directive 2007/60/EC, classified at levels ranging from very high to very low. These classifications are shown in Table 3. For each port, the highest classification among the areas overlapping its zone of influence was considered.

Table 3 – Flood and overtopping risk classification for mainland ports.

Ports	Safeguard strip	Risk of flooding
Viana do Castelo	Yes	Very low
Leixões	Yes	Very high
Aveiro	No	Medium
Figueira da Foz	Yes	High
Lisbon	No	Medium
Setúbal	No	Low
Sines	Yes	Very low
Faro	No	Very low
Portimão	No	Medium

From these different sources, the data was standardised into a common scale of coastal overtopping and flood risk, with three levels: low, medium and high.

3.4.8 Other specific parameters

In addition to the general parameters considered, some specific criteria had to be analysed individually, directly related to the viability of certain NbS. This analysis was carried out in detail for each port, with the support of time-lapse satellite images available on Google Earth. Among the aspects observed were the presence of potentially suitable areas for implementing the solutions, as well as relevant harbour structures such as breakwaters and seawalls. The type of material used to make up these structures and the associated degree of artificiality were also assessed, which helps to identify the need and relevance of applying certain NbS. A more detailed description of these parameters will be presented in their respective topics in the Results and Discussion Section.

4 RESULTS AND DISCUSSION

4.1 Selected articles from Scopus

This section presents a synthesis of the two selected studies, which served as the primary sources for identifying and analysing nature-based solutions applicable to port infrastructures.

4.1.1 Seawalls with topographic complexity

The first of these is entitled *Eco-Engineering of Seawalls—An Opportunity for Enhanced Climate Resilience From Increased Topographic Complexity* (Salaudun et al., 2021). This article investigates the benefits of ecological interventions, such as increasing topographic complexity and surface roughness, which are already known to have ecological benefits, but in this case in the context of reducing wave overtopping and flood risk. This study is also important for adapting to climate change, in the sense of coping with extreme event conditions.

This study was conducted through experimental analysis in a two-dimensional wave channel measuring 22 metres in length, 0.6 metres in width, and 1 metre in height, situated within a laboratory at the Water Research Facility, University of Warwick, UK. The channel was designed to resemble a coastline, with a slope of 1:20, extending one metre from the wavemaker (Figure 14-A). The wavemaker was equipped with the capacity to generate waves of a regular or random nature. This enabled the testing of two types of wave simulations for each seawall: non-impulsive waves, which have a pulsating characteristic, simulate deep-water waves, where the height is small in relation to the depth; and impulsive waves, which have a substantial force that can reach 10 to 40 times the force of non-impulsive waves. They are also characterised by breaking over coastal defence structures.

The reference condition was assumed to be a traditional, flat and smooth vertical seawall measuring 0.25 m in height, constructed from a thick PVC board. This was then compared with two types of test seawall: a subtractive wall featuring 5 mm drilled holes, designed to resemble NbS, such as “drilled rock pools” in intertidal breakwaters; and various additive wall configurations, intended to imitate “textured concrete” tiles or “textured surfaces”, with surface protrusions varying in length (0.01, 0.03 and 0.05 m) and density (25 rods/0.01 m², 50 rods/0.01 m² and 98 rods/0.01 m²) (Figure 14-B). For the second type, the previous type of seawall was used, with the protrusions arranged in a regular rectangular pattern (Figure 14-C).

Overtopping is defined as the average water discharge per linear metre of width of the structure and was measured using an overtopping detector on a container, which also served to measure the volume of water spilled. The height of the water surface and the period in the channel were also measured through two groups with three wave gauges. The first group was situated in close proximity to the wave paddle, thus simulating the measurement in deep waters, while the second was positioned in close proximity to the seawall, thereby simulating conditions in shallow waters. In this study, the following aspects were given full consideration: the minimisation of scale effects, the accuracy of measurement techniques, and the agreement between the results and those predicted in the literature.

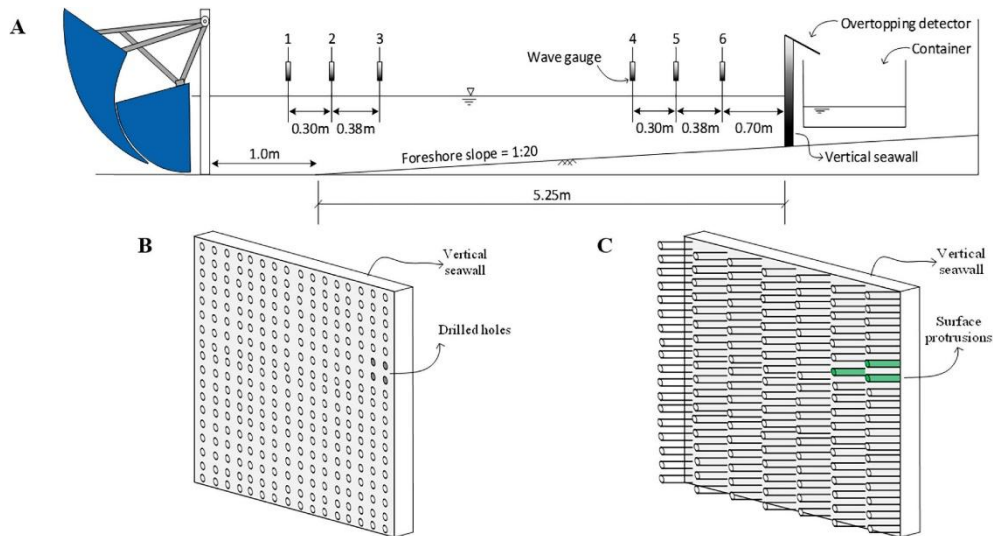


Figure 14 – Illustration of the wave channel and vertical seawalls. (A) Schematic of experimental set-up for the plain vertical wall configuration. (B) Vertical wall with holes. (C) Vertical wall with protrusions. (Salauddin et al., 2021).

For the impulsive wave test, the reference and subtractive seawalls obtained mean overtopping rates within the 5% limits of the empirical projections given by (EurOtop, 2018). Tests involving seawalls with protrusions demonstrated a reduction in the mean overtopping rate with increasing density, for a constant length of the elements, as well as with increasing length, while maintaining the same density. Consequently, the most significant reduction was observed in the test with maximum density and length of the elements. This reduction reached an average of 90% on all free edges and 100% for the relative height of the crest of 2.86. In contrast, for non-impulsive waves, all test conditions demonstrated insignificant impact on the mean overtopping rate, in relation to the predicted values.

The assessment of the probability of overtopping waves had a similar effect. In the tests with impulsive waves, the proportion reduced with increasing roughness, with the optimal scenario being that with protrusions of greater length and density (average reduction of 80%). The reference and subtractive scenarios were in alignment with the predicted values. Additionally, no substantial reduction was observed for any of the seawalls in the tests with non-impulsive waves.

The findings demonstrated that seawall designs characterised by topographic complexity offer mutual benefits in terms of reducing wave energy and provide protection against flooding. These structures also contribute to ecological enhancement, facilitating the recovery of biodiversity in coastal habitats.

4.1.2 Bioinspired Underwater Breakwaters

Breakwaters, a common coastal engineering solution, are typically composed of concrete walls or rock spurs. However, these structures often require substantial spatial requirements, can compromise the natural landscape, and may diminish local biodiversity, despite their singular function. A more ecologically sustainable alternative is represented by submerged breakwaters (SBs). Despite their relative visual amenability, the employment of grey solutions remains an unsustainable problem. Therefore, the subsequent article will examine a nature-inspired submerged breakwater. The study is entitled Bioinspired Coastal

Barriers: A Preliminary Laboratory Study on the Hydraulic Performances of Shapes Inspired by Marine Organisms (Perricone et al., 2024).

Three models inspired by the marine ecosystem were studied. The first model, designated L-type, exhibited a slightly flattened shape that resembled a leaf of seaweed. Seagrasses are natural wave attenuators, which is why this shape was selected. The second model (T-type) explored more abstractly the hydrodynamic shapes of fish and dolphins. The final model (HT-Type) incorporated a circular “head” at the top to enhance the visibility and buoyancy of the structure, resembling a sea buoy. The three models are shown in Figure 15. For the purpose of comparison, a cylindrical reference model (C-Type) was also utilised.

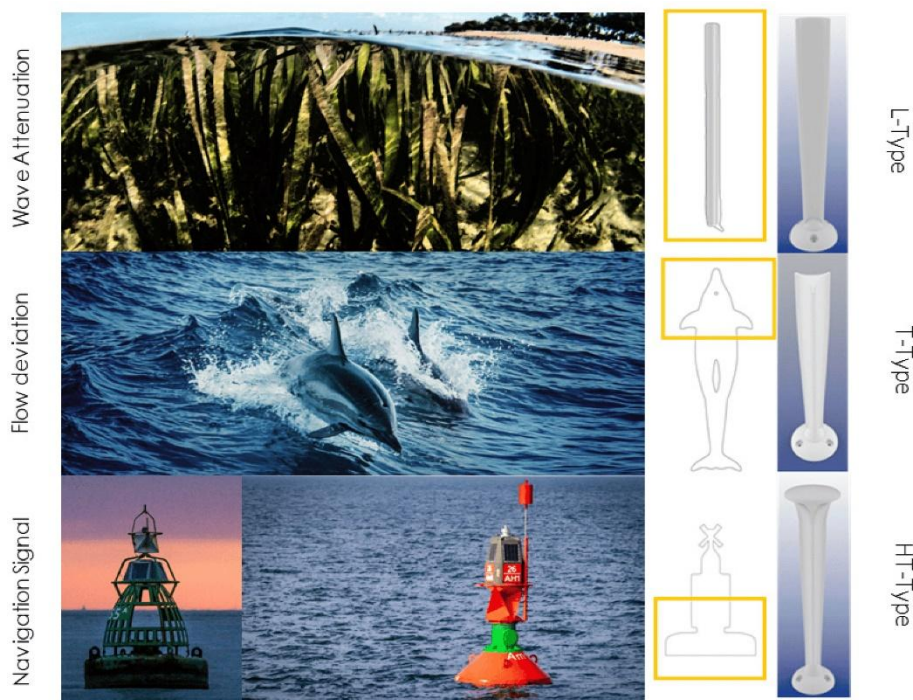


Figure 15 – Design inspirations and related models (Perricone et al., 2024).

A total of sixteen models of each type were produced using a 3D printer, with a scale of 1:25 employed. Polyethylene terephthalate glycol was selected as material for the printing process due to its recyclability and the favourable physical and chemical characteristics it exhibits. Subsequent to the printing process, the models underwent testing at the University of Campania’s L.Vantelli Maritime Engineering Laboratory. The testing was conducted within a wave flume that measured 13.4 metres in length, 0.8 metres in width, and 0.6 metres in depth. The flume was subdivided into a horizontal segment extending up to 3 metres from the wave generator, followed by a sloping segment with a gradient of 1:22. The generation of waves was facilitated by a piston-type wave paddle, capable of producing both regular and irregular waveforms (Figure 16). The models were arranged in a linear configuration on a perforated metal plate. The T-Type and HT-type models were tested in two positions: the first with the tip of the triangle facing the wave front, and the second with the base of the triangle facing the wave front. The second rotated arrangement of the models was designated rT-Type and rHT-Type. Three wave gauges were positioned in close proximity to the model to separate incident and reflected waves, and two gauges on the rear sides to assess wave transmission. A gravel beach was placed at the end of the flume to minimise wave reflections.

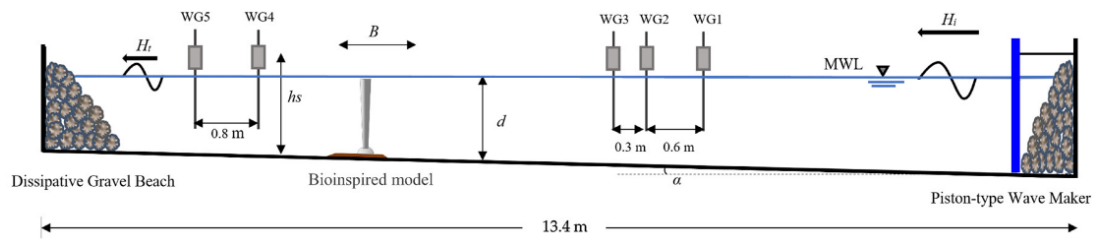


Figure 16 – Schematic view of the wave flume and experimental equipment (Perricone et al., 2024).

A series of four wave conditions were simulated, with each condition representing a weather spectrum and a wave energy. The conditions encompassed three regular waves: poor, mild and extreme; and one irregular wave: storm. The regular waves represent calm seas, while the extreme waves represent higher, uninterrupted waves. The irregular waves simulate more demanding conditions with random waves.

The effectiveness of the structures was measured using three parameters: the transmission coefficient (K_t), the reflection coefficient (K_r), and the dissipation coefficient (K_d). K_t is defined as the ratio between the transmitted significant wave height and the incident significant wave height, with K_t ranging from 0 to 1. A K_t of 0 indicates no transmission, while a K_t of 1 indicates no reduction in wave height. K_r is the ratio between the reflected significant wave height and the incident significant wave height. Finally, K_d is calculated using the formula $K_d = 1 - K_r^2 - K_t^2$.

Following the experimental phase, a graph was constructed with the average of each coefficient for each structure model and each wave condition. The T-type and rT-type models exhibited the lowest K_t values. It was also observed that the addition of the ‘head’, resulting in the HT-type model, caused a negative effect on wave transmission, and that rotating the model (rT-type) caused an increase in the values. A comparison of the observed values of K_t with the incident wave’s steepness reveals that for both poor and extreme waves, the range of steepness remains practically equivalent. However, as the energy of regular waves increases, the non-linearity becomes increasingly pronounced.

With regard to the analysis of wave reflection, the lowest observed value was recorded for the C-type model. For all models, poor and mild weather waves exhibited higher values than those observed for extreme type waves. Storm waves demonstrated the highest K_r values due to their random nature, a phenomenon that is corroborated by the graph of K_r versus incident wave steepness, where the values for storm waves remained practically constant. However, for monochromatic waves, the observed effect is non-linear.

In the final analysis, the investigation of K_d demonstrated that the head models exerted a direct and unfavourable influence on wave dissipation. Lower K_d values are associated with higher K_t or K_r values, a circumstance that is considered undesirable. This occurrence can be explained by the turbulence that the heads generate in the water, a phenomenon that has a calming effect or even alters its structure.

The experimental findings indicated that the C-Type and L-Type models exhibited constant hydraulic behaviour, while the T-Type and rT-Type models demonstrated a more effective reduction in wave transmission, resulting in increased turbulence and wave dissipation. This phenomenon is advantageous in calm waves, where higher transmission prevents wave stagnation and promotes natural circulation, and in strong waves, where lower

transmission improves coastal protection by reducing wave energy. The HT-Type and rHT-Type models exhibited less clear results due to the effect of the head, which acts as a turbulence reducer.

In order to comprehend the manner in which the diverse bioinspired models influence wave propagation and dissipation, the hydrodynamic penetration coefficient of each geometry was computed in a simplified manner, employing two geometric parameters: the width and the thickness of the reference for drag. The relationship between these parameters was analysed and showed a favourable correlation with the transmission coefficient, indicating that the geometry of the models has a significant impact on their hydrodynamic efficiency.

It can thus be concluded that bioinspired models have proven effective in dissipating wave energy, with lower transmission coefficients when compared to traditional solutions. A key advantage of these models is that they require less material, have less impact on the seabed and can be easily removed or replaced. Furthermore, they can be combined with other techniques, such as beach drainage and coastal vegetation, to increase their efficiency and extend the life of the interventions. Finally, the study presents sustainable alternatives that meet the need for coastal protection without causing adverse visual impacts, which are inspired by and integrate nature.

4.2 Characterisation of commercial Ports

A total of nine commercial ports is located along the coastline, from north to south. The Figure 17 provides a visual representation of the subject.



Figure 17 – Map of the ports of mainland Portugal, inspired in AIA (2020).

4.2.1 Viana do Castelo and Leixões ports

The initial two ports are under the jurisdiction of the Administração dos Portos de Douro, Leixões e Viana do Castelo, S.A. (APDL) [Administration of the Ports of Douro,

Leixões and Viana do Castelo], and situated in the northern region of the country. The Port of Viana do Castelo is located on the south bank of the mouth of the Lima River and is considered the third busiest port in the country, having been important since the Middle Ages (Figure 18). The port is operational on a continuous basis and boasts a cargo-handling capacity in excess of 1,000,000 tons per annum, with a maximum draught of 8 meters and a length of up to 180 meters (APDL, n.d.-d).



Figure 18 – Map of the jurisdiction area of the Viana do Castelo port, adapted from APDL (2021).

The Port of Leixões, constructed at the close of the 19th century at the mouth of the Leça River, in the city of Matosinhos, is the second largest artificial port in Portugal and the largest port infrastructure in the northern region of the country (APDL, n.d.-a). Its judicial authority encompasses the port and the coastal areas extending to the Douro River mouth, which traverses the wider Porto metropolitan zone (Figure 19). Its strategic and centralized position gives it the passage of important national and international routes. Consequently, it handles approximately 20 million tons of goods annually, encompassing a wide range of cargo types, constituting 20% of Portugal's foreign trade by sea (APP, n.d.-c). Additionally, it serves as a significant hub for large passenger cruise ships, further augmenting its logistical and transportational capabilities.

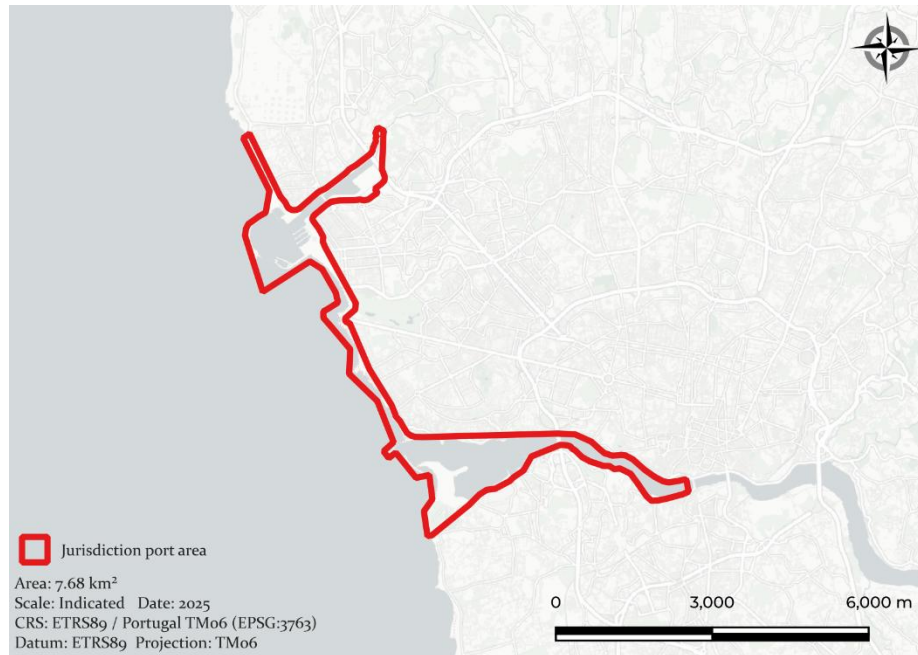


Figure 19 – Map of the jurisdiction area of the Leixões port, adapted from APDL (2021).

4.2.2 Aveiro port

A little further downstream, the Port of Aveiro is located on the banks of the lagoon that forms the Ria de Aveiro. It is administered by the Administração do Porto de Aveiro, S.A. (APA) [Administration of the Port of Aveiro] and is also situated in a privileged region, where the road and rail infrastructures are well structured and provide an efficient flow of goods to the north of Portugal and Spain (Figure 20). The port boasts an organised and integrated area, comprising seven specialised terminals, approximately four kilometres of quays, and two intermodal logistics zones (APP, n.d.-b). It functions as a multifunctional hub, accommodating approximately five million tons of cargo. Notably, the port is situated within a special protection zone, which is of significant importance for the conservation of wetlands.



Figure 20 – Map of the jurisdiction area of the Aveiro port, adapted from APA (2023).

4.2.3 Figueira da Foz port

The port of Figueira da Foz, located on the banks of the Mondego River in the city of the same name, is overseen by the Administração do Porto da Figueira da Foz, S.A. (APFF) [Administration of the Port of Figueira da Foz]. Serviced by uncongested road and rail networks, it caters to the markets of the Central region of Portugal and Castilla y Leon in Spain (Figure 21). The port features two terminals dedicated to the commercial sector, with a total annual handling capacity of approximately 2.2 million tons. The harbour area is not included in designated conservation areas, yet it is a site of interest for nature conservation and is of significant importance to avian life (APFF, n.d.-a).

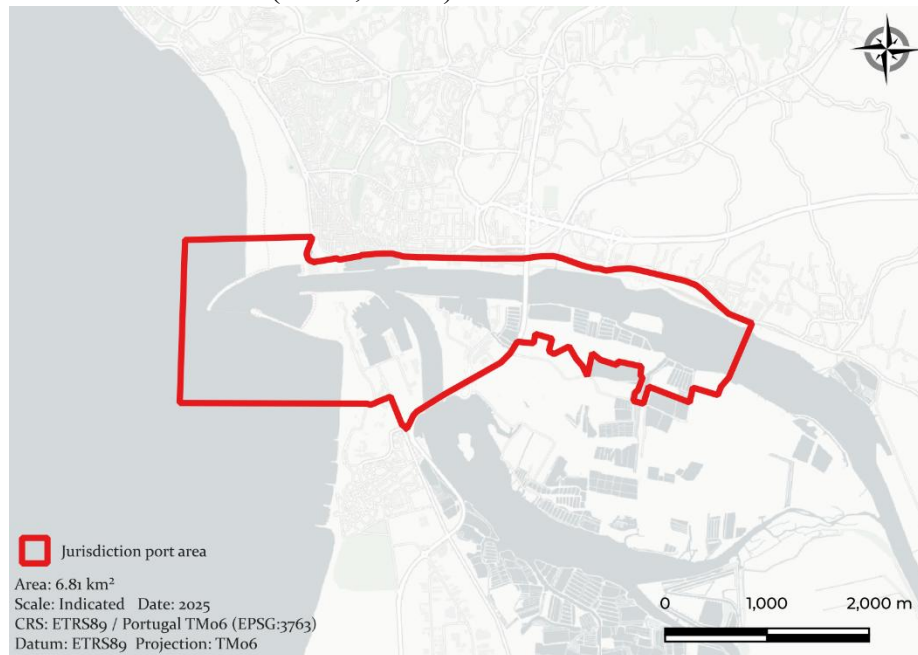


Figure 21 – Map of the jurisdiction area of the Figueira da Foz port, adapted from APA & APFF (2024).

4.2.4 Lisbon port

The port of Lisbon has historically served as the nation's primary commercial port, maintaining its position as the foremost maritime transport hub to this day. Strategically situated at the confluence of the Tagus River and the Atlantic Ocean within a natural port in the Tagus estuary, it is well-suited to accommodate a wide range of vessels (Figure 22). The port's strategic location at the intersection of major international trade routes and the Atlantic coastline of Europe positions it as a pivotal hub for global commerce and transportation (APP, n.d.-d). The administration of the port is overseen by the Administração do Porto de Lisboa, S.A. (APL) [Administration of the Port of Lisbon].

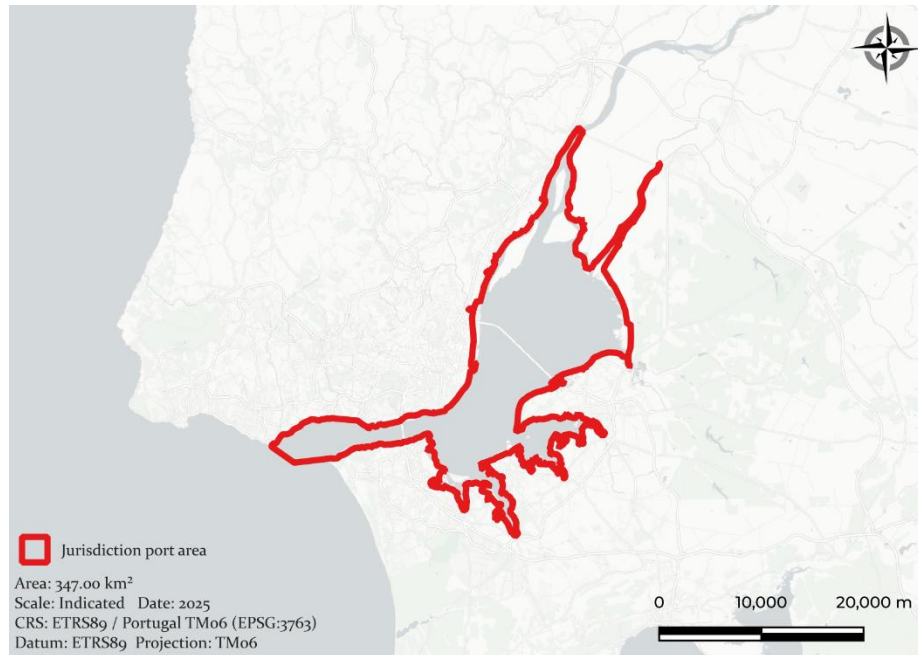


Figure 22 – Map of the jurisdiction area of the Lisbon port, adapted from APL (n.d.-b).

4.2.5 Setúbal port

The port of Setúbal, located at the mouth of the Sado River, 30 kilometres south of Lisbon, is managed by Administração dos Portos de Setúbal e Sessimbra, S.A. (APSS) [Port Administration of Setúbal and Sesimbra] (Figure 23). The port is equipped with twelve specialized terminals, five of which are designated for public service. Direct connections to the country's primary road and rail networks, as well as to Spain, are available, and the port is equipped to accommodate a range of vessel types, including medium-sized cargo ships, container ships, and bulk carriers. The port has a leading national role in roll-on/roll-off traffic of new light vehicles, accounting for approximately 90% of the national total, and in general fractional cargo traffic, with around 43% (APP, n.d.-e).

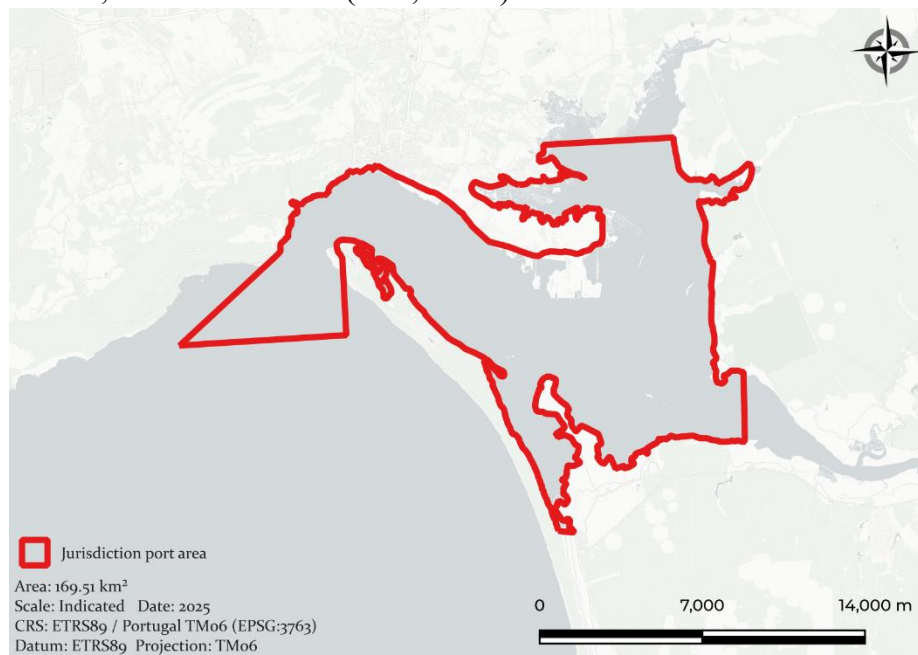


Figure 23 – Map of the jurisdiction area of the Setúbal port, adapted from APSS (n.d.-a).

4.2.6 Sines and Algarve ports

The port of Sines, the largest artificial port in Portugal, is the southernmost port on the continent mentioned in this work. The Sines Port Administration was established in 1977, following the construction of the port in 1973 (Administração dos Portos de Sines e do Algarve S.A., n.d.-f). The port is currently operational on a 24-hour, year-round basis, providing a range of services. As a deep-water port, it handles more than half of the port traffic in Portugal. The port's primary function is as the conduit for the nation's energy supply, encompassing containers, natural gas, coal, oil, and its derivatives (APP, n.d.-f). According to the map shown in Figure 24, the Port of Sines is the third largest port in Portugal with 259 km² of land and sea area. However, unlike the country's two largest ports - Lisbon and Setúbal, located on wide estuaries protected by natural coastal formations - the Port of Sines was built directly on the ocean and thereby being subjected to distinct maritime conditions.

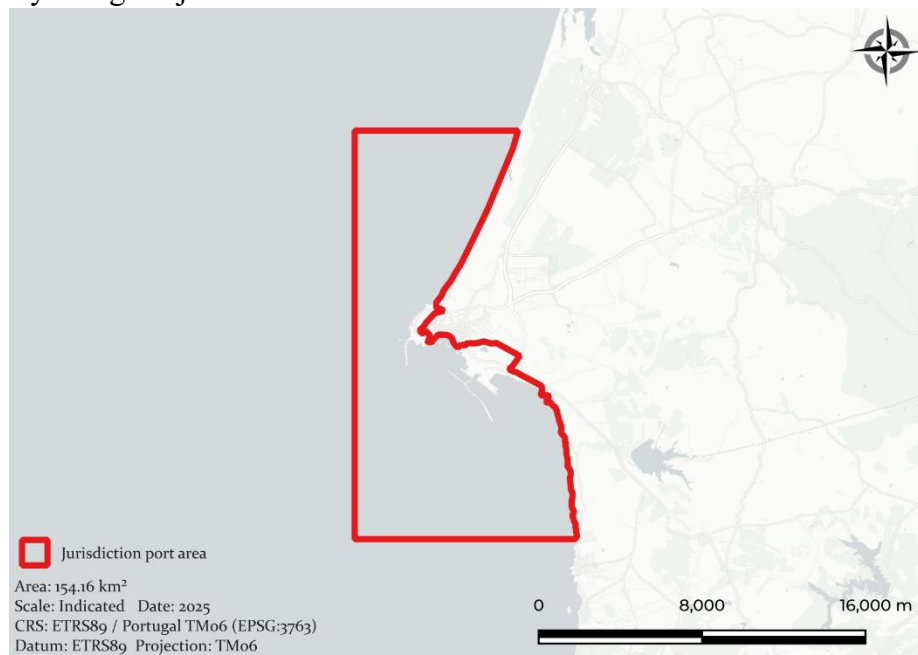


Figure 24 – Map of the jurisdiction area of the Sines port, adapted from APS (2017).

The Algarve, a region in the south of Portugal, is renowned for its beautiful beaches and natural landscapes. The ports of Portimão and Faro, located in this region, were previously under the administration of the Instituto Português e dos Transportes Marítimos (IPTM) [Port and Maritime Transport Institute]. However, in 2014 they were added to the administration of the port of Sines, which was then known as the Administração dos Portos de Sines e do Algarve (APS) [Administration of the Ports of Sines and the Algarve]. The Algarve's ports benefit from a strategic location between the Atlantic Ocean and the Mediterranean Sea, and the region as a whole is a popular European summer holiday destination (APS, n.d.-d, n.d.-e).

The port of Portimão is located at the mouth of the River Arade, an important communication route throughout history (Figure 25). The area is notable for its diverse fauna and flora in the marshland and nesting areas. It is also strategically located in close proximity to the city centre, offering convenient access to a range of amenities such as hotels, restaurants, and stunning beaches. Consequently, its primary function is tourism, which contributes to the regional economy, in addition to its cargo shipping operations (APS, n.d.-c).

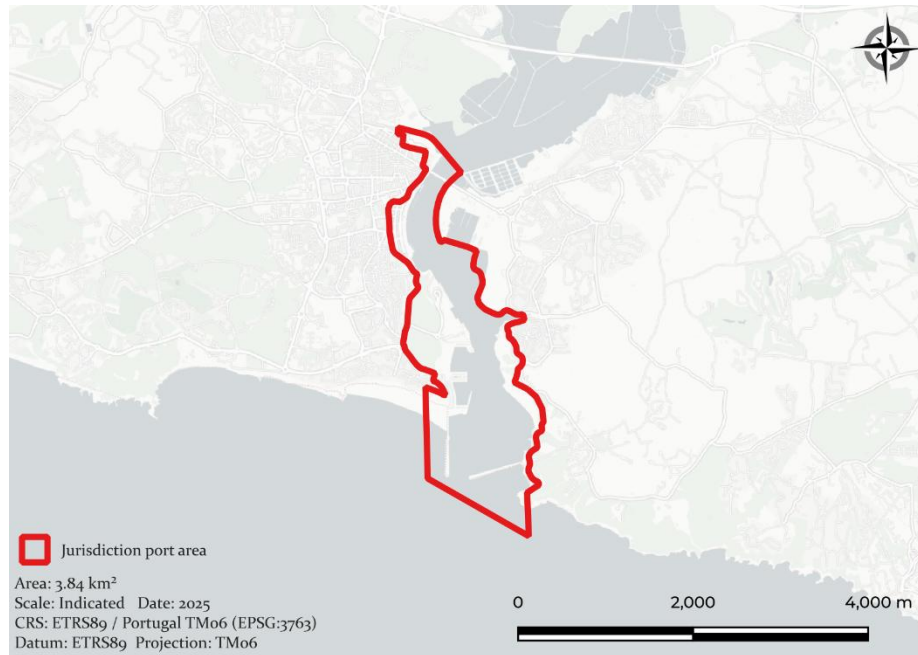


Figure 25 – Map of the jurisdiction area of the Portimão port, adapted from Decreto-Lei n.º 44/2014 de 20 de março, 2014.

The port of Faro, situated slightly further to the right of Portimão, is located within the Ria Formosa Natural Park, a lagoon system that extends for 60 kilometres along the southern Portuguese coast. The transition zone between land and sea is characterised by a variety of ecological features, including marshes, sandbanks, dunes, salt marshes, freshwater and brackish lagoons, which collectively support a diverse array of fauna and flora. It is therefore the most significant wetland in the country and of international importance for the conservation of birds (VisitAlgarve, n.d.). The commercial quay is located further into the estuary, where it is protected from direct ocean waves, and is in close proximity to the city (Figure 26). The structure is approximately 200 metres in length and 8 metres in depth (APS, n.d.-a).



Figure 26 – Map of the jurisdiction area of the Faro port, adapted from Decreto-Lei n.º 44/2014 de 20 de março, 2014.

4.2.7 Madeira ports

Operated by Administração dos Portos da Região Autónoma da Madeira, S.A. (APRAM) [Port Administration of the Autonomous Region of Madeira], the Madeira Archipelago has three ports, two on the island of Madeira and one on the island of Porto Santo, as shown in Figure 27.



Figure 27 – Map of the ports of Madeira Archipelago, inspired in AIA (2020).

The construction of the first port, in the bay of Funchal (Figure 28), dates back to the second half of the 18th century. Since then, it has been improved until 2004, when it was dedicated exclusively to tourism and the loading and unloading services were transferred to the port of Caniçal (Figure 29). The port of Funchal is the main gateway to the island, prepared to receive more than half a million tourists by sea. The port of Caniçal is therefore dedicated exclusively to cargo handling (APP, n.d.-g).

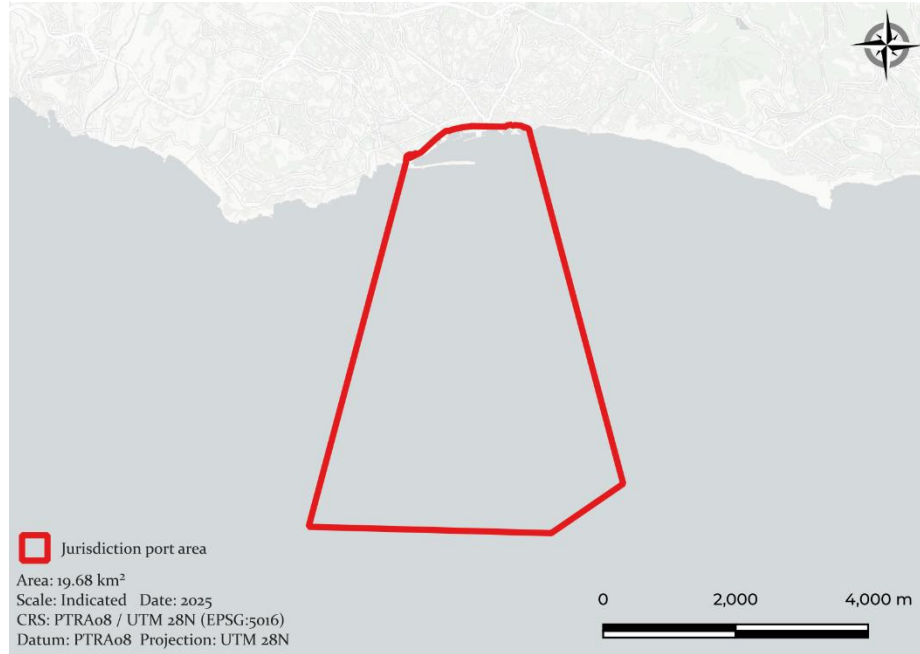


Figure 28 – Map of the jurisdiction area of the Funchal port.

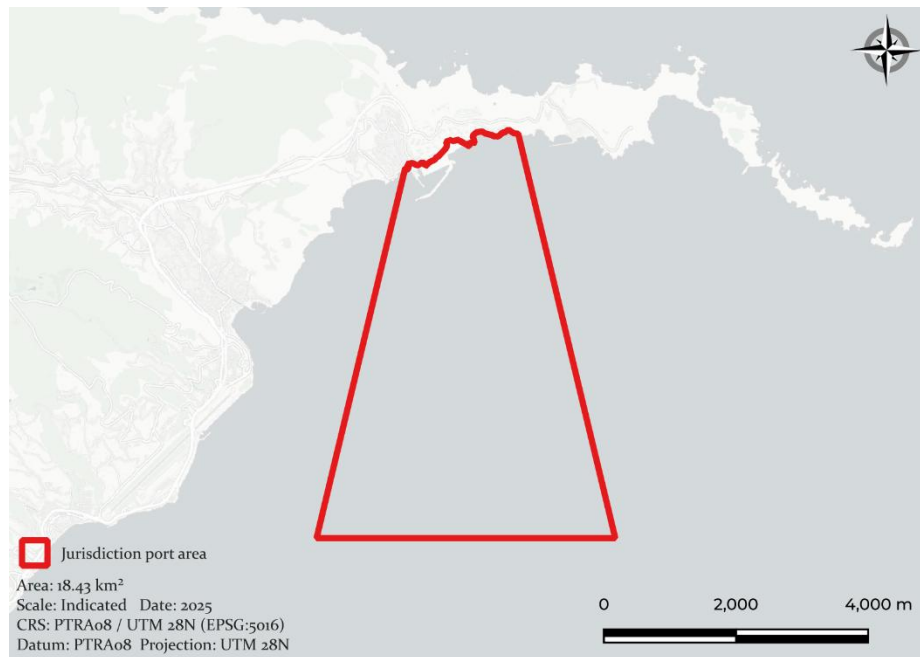


Figure 29 – Map of the jurisdiction area of the Caniçal port.

There is also the port of Porto Santo, a mixed facility located on the island of the same name and used mainly for inter-island traffic in the archipelago (Figure 30).

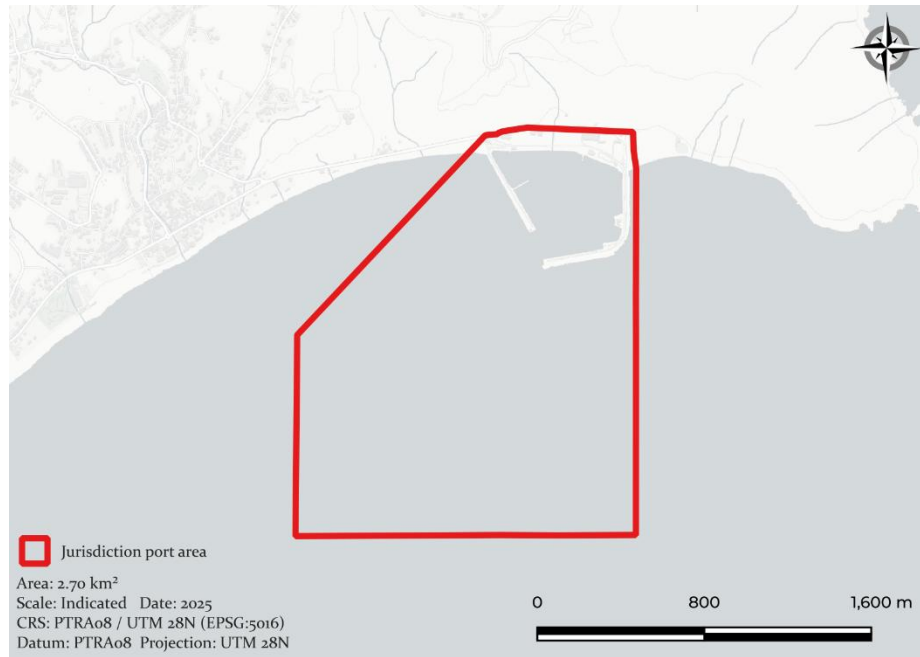


Figure 30 – Map of the jurisdiction area of the Porto Santo port.

4.2.8 Azores ports

The archipelago known as the Azores Autonomous Region consists of nine inhabited islands, each of which has at least one port. Two islands further west, Corvo and Flores, are part of the western group. Two islands further east, São Miguel and Santa Maria, are part of the eastern group. The remaining islands, which are closer together, belong to the central group. Figure 31 shows all the Azorean ports.



Figure 31 – Map of the ports of Azores archipelago, inspired in AIA (2020).

The Azores Ports Authority is the result of the merger of the three previous administrations: Administration of the Ports of S. Miguel and Santa Maria, Administration of the Ports of Terceira and Graciosa and Administration of the Ports of the Triangle and Western Group in 2011 (APP, n.d.-h). Corvo port

The port in the south of the island of Corvo, shown in Figure 32, is called Porto da Casa. It is a small port with an 80-metre-long quay that can accommodate ships with a draught of up to 3 metres (PA, n.d.-o).



Figure 32 – Map of the jurisdiction area of the Corvo port, adapted from PA (2011).

4.2.8.1 Flores ports

Porto das Poças, located in the city of Santa Cruz das Flores, is a port infrastructure for small commercial, fishing and passenger vessels (PA, n.d.-k). It is still in the process of being rehabilitated, so its map has been drawn up on the basis of the aforementioned documents, as well as the most recent satellite images (Figure 33).



Figure 33 – Map of the jurisdiction area of the Santa Cruz das Flores port, adapted from PA (2011).

The port of Lajes das Flores is located in the town of the same name, a little further down the coast from Santa Cruz das Flores (Figure 34). It is also a small port open to commercial shipping, marinas and fishing (PA, n.d.-g).



Figure 34 – Map of the jurisdiction area of the Lajes das Flores port, adapted from PA (2011).

4.2.8.2 Graciosa port

O The port of Praia da Graciosa, built in 1980 on the west coast of Graciosa Island, is protected by a 450-metre breakwater (PA, n.d.-e). It is the only port in the archipelago that does not yet have a graphic representation of its boundaries. The map was drawn using only the coordinates and interpretation of Decree 24/2011/A as well as satellite images. The map is shown in Figure 35.



Figure 35 – Map of the jurisdiction area of the Graciosa port, adapted from PA (2011).

4.2.8.3 Faial port

Located on the south coast of the island of Faial (see Figure 36), the Port of Horta has various services, commercial quays and a passenger terminal.



Figure 36 – Map of the jurisdiction area of the Horta port, adapted from PA (2011).

4.2.8.4 Pico ports

Pico Island is serviced by three distinct port facilities, each strategically located in its respective coastal region: one at the northernmost point, one at the southernmost point, and one at the westernmost point. The northern port is located at São Roque do Pico (see Figure 37) and is equipped with a commercial quay (PA, n.d.-l).



Figure 37 – Map of the jurisdiction area of the São Roque do Pico port, adapted from PA (2011).

The southern port located in Lajes do Pico (see Figure 38) is equipped with a local water sports centre and various quayside areas (PA, n.d.-h).



Figure 38 – Map of the jurisdiction area of the Lajes do Pico port, adapted from PA (2011).

The Madalena port (see Figure 39), located in front of the Horta Port, is designated for small boats with a maximum length of 50 metres (PA, n.d.-d).



Figure 39 – Map of the jurisdiction area of the Madalena port, adapted from PA (2011).

4.2.8.5 São Jorge ports

São Jorge, shaped like a boat, has harbours in the two towns on the south coast of the island: Porto de Velas and Porto da Calheta, both small port structures (Figure 40 and Figure 41) (PA, n.d.-m, n.d.-b).



Figure 40 – Map of the jurisdiction area of the Velas port, adapted from PA (2011).

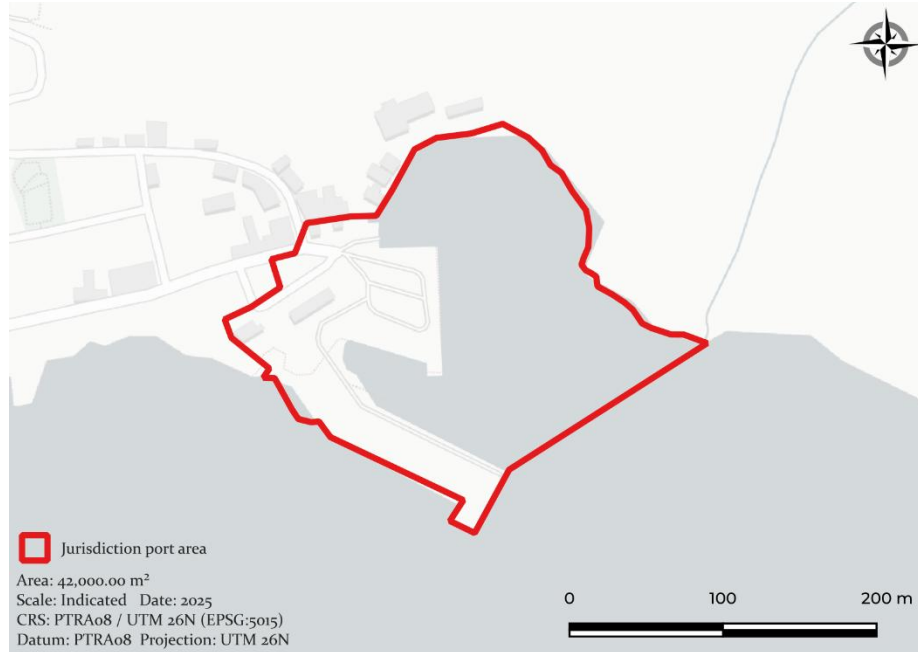


Figure 41 – Map of the jurisdiction area of the Calheta port, adapted from PA (2011).

4.2.8.6 Terceira ports

On Terceira Island, two ports of slightly greater size than the preceding ones are situated to the east and south. Figure 42 illustrates the port of Praia da Vitória in the bay of the same name, while Figure 43 depicts the port of Angra do Heroísmo.



Figure 42 – Map of the jurisdiction area of the Praia da Vitória port, adapted from PA (2011).

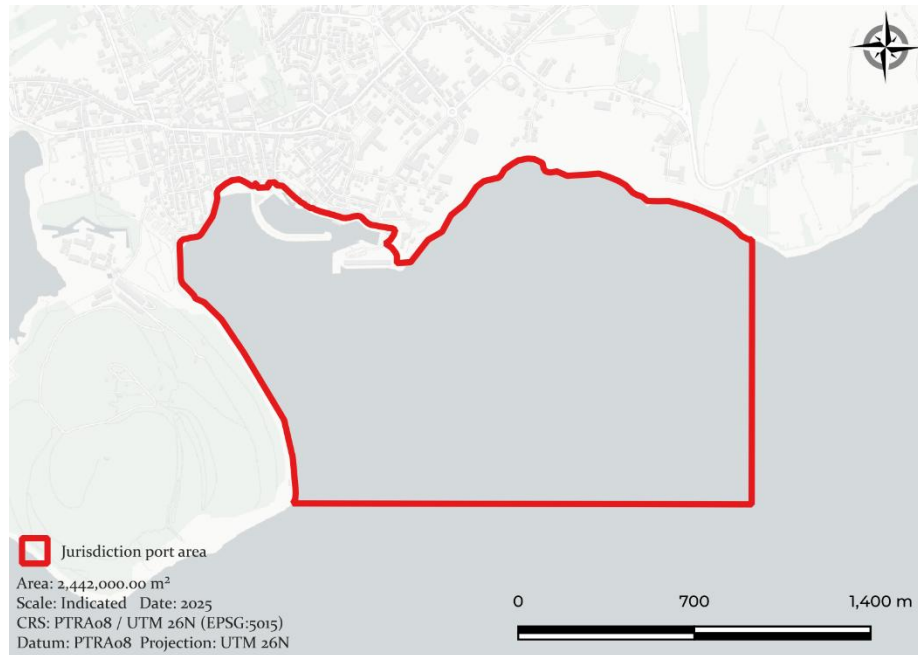


Figure 43 – Map of the jurisdiction area of the Angra do Heroísmo port, adapted from PA (2011).

4.2.8.7 São Miguel port

Finally, the easternmost ports in the Azores, for example, Ponta Delgada (see Figure 44) possess infrastructure for cargo, cruise passengers and ferries, as well as for fishing activities. The commercial quay is dedicated to the berthing of bulk carriers, container ships and other cargo vessels (PA, n.d.-j).

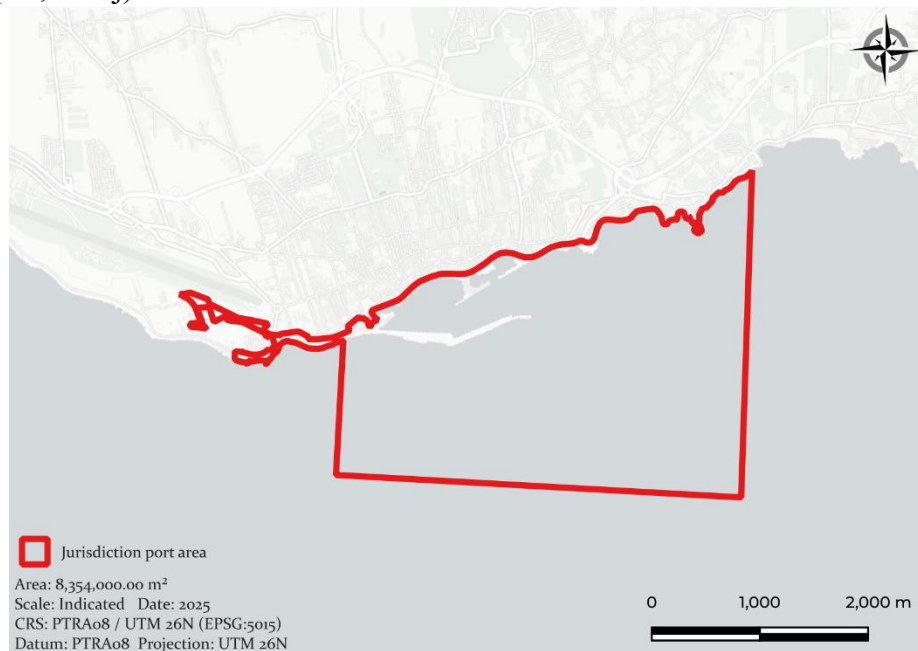


Figure 44 – Map of the jurisdiction area of the Ponta Delgada port, adapted from PA (2011).

4.2.8.8 Santa Maria port

The port of Vila do Porto is also well structured, with a commercial quay, ferry quay, passenger terminal, fishing port and a marina (PA, n.d.-n). The perimeter can be observed in Figure 45.

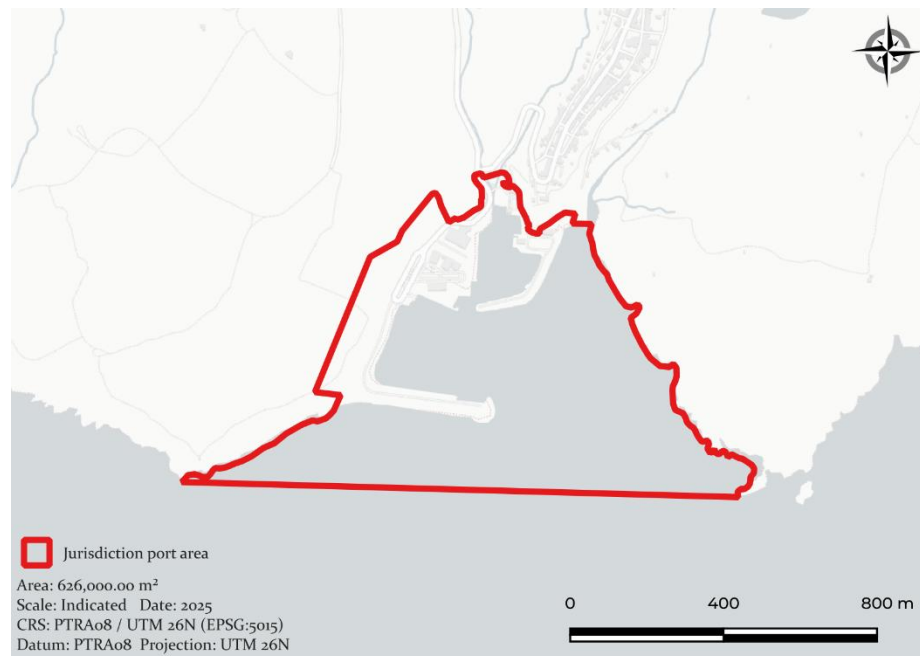


Figure 45 – Map of the jurisdiction area of the Vila do Porto port, adapted from PA (2011).

4.3 Port characterisation parameters and results

In accordance with the methodological structure delineated in the preceding section, the data for each parameter was meticulously compiled and analysed. This topic presents the specific results for each parameter and a brief discussion of each parameter, highlighting its relevance for analysing port environments when applying green techniques.

4.3.1 Biodiversity

The data on the species found in the harbours obtained from the GBIF and OBIS platforms consulted did not contain all the information on the number of individuals per occurrence. This limitation can be attributed to the diversity of sources from which the records originate, such as museums, academic studies and environmental surveys, which do not always follow a uniform standard of collection and description. Furthermore, many of these records are not aimed at population quantification, but are restricted to noting the presence of a particular species in a locality.

It was also noted that of the 26 ports analysed, only 15 had records available. This gap may reflect shortcomings in the spatial coverage of the data, caused, among other factors, by the absence of marine biodiversity monitoring campaigns in certain regions or the limited public sharing of data by local institutions. Given these restrictions, the only biodiversity metric that could be calculated from the data obtained was species richness, the result of which is shown in Table 4.

Table 4 – Species richness (R) by ports.

Port	R	Port	R
Aveiro	20	Madalena	2
Canical	8	Ponta Delgada	5
Faro	26	Portimão	15
Figueira da Foz	3	Porto Santo	3
Funchal	8	Praia da Vitória	7
Horta	3	Setúbal	22
Leixões	16	Sines	13
Lisbon	49		

As demonstrated, the ports with the greatest species richness are Lisbon, Faro, Setúbal and Aveiro. The ports of Lisbon and Setúbal stand out in particular, as they have the largest jurisdictional areas among those analysed, with 347 km² and 170 km², respectively. In contrast, ports such as Horta and Madalena have significantly smaller areas, of only 0.70 km² and 0.22 km², which is reflected in a lower recorded diversity. In order to facilitate a more equitable comparison, the species richness density (d) was calculated. This is defined as the number of unique species per square kilometre of port area. The minimum-maximum normalisation method was employed to arrange the values on a scale from 0 to 1 and was calculated using the equation (4.1).

$$D' = \frac{d - d_{min}}{d_{max} - d_{min}} \quad (4.1)$$

The densities obtained were then classified into three categories: high (values above 67% of the normalized range), medium (between 33% and 66%) and low (below 33%). The compared values of normalized density (D') and richness (S) can be seen in the Figure 46.

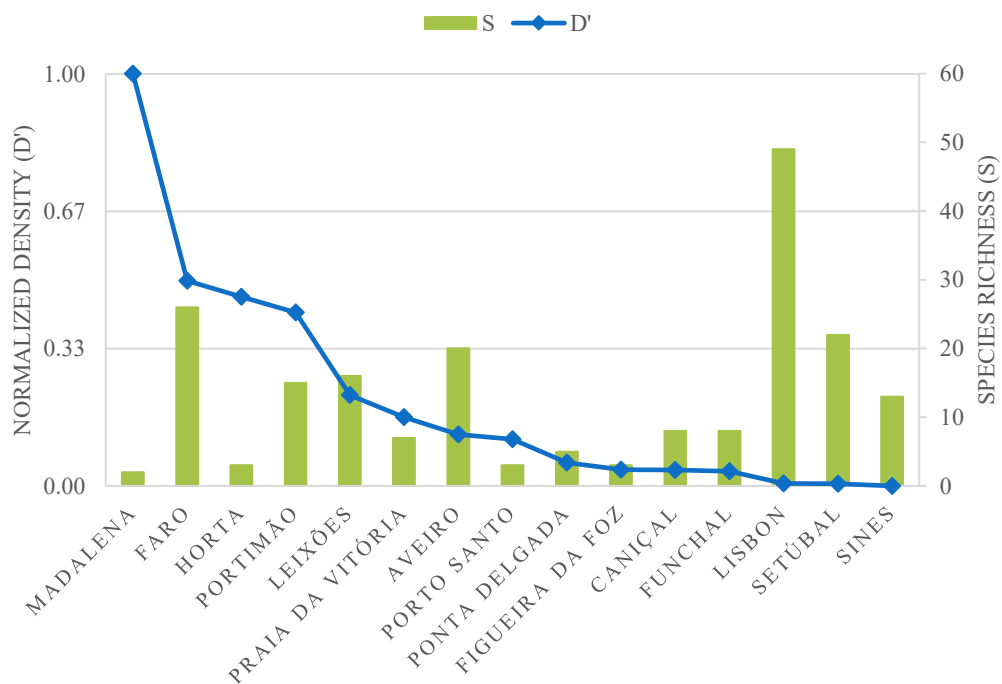


Figure 46 – Graph of normalized density (D') and species richness (S) by port.

The graph shows that the port of Madalena has a density classified as high, while the ports of Faro, Horta and Portimão have a medium density. The other ports, including Lisbon — which has the highest species richness in absolute terms — fall into the low-density category. However, these values do not accurately represent real biological diversity, since ports with very small areas tend to generate artificially high densities, while ports with large areas have proportionally lower densities. This distortion highlights the limitation of the density metric in contexts with large spatial scale variations. Furthermore, as evidenced in the scatter plot between port area and species richness (Figure 47), there is no clear linear relationship between these variables, which indicates that the size of the port jurisdictional area is not, in itself, a determining factor in the recorded biodiversity.

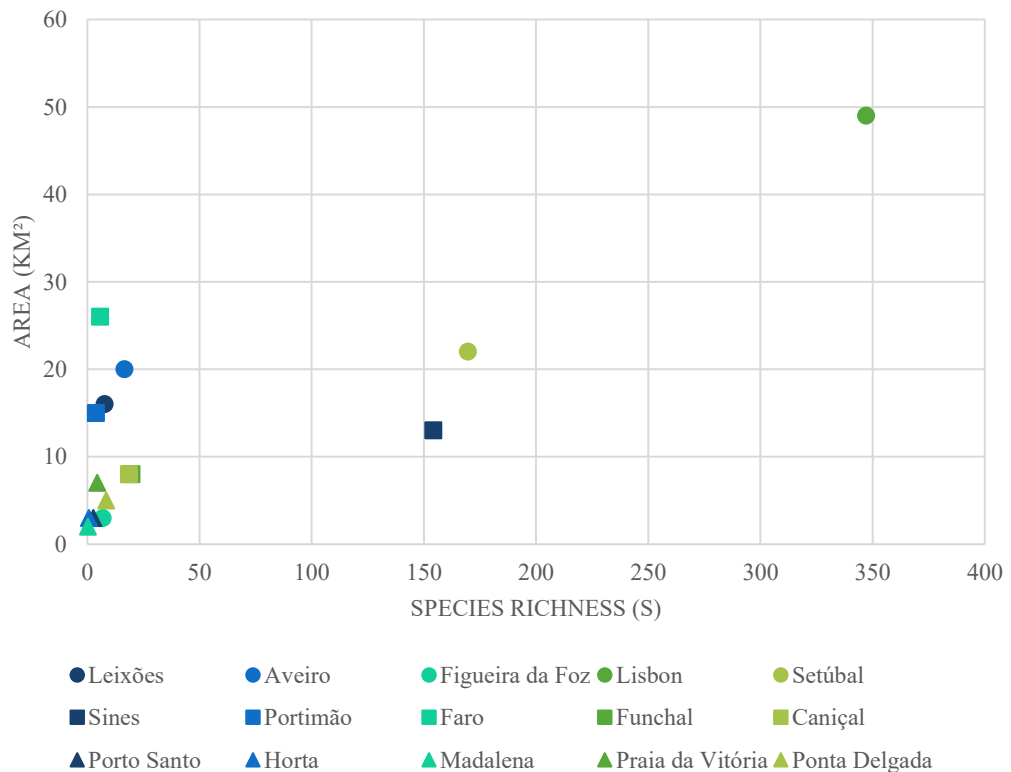


Figure 47 – Scatter plot of area in kilometres versus species richness.

Following the analysis, it was determined that the species density parameter was not adequate to accurately represent biodiversity in the ports analysed. It was observed that ports with large areas and high richness presented proportionally very low densities. On the other hand, ports with extremely small areas and minimal richness resulted in artificially elevated densities. As outliers, these cases have a tendency to distort interpretation. Furthermore, an analysis of the scatter plot between species density and port area reveals an absence of a linear relationship between the variables, suggesting that the size of the port area is not the only — nor the primary — factor influencing the recorded biodiversity.

The species richness index, which was the sole metric capable of calculation with the available data, also proved to be deficient in its representation. It is also noteworthy that several ports did not present any record of occurrence in the databases consulted. This is not indicative of the ecological reality, but rather reflects the absence of data on these platforms. It is acknowledged that biodiversity is present in these locations; however, this has not been documented in the two databases utilised in this analysis.

4.3.2 Ecosystem and artificiality

Characterising the type of ecosystem and degree of artificiality of port environments is crucial to understanding the inherent vulnerability and existing anthropogenic pressures. The information resulting from the visual analysis is shown in Table 5.

Table 5 – Ecosystem and artificiality of the ports.

Ports	Ecosystem	Artificiality
Viana do Castelo	Lima River	Medium
Leixões	Leça River	High
Aveiro	Aveiro Estuary	Medium
Figueira da Foz	Mondego River	High
Lisbon	Tegus River	Medium
Setúbal	Sado River	Medium
Sines	Atlantic Ocean	High
Faro	Formosa Estuary	Low
Portimão	Arade River	Medium
Funchal	Atlantic Ocean	High
Canical	Atlantic Ocean	High
Porto Santo	Atlantic Ocean	High
Corvo	Atlantic Ocean	Low
Santa Cruz das Flores	Atlantic Ocean	Low
Lajes das Flores	Atlantic Ocean	Low
Horta	Atlantic Ocean	High
Praia da Graciosa	Atlantic Ocean	Medium
São Roque do Pico	Atlantic Ocean	Low
Lajes do Pico	Atlantic Ocean	Low
Madalena	Atlantic Ocean	Medium
Velas	Atlantic Ocean	Medium
Calheta	Atlantic Ocean	Low
Praia da Vitória	Atlantic Ocean	Medium
Angra do Heroísmo	Atlantic Ocean	High
Vila do Porto	Atlantic Ocean	Low
Ponta Delgada	Atlantic Ocean	Medium

The table presents the ports in the same order as they were described in Section 4.2, starting with the ports located on the mainland, organised from north to south, followed by the ports of the RAM and finally the ports of the Autonomous Region of the Azores. All the harbours located on the islands are classified as marine, as they are located directly on the open sea in the Atlantic Ocean. In quantitative terms, the harbours in the autonomous regions represent the majority of all Portuguese commercial harbours. On the other hand, all the mainland ports, with the exception of the Port of Sines – an entirely artificial harbour – are located in estuarine or river environments, with the respective rivers duly identified in the table.

It is important to emphasise the distinction made between the concepts of ecosystem and degree of artificiality. Although, in general, harbours built on the open sea can be considered more artificial because they don't have the protection of pre-existing natural systems, in this study we opted for a more precise criterion, based on the degree of anthropic intervention. Thus, aspects such as the channelling of rivers, the robustness of protective structures and the predominant use of artificial and smooth materials – such as concrete – were the main indicators

adopted. In this way, small harbours located in a marine environment, such as the port of Corvo, were classified as being of low artificiality due to their limited structural intervention.

4.3.3 Depth

The results of the research into the depth of each harbour, followed by its source, are shown in Table 6.

Table 6 – Port depth values.

Ports	Depth (m ZH)	Source
Viana do Castelo	-8.00	
Leixões	-16.85	
Aveiro	-13.20	
Figueira da Foz	-8.00	
Lisbon	-18.00	(Portela, 2023)
Setúbal	-15.00	
Sines	-18.00	
Faro	-11.50	
Portimão	-8.00	
Funchal	-11.00	(APRAM S.A., n.d.-a)
Canical	-15.00	(APRAM S.A., n.d.-a)
Porto Santo	-7.00	(APRAM S.A., n.d.-c)
Corvo	-3.50	(PA S.A., n.d.-l)
Santa Cruz das Flores	-4.00	(PA S.A., n.d.-h)
Lajes das Flores	-5.50	(PA S.A., n.d.-e)
Horta	-8.50	(PA S.A., n.d.-c)
Praia da Graciosa	-6.00	(PA S.A., n.d.-e)
São Roque do Pico	-6.50	(PA S.A., n.d.-j)
Lajes do Pico	...	(PA S.A., n.d.-g)
Madalena	...	(PA S.A., n.d.-d)
Velas	-8.00	(PA S.A., n.d.-m)
Calheta	...	(PA S.A., n.d.-b)
Praia da Vitória	-12.00	(PA S.A., n.d.-f)
Angra do Heroísmo	-8.00	(PA S.A., n.d.-i)
Vila do Porto	-7.00	(PA S.A., n.d.-n)
Ponta Delgada	-12.00	(PA S.A., n.d.-j)

While depth data was largely available, no information was found for the ports of Lajes do Pico, Madalena and Calheta. These values were not only used to create the ERP, but also for other analyses that will be described in the following topics.

4.3.4 Vessel traffic

The consolidated figures, representing the annual average of cargo handled and ship traffic, are shown in Table 7 and illustrated graphically in Figure 48.

Table 7 – Average Annual Cargo and Vessels Traffic of the ports.

Port	Average Annual Cargo Traffic (TON)	Average Annual Vessel Traffic (Nº)	Source
Viana do Castelo	371,663.90	213.50	(APDL S.A., n.d.-c)
Leixões	17,162,107.70	2,562.56	(APDL S.A., n.d.-b)
Aveiro	5,297,734.50	1,027.80	(APA S.A., n.d.-a)
Figueira da Foz	2,027,573.70	465.70	(APFF S.A., n.d.-b)
Lisbon	11,229,199.50	2,247.10	(APL S.A., 2024)
Setúbal	6,391,709.40	1,640.60	(APSS S.A., 2025)
Sines	45,904,181.90	2,602.56	(APS S.A., n.d.-a)
Faro	130,122.90	31.80	(APS S.A., n.d.-c)
Portimão	207.50	60.30	(APS S.A., n.d.-c)
Funchal	3,749.78	1,028.67	(APRAM S.A., n.d.)
Canical	929,445.56	219.78	(APRAM S.A., n.d.)
Porto Santo	25,778.56	1,058.78	(APRAM S.A., n.d.)
Ponta Delgada	1,475,282.25	856.00	(PA S.A, n.d.)
Praia da Vitória	494,644.75	605.75	(PA S.A, n.d.)
Horta	298,800.00	303.50	(PA S.A, n.d.)
Velas	70,153.75	277.00	(PA S.A, n.d.)
São Roque do Pico	93,802.00	236.25	(PA S.A, n.d.)
Vila do Porto	38,798.50	218.25	(PA S.A, n.d.)
Praia da Graciosa	30,292.00	192.00	(PA S.A, n.d.)
Lajes das Flores	29,175.75	48.50	(PA S.A, n.d.)
Calheta	6,357.75	47.25	(PA S.A, n.d.)
Angra do Heroísmo	0.00	25.25	(PA S.A, n.d.)
Lajes do Pico	0.00	1.50	(PA S.A, n.d.)
Madalena	356.25	4.00	(PA S.A, n.d.)
Corvo	0.00	2.25	(PA S.A, n.d.)
Santa Cruz das Flores	0.00	0.00	(PA S.A, n.d.)

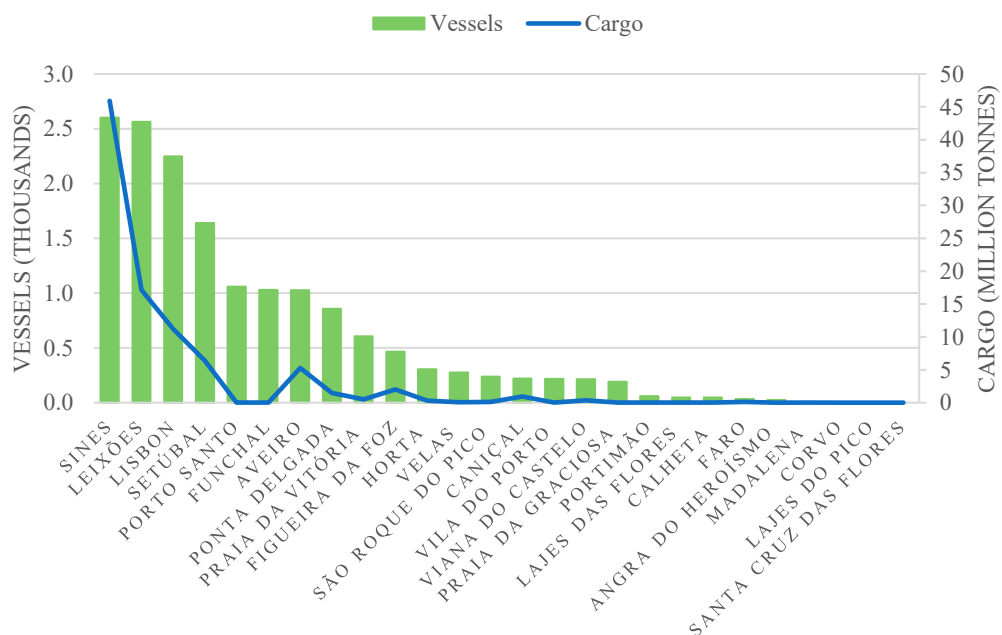


Figure 48 – Graph of the average annual movement of ships and cargo in the ports.

At the end of the analysis, only the data on ship traffic was taken into account when calculating the ERP index. This is due to the fact that, in addition to cargo vessels, it is also necessary to include cruise ship and passenger traffic, in order to more comprehensively reflect the anthropogenic pressure on the port environment. Even so, the comparison between the two approaches (cargo handling versus total vessel handling) proved useful in understanding the differences in the representation of the potential impact.

The results for the average annual ship movement per square kilometre of port area for can be observed in the bar chart in Figure 49. The colour coding system employed in this study is as follows: darker blue indicates ports with values above 600 ships/km², medium blue indicates values between 200 and 600 ships/km², and light blue indicates ports with traffic below 200 ships/km². The colour coding system thus allows for the distinction between high, medium and low traffic, respectively.

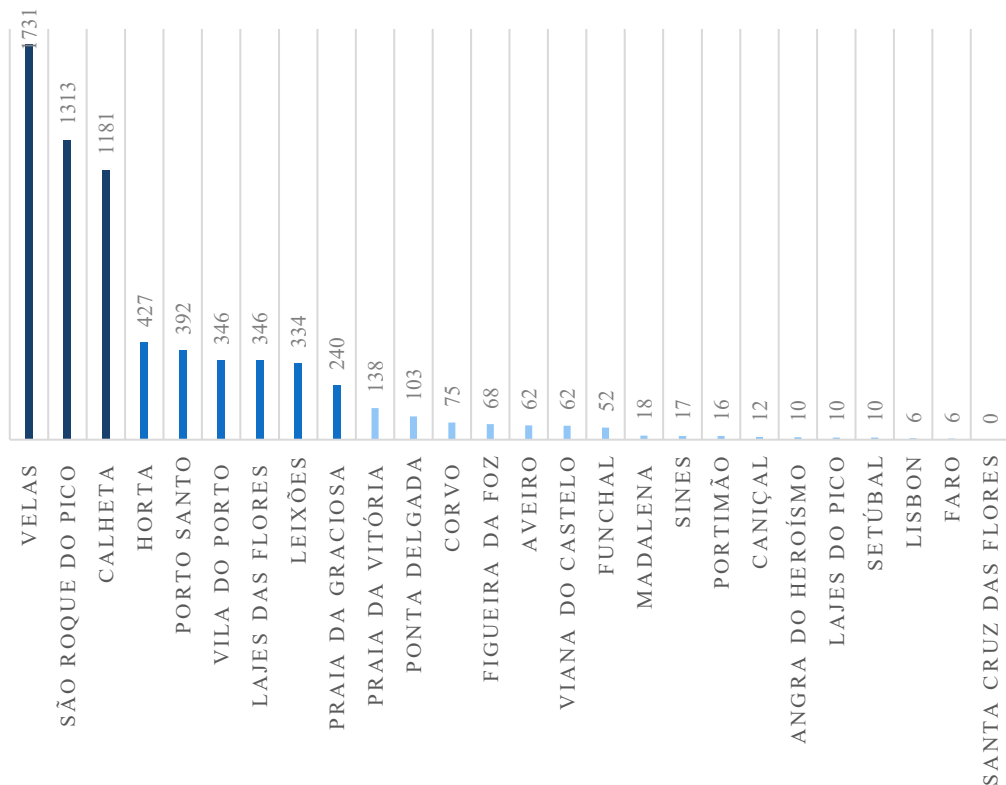


Figure 49 – Annual ship movements by area in square kilometres of the ports.

4.3.5 Ecological restoration potential

As illustrated in Table 8, the points awarded to each port are documented, alongside the respective final scores. The graph in Figure 50 demonstrates the ports with high (10 to 12 points), medium (7 to 9 points) and low (4 to 6 points) ERP in descending order.

Table 8 – Ecological Restoration Potential classification of the ports.

Ports	Artificiality	Ecosystem	Biodiversity absent	Traffic per km ²	Depth	Score
Viana do Castelo	2	2	1	1	1	7
Leixões	3	2	0	2	3	10
Aveiro	2	2	0	1	2	7
Figueira da Foz	3	2	0	1	1	7
Lisbon	2	2	0	1	3	8
Setúbal	2	2	0	1	2	7
Sines	3	1	0	1	3	8
Faro	1	2	0	1	2	6
Portimão	2	2	0	1	1	6
Funchal	3	1	0	1	2	7
Canical	3	1	0	1	2	7
Porto Santo	3	1	0	2	1	7
Corvo	1	1	1	1	1	5
Santa Cruz das Flores	1	1	1	1	1	5
Lajes das Flores	1	1	1	2	1	6
Horta	3	1	0	2	1	7
Praia da Graciosa	2	1	1	2	1	7
São Roque do Pico	1	1	1	3	1	7
Lajes do Pico	1	1	1	1	1	5
Madalena	2	1	0	1	1	5
Velas	2	1	1	3	1	8
Calheta	1	1	1	3	1	7
Praia da Vitória	2	1	0	1	2	6
Angra do Heroísmo	3	1	1	1	1	7
Vila do Porto	1	1	1	2	1	6
Ponta Delgada	2	1	0	1	2	6

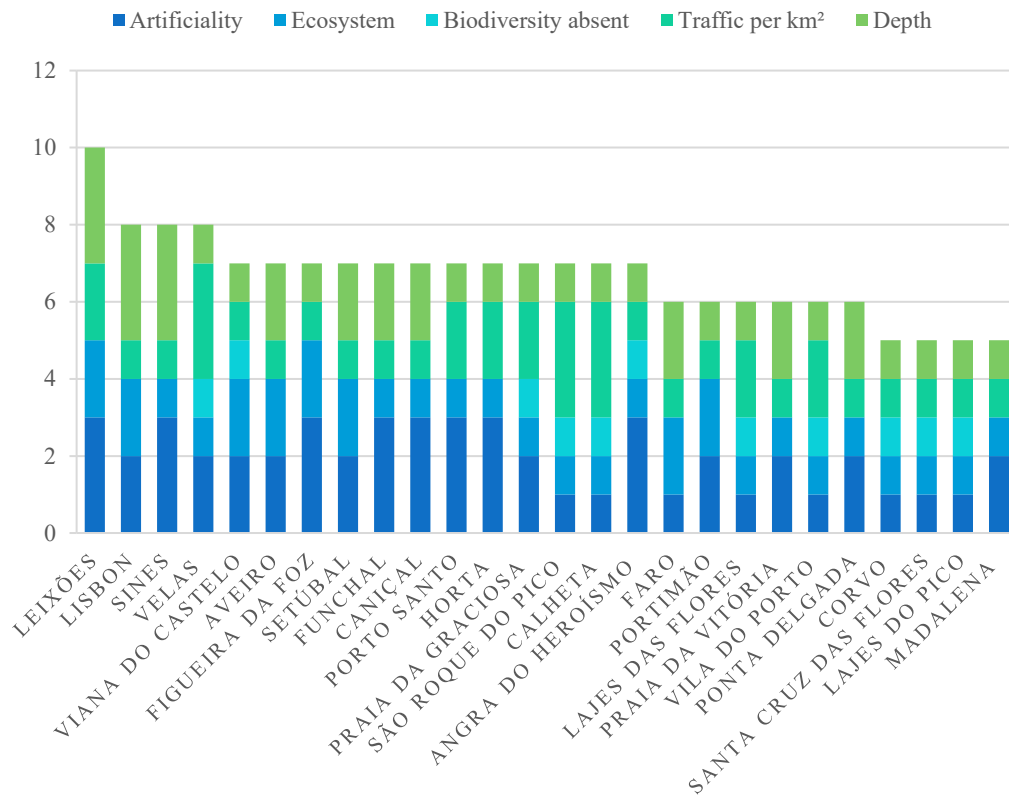


Figure 50 – Graphical representation of the ERP index score for the ports.

4.3.6 Presence of environmental protection zones

The classification of ports in terms of their proximity to environmental protection zones, including SPAs, SCIs and ZECs, is detailed in Table 9. This analysis is relevant to understanding the need for conservation measures, whether due to the scarcity of natural habitats or the absence or vulnerability of certain species, especially birds.

Table 9 – Classification of the presence of environmental protection zones located near port areas.

Ports	ZPE area - Birds Directive	SIC and ZEC area - Habitats Directive
Viana do Castelo	No	Yes
Leixões	No	No
Aveiro	Yes	Yes
Figueira da Foz	Yes	Yes
Lisbon	Yes	Yes
Setúbal	Yes	Yes
Sines	Yes	Yes
Faro	Yes	Yes
Portimão	No	Yes
Funchal	No	No
Canical	Yes	Yes
Porto Santo	No	No
Corvo	Yes	No
Santa Cruz das Flores	No	Yes
Lajes das Flores	Yes	No
Horta	No	Yes

Table 9 – Classification of the presence of environmental protection zones located near port areas.

Ports	ZPE area - Birds Directive	SIC and ZEC area - Habitats Directive
Praia da Graciosa	No	No
São Roque do Pico	No	No
Lajes do Pico	Yes	Yes
Madalena	No	Yes
Velas	No	No
Calheta	No	No
Praia da Vitória	No	No
Angra do Heroísmo	No	No
Vila do Porto	Yes	No
Ponta Delgada	No	No

4.3.7 Risk of overtopping

The standardisation of overtopping risk data from various sources has enabled a comparative assessment of the coastal vulnerability of ports. The final classification is shown below in Table 10.

Table 10 – Flood and overtopping risk classification for the ports.

Ports	Risk of Coastal Flooding and Overtopping
Viana do Castelo	Medium
Leixões	High
Aveiro	Low
Figueira da Foz	High
Lisbon	Low
Setúbal	Low
Sines	Medium
Faro	Low
Portimão	Low
Funchal	High
Canical	High
Porto Santo	Medium
Corvo	Medium
Santa Cruz das Flores	Low
Lajes das Flores	Medium
Horta	Medium
Praia da Graciosa	High
São Roque do Pico	Medium
Lajes do Pico	Medium
Madalena	Medium
Velas	Medium
Calheta	Medium
Praia da Vitória	Medium
Angra do Heroísmo	Low
Vila do Porto	Low
Ponta Delgada	Medium

4.4 Assessment framework for NbS application in the port context

Each technique identified was analysed individually in order to define the parameters required for its application. The following topics initially present the justification for the relevance of each parameter selected, followed by an integrated analysis of the variables involved, in order to support the decision as to whether or not the solution can be implemented in each port. It should be emphasised that this is a qualitative analysis, in which the author used the parameters obtained – also predominantly qualitative – as the basis for the assessment. However, in certain cases, it was necessary to take into account the specific and contextual characteristics of each port, since they have different particularities and demands, which are not always fully captured by the criteria analysed. Furthermore, as it was seen throughout the work, the data collection process faced limitations, both due to the lack of information in some sources and the lack of standardisation between them.

4.4.1 Polehulas and pontoonhulas

Polehulas and pontoonhulas are nature-based solutions developed to increase the structural complexity of anthropized aquatic environments, favouring colonisation by marine organisms, especially molluscs and macroalgae. As well as acting as a habitat for filter species, these structures contribute to improving water quality by promoting greater oxygenation and transparency. Because they are compact, versatile and low-cost, they can be installed in different harbour areas without compromising logistics operations.

Based on three main criteria - the degree of artificiality of the port, the presence of ecological conservation zones (ZEC and SIC), and the ERP index - 20 Portuguese commercial ports were selected as suitable for the application of these techniques. The main criterion considered in the analysis was the presence of environmental conservation zones, and all the ports were classified according to this parameter. For ports that did not have formally protected areas, the selection was based on the two complementary criteria. In these cases, harbours with at least one of these criteria rated high or both rated medium were classified as suitable. Table 11 shows the classification of the harbours according to these parameters and the final decision on the applicability of the solution.

Table 11 – Parameters and choice of application for polehulas and pontoonhulas NbS for ports.

Port	Artificiality	SIC and ZEC areas	ERP	Choice
Viana do Castelo	Medium	Yes	Medium	☑
Leixões	High	No	High	☑
Aveiro	Medium	Yes	Medium	☑
Figueira da Foz	High	Yes	Medium	☑
Lisbon	Medium	Yes	Medium	☑
Setúbal	Low	Yes	Medium	☑
Sines	High	Yes	Medium	☑
Faro	Low	Yes	Low	☑
Portimão	Medium	Yes	Low	☑
Funchal	High	No	Medium	☑
Canical	High	Yes	Medium	☑
Porto Santo	High	No	Medium	☑
Corvo	Low	No	Low	⊖
Santa Cruz das Flores	Low	Yes	Low	☑

Table 11 – Parameters and choice of application for polehulas and pontoonhulas NbS for ports.

Port	Artificiality	SIC and ZEC areas	ERP	Choice
Lajes das Flores	Low	No	Low	⊖
Horta	High	Yes	Medium	✔
Praia da Graciosa	Medium	No	Medium	✔
São Roque do Pico	Low	No	Medium	⊖
Lajes do Pico	Low	Yes	Low	✔
Madalena	Medium	Yes	Low	✔
Velas	Medium	No	Medium	✔
Calheta	Low	No	Medium	✔
Praia da Vitória	Medium	No	Low	⊖
Angra do Heroísmo	High	No	Medium	✔
Vila do Porto	Low	No	Low	⊖
Ponta Delgada	Medium	No	Low	⊖

The choice of ports was mainly influenced by the lack of natural substrates, which is common in highly artificialized environments where fauna finds it difficult to settle and thrive. The ERP was used in this case as an indicator to detect this lack and therefore guide the prioritisation of interventions. The presence of conservation zones reinforced the ecological relevance of certain harbours and the potential benefit of the technique in supporting local biodiversity.

It is worth noting that, despite the prioritisation of degraded areas, the analysis showed that polehulas and pontoonhulas are widely applicable techniques in practically any type of port environment, with moderate salinity – a condition generally present in coastal areas of the Atlantic Ocean, as well as in estuaries and river environments according to the Associação Portuguesa dos Recursos Hídricos (APRH) [Portuguese Water Resources Association]. The salinity parameter was therefore disregarded in this analysis.

4.4.2 Bird island

To assess the availability of material in Portuguese ports, the parameters depth and degree of artificiality were taken into account, assuming that deeper and highly artificialized ports tend to require more frequent dredging operations. This approach was adopted as a substitute for the lack of direct data on dredging volume or frequency. Artificiality was also considered to indicate the need for environmental compensatory measures. With regard to the implementation area, satellite images were analysed in order to identify areas with sandbanks or shallow bottoms that were at least of a size compatible with the Le Havre project (300 m x 150 m). Ports that had physical space, but whose depth or type of bottom did not suggest the presence of visible sandy substrate, were not considered viable for the application of this technique.

In addition to these essential criteria, secondary parameters were assessed which, although not decisive, reinforce the relevance of implementing Bird Island. These include the presence of ZPEs areas aimed at bird conservation, which strengthens the project's ecological justification. In addition, ports located in ecosystems such as estuaries and deltas were considered more favourable because they are habitats naturally used by migratory and resident birds, acting as ecological corridors and increasing the chances of the technique's success. Table

12 shows the results of the assessment and indicates the harbours considered suitable for applying the Bird Island technique.

Table 12 – Parameters and choice of application for bird island NbS for the ports.

Port	ZPE area	Depth	Ecosystem	Artificiality	Area of implementation	Choice
Viana do Castelo	No	Shallow	River	Medium	No	⊖
Leixões	No	Deep	River	High	No	⊖
Aveiro	Yes	Medium	Estuary	Medium	No	⊖
Figueira da Foz	Yes	Shallow	River	High	No	⊖
Lisbon	Yes	Deep	River	Medium	Yes	☑
Setúbal	Yes	Medium	River	Low	Yes	☑
Sines	Yes	Deep	Ocean	High	No	⊖
Faro	Yes	Medium	Estuary	Low	Yes	☑
Portimão	No	Shallow	River	Medium	No	⊖
Funchal	No	Medium	Ocean	High	No	⊖
Canical	Yes	Medium	Ocean	High	No	⊖
Porto Santo	No	Shallow	Ocean	High	No	⊖
Corvo	Yes	Shallow	Ocean	Low	No	⊖
Santa Cruz das Flores	No	Shallow	Ocean	Low	No	⊖
Lajes das Flores	Yes	Shallow	Ocean	Low	No	⊖
Horta	No	Shallow	Ocean	High	No	⊖
Praia da Graciosa	No	Shallow	Ocean	Medium	No	⊖
São Roque do Pico	No	Shallow	Ocean	Low	No	⊖
Lajes do Pico	Yes	No data	Ocean	Low	No	⊖
Madalena	No	No data	Ocean	Medium	No	⊖
Velas	No	Shallow	Ocean	Medium	No	⊖
Calheta	No	No data	Ocean	Low	No	⊖
Praia da Vitória	No	Medium	Ocean	Medium	No	⊖
Angra do Heroísmo	No	Shallow	Ocean	High	No	⊖
Vila do Porto	Yes	Shallow	Ocean	Low	No	⊖
Ponta Delgada	No	Medium	Ocean	Medium	No	⊖

Only three harbours were considered suitable for the application of this technique, given that their implementation conditions are more restrictive. The selected ports share the characteristic of being located on large rivers, which favours both the availability of physical space and natural protection against intense waves and the transport of sandy sediments. In contrast, the island harbours were all built directly in marine areas, generally associated with greater depths, which hinders the viability of the technique. The other mainland harbours located on rivers, on the other hand, are on smaller waterways or have no sandbanks, which limits the conditions necessary to implement the solution.

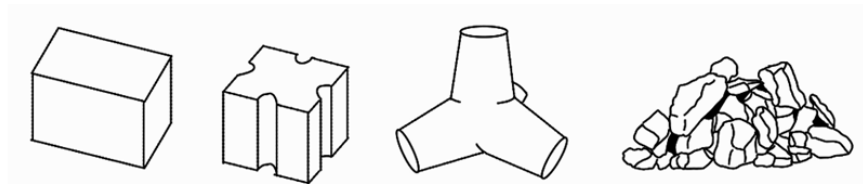
4.4.3 Eco-concrete breakwater

Structures with increased complexity for breakwaters are NbS designed to replace or adapt traditionally used smooth concrete blocks, with the aim of creating micro-habitats that favour the colonisation of marine organisms in highly artificialized environments. In this context, the proposed application of the technique focuses where wave agitation is lower and

biological settlement is more feasible. Thus, the application of this technique is restricted to places where breakwaters or equivalent structures already exist. Of the ports analysed, all have these structures, with the exception of the ports of Lisbon and Setúbal, located in large estuaries where natural protection already reduces the need for artificial breakwaters.

In addition, the degree of artificiality of the substrate present in the breakwaters was assessed. Different types of construction elements were identified in Portuguese harbours, such as vertical concrete walls, tetrapods - three-dimensional blocks with smooth surfaces - antifer cubes, rectangular concrete blocks also with smooth surfaces, and irregular rip-rap rocks (see Figure 51). For classification purposes, high artificiality was attributed to structures with predominantly smooth surfaces, such as vertical walls, concrete cobblestones and antifer cubes; medium artificiality to tetrapods; and low artificiality to rip-rap type rocks. The materials found in the breakwaters of each harbour are contained in Table 20 in Appendix B. As breakwaters often combine more than one type of substrate, the assessment of the degree of artificiality considered the relative proportion of each element.

Figure 51 – Types of breakwaters blocks founded in the ports.



From left to right: rectangular concrete block, antifer cube, tetrapod and rip rap.

To complement the analysis and assess the need for ecological intervention, the ERP index and the presence of areas classified under the Habitats (ZEC and SIC) or Birds Directives (ZPE) were taken into account, given that ecologically optimised structures can provide food and shelter for coastal birds. Table 13 summarises the results obtained and indicates the ports considered suitable for the application of this NbS.

Table 13 – Parameters and choice of application for eco-concrete breakwater NbS for the ports.

Port	Substrate artificiality	ZPE, ZEC or SIC areas	ERP	Choice
Viana do Castelo	Medium	Yes	Medium	☑
Leixões	Low to medium	No	High	☑
Aveiro	Medium to high	Yes	Medium	☑
Figueira da Foz	Medium	Yes	Medium	☑
Lisbon	Low	Yes	Medium	⊖
Setúbal	Low	Yes	Medium	⊖
Sines	High	Yes	Medium	☑
Faro	Medium	Yes	Low	☑
Portimão	Medium	Yes	Low	☑
Funchal	Medium	No	Medium	☑
Caniçal	High	Yes	Medium	☑
Porto Santo	Medium to high	No	Medium	☑
Corvo	Medium	Yes	Low	☑
Santa Cruz das Flores	High	Yes	Low	☑
Lajes das Flores	High	Yes	Low	☑
Horta	Medium	Yes	Medium	☑
Praia da Graciosa	Medium	No	Medium	☑

Table 13 – Parameters and choice of application for eco-concrete breakwater NbS for the ports.

Port	Substrate artificiality	ZPE, ZEC or SIC areas	ERP	Choice
São Roque do Pico	Medium	No	Medium	✓
Lajes do Pico	High	Yes	Low	✓
Madalena	Medium	Yes	Low	✓
Velas	Medium to high	No	Medium	✓
Calheta	High	No	Medium	✓
Praia da Vitória	Medium to high	No	Low	✓
Angra do Heroísmo	Medium	No	Medium	✓
Vila do Porto	Medium	Yes	Low	✓
Ponta Delgada	Medium	No	Low	✓

This technique, like polehulas and pontoonhulas, can be applied in any harbour that has breakwaters and seeks to compensate for the artificiality of its structures by introducing topographical complexity. In this study, 24 harbours were identified as potential candidates for its implementation, excluding only those without breakwaters. This is a low-cost solution whose application requires only the modification of the concrete block mould and can be adapted to different types of structural blocks.

4.4.4 Eco-basins

Eco-basins consist of ecological basins that promote the colonisation of molluscs, crabs, macroalgae, small fish and other forms of macrofauna, contributing significantly to increasing the structural heterogeneity and ecological complexity of the port environment. These structures were originally implemented in an estuarine intertidal zone, which emphasises the need for certain environmental conditions for their application. Among the fundamental requirements for their installation are the presence of regular tidal variation – so that the basins are periodically soaked and exposed – and the existence of sheltered areas with low wave energy.

Therefore, the selection of harbours suitable for implementing the technique was initially based on identifying sites with these characteristics by analysing satellite images. Ports that were partially protected from the direct action of waves and located in areas subject to tidal oscillation were considered suitable. Although estuaries and rivers naturally offer these conditions, the possibility of application in sheltered ocean areas was also accepted.

After identifying potential implementation sites, the type of substrate available was analysed. The materials found included smooth concrete blocks (cobblestones), rip-rap rocks, sand and gravel (Table 21, Appendix B). According to the classification previously adopted, substrates with smooth concrete were considered to be highly artificial, while the others were classified as low artificiality.

Additionally, as an environmental criterion, the presence of ecological protection zones – ZPE, ZEC and SIC – was considered, since the installation of these basins can increase the availability of food for seabirds, especially in areas of recognised ecological value, reinforcing the conservation objectives established by the Birds and Habitats Directives. The choices for each port are shown in

Table 14.

Due to the versatility of this technique - which allows the installation of structures with varying dimensions, between 5 and 150 metres in length - the mere presence of a suitable site was considered a sufficient criterion for the selection of NbS in each port assessed.

Table 14 – Parameters and choice of application for eco-basins NbS for the ports.

Port	Location sheltered from waves	Location is in the intermareal zone	Substrate artificiality	ZPE, ZEC or SIC areas	Choice
Viana do Castelo	Yes	Yes	Low	Yes	☑
Leixões	Yes	Yes	Low	No	☑
Aveiro	Yes	Yes	Medium	Yes	☑
Figueira da Foz	No	-	-	Yes	⊖
Lisbon	Yes	Yes	Low	Yes	☑
Setúbal	Yes	Yes	Low	Yes	☑
Sines	No	-	-	Yes	⊖
Faro	Yes	Yes	Low	Yes	☑
Portimão	No	-	-	Yes	⊖
Funchal	No	-	-	No	⊖
Canical	No	-	-	Yes	⊖
Porto Santo	Yes	Yes	Low	No	☑
Corvo	No	-	-	Yes	⊖
Santa Cruz das Flores	No	-	-	Yes	⊖
Lajes das Flores	No	-	-	Yes	⊖
Horta	Yes	No	Low	Yes	⊖
Praia da Graciosa	No	-	-	No	⊖
São Roque do Pico	No	-	-	No	⊖
Lajes do Pico	No	-	-	Yes	⊖
Madalena	No	-	-	Yes	⊖
Velas	No	-	-	No	⊖
Calheta	No	-	-	No	⊖
Praia da Vitória	No	-	-	No	⊖
Angra do Heroísmo	No	-	-	No	⊖
Vila do Porto	No	-	-	Yes	⊖
Ponta Delgada	Yes	No	Low	No	⊖

Only seven harbours were considered potential for the application of this technique, since its implementation requires sheltered areas - an uncommon condition among harbours mostly located on the open sea. The only seaport included as viable was Porto Santo. It should be noted that the parameter used to verify the presence of an intertidal zone may not be entirely accurate, since the analysis was carried out on the basis of satellite images taken on different dates.

Despite the small number of eligible harbours, this is an easy-to-install technique that does not require large areas to implement. The feasibility of its application depends above all on local interest and the availability of a physically suitable space.

4.4.5 Seawalls with topographic complexity

Unlike the other NbS analysed, the seawalls with increased complexity were proposed and tested in a laboratory environment, on a reduced scale. For this reason, it is not yet possible to precisely determine the ideal dimensions for full-scale implementation. In any case, the feasibility of applying the technique is dependent on the existence or possibility of installing or replacing artificial vertical walls. The main purpose of this solution is to increase the surface roughness of these structures, which contributes to reducing the risk of wave overtopping and coastal flooding, while at the same time improving the quality of the marine habitat and increasing biodiversity in the surrounding area.

The first criterion analysed was the presence of vertical walls in the harbours. Subsequently, the constituent material of these structures was assessed. The materials identified included natural stone, concrete blocks, cast-in-place concrete and brick masonry. According to the methodology adopted in this study, structures made of smooth, artificial materials such as concrete and bricks were classified as highly artificial, while those made of natural stone were considered to be of low artificiality. In Table 22 in Appendix B, the materials found in the seawalls of each harbour are documented.

The second relevant criterion was the risk of overtopping and coastal flooding, given the main function of this NbS in protecting against extreme hydrodynamic events. In addition, the type of ecosystem was considered, since ports located in areas open to the ocean or with large estuarine inlets are more susceptible to the incidence of impulsive waves - a context in which the effectiveness of textured seawalls is maximised. In addition, port traffic was analysed, since high volumes of shipping can increase the risk of marginal erosion and justify coastal reinforcement interventions, and depth, since deep water near structures can favour the occurrence of higher energy waves.

Finally, with regard to biodiversity conservation, the presence of Natura 2000 protected areas (SIC and ZEC) in the vicinity of the structures analysed was taken into account. These elements were put together to support the selection of the technique in the ports studied, as shown in Table 15.

Table 15 – Parameters and choice of application for seawalls with topographic complexity NbS for the ports.

Port	Existence of seawalls	Risk of Overtopping	Ecosystem	SIC/ ZEC areas	Average Annual Vessel Traffic	Depth	Choice
Viana do Castelo	No	Medium	River	No	Low	Shallow	⊖
Leixões	Yes	High	River	No	High	Deep	☑
Aveiro	Yes	Low	Estuary	Yes	High	Medium deep	☑
Figueira da Foz	Yes	High	River	Yes	Medium	Shallow	⊖
Lisbon	Yes	Low	River	Yes	High	Deep	☑

Table 15 – Parameters and choice of application for seawalls with topographic complexity NbS for the ports.

Port	Existence of seawalls	Risk of Overtopping	Ecosystem	SIC/ ZEC areas	Average Annual Vessel Traffic	Depth	Choice
Setúbal	Yes	Low	River	Yes	High	Medium deep	⊖
Sines	Yes	Medium	Ocean	Yes	High	Deep	⊖
Faro	No	Low	Estuary	Yes	Low	Medium deep	⊖
Portimão	Yes	Low	River	No	Low	Shallow	⊖
Funchal	No	High	Ocean	No	High	Medium deep	⊖
Canical	Yes	High	Ocean	Yes	Low	Medium deep	☑
Porto Santo	No	Medium	Ocean	No	High	Shallow	⊖
Corvo	No	Medium	Ocean	Yes	Low	Shallow	⊖
Santa Cruz das Flores	Yes	Low	Ocean	No	Low	Shallow	⊖
Lajes das Flores	Yes	Medium	Ocean	Yes	Low	Shallow	⊖
Horta	No	Medium	Ocean	No	Low	Shallow	⊖
Praia da Graciosa	No	High	Ocean	No	Low	Shallow	⊖
São Roque do Pico	Yes	Medium	Ocean	No	Low	Shallow	⊖
Lajes do Pico	Yes	Medium	Ocean	Yes	Low	No data	☑
Madalena	No	Medium	Ocean	No	Low	No data	⊖
Velas	No	Medium	Ocean	No	Low	Shallow	⊖
Calheta	Yes	Medium	Ocean	No	Low	No data	⊖
Praia da Vitória	No	Medium	Ocean	No	Medium	Medium deep	⊖
Angra do Heroísmo	Yes	Low	Ocean	No	Low	Shallow	⊖
Vila do Porto	No	Low	Ocean	Yes	Low	Shallow	⊖
Ponta Delgada	Yes	Medium	Ocean	No	High	Medium deep	⊖

According to the analysis carried out, this technique proved viable for application in only five ports. The small number is mainly due to the fact that it is a solution that requires more complex interventions. In some cases, the harbours have preserved natural walls, which cannot be replaced by artificial structures that imitate natural forms from an ecological point of view. In others, the existing structures are already less artificial, as in the case of rockfills, with spaces that favour local biodiversity. In these contexts, a more suitable alternative may be the use of living seawalls, modular structures that can be attached to existing walls to increase their topographical and ecological complexity.

As for the risk of overtopping parameter, it is understood that this reflects a general condition of the area and does not necessarily accurately capture the specific reality of each

site. As this technique is strongly orientated towards coastal protection, a more in-depth analysis of this aspect would be necessary to guarantee its effectiveness. It should also be noted that, due to the lack of more precise data, the selection of suitable harbours was made on the basis of an interpretative margin, based on the reading of spatial images.

4.4.6 Bioinspired underwater breakwaters

Finally, the last technique analysed refers to SBs, with geometries inspired by nature. Like seawalls with increased complexity, these devices have been tested in laboratory environments and on a small scale, which limits practical knowledge about their implementation on a full scale. The main function of these breakwaters is to dissipate wave energy, making them a coastal protection solution with a low environmental and visual impact.

Given this purpose, the parameters considered for their application were: (i) the risk of overtopping and coastal flooding, since the presence of these risks justifies the adoption of energy dissipation structures; (ii) the type of ecosystem, with emphasis on the location of the harbour in relation to exposure to wave energy - harbours located in the open sea or large estuaries are naturally more vulnerable to erosion and overtopping; and (iii) the depth of the installation zone. This last factor is particularly relevant, as the efficiency of underwater breakwaters depends on their relative depth: moderate depths allow greater interaction with the wave profile, optimising their dissipation capacity. Depths of more than 10 metres tend to significantly reduce their effectiveness, since much of the wave energy is dissipated in the surface layer, and structures installed at greater depths are unable to effectively interfere with the propagation of the incident wave. Table 16 below shows the results of the assessment of Portuguese ports in terms of the applicability of this technique.

Table 16 – Parameters and choice of application for bioinspired underwater breakwaters NbS for the ports.

Port	Ecosystem	Depth	Risk of Overtopping	Choice
Viana do Castelo	River	Shallow	Medium	☑
Leixões	River	Deep	High	☐
Aveiro	Estuary	Medium deep	Low	☐
Figueira da Foz	River	Shallow	High	☑
Lisbon	River	Deep	Low	☐
Setúbal	River	Medium deep	Low	☐
Sines	Ocean	Deep	Medium	☐
Faro	Estuary	Medium deep	Low	☐
Portimão	River	Shallow	Low	☐
Funchal	Ocean	Medium deep	High	☑
Canical	Ocean	Medium deep	High	☑
Porto Santo	Ocean	Shallow	Medium	☑
Corvo	Ocean	Shallow	Medium	☑
Santa Cruz das Flores	Ocean	Shallow	Low	☑
Lajes das Flores	Ocean	Shallow	Medium	☑
Horta	Ocean	Shallow	Medium	☑
Praia da Graciosa	Ocean	Shallow	High	☑
São Roque do Pico	Ocean	Shallow	Medium	☑
Lajes do Pico	Ocean	No data	Medium	☑
Madalena	Ocean	No data	Medium	☑

Table 16 – Parameters and choice of application for bioinspired underwater breakwaters NbS for the ports.

Port	Ecosystem	Depth	Risk of Overtopping	Choice
Velas	Ocean	Shallow	Medium	✓
Calheta	Ocean	No data	Medium	✓
Praia da Vitória	Ocean	Medium deep	Medium	✓
Angra do Heroísmo	Ocean	Shallow	Low	✓
Vila do Porto	Ocean	Shallow	Low	✓
Ponta Delgada	Ocean	Medium deep	Medium	✓

This was the only technique analysed that did not focus on environmental parameters, since its main objective is to provide protection against the action of strong waves and to attenuate the visual impact of coastal infrastructures. It is an easy-to-apply solution with low implementation complexity and little impact on marine habitats. As a result of the analysis, nineteen harbours were identified as potentially suitable for its implementation. The proposed application focused mainly on ports located directly on the sea, where the demand for containment structures is most significant. However, the technique is also viable in riverbeds, provided the right physical conditions are met.

It should be noted that the requirement for shallow depths is not clearly defined in the literature analysed, and this is a criterion assumed by the author based on the interpretation of the cases studied.

4.4.7 General overview

In summary, the results relating to the selection of ports with potential for the application of the different nature-based solutions have been consolidated in Table 17, providing a comparative overview of the techniques analysed. For the purpose of organisation and clarity, the NbS have been numbered from 1 to 6, according to the order of presentation in the subtopics of this results section: (1) Polehulas and Pontoonhulas; (2) Bird Island; (3) Eco-concrete Breakwaters; (4) Eco-basins; (5) Seawalls with topographic complexity; and (6) Bioinspired Submerged Seawalls.

Table 17 – Summary of NbS application potential choices for each port.

Port	Implementation					
	1	2	3	4	5	6
Viana do Castelo	✓	⊖	✓	✓	⊖	✓
Leixões	✓	⊖	✓	✓	✓	⊖
Aveiro	✓	⊖	✓	✓	✓	⊖
Figueira da Foz	✓	⊖	✓	⊖	⊖	✓
Lisbon	✓	✓	⊖	✓	✓	⊖
Setúbal	✓	✓	⊖	✓	⊖	⊖
Sines	✓	⊖	✓	⊖	⊖	⊖
Faro	✓	✓	✓	✓	⊖	⊖
Portimão	✓	⊖	✓	⊖	⊖	⊖
Funchal	✓	⊖	✓	⊖	⊖	✓
Caniçal	✓	⊖	✓	⊖	✓	✓
Porto Santo	✓	⊖	✓	✓	⊖	✓
Corvo	⊖	⊖	✓	⊖	⊖	✓
Santa Cruz das Flores	✓	⊖	✓	⊖	⊖	✓

Table 17 – Summary of NbS application potential choices for each port.

Port	Implementation					
	1	2	3	4	5	6
Lajes das Flores	⊖	⊖	☑	⊖	⊖	☑
Horta	☑	⊖	☑	⊖	⊖	☑
Praia da Graciosa	☑	⊖	☑	⊖	⊖	☑
São Roque do Pico	⊖	⊖	☑	⊖	⊖	☑
Lajes do Pico	☑	⊖	☑	⊖	☑	☑
Madalena	☑	⊖	☑	⊖	⊖	☑
Velas	☑	⊖	☑	⊖	⊖	☑
Calheta	☑	⊖	☑	⊖	⊖	☑
Praia da Vitória	⊖	⊖	☑	⊖	⊖	☑
Angra do Heroísmo	☑	⊖	☑	⊖	⊖	☑
Vila do Porto	⊖	⊖	☑	⊖	⊖	☑
Ponta Delgada	⊖	⊖	☑	⊖	⊖	☑

Thus, the techniques with the greatest potential for application in Portuguese ports were, respectively: eco-concrete breakwaters (24 ports), polehulas and pontoonhulas (20 ports) and bioinspired submerged seawalls (19 ports). This result is justified by the wide availability of suitable sites for their installation, the low cost of implementation and the requirement for a reduced number of technical parameters for their analysis. On the other hand, the eco-basins (7 harbours), seawalls with topographic complexity (5 harbours) and bird island (3 harbours) techniques showed less applicability, the greater the need for specific areas and the greater the degree of planning and intervention required.

It was also noted that all the ports analysed have the potential to apply at least two of the proposed techniques, in some cases up to four. It should be emphasised that these solutions can be implemented in a complementary manner, since they do not interfere with each other.

5 FINAL CONSIDERATIONS ABOUT THE METHODOLOGY

Despite the progress made in this research, it is important to recognise some methodological limitations that had an impact on the study and the results obtained. The initial phase of selecting scientific articles, based on the Radfar et al. (2024) protocol, was fundamental in guiding the first steps of the investigation into a topic that was still unfamiliar to the author. However, as the work matured, it became clear that greater prior familiarity with the scope of the research would have enabled more careful choices of the studies to be analysed. Some of the articles selected, for example, did not present practical case studies, which limited the analysis of solutions that had already been tested in real contexts - an essential aspect for the purpose of the work. In contrast, the subsequent inclusion of the EcoShape case studies proved to be more in line with the research objectives, since they included solutions applied on a real scale and clearly documented.

In addition, collecting data on Portuguese ports faced considerable challenges, mainly due to the decentralisation of information. Although it is a single country, each port administration has autonomy and adopts different criteria for publishing documents and data, which made it difficult to obtain standardised information. This difficulty was accentuated in the case of the autonomous regions, whose data was often not integrated into national databases, requiring specific treatment and standardisation by the author. This fragmentation resulted in gaps that affected the uniformity of the analysis.

Another critical point of the research concerns the attempt to incorporate a biodiversity-related parameter into the feasibility analysis of the solutions. Because she did not have a background in biological sciences, the author faced limitations in understanding and measuring complex ecological aspects. The parameter initially considered most relevant - species richness - turned out to be inaccurate given the scarcity of reliable data, especially in relation to harbours located on the archipelagos. The absence of records in some regions and the low representativeness of the available data made it impossible to use it in the analysis, even after attempts at normalisation or correlation with the study areas.

In response to the lack of biodiversity data, the ERP index was proposed, based on a qualitative weighting of various factors that could indicate the need for environmental restoration. Although this index partially filled the gap left by the exclusion of the initial ecological parameter, its lack of support in scientific literature limits its validity as a consolidated methodological tool. Even so, the ERP proved useful for supporting the analysis in an exploratory context, in line with the qualitative approach of the research.

Finally, it should be noted that the scale of the study, covering all 26 Portuguese commercial ports, required a more generalised approach when defining the parameters of analysis. This imposed restrictions on the individual depth of the assessments, which could have been more detailed if the focus had been limited to a smaller number of ports. The lack of detailed information on the structures and materials used in the ports also reduced the accuracy of the analyses, an aspect that could have been minimised with a strategy of direct communication with the port authorities.

6 CONCLUSIONS AND FUTURE PERSPECTIVES

The aim of this research was to analyse the feasibility of applying nature-based solutions in Portuguese commercial ports, helping to strengthen the concept of greening the grey in the field of civil and port engineering. To this end, specific methodologies were developed both for selecting the most suitable techniques and for defining analysis parameters to guide the assessment of the potential for application in each port. The results obtained indicate that all the ports analysed show viability for at least two NbS, which highlights not only the need for ecological compensation measures, but also the concrete opportunity for integrating these solutions into highly artificialized contexts.

The general objective of this research was to analyse and promote the implementation of green engineering strategies in port environments, in line with global sustainable development goals. To achieve this, the following specific objectives were established: a literature review on the concept of greening the grey and its international application cases; an analysis of the various types of coastal and port environments, with an emphasis on the ecological concepts that characterise them; a survey of NbS applicable to coastal and port infrastructures; the identification and mapping of commercial ports in Portugal; and finally, an assessment of the feasibility of applying the different NbS in each of these ports. The methodological approach included consulting case studies from the EcoShape network, carefully selecting scientific articles indexed in the Scopus database and collecting technical information from the websites of port authorities and institutional documents. Based on this set of data, it was possible to systematically assess the potential for applying NbS in Portuguese ports.

The methodology adopted in this research consisted of drawing up an inventory of techniques that incorporate biomimicry principles and aim to reduce the environmental impacts caused by port infrastructures. The research, of a theoretical-empirical nature and qualitative approach, began with a review of the scientific literature in the Scopus database in order to identify innovative nature-based solutions applied to the global port context. This review was complemented by case studies of the EcoShape project, as well as conceptual analyses of port engineering and the different types of coastal environments. Next, all of Portugal's commercial ports - including those located in the autonomous regions - were identified, described and represented cartographically. The relevant information for each port was obtained from the websites of the respective port administrations and the Association of Ports of Portugal. Based on this data, a set of qualitative parameters was defined - based on the environmental and operational characteristics of each port - to assess the suitability and feasibility of applying the NbS inventoried.

The research resulted in an inventory of six nature-based solutions developed especially for coastal and harbour environments. Of these, four focus on increasing marine biodiversity by restoring degraded habitats. This recovery is achieved through different mechanisms, such as providing a suitable substrate, increasing submerged topographic complexity and building specific structures, such as artificial islands for birds. These results show that the application of green engineering techniques to coastal and port infrastructures can make a significant contribution to promoting local biodiversity, while at the same time favouring the restoration of the ecological health of the surrounding ecosystems.

The remaining two NbS, aimed at coastal protection, use structures already consolidated in port engineering, but with adaptations that incorporate biomimetic principles, such as increasing surface complexity and imitating natural forms. Their studies show that these

solutions are capable of improving the adaptability and resilience of infrastructure in the face of extreme weather events, reducing the associated risks. In addition, these techniques maintain the operational functionality of the structures, while adding ecological value and promoting greater integration between the built infrastructure and the natural environment.

The case studies analysed on the EcoShape website reinforce the applicability and viability of the proposed solutions. The eco-concrete breakwater technique, for example, can be incorporated directly into the production process with an estimated increase of just 2% to 3% in the total cost of implementation. Polehulas and pontoonhulas, meanwhile, have proven to be effective in restoring natural habitats, using simple, low-cost materials and showing significant results in terms of biological colonisation. Finally, the bird island proved to be economically viable when integrated into the harbour dredging process, without entailing significant additional costs. Furthermore, this solution responded positively to the concerns of local communities, who are often opposed to interventions that degrade the environment. These case studies prove that NbS can be advantageous not only from an ecological point of view, but also from an economic and social point of view, since they reduce operating costs in the long term and promote acceptance by stakeholders.

The analysis of Portuguese commercial ports revealed that all of them are viable for the application of at least two of the NbS techniques listed. The techniques with the greatest potential for application were those whose implementation requires the fewest technical parameters and which require smaller or less specific spaces. This result corroborates the initial hypothesis of this research by demonstrating that there are concrete opportunities for integrating ecological solutions into existing port systems, while respecting their physical and operational particularities.

In view of the results obtained and the fulfilment of the proposed objectives, it is considered that this research can serve as a basis for relevant developments on different research fronts. One of the main recommendations is to carry out studies conducted by specialists in the field of biology, aimed at measuring biodiversity in port environments. Work of this nature could fill the data gap found in this study and provide more solid support for the ecological assessment of each port area, favouring more accurate diagnoses of the need for environmental restoration.

At the same time, it is recommended the development and scientific validation of a specific index of ecological restoration potential for ports. Such an index would make it possible to standardise the analysis of different port contexts, combining environmental, spatial and functional criteria, and offering a useful tool for both researchers and managers. The construction of this index could take as a starting point the experience gained with the ERP proposed in this work, refining its foundations and testing its applicability in different scenarios.

In addition, it is suggested that more focussed investigations be carried out in specific ports, so as to allow a more in-depth analysis of local conditions and the feasibility of implementing certain NbS. Detailed case studies, with on-site surveys and co-operation with port authorities, could more accurately identify application sites and the potential benefits of each solution.

Another natural outcome of this work would be the practical application of one of the suggested solutions in one of the ports studied, with the direct involvement of the port administrations. Such a pilot application would make it possible to test the technical and economic viability of NbS in a real context, as well as providing valuable data on its environmental, social and operational impacts. More broadly, we encourage Portuguese port

authorities to consider incorporating eco-based techniques into their maintenance, expansion or climate change adaptation projects, even on an experimental basis.

Finally, it is worth highlighting the potential use of the results of this dissertation as a subsidy for public policies aimed at mitigating environmental impacts in port areas. Systematising nature-based techniques and analysing their applicability in the Portuguese context can support the formulation of guidelines and regulations that encourage more sustainable practices in the sector. In this sense, it is recommended to encourage the adoption of NbS as a standard in coastal engineering projects, promoting the integration of infrastructure, biodiversity and climate resilience.

REFERENCES

- Administração do Porto da Figueira da Foz S.A. (n.d.-a). *Environmental management*. Retrieved 24 April 2025, from <https://portofigueiradafoz.pt/gestao-ambiental/en/>
- Administração do Porto da Figueira da Foz S.A. (n.d.-b). *Estatísticas*. Retrieved 30 April 2025, from <https://app.powerbi.com/view?r=eyJrIjoiZjBhMjIwYzktYjc4MS00NDRhLTlhN2YtOTY0OWY3NWlWnJcwIiwidCI6IjY4MmM5MzA5LWQwZDctNDZjNi1iMmZILTM4OGZlMDMzYThiMSIsImMiOjh9&pageName=ReportSection>
- Administração do Porto da Figueira da Foz S.A. (n.d.-c). *Porto da Figueira da Foz*. Retrieved 28 March 2025, from <https://portofigueiradafoz.pt/>
- Administração do Porto de Lisboa S.A. (n.d.-a). *Homepage - Porto de Lisboa*. Retrieved 24 April 2025, from <https://www.portodelisboa.pt/en/home>
- Administração do Porto de Lisboa S.A. (n.d.-b). *Port map - Porto de Lisboa*. Retrieved 28 March 2025, from <https://www.portodelisboa.pt/en/mapa-do-porto>
- Administração do Porto de Lisboa S.A. (2024). *Movimentação Portuária*. <https://www.portodelisboa.pt/documents/20121/181094/MOVIMENTA%C3%87%C3%83O+PORTU%C3%81RIA+2024-PT+ING+VF.pdf/989cb170-9b87-069f-3ff7-8029842da1b1?t=1743416454557>
- Administração dos Portos da Região Autónoma da Madeira S.A. (n.d.-a). *Caniçal - Características do porto*. Retrieved 1 May 2025, from <https://apram.pt/caracteristicas-porto?port=Cani%C3%A7al>
- Administração dos Portos da Região Autónoma da Madeira S.A. (n.d.-b). *Funchal - Características do porto*. Retrieved 1 May 2025, from <https://apram.pt/caracteristicas-porto?port=Funchal>
- Administração dos Portos da Região Autónoma da Madeira S.A. (n.d.-c). *Porto Santo - Características do porto*. Retrieved 1 May 2025, from <https://apram.pt/caracteristicas-porto?port=Porto%20Santo>
- Administração dos Portos da Região Autónoma da Madeira S.A. (n.d.-d). *Relatórios e Documentos*. Retrieved 1 April 2025, from <https://apram.pt/estatisticas>
- Administração dos Portos de Setúbal e Sesimbra S.A. (n.d.-a). *Área de Jurisdição*. Retrieved 28 March 2025, from <https://www.portodesetubal.pt/apss/pagina/42/area-de-jurisdicao>
- Administração dos Portos de Setúbal e Sesimbra S.A. (n.d.-b). *Porto de Setúbal*. Retrieved 24 April 2025, from <https://www.portodesetubal.pt/apss/pagina/20/porto-de-setubal>
- Administração dos Portos de Setúbal e Sesimbra S.A. (2025). *Dados Estatísticos - Dezembro de 2024 (01-12-2024 a 31-12-2024)*. https://www.portodesetubal.pt/docs/upload_docs/Acumulado_12_Ddezembro_2024_Internet.pdf
- Administração dos Portos de Sines e do Algarve S.A. (n.d.-a). *Movimento de Navios, Mercadorias e Contentores - Sines*. Retrieved 1 April 2025, from <https://www.apsinesalgarve.pt/media/4878/estat%C3%ADstica-do-porto-de-sines-jan-dez-20242023.pdf>
- Administração dos Portos de Sines e do Algarve S.A. (n.d.-b). *Cais Comercial*. Retrieved 25 April 2025, from <https://www.apsinesalgarve.pt/porto-de-faro/o-porto/cais-comercial/>
- Administração dos Portos de Sines e do Algarve S.A. (n.d.-c). *Movimento de Navios, Mercadorias e Passageiros - Algarve*. Retrieved 1 April 2025, from

- <https://www.apsinesalgarve.pt/media/4879/estat%C3%ADstica-dos-portos-de-faro-portim%C3%A3o-jan-dez-20242023.pdf>
- Administração dos Portos de Sines e do Algarve S.A. (n.d.-d). *Porto de Faro - Localização Estratégica*. Retrieved 28 March 2025, from <https://www.apsinesalgarve.pt/porto-de-faro/o-porto/localiza%C3%A7%C3%A3o-estrat%C3%A9gica/>
- Administração dos Portos de Sines e do Algarve S.A. (n.d.-e). *Porto de Portimão - Localização Estratégica*. Retrieved 28 March 2025, from <https://www.apsinesalgarve.pt/porto-de-portimao/o-porto/localiza%C3%A7%C3%A3o-estrat%C3%A9gica/>
- Administração dos Portos de Sines e do Algarve S.A. (n.d.-f). *Porto de Sines - Características Gerais*. Retrieved 28 March 2025, from <https://www.apsinesalgarve.pt/porto-de-sines/o-porto/caracter%C3%ADsticas-gerais/>
- Administração dos Portos de Sines e do Algarve S.A. (2017). *Área de Jurisdição Terrestre e Marítima do Porto de Sines*. https://www.apsinesalgarve.pt/media/2450/%C3%A1rea-de-jurisdic%C3%A7%C3%A3o-do-porto-de-sines_.pdf
- Administração dos Portos do Douro Leixões e Viana do Castelo S.A. (n.d.-a). *Porto de Leixões*. Retrieved 28 March 2025, from <https://leixoes.apdl.pt/o-porto/>
- Administração dos Portos do Douro Leixões e Viana do Castelo S.A. (n.d.-b). *Porto de Leixões - Movimento de Navios Anual*. Retrieved 1 April 2025, from <https://leixoes.apdl.pt/estatisticas/navios/movimento-de-navios-anual/>
- Administração dos Portos do Douro Leixões e Viana do Castelo S.A. (n.d.-c). *Porto de Viana - Movimento de Navios Anual*. Retrieved 1 April 2025, from <https://viana.apdl.pt/estatisticas/navios/movimento-de-navios-anual/>
- Administração dos Portos do Douro Leixões e Viana do Castelo S.A. (n.d.-d). *Porto de Viana do Castelo*. Retrieved 28 March 2025, from <https://viana.apdl.pt/o-porto/>
- Administração dos Portos do Douro Leixões e Viana do Castelo S.A. (2021). *Relatório de Sustentabilidade 2021*. https://www.apdl.pt/media/jlednnq1/af_apdl-relatorio-de-sustentabilidade_a4_pt_digital.pdf
- Administração dos Portos do Douro Leixões e Viana do Castelo S.A. (2025). *Áreas de Negócio*. <https://www.apdl.pt/>
- Administração Porto de Aveiro S.A. (n.d.-a). *Estatísticas*. Retrieved 1 April 2025, from <https://app.powerbi.com/view?r=eyJrIjoiYmQ1NjA0MWYtNGE0Ny00YjJhLWE0NGMtNTE2ZjVjMzlkOWZlIiwidCI6IjY4MmM5MzA5LWQwZDctNDZjNi1iMmZlLTM4OGZlMDMzYThtMSIsImMiOjh9>
- Administração Porto de Aveiro S.A. (n.d.-b). *Homepage*. Retrieved 28 March 2025, from <https://portodeaveiro.pt/home/pt/>
- Administração Porto de Aveiro S.A. (2023). *Relatório de Sustentabilidade 2023*. <https://portodeaveiro.pt/uploads/2025-01-16-09-43-55-Relatorio-Sustentabilidade-APA2023vfinal.pdf>
- Administração Porto de Aveiro S.A., & Administração do Porto da Figueira da Foz S.A. (2024). *Plano de Prevenção de Riscos de Corrupção e Infrações Conexas*. <https://portodeaveiro.pt/uploads/2024-12-27-17-19-06-20241226-PPR--Verso-Final-Website.pdf>
- Ambientes Inovadores de Aprendizagem. (2020). *Aula 3 - Geografia A* (p. 2). https://aia.madeira.gov.pt/images/files/telensino/GEOGRAFIA_11_Aula3_28abril.pdf
- Associação dos Portos de Portugal. (n.d.-a). *Porto de Aveiro*. Retrieved 24 April 2025, from <https://www.portosdeportugal.pt/app/portos/aveiro.php>

- Associação dos Portos de Portugal. (n.d.-b). *Porto de Leixões*. Retrieved 28 March 2025, from <https://www.portosdeportugal.pt/app/portos/leixoes.php>
- Associação dos Portos de Portugal. (n.d.-c). *Porto de Lisboa*. Retrieved 24 April 2025, from <https://www.portosdeportugal.pt/app/portos/lisboa.php>
- Associação dos Portos de Portugal. (n.d.-d). *Porto de Setúbal*. Retrieved 24 April 2025, from <https://www.portosdeportugal.pt/app/portos/setubal.php>
- Associação dos Portos de Portugal. (n.d.-e). *Porto de Sines*. Retrieved 24 April 2025, from <https://www.portosdeportugal.pt/app/portos/sines.php>
- Associação dos Portos de Portugal. (n.d.-f). *Portos da Madeira*. Retrieved 25 April 2025, from <https://www.portosdeportugal.pt/app/portos/madeira.php>
- Associação dos Portos de Portugal. (n.d.-g). *Portos dos Açores*. Retrieved 26 April 2025, from <https://www.portosdeportugal.pt/app/portos/acoes.php>
- Associação dos Portos de Portugal. (2014, July 30). *Portos de Portugal. Viagem ao centro do mundo*. YouTube. <https://www.youtube.com/watch?v=29bwGiehKQI>
- Associação Portuguesa dos Recursos Hídricos. (n.d.). *Água do mar*. Retrieved 3 May 2025, from <https://aprh.pt/pt/publicacoes/glossario/a/agua-do-mar/>
- Begon, M., Townsend, C. R., & Harper, J. L. (2006). *Ecology: From Individuals to Ecosystems* (4th ed.). Blackwell Publishing.
- Browder, G., Ozment, S., Bescos, I. R., Gartner, T., & Lange, G.-M. (2019). *Integrating Green and Gray: Creating Next Generation Infrastructure*. <https://hdl.handle.net/10986/31430>
- Cabral, I., Keim, J., Engelmann, R., Kraemer, R., Siebert, J., & Bonn, A. (2017). Ecosystem services of allotment and community gardens: A Leipzig, Germany case study. *Urban Forestry & Urban Greening*, 23, 44–53. <https://doi.org/10.1016/J.UFUG.2017.02.008>
- Coastal Engineering Research Center (US). (1984). The coastal area. In *Shore protection manual* (Vol. 1, pp. 1–2). Department of the Army, Waterways Experiment Station, Corps of Engineers.
- Cohen-Shacham, E., Maginnis, S., Smith, M., Andrade, A., Jones, M., Dudley, N., Martinez, C., & Kumar, C. (2016). Nature-based solutions to address global societal challenges. In E. Cohen-Shacham, G. Walters, C. Janzen, & S. Maginnis (Eds.), *Nature-based solutions to address global societal challenges* (pp. 5–11). IUCN International Union for Conservation of Nature. <https://doi.org/10.2305/iucn.ch.2016.13.en>
- Council Directive 92/43/EEC on the Conservation of Natural Habitats and of Wild Fauna and Flora, Pub. L. No. 43, L 206 7 (1992). <http://data.europa.eu/eli/dir/1992/43/2013-07-01>
- Day, J. W., Christian, R. R., Boesch, D. M., Yáñez-Arancibia, A., Morris, J., Twilley, R. R., Naylor, L., Schaffner, L., & Stevenson, C. (2008). Consequences of Climate Change on the Ecogeomorphology of Coastal Wetlands. *Estuaries and Coasts*, 31(3), 477–491. <https://doi.org/10.1007/s12237-008-9047-6>
- Decreto Legislativo Regional n.º 24/2011/A, Pub. L. No. 24/2011/A, Diário da República, 1.ª série — N.º 160 4303 (2011). <https://files.dre.pt/1s/2011/08/16000/0429404316.pdf>
- Decreto Legislativo Regional n.º 25/2003/M, Pub. L. No. 25/2003/M, Diário da República, Série I-A, n.º 194 5501 (2003). <https://diariodarepublica.pt/dr/detalhe/decreto-legislativo-regional/25-2003-655964>
- Decreto-Lei n.º 44/2014 de 20 de março, Pub. L. No. 44, Diário da República 2105 (2014). <https://diariodarepublica.pt/dr/detalhe/decreto-lei/44-2014-571959>
- Direção Regional do Ordenamento do Território e dos Recursos Hídricos. (n.d.). *Riscos Ambientais - Galgamentos e Inundações Costeiras*. Retrieved 2 May 2025, from

- <https://rea.azores.gov.pt/reaa/100/riscos-ambientais/1499/galgamentos-e-inundacoes-costeiras>
- Directive 2009/147/EC on the Conservation of Wild Birds, Pub. L. No. 147, 7 (2009). <https://eur-lex.europa.eu/eli/dir/2009/147/2019-06-26>
- Divisão de Análise de Riscos e Ordenamento do Território. (2023). *Avaliação de risco da Região Autónoma da Madeira*. https://www.procivmadeira.pt/images/prevencao_preparacao/Corpo%20ARRAM_2023.pdf
- EcoShape. (2024a). *Bird Island construction - expansion of Port 2000 Le Havre - EcoShape*. <https://www.ecoshape.org/en/cases/bird-island-construction-expansion-of-port-2000-le-havre-fr/>
- EcoShape. (2024b). *Cases archive*. <https://www.ecoshape.org/en/cases/>
- EcoShape. (2024c). *Eco-concrete breakwater structures - IJmuiden - EcoShape*. <https://www.ecoshape.org/en/cases/eco-concrete-breakwater-structures-ijmuiden-nl/>
- EcoShape. (2024d). *Habitat opportunities in harbours - Port of Rotterdam - EcoShape*. <https://www.ecoshape.org/en/cases/habitat-opportunities-in-harbours-port-of-rotterdam-nl/>
- EcoShape. (2024e). *Rich Revetment for coastal protection - Eastern Scheldt - EcoShape*. <https://www.ecoshape.org/en/cases/rich-revetment-for-coastal-protection-eastern-scheldt-nl/>
- EURAXESS. (n.d.). *Technology Readiness Level (TRL)*. EURAXESS. Retrieved 20 January 2025, from <https://euraxess.ec.europa.eu/career-development/researchers/manual-scientific-entrepreneurship/major-steps/trl>
- European Commission. (2015). *Towards an EU research and innovation policy agenda for nature-based solutions & re-naturing cities : final report of the Horizon 2020 expert group on 'Nature-based solutions and re-naturing cities' : (full version)*. Publications Office of the European Union. <https://op.europa.eu/s/zWK4>
- EurOtop. (2018). *Manual on wave overtopping of sea defences and related structures: An overtopping manual largely based on European research, but for worldwide application*. (J. W. Van der Meer, N. W. H. Allsop, T. Bruce, J. De Rouck, A. Kortenhaus, T. Pullen, H. Schüttrumpf, P. Troch, & B. Zanuttigh, Eds.; 2nd ed.). www.overtopping-manual.com
- Gerling, C., Ranieri, C., Fernandes, L., Golveia, M. T. de J., & Rocha, V. (2016). *MANUAL DE ECOSISTEMAS MARINHOS E COSTEIROS PARA EDUCADORES* (P. Pechmann, Ed.).
- Global Biodiversity Information Facility. (n.d.). *Free and open access to biodiversity data*. Retrieved 28 April 2025, from <https://www.gbif.org/>
- Google LLC. (2025). *Google Earth*. <https://earth.google.com/web>
- Instituto da Conservação da Natureza e das Florestas IP. (n.d.). *Map viewer*. Retrieved 1 May 2025, from <https://sig.icnf.pt/portal/apps/mapviewer/index.html?layers=a158877a57eb4f5fbad767d36e261fab>
- Instituto das Florestas e Conservação da Natureza IP-RAM. (2024, April 22). *Áreas Classificadas da RAM*. <https://ifcn.madeira.gov.pt/pt/areas-protegidas/areas-classificadas-da-ram.html>
- IPCC. (1992). *Policymaker Summary of Working Group I (Scientific Assessment of Climate Change)*.

- Mangor, K., Drønen, N. K., Kaergaard, K. H., & Kristensen, S. E. (2017). *SHORELINE MANAGEMENT GUIDELINES*. www.dhigroup.com
- Manning, C. G. (2023, September 27). *Technology Readiness Levels*. NASA. <https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/>
- Morris, R. L., Chapman, M. G., Firth, L. B., & Coleman, R. A. (2017). Increasing habitat complexity on seawalls: Investigating large- and small-scale effects on fish assemblages. *Ecology and Evolution*, 7(22), 9567–9579. <https://doi.org/https://doi.org/10.1002/ece3.3475>
- Naylor, L., Kippen, H., Coombes, M., Horton, B., MacArthur, M., & Jackson, N. (2017). *Greening the Grey: a framework for integrated green grey infrastructure (IGGI)*. <http://eprints.gla.ac.uk/150672/>
- Ocean Biodiversity Information System. (n.d.). *Homepage*. Retrieved 28 April 2025, from <https://obis.org/>
- Pamukcu-Albers, P., Ugolini, F., La Rosa, D., Grădinaru, S. R., Azevedo, J. C., & Wu, J. (2021). Building green infrastructure to enhance urban resilience to climate change and pandemics. In *Landscape Ecology* (Vol. 36, Issue 3, pp. 665–673). Springer Science and Business Media B.V. <https://doi.org/10.1007/s10980-021-01212-y>
- Perricone, V., Contestabile, P., Mele, A., Hassanpour, N., Vicinanza, D., & Buono, M. (2024). Bioinspired Coastal Barriers: A Preliminary Laboratory Study on the Hydraulic Performances of Shapes Inspired by Marine Organisms. *Sustainability (Switzerland)*, 16(11). <https://doi.org/10.3390/su16114839>
- Pilkington, C. (2007, January 12). *Coastal Wiki*. https://www.coastalwiki.org/wiki/File:Classification_coast.jpg
- Portal do Governo dos Açores. (n.d.). *Distribuição das áreas Rede Natura 2000*. Retrieved 1 May 2025, from <https://www.azores.gov.pt/Gra/srrn-natureza/conteudos/livres/Distribui%C3%A7%C3%A3o+%C3%A1reas+Rede+Natura+2000.htm>
- Portela, L. I. (2023). *Evolução da cota de dragagem dos acessos marítimos aos portos de Portugal continental*.
- Portos dos Açores S.A. (n.d.-a). *Áreas de Jurisdição*. Retrieved 28 March 2025, from <https://portosdosacores.pt/autoridade-portuaria/areas-de-jurisdicao/>
- Portos dos Açores S.A. (n.d.-b). *Porto da Calheta*. Retrieved 26 April 2025, from <https://portosdosacores.pt/portos/porto-da-calheta/>
- Portos dos Açores S.A. (n.d.-c). *Porto da Horta*. Retrieved 26 April 2025, from <https://portosdosacores.pt/portos/porto-da-horta/>
- Portos dos Açores S.A. (n.d.-d). *Porto da Madalena*. Retrieved 26 April 2025, from <https://portosdosacores.pt/portos/porto-da-madalena/>
- Portos dos Açores S.A. (n.d.-e). *Porto da Praia da Graciosa*. Retrieved 26 April 2025, from <https://portosdosacores.pt/portos/porto-da-praia-da-graciosa/>
- Portos dos Açores S.A. (n.d.-f). *Porto da Praia da Vitória*. Retrieved 26 April 2025, from <https://portosdosacores.pt/portos/porto-da-praia-da-vitoria/>
- Portos dos Açores S.A. (n.d.-g). *Porto das Lajes das Flores*. Retrieved 26 April 2025, from <https://portosdosacores.pt/portos/porto-das-lajes-das-flores/>
- Portos dos Açores S.A. (n.d.-h). *Porto das Lajes do Pico*. Retrieved 26 April 2025, from <https://portosdosacores.pt/portos/porto-das-lajes-do-pico/>

- Portos dos Açores S.A. (n.d.-i). *Porto de Angra do Heroísmo*. Retrieved 26 April 2025, from <https://portosdosacores.pt/portos/porto-angra-do-heroismo/>
- Portos dos Açores S.A. (n.d.-j). *Porto de Ponta Delgada*. Retrieved 26 April 2025, from <https://portosdosacores.pt/portos/porto-de-ponta-delgada/>
- Portos dos Açores S.A. (n.d.-k). *Porto de Santa Cruz das Flores*. Retrieved 26 April 2025, from <https://portosdosacores.pt/portos/porto-sta-cruz-das-flores/>
- Portos dos Açores S.A. (n.d.-l). *Porto de São Roque do Pico*. Retrieved 26 April 2025, from <https://portosdosacores.pt/portos/porto-de-sao-roque/#>
- Portos dos Açores S.A. (n.d.-m). *Porto de Velas*. Retrieved 26 April 2025, from <https://portosdosacores.pt/portos/porto-das-velas/>
- Portos dos Açores S.A. (n.d.-n). *Porto de Vila do Porto*. Retrieved 26 April 2025, from <https://portosdosacores.pt/portos/porto-de-vila-do-porto/>
- Portos dos Açores S.A. (n.d.-o). *Porto do Corvo*. Retrieved 26 April 2025, from <https://portosdosacores.pt/portos/porto-do-corvo/>
- Portos dos Açores S.A. (n.d.). *Relatórios e Contas*. Retrieved 1 April 2025, from <https://portosdosacores.pt/autoridade-portuaria/relatorios-e-contas/>
- Prudencio, L., & Null, S. E. (2018). Stormwater management and ecosystem services: a review. *Environmental Research Letters*, 13(3), 33002. <https://doi.org/10.1088/1748-9326/aaa81a>
- Radfar, S., Mahmoudi, S., Moftakhari, H., Meckley, T., Bilskie, M. V., Collini, R., Alizad, K., Cherry, J. A., & Moradkhani, H. (2024). Nature-based solutions as buffers against coastal compound flooding: Exploring potential framework for process-based modeling of hazard mitigation. *Science of The Total Environment*, 938, 173529. <https://doi.org/10.1016/J.SCITOTENV.2024.173529>
- Ran, J., & Tang, M. (2018). Passive cooling of the green roofs combined with night-time ventilation and walls insulation in hot and humid regions. *Sustainable Cities and Society*, 38, 466–475. <https://doi.org/10.1016/J.SCS.2018.01.027>
- Salauddin, M., O’Sullivan, J. J., Abolfathi, S., & Pearson, J. M. (2021). Eco-Engineering of Seawalls—An Opportunity for Enhanced Climate Resilience From Increased Topographic Complexity. *Frontiers in Marine Science*, 8. <https://doi.org/10.3389/fmars.2021.674630>
- Sistema Nacional de Informação de Ambiente. (n.d.). *Visualizador SNIAmb*. Retrieved 3 May 2025, from <https://sniamb.apambiente.pt/content/geo-visualizador?language=pt-pt>
- Strain, E. M. A., Olabarria, C., Mayer-Pinto, M., Cumbo, V., Morris, R. L., Bugnot, A. B., Dafforn, K. A., Heery, E., Firth, L. B., Brooks, P. R., & Bishop, M. J. (2018). Eco-engineering urban infrastructure for marine and coastal biodiversity: Which interventions have the greatest ecological benefit? *Journal of Applied Ecology*, 55(1), 426–441. <https://doi.org/https://doi.org/10.1111/1365-2664.12961>
- Sutton, T., & Dassau, O. (2002). *QGIS (3.40.4 'Bratislava')*. <https://www.qgis.org/>
- UN Climate Change Global Innovation Hub (UGIH). (2022). *COP26 EVENT REPORT*.
- United Nations. (2015, September 25). *Transforming our world: the 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs*. <https://sdgs.un.org/2030agenda>
- USACE. (2003). Coastal Engineering Manual. In *Engineer Manuals 1110-2-1100* (pp. A1–A92). https://www.publications.usace.army.mil/Portals/76/Publications/EngineerManuals/EM_1110-2-1100_App_A.pdf

- VisitAlgarve. (n.d.). *Parque Natural da Ria Formosa*. Retrieved 25 April 2025, from <https://visitalgarve.pt/equipamento/8420/parque-natural-da-ria-formosa>
- Xu, K., Zhuang, Y., Bin, L., Wang, C., & Tian, F. (2023). Impact assessment of climate change on compound flooding in a coastal city. *Journal of Hydrology*, *617*, 129166. <https://doi.org/10.1016/J.JHYDROL.2023.129166>

APPENDIX A – SELECTION OF ARTICLES BY THE SCOPUS DATABASE

Table 18 – Selected articles from Scopus.

ID	Authors	Title
1	Anderson & Renaud (2021)	A review of public acceptance of nature-based solutions: The ‘why’, ‘when’, and ‘how’ of success for disaster risk reduction measures
2	Zell et al. (2019)	Adapt and thrive: Strategies for life along a dynamic and changing coastline
3	Park et al. (2023)	Adaptation strategies for future coastal flooding: Performance evaluation of green and grey infrastructure in South Korea
4	Bulleri et al. (2022)	Adding functions to marine infrastructure: Pollutant accumulation, physiological and microbiome changes in sponges attached to floating pontoons inside marinas
5	Delgado-Lemus & Moreno-Calles (2022)	Agroforestry Contributions to Urban River Rehabilitation
6	Dafforn et al. (2015)	Application of management tools to integrate ecological principles with the design of marine infrastructure
7	Zhu et al. (2020)	Aquaculture farms as nature-based coastal protection: Random wave attenuation by suspended and submerged canopies
8	Loke et al. (2019)	Area-independent effects of water-retaining features on intertidal biodiversity on eco-engineered seawalls in the tropics
9	Bone, Hall, Stafford, Mir, et al. (2024)	Artificial rockpools create habitat refugia on seawalls at high tide
10	Farrugia Drakard et al. (2023)	Artificial rockpools: Seaweed colonisation and productivity vary between sites but are consistent across environmental contexts
11	Mamo et al. (2022)	Beyond coastal protection: A robust approach to enhance environmental and social outcomes of coastal adaptation
12	Perricone et al. (2024)	Bioinspired Coastal Barriers: A Preliminary Laboratory Study on the Hydraulic Performances of Shapes Inspired by Marine Organisms

Table 18 – Selected articles from Scopus.

ID	Authors	Title
13	Strain et al. (2019)	Building blue infrastructure: Assessing the key environmental issues and priority areas for ecological engineering initiatives in Australia's metropolitan embayments
14	Van Eekelen et al. (2019)	Building with nature: More than 10 years of pre-competitive knowledge development
15	Morris et al. (2018)	Can transplanting enhance mobile marine invertebrates in ecologically engineered rock pools?
16	Mullarney & Fisher (2022)	Challenges for the use of Mangrove Forests as Nature-Based Solutions in Aotearoa New Zealand: from the Physical to the Social-Environmental
17	Schipper et al. (2021)	Characterization of sdfs towards coastal management: Sustainability performance and cross-linking consequences
18	Sedano et al. (2021)	Coastal armouring affects intertidal biodiversity across the Alboran Sea (Western Mediterranean Sea)
19	Foti et al. (2020)	Coastal defence techniques and climate change: a review
20	Masria et al. (2015)	Coastal protection measures, case study (Mediterranean zone, Egypt)
21	Chong et al. (2021)	Coastal protection using building with nature concept: A case study from Chongming Dongtan Shoal, China
22	Fairchild et al. (2021)	Coastal wetlands mitigate storm flooding and associated costs in estuaries
23	Smith et al. (2020)	Coming to terms with living shorelines: A scoping review of novel restoration strategies for shoreline protection
24	Komyakova et al. (2022)	Conceptualisation of multiple impacts interacting in the marine environment using marine infrastructure as an example
25	Castagno et al. (2021)	Conservation practice insights from a comparative case study of two shoreline stabilization projects in Boston Harbor, MA
26	Charuka et al. (2023)	Contemporary Global Coastal Management Strategies and Coastal Infrastructure and Their Application in Ghana: A Systematic Literature Review

Table 18 – Selected articles from Scopus.

ID	Authors	Title
27	Howie & Bishop (2021)	Contemporary Oyster Reef Restoration: Responding to a Changing World
28	Gurgel Vasconcelos et al. (2024)	Contrasting short-term shoreline behaviour after the construction of sinusoidal groynes in NE Brazil
29	Saengsupavanich et al. (2023)	Current challenges in coastal erosion management for southern Asian regions: examples from Thailand, Malaysia, and Sri Lanka
30	Morris et al. (2024)	Current extent and future opportunities for living shorelines in Australia
31	O’Shaughnessy et al. (2020)	Design catalogue for eco-engineering of coastal artificial structures: a multifunctional approach for stakeholders and end-users
32	Bredes et al. (2023)	Developing guidance for the application of Natural and Nature Based Features (NNBF) on developed shores: A case study from New Jersey, USA
33	Dafforn (2017)	Eco-engineering and management strategies for marine infrastructure to reduce establishment and dispersal of non-indigenous species
34	Hadary et al. (2022)	Eco-engineering for Climate Change—Floating to the Future
35	Morris et al. (2016)	Eco-engineering in urbanised coastal systems: Consideration of social values
36	Ushiyama et al. (2019)	Eco-engineering increases habitat availability and utilisation of seawalls by fish
37	Strain, Heath, et al. (2018)	Eco-engineering of modified shorelines recovers wrack subsidies
38	Salauddin et al. (2021)	Eco-Engineering of Seawalls—An Opportunity for Enhanced Climate Resilience From Increased Topographic Complexity
39	Toft et al. (2021)	Effectiveness of living shorelines in the Salish Sea
40	Orchard & Schiel (2021)	Enabling nature-based solutions for climate change on a peri-urban sandspit in Christchurch, New Zealand
41	Pioch et al. (2018)	Enhancing eco-engineering of coastal infrastructure with eco-design: Moving from mitigation to integration

Table 18 – Selected articles from Scopus.

ID	Authors	Title
42	Bone, Stafford, Hall, Boyd, et al. (2022)	Estuarine Infauna Within Incidentally Retained Sediment in Artificial Rockpools
43	Heery et al. (2020)	Evaluating seaweed farming as an eco-engineering strategy for 'blue' shoreline infrastructure
44	Jacob et al. (2023)	Evaluation of seagrass as a nature-based solution for coastal protection in the German Wadden Sea
45	Paxton et al. (2024)	Evidence on the ecological and physical effects of built structures in shallow, tropical coral reefs: a systematic map
46	Almström et al. (2022)	Experiences of nature-based solutions for mitigating ship-induced erosion in confined coastal waters
47	Schaefer, Sedano, et al. (2023)	Facilitation of non-indigenous ascidian by marine eco-engineering interventions at an urban site
48	Vozzo et al. (2024)	From experiment to intervention: A case study of scaling up marine eco-engineering from research to application
49	Sedano et al. (2020)	From sessile to vagile: Understanding the importance of epifauna to assess the environmental impacts of coastal defence structures
50	Lin et al. (2021)	Geomorphology and sediment dynamics of the Liyashan oyster reefs, Jiangsu Coast, China
51	Atchison (2019)	Green and Blue Infrastructure in Darwin; Carbon Economies and the Social and Cultural Dimensions of Valuing Urban Mangroves in Australia
52	Chee et al. (2021)	Habitat Complexity Affects the Structure but Not the Diversity of Sessile Communities on Tropical Coastal Infrastructure
53	Castagno et al. (2022)	How Much Marsh Restoration Is Enough to Deliver Wave Attenuation Coastal Protection Benefits?
54	Smith et al. (2017)	Hurricane damage along natural and hardened estuarine shorelines: Using homeowner experiences to promote nature-based coastal protection
55	Almaghraby et al. (2022)	Hydrodynamic assessment of artificial shell blocks for coastal protection
56	Chen et al. (2024)	Hydrodynamic modeling study of nature-based hybrid coastal defense strategy applied in salt marsh restoration

Table 18 – Selected articles from Scopus.

ID	Authors	Title
57	Tanaya et al. (2021)	Improvement of the coral growth and cost-effectiveness of hybrid infrastructure by an innovative breakwater design in Naha Port, Okinawa, Japan
58	Bone, Hall, Stafford, & Herbert (2024)	Inconsistent bioreceptivity of three mortar mixes in subtidal sites
59	Morris et al. (2017b)	Increasing habitat complexity on seawalls: Investigating large- and small-scale effects on fish assemblages
60	Schaefer et al. (2024)	Influence of habitat features on the colonisation of native and non-indigenous species
61	Palinkas et al. (2022)	Innovations in Coastline Management With Natural and Nature-Based Features (NNBF): Lessons Learned From Three Case Studies
62	Sutton-Grier et al. (2018)	Investing in natural and nature-based infrastructure: Building better along our coasts
63	Li et al. (2022)	Laboratory investigation on morphology response of submerged artificial sandbar and its impact on beach evolution under storm wave condition
64	Chee et al. (2017)	Land reclamation and artificial islands: Walking the tightrope between development and conservation
65	Kuwaie & Crooks (2021)	Linking climate change mitigation and adaptation through coastal green–gray infrastructure: a perspective
66	Hsiung et al. (2020)	Little evidence that lowering the pH of concrete supports greater biodiversity on tropical and temperate seawalls
67	Lawson et al. (2023)	Littoral Drift Impoundment at a Sandbar Breakwater: Two Case Studies along the Bight of Benin Coast (Gulf of Guinea, West Africa)
68	Vozzo et al. (2021)	Making seawalls multifunctional: The positive effects of seeded bivalves and habitat structure on species diversity and filtration rates
69	Pelckmans et al. (2023)	Mangrove ecosystem properties regulate high water levels in a river delta
70	Ganju (2019)	Marshes Are the New Beaches: Integrating Sediment Transport into Restoration Planning

Table 18 – Selected articles from Scopus.

ID	Authors	Title
71	O'Shaughnessy et al. (2023)	Metrics matter: Multiple diversity metrics at different spatial scales are needed to understand species diversity in urban environments
72	Siemes et al. (2023)	Morphological Response of a Highly Engineered Estuary to Altering Channel Depth and Restoring Wetlands
73	Wu & Hong (2023)	Nature-based solutions as sustainability alternatives for shipping: A systematic review
74	Mayer-Pinto et al. (2023)	Physical and biogenic complexity mediates ecosystem functions in urban sessile marine communities
75	Di Risio & Iagnemma (2024)	Physics and Coastal Planning Strategies: Two Sides of the Same Coin
76	Thompson et al. (2023)	Population structure and reproductive states of the dogwhelk <i>Nucella lapillus</i> differ between artificial structures and natural rocky shores
77	Rifai et al. (2023)	Potential of seagrass habitat restorations as nature-based solutions: Practical and scientific implications in Indonesia
78	Niazi et al. (2021)	Probabilistic characterization of the vegetated hydrodynamic system using non-parametric bayesian networks
79	Selfati et al. (2018)	Promoting restoration of fish communities using artificial habitats in coastal marinas
80	Rubinato et al. (2020)	Protecting coastlines from flooding in a changing climate: A preliminary experimental study to investigate a sustainable approach
81	Bradford et al. (2020)	Provision of refugia and seeding with native bivalves can enhance biodiversity on vertical seawalls
82	Brooks et al. (2021)	Resistance of salt marsh substrates to near-instantaneous hydrodynamic forcing
83	W. Xu et al. (2024)	Review of wave attenuation by artificial oyster reefs based on experimental analysis
84	Eichmanns et al. (2021)	Sand trapping fences as a nature-based solution for coastal protection: An international review with a focus on installations in Germany

Table 18 – Selected articles from Scopus.

ID	Authors	Title
85	van der Spek et al. (2020)	Sandbar breakwater: An innovative nature-based port solution
86	Chi et al. (2023)	Sandy shoreline recovery ability after breakwater removal
87	Bauer et al. (2024)	Scale-dependent topographic complexity underpins abundance and spatial distribution of ecosystem engineers on natural and artificial structures
88	Vandenhove et al. (2024)	Secular shoreline response to large-scale estuarine shoal migration and welding
89	Tagliabue et al. (2023)	Sediment and bottom water eDNA metabarcoding to support coastal management
90	Rivosecchi & Singh (2023)	Small Island City Flood Risk Assessment: The Case of Kingston, Jamaica
91	O’Shaughnessy et al. (2021)	Spatially Variable Effects of Artificially-Created Physical Complexity on Subtidal Benthos
92	Taneja et al. (2020)	Sustainable port development: A case study of port of Kuala Tanjung, Indonesia
93	Zheng et al. (2023)	Synergy between coastal ecology and disaster mitigation in China: Policies, practices, and prospects
94	Clifton et al. (2022)	The ecological benefits of adding topographic complexity to seawalls vary across estuarine gradients
95	Gauff et al. (2023)	The elephant in the room: Introduced species also profit from refuge creation by artificial fish habitats
96	Farrugia Drakard et al. (2024)	The influence of environmental context on community composition in artificial rockpools associated with seawalls
97	Bone, Stafford, Hall, & Herbert (2022)	The intrinsic primary bioreceptivity of concrete in the coastal environment – A review
98	Waltham & Sheaves (2020)	Thermal exposure risks to mobile tropical marine snails: Are eco-engineered rock pools on seawalls scale-specific enough for comprehensive biodiversity outcomes?
99	Schaefer, Mayer-Pinto, et al. (2023)	Understanding the role of microhabitats in intertidal rock pools to guide future eco-engineering designs

Table 18 – Selected articles from Scopus.

ID	Authors	Title
100	Hitzegrad et al. (2024)	Understanding the Role of Sharp Edges in the Propagation of Surface Gravity Waves
101	Mamo et al. (2021)	Upgrades of coastal protective infrastructure affect benthic communities
102	Johnston et al. (2023)	Using dune restoration on an urban beach as a coastal resilience approach
103	Boechat Albernaz et al. (2023)	Vegetation Reconfigures Barrier Coasts and Affects Tidal Basin Infilling Under Sea Level Rise
104	Safak et al. (2020)	Wave transmission through living shoreline breakwalls
105	Aguilera et al. (2022)	Weak effects of age but important role of microhabitats in community differences between breakwaters and natural rocky shores across a latitudinal gradient
106	Paxton et al. (2023)	What evidence exists on the performance of nature-based solutions interventions for coastal protection in biogenic, shallow ecosystems? A systematic map protocol
107	Song et al. (2018)	Simulation modeling for a resilience improvement plan for natural disasters in a coastal area

Table 19 – Article selection table.

ID	Title pre-selection	Selection by abstracts			Decision
		Question 1	Question 2	Question 3	
1	Possibly relevant	Yes	Partially	Partially	-
2	Possibly relevant	Yes	Partially	Partially	Include*
3	Relevant	Yes	No	Partially	-
6	Relevant	Yes	Partially	Partially	-
7	Relevant	Yes	Partially	No	-
8	Possibly relevant	Yes	Partially	No	-
12	Possibly relevant	Yes	Partially	Partially	Include
13	Relevant	Partially	No	Partially	-
14	Possibly relevant	Yes	Partially	No	-
15	Possibly relevant	Yes	Partially	No	-
16	Possibly relevant	Yes	No	Yes	-
17	Relevant	Partially	Partially	Yes	-
19	Relevant	Partially	Partially	Partially	-
20	Possibly relevant	Yes	Partially	Yes	-
21	Relevant	Yes	Yes	No	Include
31	Relevant	Yes	Partially	Partially	-
32	Relevant	Yes	Partially	Partially	-
34	Possibly relevant	Yes	Partially	Partially	Include*
35	Relevant	Partially	Yes	Partially	Include
36	Relevant	Partially	Partially	No	-
37	Possibly relevant	Yes	Partially	No	-
38	Relevant	Yes	Partially	No	Include
40	Possibly relevant	Partially	No	No	-
41	Relevant	No	Partially	Partially	-
43	Relevant	Yes	Partially	No	-
44	Relevant	Yes	Partially	Yes	Include
45	Possibly relevant	Partially	Partially	No	-
46	Relevant	Yes	Partially	Partially	Include
48	Relevant	Yes	Partially	Partially	Include
49	Possibly relevant	Partially	Partially	No	-
51	Possibly relevant	Partially	No	Yes	-
54	Possibly relevant	Partially	No	No	-
55	Possibly relevant	Partially	No	No	-
56	Possibly relevant	Yes	Partially	Partially	-
61	Possibly relevant	Yes	Partially	Yes	Include
62	Relevant	Partially	Yes	Partially	-
65	Relevant	Yes	Partially	Yes	Include
67	Possibly relevant	Yes	Partially	Partially	-
73	Relevant	Partially	Partially	No	-

Table 19 – Article selection table.

ID	Title pre-selection	Selection by abstracts			Decision
		Question 1	Question 2	Question 3	
77	Possibly relevant	Yes	Partially	Yes	-
79	Possibly relevant	Partially	Yes	Partially	-
80	Relevant	Partially	Partially	Partially	-
81	Possibly relevant	Partially	Partially	No	-
84	Relevant	Yes	No	Partially	-
85	Relevant	Yes	Partially	Partially	Include
92	Relevant	Yes	Yes	Partially	Include
93	Possibly relevant	Yes	Partially	Yes	Include
94	Possibly relevant	Yes	Partially	Partially	-
96	Possibly relevant	Yes	Partially	No	Include
98	Relevant	Yes	Partially	No	-
102	Possibly relevant	Yes	Partially	No	-
103	Possibly relevant	Partially	Partially	No	-
105	Possibly relevant	Yes	Partially	No	-
106	Relevant	Yes	Yes	No	-
107	Relevant	Yes	Partially	Partially	-

* The inability to download these files resulted in their exclusion from the reading stage of the study.

CONSULTED REFERENCES

- Aguilera, M. A., Bulleri, F., & Thiel, M. (2022). Weak effects of age but important role of microhabitats in community differences between breakwaters and natural rocky shores across a latitudinal gradient. *Global Ecology and Biogeography*, *31*(11), 2368–2380. <https://doi.org/10.1111/geb.13585>
- Almaghraby, M. M., Kansoh, R. M., & Iskander, M. M. (2022). Hydrodynamic assessment of artificial shell blocks for coastal protection. *Ocean Engineering*, *266*. <https://doi.org/10.1016/j.oceaneng.2022.112743>
- Almström, B., Danielsson, P., Göransson, G., Hallin, C., & Larson, M. (2022). Experiences of nature-based solutions for mitigating ship-induced erosion in confined coastal waters. *Ecological Engineering*, *180*. <https://doi.org/10.1016/j.ecoleng.2022.106662>
- Anderson, C. C., & Renaud, F. G. (2021). A review of public acceptance of nature-based solutions: The ‘why’, ‘when’, and ‘how’ of success for disaster risk reduction measures. *Ambio*, *50*(8), 1552–1573. <https://doi.org/10.1007/s13280-021-01502-4>
- Atchison, J. (2019). Green and Blue Infrastructure in Darwin; Carbon Economies and the Social and Cultural Dimensions of Valuing Urban Mangroves in Australia. *Urban Science*, *3*(3). <https://doi.org/10.3390/urbansci3030086>
- Bauer, F., Knights, A. M., Griffin, J. N., Hanley, M. E., Foggo, A., Brown, A., Jones, E., & Firth, L. B. (2024). Scale-dependent topographic complexity underpins abundance and spatial distribution of ecosystem engineers on natural and artificial structures. *Science of the Total Environment*, *938*. <https://doi.org/10.1016/j.scitotenv.2024.173519>
- Boechat Albernaz, M., Brückner, M. Z. M., van Maanen, B., van der Spek, A. J. F., & Kleinmans, M. G. (2023). Vegetation Reconfigures Barrier Coasts and Affects Tidal Basin Infilling Under Sea Level Rise. *Journal of Geophysical Research: Earth Surface*, *128*(4). <https://doi.org/10.1029/2022JF006703>
- Bone, J. R., Hall, A. E., Stafford, R., & Herbert, R. J. H. (2024). Inconsistent bioreceptivity of three mortar mixes in subtidal sites. *Ecological Engineering*, *204*. <https://doi.org/10.1016/j.ecoleng.2024.107265>
- Bone, J. R., Hall, A. E., Stafford, R., Mir, N. F., Benny, J., & Herbert, R. J. H. (2024). Artificial rockpools create habitat refugia on seawalls at high tide. *Ecological Engineering*, *206*. <https://doi.org/10.1016/j.ecoleng.2024.107318>
- Bone, J. R., Stafford, R., Hall, A. E., Boyd, I., George, N., & Herbert, R. J. H. (2022). Estuarine Infauna Within Incidentally Retained Sediment in Artificial Rockpools. *Frontiers in Marine Science*, *8*. <https://doi.org/10.3389/fmars.2021.780720>
- Bone, J. R., Stafford, R., Hall, A. E., & Herbert, R. J. H. (2022). The intrinsic primary bioreceptivity of concrete in the coastal environment – A review. *Developments in the Built Environment*, *10*. <https://doi.org/10.1016/j.dibe.2022.100078>
- Bradford, T. E., Astudillo, J. C., Lau, E. T. C., Perkins, M. J., Lo, C. C., Li, T. C. H., Lam, C. S., Ng, T. P. T., Strain, E. M. A., Steinberg, P. D., Steinberg, P. D., & Leung, K. M. Y. (2020). Provision of refugia and seeding with native bivalves can enhance biodiversity on vertical seawalls. *Marine Pollution Bulletin*, *160*. <https://doi.org/10.1016/j.marpolbul.2020.111578>
- Bredes, A., Miller, J. K., Kerr, L., Gannon, K., & Day, I. (2023). Developing guidance for the application of Natural and Nature Based Features (NNBF) on developed shores: A case study from New Jersey, USA. *Regional Studies in Marine Science*, *62*. <https://doi.org/10.1016/j.rsma.2023.102959>

- Brooks, H., Möller, I., Carr, S., Chirol, C., Christie, E., Evans, B., Spencer, K. L., Spencer, T., & Royse, K. (2021). Resistance of salt marsh substrates to near-instantaneous hydrodynamic forcing. *Earth Surface Processes and Landforms*, 46(1), 67–88. <https://doi.org/10.1002/esp.4912>
- Bulleri, F., Pretti, C., Bertolino, M., Magri, M., Pittaluga, G. B., Sicurelli, D., Tardelli, F., Manzini, C., Vannini, C., Verani, M., Zampieri, G., & De Marchi, L. (2022). Adding functions to marine infrastructure: Pollutant accumulation, physiological and microbiome changes in sponges attached to floating pontoons inside marinas. *Science of the Total Environment*, 848. <https://doi.org/10.1016/j.scitotenv.2022.157773>
- Castagno, K. A., Bowden, A. A., Roberts, E. J., Burns, S. E., Harlan, S. L., Senier, L., & Scyphers, S. B. (2021). Conservation practice insights from a comparative case study of two shoreline stabilization projects in Boston Harbor, MA. *Conservation Science and Practice*, 3(8). <https://doi.org/10.1111/csp2.465>
- Castagno, K. A., Ganju, N. K., Beck, M. W., Bowden, A. A., & Scyphers, S. B. (2022). How Much Marsh Restoration Is Enough to Deliver Wave Attenuation Coastal Protection Benefits? *Frontiers in Marine Science*, 8. <https://doi.org/10.3389/fmars.2021.756670>
- Charuka, B., Angnuureng, D. B., & Agblorti, S. K. M. (2023). Contemporary Global Coastal Management Strategies and Coastal Infrastructure and Their Application in Ghana: A Systematic Literature Review. *Sustainability (Switzerland)*, 15(17). <https://doi.org/10.3390/su151712784>
- Chee, S. Y., Othman, A. G., Sim, Y. K., Mat Adam, A. N., & Firth, L. B. (2017). Land reclamation and artificial islands: Walking the tightrope between development and conservation. *Global Ecology and Conservation*, 12, 80–95. <https://doi.org/10.1016/j.gecco.2017.08.005>
- Chee, S. Y., Yee, J. C., Cheah, C. B., Evans, A. J., Firth, L. B., Hawkins, S. J., & Strain, E. M. A. (2021). Habitat Complexity Affects the Structure but Not the Diversity of Sessile Communities on Tropical Coastal Infrastructure. *Frontiers in Ecology and Evolution*, 9. <https://doi.org/10.3389/fevo.2021.673227>
- Chen, Z., Luo, F., Zhou, G., Zhu, F., Wu, H., Li, R., & Zhang, C. (2024). Hydrodynamic modeling study of nature-based hybrid coastal defense strategy applied in salt marsh restoration. *Estuarine, Coastal and Shelf Science*, 298. <https://doi.org/10.1016/j.ecss.2024.108666>
- Chi, S., Zhang, C., & Zheng, J. (2023). Sandy shoreline recovery ability after breakwater removal. *Frontiers in Marine Science*, 10. <https://doi.org/10.3389/fmars.2023.1191386>
- Chong, Z., Zhang, M., Wen, J., Wang, L., Mi, J., Bricker, J., Nmor, S., & Dai, Z. (2021). Coastal protection using building with nature concept: A case study from Chongming Dongtan Shoal, China. *Acta Oceanologica Sinica*, 40(10), 152–166. <https://doi.org/10.1007/s13131-021-1761-y>
- Clifton, G. A., Dafforn, K. A., & Bishop, M. J. (2022). The ecological benefits of adding topographic complexity to seawalls vary across estuarine gradients. *Ecological Engineering*, 182. <https://doi.org/10.1016/j.ecoleng.2022.106735>
- Dafforn, K. A. (2017). Eco-engineering and management strategies for marine infrastructure to reduce establishment and dispersal of non-indigenous species. *Management of Biological Invasions*, 8(2), 153–161. <https://doi.org/10.3391/mbi.2017.8.2.03>
- Dafforn, K. A., Mayer-Pinto, M., Morris, R. L., & Waltham, N. J. (2015). Application of management tools to integrate ecological principles with the design of marine

- infrastructure. *Journal of Environmental Management*, 158, 61–73. <https://doi.org/10.1016/j.jenvman.2015.05.001>
- Delgado-Lemus, T. S., & Moreno-Calles, A. I. (2022). Agroforestry Contributions to Urban River Rehabilitation. *Sustainability (Switzerland)*, 14(13). <https://doi.org/10.3390/su14137657>
- Di Risio, M., & Iagnemma, L. (2024). Physics and Coastal Planning Strategies: Two Sides of the Same Coin. In *Lecture Notes in Civil Engineering: Vol. 467 LNCE*. https://doi.org/10.1007/978-3-031-54118-6_41
- Eichmanns, C., Lechthaler, S., Zander, W., Vélez Pérez, M., Blum, H., Thorenz, F., & Schüttrumpf, H. (2021). Sand trapping fences as a nature-based solution for coastal protection: An international review with a focus on installations in Germany. *Environments - MDPI*, 8(12). <https://doi.org/10.3390/environments8120135>
- Fairchild, T. P., Bennett, W. G., Smith, G., Day, B., Skov, M. W., Möller, I., Beaumont, N., Karunarathna, H., & Griffin, J. N. (2021). Coastal wetlands mitigate storm flooding and associated costs in estuaries. *Environmental Research Letters*, 16(7). <https://doi.org/10.1088/1748-9326/ac0c45>
- Farrugia Drakard, V., Evans, A. J., Crowe, T. P., Moore, P. J., Coughlan, J., & Brooks, P. R. (2023). Artificial rockpools: Seaweed colonisation and productivity vary between sites but are consistent across environmental contexts. *Marine Environmental Research*, 188. <https://doi.org/10.1016/j.marenvres.2023.106022>
- Farrugia Drakard, V., Evans, A. J., Crowe, T. P., Moore, P. J., Coughlan, J., & Brooks, P. R. (2024). The influence of environmental context on community composition in artificial rockpools associated with seawalls. *Marine Environmental Research*, 193. <https://doi.org/10.1016/j.marenvres.2023.106308>
- Foti, E., Musumeci, R. E., & Stagnitti, M. (2020). Coastal defence techniques and climate change: a review. *Rendiconti Lincei*, 31(1), 123–138. <https://doi.org/10.1007/s12210-020-00877-y>
- Ganju, N. K. (2019). Marshes Are the New Beaches: Integrating Sediment Transport into Restoration Planning. *Estuaries and Coasts*, 42(4), 917–926. <https://doi.org/10.1007/s12237-019-00531-3>
- Gauff, R. P. M., Joubert, E., Curd, A., Carlier, A., Chavanon, F., Ravel, C., & Bouchoucha, M. (2023). The elephant in the room: Introduced species also profit from refuge creation by artificial fish habitats. *Marine Environmental Research*, 185. <https://doi.org/10.1016/j.marenvres.2022.105859>
- Gurgel Vasconcelos, Y., Pereira de Paula, D., Manuel Ferreira, Ó., & Leisner, M. M. (2024). Contrasting short-term shoreline behaviour after the construction of sinusoidal groynes in NE Brazil. *Journal of South American Earth Sciences*, 136. <https://doi.org/10.1016/j.jsames.2024.104832>
- Hadary, T., Martínez, J. G., Sella, I., & Perkol-Finkel, S. (2022). Eco-engineering for Climate Change—Floating to the Future. *Lecture Notes in Civil Engineering*, 158, 409–421. https://doi.org/10.1007/978-981-16-2256-4_25
- Heery, E. C., Lian, K. Y., Loke, L. H. L., Tan, H. T. W., & Todd, P. A. (2020). Evaluating seaweed farming as an eco-engineering strategy for ‘blue’ shoreline infrastructure. *Ecological Engineering*, 152. <https://doi.org/10.1016/j.ecoleng.2020.105857>

- Hitzegrad, J., Köster, S., Windt, C., & Goseberg, N. (2024). Understanding the Role of Sharp Edges in the Propagation of Surface Gravity Waves. *Journal of Geophysical Research: Oceans*, 129(2). <https://doi.org/10.1029/2023JC020336>
- Howie, A. H., & Bishop, M. J. (2021). Contemporary Oyster Reef Restoration: Responding to a Changing World. *Frontiers in Ecology and Evolution*, 9. <https://doi.org/10.3389/fevo.2021.689915>
- Hsiung, A. R., Tan, W. T., Loke, L. H. L., Firth, L. B., Heery, E. C., Ducker, J., Clark, V., Pek, Y. S., Birch, W. R., Ang, A. C. F., Chai, T. M. F., & Todd, P. A. (2020). Little evidence that lowering the pH of concrete supports greater biodiversity on tropical and temperate seawalls. *Marine Ecology Progress Series*, 656, 193–205. <https://doi.org/10.3354/meps13365>
- Jacob, B., Dolch, T., Wurpts, A., & Staneva, J. (2023). Evaluation of seagrass as a nature-based solution for coastal protection in the German Wadden Sea. *Ocean Dynamics*, 73(11), 699–727. <https://doi.org/10.1007/s10236-023-01577-5>
- Johnston, K. K., Dugan, J. E., Hubbard, D. M., Emery, K. A., & Grubbs, M. W. (2023). Using dune restoration on an urban beach as a coastal resilience approach. *Frontiers in Marine Science*, 10. <https://doi.org/10.3389/fmars.2023.1187488>
- Komyakova, V., Jaffrés, J. B. D., Strain, E. M. A., Cullen-Knox, C., Fudge, M., Langhamer, O., Bender, A., Yaakub, S. M., Wilson, E., Allan, B. J. M., Sella, I., & Haward, M. (2022). Conceptualisation of multiple impacts interacting in the marine environment using marine infrastructure as an example. *Science of the Total Environment*, 830. <https://doi.org/10.1016/j.scitotenv.2022.154748>
- Kuwae, T., & Crooks, S. (2021). Linking climate change mitigation and adaptation through coastal green–gray infrastructure: a perspective. *Coastal Engineering Journal*, 63(3), 188–199. <https://doi.org/10.1080/21664250.2021.1935581>
- Lawson, S. K., Udo, K., Tanaka, H., & Bamunawala, J. (2023). Littoral Drift Impoundment at a Sandbar Breakwater: Two Case Studies along the Bight of Benin Coast (Gulf of Guinea, West Africa). *Journal of Marine Science and Engineering*, 11(9). <https://doi.org/10.3390/jmse11091651>
- Li, Y., Zhang, C., Dai, W., Chen, D., Sui, T., Xie, M., & Chen, S. (2022). Laboratory investigation on morphology response of submerged artificial sandbar and its impact on beach evolution under storm wave condition. *Marine Geology*, 443. <https://doi.org/10.1016/j.margeo.2021.106668>
- Lin, H., Yu, Q., Du, Z., Fan, Y., Wang, Y., & Gao, S. (2021). Geomorphology and sediment dynamics of the Liyashan oyster reefs, Jiangsu Coast, China. *Acta Oceanologica Sinica*, 40(10), 118–128. <https://doi.org/10.1007/s13131-021-1866-3>
- Loke, L. H. L., Heery, E. C., Lai, S., Bouma, T. J., & Todd, P. A. (2019). Area-independent effects of water-retaining features on intertidal biodiversity on eco-engineered seawalls in the tropics. *Frontiers in Marine Science*, 6(JAN). <https://doi.org/10.3389/fmars.2019.00016>
- Mamo, L. T., Dwyer, P. G., Coleman, M. A., Dengate, C., & Kelaher, B. P. (2022). Beyond coastal protection: A robust approach to enhance environmental and social outcomes of coastal adaptation. *Ocean and Coastal Management*, 217. <https://doi.org/10.1016/j.ocecoaman.2021.106007>
- Mamo, L. T., Porter, A. G., Tagliafico, A., Coleman, M. A., Smith, S. D. A., Figueira, W. F., & Kelaher, B. P. (2021). Upgrades of coastal protective infrastructure affect benthic

- communities. *Journal of Applied Ecology*, 58(2), 295–303. <https://doi.org/10.1111/1365-2664.13736>
- Masria, A., Iskander, M., & Negm, A. (2015). Coastal protection measures, case study (Mediterranean zone, Egypt). *Journal of Coastal Conservation*, 19(3), 281–294. <https://doi.org/10.1007/s11852-015-0389-5>
- Mayer-Pinto, M., Bugnot, A. B., Johnston, E. L., Potts, J., Airoidi, L., Glasby, T. M., Strain, E. M. A., Scanes, P., Ushiyama, S., & Dafforn, K. A. (2023). Physical and biogenic complexity mediates ecosystem functions in urban sessile marine communities. *Journal of Applied Ecology*, 60(3), 480–493. <https://doi.org/10.1111/1365-2664.14347>
- Morris, R. L., Campbell-Hooper, E., Waters, E., Bishop, M. J., Lovelock, C. E., Lowe, R. J., Strain, E. M. A., Boon, P., Boxshall, A., Browne, N. K., Waltham, N. J., & Swearer, S. E. (2024). Current extent and future opportunities for living shorelines in Australia. *Science of the Total Environment*, 917. <https://doi.org/10.1016/j.scitotenv.2024.170363>
- Morris, R. L., Chapman, M. G., Firth, L. B., & Coleman, R. A. (2017). Increasing habitat complexity on seawalls: Investigating large- and small-scale effects on fish assemblages. *Ecology and Evolution*, 7(22), 9567–9579. <https://doi.org/10.1002/ece3.3475>
- Morris, R. L., Deavin, G., Hemelryk Donald, S., & Coleman, R. A. (2016). Eco-engineering in urbanised coastal systems: Consideration of social values. *Ecological Management and Restoration*, 17(1), 33–39. <https://doi.org/10.1111/emr.12200>
- Morris, R. L., Martinez, A. S., Firth, L. B., & Coleman, R. A. (2018). Can transplanting enhance mobile marine invertebrates in ecologically engineered rock pools? *Marine Environmental Research*, 141, 119–127. <https://doi.org/10.1016/j.marenvres.2018.08.008>
- Mullarney, J. C., & Fisher, K. T. (2022). Challenges for the use of Mangrove Forests as Nature-Based Solutions in Aotearoa New Zealand: from the Physical to the Social-Environmental. *Proceedings of the IAHR World Congress*, SS-190-SS-198. <https://doi.org/10.3850/IAHR-39WC2521-71192022SS2227>
- Niazi, M. H. K., Morales Nápoles, O., & Van Wesenbeeck, B. K. (2021). Probabilistic characterization of the vegetated hydrodynamic system using non-parametric bayesian networks. *Water (Switzerland)*, 13(4). <https://doi.org/10.3390/w13040398>
- Orchard, S., & Schiel, D. R. (2021). Enabling nature-based solutions for climate change on a peri-urban sandspit in Christchurch, New Zealand. *Regional Environmental Change*, 21(3). <https://doi.org/10.1007/s10113-021-01791-1>
- O'Shaughnessy, K. A., Hawkins, S. J., Evans, A. J., Hanley, M. E., Lunt, P., Thompson, R. C., Francis, R. A., Hoggart, S. P. G., Moore, P. J., Iglesias, G., Ducker, J., & Firth, L. B. (2020). Design catalogue for eco-engineering of coastal artificial structures: a multifunctional approach for stakeholders and end-users. *Urban Ecosystems*, 23(2), 431–443. <https://doi.org/10.1007/s11252-019-00924-z>
- O'Shaughnessy, K. A., Knights, A. M., Hawkins, S. J., Hanley, M. E., Lunt, P., Thompson, R. C., & Firth, L. B. (2023). Metrics matter: Multiple diversity metrics at different spatial scales are needed to understand species diversity in urban environments. *Science of the Total Environment*, 895. <https://doi.org/10.1016/j.scitotenv.2023.164958>
- O'Shaughnessy, K. A., Perkol-Finkel, S., Strain, E. M. A., Bishop, M. J., Hawkins, S. J., Hanley, M. E., Lunt, P., Thompson, R. C., Hadary, T., Shirazi, R., Yong, C. L. X., & Firth, L. B. (2021). Spatially Variable Effects of Artificially-Created Physical Complexity on Subtidal Benthos. *Frontiers in Ecology and Evolution*, 9. <https://doi.org/10.3389/fevo.2021.690413>

- Palinkas, C. M., Orton, P., Hummel, M. A., Nardin, W., Sutton-Grier, A. E., Harris, L., Gray, M., Li, M., Ball, D., Burks-Copes, K., Veatch, W., & Williams, T. (2022). Innovations in Coastline Management With Natural and Nature-Based Features (NNBF): Lessons Learned From Three Case Studies. *Frontiers in Built Environment*, 8. <https://doi.org/10.3389/fbuil.2022.814180>
- Park, S., Sohn, W., Piao, Y., & Lee, D. (2023). Adaptation strategies for future coastal flooding: Performance evaluation of green and grey infrastructure in South Korea. *Journal of Environmental Management*, 334. <https://doi.org/10.1016/j.jenvman.2023.117495>
- Paxton, A. B., Foxfoot, I. R., Cutshaw, C., Steward, D. N., Poussard, L., Riley, T. N., Swannack, T. M., Piercy, C. D., Altman, S., Puckett, B. J., Storlazzi, C. D., & Viehman, T. S. (2024). Evidence on the ecological and physical effects of built structures in shallow, tropical coral reefs: a systematic map. *Environmental Evidence*, 13(1). <https://doi.org/10.1186/s13750-024-00336-3>
- Paxton, A. B., Riley, T. N., Steenrod, C. L., Smith, C. S., Zhang, Y. S., Gittman, R. K., Silliman, B. R., Buckel, C. A., Viehman, T. S., Puckett, B. J., Puckett, B. J., & Davis, J. (2023). What evidence exists on the performance of nature-based solutions interventions for coastal protection in biogenic, shallow ecosystems? A systematic map protocol. *Environmental Evidence*, 12(1). <https://doi.org/10.1186/s13750-023-00303-4>
- Pelckmans, I., Belliard, J.-P., Dominguez-Granda, L. E., Slobbe, C., Temmerman, S., & Gourgue, O. (2023). Mangrove ecosystem properties regulate high water levels in a river delta. *Natural Hazards and Earth System Sciences*, 23(9), 3169–3183. <https://doi.org/10.5194/nhess-23-3169-2023>
- Perricone, V., Contestabile, P., Mele, A., Hassanpour, N., Vicinanza, D., & Buono, M. (2024). Bioinspired Coastal Barriers: A Preliminary Laboratory Study on the Hydraulic Performances of Shapes Inspired by Marine Organisms. *Sustainability (Switzerland)*, 16(11). <https://doi.org/10.3390/su16114839>
- Pioch, S., Relini, G., Souche, J. C., Stive, M. J. F., De Monbrison, D., Nassif, S., Simard, F., Allemand, D., Saussol, P., Spieler, R., Spieler, R., & Kilfoyle, K. (2018). Enhancing eco-engineering of coastal infrastructure with eco-design: Moving from mitigation to integration. *Ecological Engineering*, 120, 574–584. <https://doi.org/10.1016/j.ecoleng.2018.05.034>
- Rifai, H., Quevedo, J. M. D., Lukman, K. M., Sondak, C. F. A., Risandi, J., Hernawan, U. E., Uchiyama, Y., Ambo-Rappe, R., & Kohsaka, R. (2023). Potential of seagrass habitat restorations as nature-based solutions: Practical and scientific implications in Indonesia. *Ambio*, 52(3), 546–555. <https://doi.org/10.1007/s13280-022-01811-2>
- Rivosecchi, A., & Singh, M. (2023). Small Island City Flood Risk Assessment: The Case of Kingston, Jamaica. *Water (Switzerland)*, 15(22). <https://doi.org/10.3390/w15223936>
- Rubinato, M., Heyworth, J., & Hart, J. (2020). Protecting coastlines from flooding in a changing climate: A preliminary experimental study to investigate a sustainable approach. *Water (Switzerland)*, 12(9). <https://doi.org/10.3390/w12092471>
- Saengsupavanich, C., Ratnayake, A. S., Yun, L. S., & Ariffin, E. H. (2023). Current challenges in coastal erosion management for southern Asian regions: examples from Thailand, Malaysia, and Sri Lanka. *Anthropocene Coasts*, 6(1). <https://doi.org/10.1007/s44218-023-00030-w>

- Safak, I., Angelini, C., Norby, P. L., Dix, N., Roddenberry, A., Herbert, D., Astrom, E., & Sheremet, A. (2020). Wave transmission through living shoreline breakwalls. *Continental Shelf Research*, 211. <https://doi.org/10.1016/j.csr.2020.104268>
- Salauddin, M., O'Sullivan, J. J., Abolfathi, S., & Pearson, J. M. (2021). Eco-Engineering of Seawalls—An Opportunity for Enhanced Climate Resilience From Increased Topographic Complexity. *Frontiers in Marine Science*, 8. <https://doi.org/10.3389/fmars.2021.674630>
- Schaefer, N., Bishop, M. J., Bugnot, A. B., Foster-Thorpe, C., Herbert, B., Hoey, A. S., Mayer-Pinto, M., Nakagawa, S., Sherman, C. D. H., Vozzo, M. L., Vozzo, M. L., & Dafforn, K. A. (2024). Influence of habitat features on the colonisation of native and non-indigenous species. *Marine Environmental Research*, 198. <https://doi.org/10.1016/j.marenvres.2024.106498>
- Schaefer, N., Mayer-Pinto, M., Johnston, E. L., & Dafforn, K. A. (2023). Understanding the role of microhabitats in intertidal rock pools to guide future eco-engineering designs. *Marine Biology*, 170(4). <https://doi.org/10.1007/s00227-023-04196-2>
- Schaefer, N., Sedano, F., Bishop, M. J., Dunn, K., Haeusler, M. H., Yu, K. D., Zavoleas, Y., & Dafforn, K. A. (2023). Facilitation of non-indigenous ascidian by marine eco-engineering interventions at an urban site. *Biofouling*, 39(1), 80–93. <https://doi.org/10.1080/08927014.2023.2186785>
- Schipper, C. A., Dekker, G. G. J., de Visser, B., Bolman, B., & Lodder, Q. (2021). Characterization of sdgs towards coastal management: Sustainability performance and cross-linking consequences. *Sustainability (Switzerland)*, 13(3), 1–33. <https://doi.org/10.3390/su13031560>
- Sedano, F., Navarro-Barranco, C., Guerra-García, J. M., & Espinosa, F. (2020). From sessile to vagile: Understanding the importance of epifauna to assess the environmental impacts of coastal defence structures. *Estuarine, Coastal and Shelf Science*, 235. <https://doi.org/10.1016/j.ecss.2020.106616>
- Sedano, F., Pavón-Paneque, A., Navarro-Barranco, C., Guerra-García, J. M., Digenis, M., Sempere-Valverde, J., & Espinosa, F. (2021). Coastal armouring affects intertidal biodiversity across the Alboran Sea (Western Mediterranean Sea). *Marine Environmental Research*, 171. <https://doi.org/10.1016/j.marenvres.2021.105475>
- Selfati, M., El Ouamari, N., Lenfant, P., Fontcuberta, A., Lecaillon, G., Mesfioui, A., Boissery, P., & Bazairi, H. (2018). Promoting restoration of fish communities using artificial habitats in coastal marinas. *Biological Conservation*, 219, 89–95. <https://doi.org/10.1016/j.biocon.2018.01.013>
- Siemes, R. W. A., Duong, T. M., Willemsen, P. W. J. M., Borsje, B. W., & Hulscher, S. J. M. H. (2023). Morphological Response of a Highly Engineered Estuary to Altering Channel Depth and Restoring Wetlands. *Journal of Marine Science and Engineering*, 11(11). <https://doi.org/10.3390/jmse11112150>
- Smith, C. S., Gittman, R. K., Neylan, I. P., Scyphers, S. B., Morton, J. P., Joel Fodrie, F., Grabowski, J. H., & Peterson, C. H. (2017). Hurricane damage along natural and hardened estuarine shorelines: Using homeowner experiences to promote nature-based coastal protection. *Marine Policy*, 81, 350–358. <https://doi.org/10.1016/j.marpol.2017.04.013>
- Smith, C. S., Rudd, M. E., Gittman, R. K., Melvin, E. C., Patterson, V. S., Renzi, J. J., Wellman, E. H., & Silliman, B. R. (2020). Coming to terms with living shorelines: A scoping review of novel restoration strategies for shoreline protection. *Frontiers in Marine Science*, 7, 1–14. <https://doi.org/10.3389/fmars.2020.00434>

- Song, K., You, S., & Chon, J. (2018). Simulation modeling for a resilience improvement plan for natural disasters in a coastal area. *Environmental Pollution*, *242*, 1970–1980. <https://doi.org/10.1016/j.envpol.2018.07.057>
- Strain, E. M. A., Heath, T., Steinberg, P. D., & Bishop, M. J. (2018). Eco-engineering of modified shorelines recovers wrack subsidies. *Ecological Engineering*, *112*, 26–33. <https://doi.org/10.1016/j.ecoleng.2017.12.009>
- Strain, E. M. A., Morris, R. L., Bishop, M. J., Tanner, E., Steinberg, P., Swearer, S. E., MacLeod, C., & Alexander, K. A. (2019). Building blue infrastructure: Assessing the key environmental issues and priority areas for ecological engineering initiatives in Australia's metropolitan embayments. *Journal of Environmental Management*, *230*, 488–496. <https://doi.org/10.1016/j.jenvman.2018.09.047>
- Sutton-Grier, A. E., Gittman, R. K., Arkema, K. K., Bennett, R. O., Benoit, J., Blich, S., Burks-Copes, K. A., Colden, A., Dausman, A., DeAngelis, B. M., Scyphers, S. B., & Grabowski, J. H. (2018). Investing in natural and nature-based infrastructure: Building better along our coasts. *Sustainability (Switzerland)*, *10*(2). <https://doi.org/10.3390/su10020523>
- Tagliabue, A., Matterson, K. O., Ponti, M., Turicchia, E., Abbiati, M., & Costantini, F. (2023). Sediment and bottom water eDNA metabarcoding to support coastal management. *Ocean and Coastal Management*, *244*. <https://doi.org/10.1016/j.ocecoaman.2023.106785>
- Tanaya, T., Kinjo, N., Okada, W., Yasuda, M., & Kuwae, T. (2021). Improvement of the coral growth and cost-effectiveness of hybrid infrastructure by an innovative breakwater design in Naha Port, Okinawa, Japan. *Coastal Engineering Journal*, *63*(3), 248–262. <https://doi.org/10.1080/21664250.2021.1889823>
- Taneja, P., van der Hoek, A. P. L., & van Koningsveld, M. (2020). Sustainable port development: A case study of port of Kuala Tanjung, Indonesia. *Proceedings of the Coastal Engineering Conference*, *36*(2020).
- Thompson, B., Brooks, P. R., Farrugia Drakard, V., Kubin, F., Earp, H. S., Alvarez-Cienfuegos, I., Moore, P. J., & Crowe, T. P. (2023). Population structure and reproductive states of the dogwhelk *Nucella lapillus* differ between artificial structures and natural rocky shores. *Marine Environmental Research*, *189*. <https://doi.org/10.1016/j.marenvres.2023.106059>
- Toft, J. D., Dethier, M. N., Howe, E. R., Buckner, E. V., & Cordell, J. R. (2021). Effectiveness of living shorelines in the Salish Sea. *Ecological Engineering*, *167*. <https://doi.org/10.1016/j.ecoleng.2021.106255>
- Ushiana, S., Mayer-Pinto, M., Bugnot, A. B., Johnston, E. L., & Dafforn, K. A. (2019). Eco-engineering increases habitat availability and utilisation of seawalls by fish. *Ecological Engineering*, *138*, 403–411. <https://doi.org/10.1016/j.ecoleng.2019.07.022>
- van der Spek, B.-J., Bijl, E., van de Sande, B., Poortman, S., Heijboer, D., & Bliet, B. (2020). Sandbar breakwater: An innovative nature-based port solution. *Water (Switzerland)*, *12*(5). <https://doi.org/10.3390/w12051446>
- Van Eekelen, E. M. M., Sittoni, L., Van Der Goot, F., & Nieboer, H. E. (2019). Building with nature: More than 10 years of pre-competitive knowledge development. *22nd World Dredging Congress, WODCON 2019*, 29–42.
- Vandenhove, M., Castelle, B., Nicolae Lerma, A., Marieu, V., Dalet, E., Hanquiez, V., Mazeiraud, V., Bujan, S., & Mallet, C. (2024). Secular shoreline response to large-scale estuarine shoal migration and welding. *Geomorphology*, *445*. <https://doi.org/10.1016/j.geomorph.2023.108972>

- Vozzo, M. L., Bishop, M. J., Dafforn, K. A., Steinberg, P. D., Strain, E. M. A., & Pinto, M. M. (2024). From experiment to intervention: A case study of scaling up marine eco-engineering from research to application. *Environmental Science and Policy*, 158. <https://doi.org/10.1016/j.envsci.2024.103800>
- Vozzo, M. L., Mayer-Pinto, M., Bishop, M. J., Cumbo, V. R., Bugnot, A. B., Dafforn, K. A., Johnston, E. L., Steinberg, P. D., & Strain, E. M. A. (2021). Making seawalls multifunctional: The positive effects of seeded bivalves and habitat structure on species diversity and filtration rates. *Marine Environmental Research*, 165. <https://doi.org/10.1016/j.marenvres.2020.105243>
- Waltham, N. J., & Sheaves, M. (2020). Thermal exposure risks to mobile tropical marine snails: Are eco-engineered rock pools on seawalls scale-specific enough for comprehensive biodiversity outcomes? *Marine Pollution Bulletin*, 156. <https://doi.org/10.1016/j.marpolbul.2020.111237>
- Wu, X., & Hong, S. (2023). Nature-based solutions as sustainability alternatives for shipping: A systematic review. *Journal for Nature Conservation*, 76. <https://doi.org/10.1016/j.jnc.2023.126496>
- Xu, W., Tao, A., Wang, R., Qin, S., Fan, J., Xing, J., Wang, F., Wang, G., & Zheng, J. (2024). Review of wave attenuation by artificial oyster reefs based on experimental analysis. *Ocean Engineering*, 298. <https://doi.org/10.1016/j.oceaneng.2024.117309>
- Zell, J., Lehrman, B., & Ding, C. (2019). Adapt and thrive: Strategies for life along a dynamic and changing coastline. *International Conference on Sustainable Infrastructure 2019: Leading Resilient Communities through the 21st Century - Proceedings of the International Conference on Sustainable Infrastructure 2019*, 120–130. <https://doi.org/10.1061/9780784482650.013>
- Zheng, J., Xu, W., Tao, A., Fan, J., Xing, J., & Wang, G. (2023). Synergy between coastal ecology and disaster mitigation in China: Policies, practices, and prospects. *Ocean and Coastal Management*, 245. <https://doi.org/10.1016/j.ocecoaman.2023.106866>
- Zhu, L., Huguenard, K., Zou, Q.-P., Fredriksson, D. W., & Xie, D. (2020). Aquaculture farms as nature-based coastal protection: Random wave attenuation by suspended and submerged canopies. *Coastal Engineering*, 160. <https://doi.org/10.1016/j.coastaleng.2020.103737>

**APPENDIX B – SUBSTRATE AND ITS LEVEL OF ARTIFICIALITY FOR THE
NBS IMPLEMENTATION AREAS**

Table 20 – Materials for the breakwaters in each harbour.

Port	Substrate	Substrate artificiality
Viana do Castelo	Tetrapods and rip raps	Medium
Leixões	Tetrapods, antifer cubes, rectangular concrete blocks and rip raps	Low to medium
Aveiro	Tetrapods, antifer cubes, rectangular concrete blocks and rip raps	Medium to high
Figueira da Foz	Tetrapods, antifer cubes and rip raps	Medium
Sines	Antifer cubes and rip raps	High
Faro	Tetrapods, antifer cubes and rip raps	Medium
Portimão	Rectangular concrete blocks and rip raps	Medium
Funchal	Tetrapods and cobblestones	Medium
Canical	Antifer cubes and vertical walls	High
Porto Santo	Tetrapods and antifer cubes	Medium to high
Corvo	Tetrapods	Medium
Santa Cruz das Flores	Antifer cubes and rip raps	High
Lajes das Flores	Antifer cubes and vertical walls	High
Horta	Mostly tetrapods	Medium
Praia da Graciosa	Tetrapods and antifer cubes	Medium
São Roque do Pico	Tetrapods	Medium
Lajes do Pico	Antifer cubes	High
Madalena	Tetrapods, antifer cubes and rip raps	Medium
Velas	Antifer cubes and rip raps	Medium to high
Calheta	Antifer cubes, vertical walls and rip raps	High
Praia da Vitória	Tetrapods, antifer cubes and rip raps	Medium to high
Angra do Heroísmo	Tetrapods and rip raps	Medium
Vila do Porto	Tetrapods, antifer cubes and rip raps	Medium
Ponta Delgada	Tetrapods and antifer cubes	Medium

Table 21 – Materials for the eco-basin sites in each harbour.

Port	Substrate	Substrate artificiality
Viana do Castelo	Sand	Low
Leixões	Rip rap	Low
Aveiro	Rip rap and rectangular concrete blocks	Medium
Figueira da Foz	-	-
Lisbon	Gravel	Low
Setúbal	Sand and gravel	Low
Sines	-	-
Faro	Rip rap	Low
Portimão	-	-
Funchal	-	-
Canical	-	-
Porto Santo	Rip rap	Low
Corvo	-	-
Santa Cruz das Flores	-	-
Lajes das Flores	-	-
Horta	Rip rap	Low
Praia da Graciosa	-	-
São Roque do Pico	-	-
Lajes do Pico	-	-
Madalena	-	-
Velas	-	-
Calheta	-	-
Praia da Vitória	-	-
Angra do Heroísmo	-	-
Vila do Porto	-	-
Ponta Delgada	Rip rap	Low

Table 22 – Materials for the seawalls in each harbour.

Port	Substrate	Substrate artificiality
Viana do Castelo	-	-
Leixões	Rock seawalls	Low
Aveiro	Concrete seawall with blocks	High
Figueira da Foz	Rock seawalls	Low
Lisbon	Inclined wall of smooth stones	High
Setúbal	Concrete seawall	High
Sines	Rock seawalls	Low
Faro	-	-
Portimão	Vertical brick seawall	Medium
Funchal	-	-
Canical	Concrete seawall	High
Porto Santo	-	-
Corvo	-	-
Santa Cruz das Flores	Concrete seawall	High
Lajes das Flores	Concrete seawall	High
Horta	-	-
Praia da Graciosa	-	-
São Roque do Pico	Vertical seawall	High
Lajes do Pico	Vertical brick seawall	Medium
Madalena	-	-
Velas	-	-
Calheta	Rock seawalls	Low
Praia da Vitória	-	-
Angra do Heroísmo	Vertical seawall with rocks	Low
Vila do Porto	-	-
Ponta Delgada	Rock seawalls	Low