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Nature-based Solutions (NbS) for Coastal Ecosystem Resilience
Enhancement: Towards a Conceptual Model for Marine Pollution
Mitigation

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Mitigation

Master of Marine and Coastal System (MaCS)

Under the supervision of

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2024

Declaration of Authorship of Work

**Nature-based Solutions (NbS) for coastal ecosystem resilience
enhancement: Towards a conceptual model for marine pollution mitigation**

I, Gardawheh Gad Boe, declare to be the author of this work, which is original and unpublished. The sources consulted have been duly cited in the text and are included in the list of references.

Gardawheh Gad Boe

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Abstract

Coastal ecosystems, including mangroves, salt marshes, and coral reefs, perform various vital functions such as flood mitigation, erosion prevention, habitat conservation, and carbon sequestration. However, these ecosystems are encountering unparalleled challenges primarily due to climate change and anthropogenic activities that contribute to marine pollution, jeopardizing ecosystem integrity. The deterioration and destruction of coastal habitats undermine the natural resilience of these regions. Thus, the implementation of meticulously designed Nature-based Solutions (NbS) can facilitate the restoration and rehabilitation of compromised coastal ecosystems, mitigate marine pollution, and enhance economic and societal advantages in a cost-effective and sustainable manner. Examples encompass the rehabilitation of essential habitats, including seagrass and salt marshes, to safeguard biodiversity and facilitate carbon sequestration, as well as the management of coastal habitats to conserve biodiversity and shield populations from extreme weather phenomena. This master's thesis seeks to perform a thorough evaluation of the efficacy and potential of Nature-based Solutions (NbS), including habitat restoration, green infrastructure, and ecological engineering, in mitigating pollution effects and fostering long-term environmental sustainability, while also formulating a conceptual model for their effective application. The research will enhance the understanding of coastal resilience and offer pragmatic recommendations for coastal management and planning.

Keywords: coastal pollution, habitat sensitivity, habitat degradation, ecosystem services, MarESA framework, nature-based solutions, DPSIR, Ria Formosa.

Resumo

Os ecossistemas costeiros, incluindo sapais, pradarias marinhas, planícies intertidais, recifes de coral e bancos de areia sub-litorais, são cruciais para a manutenção do equilíbrio ecológico e para suporte à humanidade. Estes ecossistemas fornecem serviços essenciais, como mitigação de inundações, prevenção de erosão, sequestro de carbono, melhoria da qualidade da água, conservação de habitats e apoio à biodiversidade. Contudo, a integridade destes ecossistemas está cada vez mais ameaçada por pressões antrópicas e seus impactes acelerados pelas alterações climáticas. A poluição marinha, a degradação de habitats e a perda de biodiversidade são alguns dos desafios mais urgentes, comprometendo a resiliência natural destes ecossistemas e reduzindo a sua capacidade de fornecer serviços ecossistémicos vitais. Abordar estes desafios requer estratégias inovadoras, sustentáveis e economicamente viáveis que estejam alinhadas com os objetivos ambientais globais, incluindo os definidos pela Década do Oceano das Nações Unidas para o Desenvolvimento Sustentável.

As Soluções Baseadas na Natureza (NbS) surgem como um quadro promissor para enfrentar a degradação dos ecossistemas costeiros. As estratégias NbS, como a restauração de habitats, a engenharia ecológica e as infraestruturas verdes, são concebidas para reabilitar e melhorar as funções dos ecossistemas, promovendo simultaneamente a saúde ambiental. Esta tese explora o potencial das NbS para mitigar a poluição marinha, melhorar a resiliência dos ecossistemas e proporcionar benefícios socioeconómicos. É dada atenção especial à aplicação das NbS no sistema lagunar da Ria Formosa, uma região costeira de grande relevância biológica, ecológica, social e económica caracterizada pelas suas planícies intertidais, pradarias marinhas, sapais e bancos de areia sub-litorais.

Neste trabalho foi aplicada a metodologia *Marine Evidence-based Sensitivity Assessment* (MarESA) para avaliar a provisão de serviços ecossistémicos pelos habitats críticos da Ria Formosa e para analisar a sua vulnerabilidade e sensibilidade a diferentes pressões de poluição. Os resultados revelam que os

habitats da Ria Formosa apresentam uma distribuição espacial complexa e uma heterogeneidade notável, mantendo estabilidade tanto em intervalos intra-anuais como inter-anuais. Esta estabilidade sustenta uma diversidade significativa de espécies e serviços ecossistémicos robustos.

As pradarias marinhas e os sapais destacam-se como habitats particularmente valiosos devido ao seu papel na melhoria da qualidade da água, no sequestro de carbono e no suporte à biodiversidade. Contudo, estes biótopos são altamente sensíveis às pressões antrópicas, como o enriquecimento de nutrientes, a poluição orgânica e o aumento da turvação da água. As planícies intertidais desempenham um papel complementar ao promover o crescimento das pradarias marinhas através da melhoria da transparência da água, enquanto os sapais, por sua vez, contribuem para a retenção de sedimentos, contribuindo ativamente para a estabilidade do ecossistema.

As interconexões entre estes habitats destacam a necessidade de abordagens de gestão integrada que colmatem os impactes cumulativos do crescimento populacional, do turismo e da poluição. Principais fatores de stress, como as dragagens, a introdução de águas residuais tratadas e não-tratadas e o enriquecimento de nutrientes, comprometem a conservação a longo prazo dos ecossistemas da Ria Formosa. Consequentemente, a implementação de estratégias NbS direcionadas, como a restauração de pradarias marinhas e sapais, é fundamental para melhorar a resiliência e a funcionalidade dos serviços ecossistémicos da Ria Formosa.

A presente dissertação destaca a importância ecológica das pradarias marinhas e das planícies intertidais, defendendo a sua proteção e conservação como prioridades nas estratégias de mitigação da poluição. Os sapais e os bancos de areia sub-litorais, embora moderadamente sensíveis às pressões antrópicas, desempenham papéis vitais na promoção da biodiversidade e na mitigação dos impactes da poluição. A restauração e conservação destes habitats costeiros não só contribuem para a melhoria da qualidade da água, como promovem o

sequestro de carbono, mitigam os impactos das mudanças climáticas e reforçam a resiliência dos sistemas de gestão de água.

Um aspeto crucial para o avanço das NbS é a integração destas soluções em quadros políticos locais, regionais e nacionais, como estratégias de longo prazo, incluídas por exemplo em Planos de Adaptação Climática e/ou Estratégias e Planos de Ação para a Biodiversidade. Esforços colaborativos entre vários atores são essenciais para garantir o desenvolvimento sustentável e a implementação eficaz das NbS. Além disso, salvaguardas sociais e ambientais devem ser integradas nas estratégias NbS de forma a assegurar a sua equidade e inclusão. A mobilização de recursos, tanto nacionais como internacionais, é fundamental para ampliar os esforços das NbS em consonância com compromissos globais, como o *Nature Compact*.

Os resultados obtidos durante o presente trabalho estão completamente alinhados com os atuais objetivos políticos da União Europeia (EU) sobre NbS, que enfatizam a integração destas abordagens na investigação, inovação e política a vários níveis de atuação. Os objetivos seguintes da UE incluem expandir a informação sobre o custo/benefício destas soluções com base em evidências científicas.

Palavras-chave: poluição costeira, sensibilidade do habitat, degradação do habitat, serviços ecossistémicos, enquadramento MarESA, soluções baseadas na natureza, DPSIR, Ria Formosa.

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List of Abbreviations

1. AD – Atmospheric Deposition
2. CISES – The Common International Classification of Ecosystem Services
3. DPSIR – Drivers, Pressures, State, Impact, Response
4. ES – Ecosystem Services
5. Emodnet - European Marine Observation and Data Network
6. EUNIS – European Nature Information System
7. IPBES – Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
8. IUCN – International Union for Conservation of Nature
9. MarESA – Marine Evidence-based Sensitivity Assessment
10. MPAs – Marine Protected Areas
11. NbS – Nature-based Solutions
12. POPs – Persistent Organic Pollutants
13. Ramsar – Ramsar Convention on Wetlands
14. RFaSPM – Ria Formosa asset pollution sensitivity matrix
15. UaBM – Universal asset Bioremediation matrix
16. UaSM – Universal Asset-Service Matrix
17. UaPSM - Universal Asset-Pollution Sensitivity Matrix

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1. General Introduction

The coastal zone, characterized as the boundary between land and sea, is shaped by both marine and terrestrial processes, leading to distinctive and varied ecosystems and habitats that offer numerous services, including provisioning, supporting, and regulatory functions for both natural and human communities residing within them (Filho et al., 2022). Wetlands, encompassing estuaries, lagoons, marshes, and mangrove habitats, represent some of the most productive and valuable coastal ecosystems globally (Filho et al., 2022). These ecosystems offer various services, including nutrient cycling, support for marine and terrestrial organisms, and biophysical buffering against disasters like storms and coastal erosion (Lakshmi, 2021). Nevertheless, these regions are also experiencing significant strain from various concurrent and cumulative challenges, such as urbanization, coastal pollution, biodiversity decline, and climate change (Filho et al., 2022).

Marine ecosystems therefore experience intense pressure from non-point source pollution from urban runoff and agricultural waste and point sources that contribute heavy metals, solid wastes, and other toxins. This pollution introduces excess nutrients and chemicals into coastal waters, degrading water quality, destroying habitats, and creating dead zones (Macko, 2018). Therefore, as coastal populations grow and climate change intensifies, exacerbating water challenges, pollution prevention and effective management are vital to maintaining healthy marine ecosystems (Macko, 2018). Owing to the complexity, innovative approaches culminating in effective pollution prevention programs built in integrated coastal zones and water management plans play a crucial role in efforts to reduce nonpoint and point sources of pollution for healthier marine ecosystems (Macko, 2018).

As human activities persist in imposing significant stress on these ecosystems, causing a notable deterioration in the vitality of coastlines, which in turn leads to a substantial decline in coastal health and integrity, climate change and related pressures, including sea-level rise and ocean acidification, are simultaneously exacerbating the deterioration of coastal regions, hindering their capacity to provide diverse ecosystem services (McDonald et al., 2020).

Coastal zones therefore face global changes associated with climate change and localized stressors from human activities, including erosion, pollution, and land-use alterations, which jeopardize biodiversity and the well-being of coastal communities. Consequently, the coast has been designated as a priority in climate science by the UNFCCC.

Nonetheless, marine pollution continues to be one of the most widespread environmental challenges. This results from its diverse causes and origins, stemming from human activities such as agricultural runoff, dredging, wastewater discharges, and industrial pollution (Pawar, 2016). Moreover, even if all coastal and ocean challenges recognized by the UN Ocean Decade for Sustainable Development are adequately managed, pollution will continue to compromise ecosystem sustainability and integrity if not controlled.

The EU and G7 Ministers of Climate, Energy, and the Environment acknowledged that robust ecosystems exhibit greater resilience to climate change by facilitating adaptation and significantly contributing to climate mitigation through carbon sequestration, while also being vulnerable to climate change effects that lead to ecosystem degradation and biodiversity loss (G7, 2022). In a similar vein, the EU Marine Strategy Framework Directive (MSFD) seeks to enhance the protection of the marine environment throughout Europe by attaining and sustaining Good Environmental Status (GES) of EU marine waters and safeguarding the resource base essential for marine-related economic and social activities (Cardoso et al., 2010), acknowledging the detrimental effects of pollution on the marine ecosystem. The Directive defines GES as "the environmental status of marine waters that

provide ecologically diverse and dynamic oceans and seas that are clean, healthy, and productive" and highlights eleven qualitative descriptors to assess it. Among these, a maximum of six pertain specifically to pollution and its related pressures, encompassing: eutrophication (D5), sea floor integrity (D6), contaminant concentrations (D8), contaminants in seafood (D9), marine litter (D10), and the introduction of energy (including underwater noise) (D11) (Cardoso et al., 2010; Caroppo et al., 2013; Ndah et al., 2022). The Marine Strategy Framework Directive (MSFD) promotes the use of bioindicators as nature-based methods for assessing the condition of natural ecosystems. This indicates that the improvement of ecosystem components may also provide a basis for developing nature-positive solutions for pollution remediation that comply with the MSFD and other international environmental frameworks.

1.1. Aims and Objectives

This study seeks to analyse the Ria Formosa ecological characteristics concerning the ecosystem services it offers and the sustainability challenges presented by pollution. The study evaluated Ria Formosa's resilience to pollution, acting as an essential base to formulate frameworks and models that illustrate how NbS can mitigate marine pollution, yielding various co-benefits, including enhanced water quality, biodiversity conservation, and increased ecosystem resilience.

The present work focused on the following objectives:

1. Evaluate the bioremediation services offered by critical habitats in Ria Formosa.
2. Assess human-induced pollution pressure and its effects on ecosystem services in the Ria Formosa
3. Develop a systematic methodology for conceptualizing the development and execution of NbS in Ria Formosa.
4. Develop pragmatic guidelines for coastal management and planning, incorporating novel information and tools to enhance the understanding of ecosystem resilience.

1.2. Evolution of Nature-based solutions

Owing to the complexity and implications of the issues described earlier, these G7 ministers in their 2030 plan stressed the importance of protecting, conserving, sustainably managing, and restoring ecosystems for halting and reversing biodiversity loss in an integrated way that promotes mutually beneficial benefits (G7, 2022; EU, 2024). The EU Commission strongly highlights Nature-based Solutions (NbS) as cost-efficient strategies derived from nature that provide environmental, social, and economic benefits while improving resilience (EU, 2023). These solutions employ natural ecosystems, such as wetlands and peatlands, to sequester carbon dioxide, purify water, and enhance biodiversity, thus offering a sustainable method for achieving environmental and climate goals. The International Union for Conservation of Nature (IUCN) defines NbS as 'actions to safeguard, sustainably manage, and restore natural or altered ecosystems that address societal challenges, functioning effectively and adaptively while concurrently providing advantages to both humanity and the environment' (Cohen-Sacham, 2016). Both definitions are complementary and emphasize that NbS are vital instruments for concurrently mitigating carbon emissions and safeguarding water quality, aiding in the achievement of net zero greenhouse gas emissions by 2050, halting and reversing biodiversity loss by 2030, and fulfilling the Sustainable Development Goals (SDGs) by 2030 (G7, 2022). Consequently, researchers and policymakers are prioritizing NbS as a sustainable approach to bolster the resilience of current ecosystems and mitigate the impacts of climate change and pollution. Moreover, recognizing the imperative for a consistent global standard to attain maximum efficacy of NbS, IUCN formulated a comprehensive global framework for the design, validation, and enhancement of NbS. This standard promotes a shared comprehension of effective NbS, clarifying their systematic planning, design, and execution, thereby facilitating the transition from pilot projects to extensive landscape implementations of successful NbS initiatives. It juxtaposes the concurrent provision of benefits for biodiversity and human well-being against specific challenges, including marine pollution, food security, and disaster risk mitigation. Without a standard, NbS initiatives may not deliver the

expected environmental, social, and economic benefits, thereby eroding public, governmental, and investor trust in these approaches. In light of the growing evidence regarding the advantages of NbS for tackling diverse marine and coastal issues, this thesis outlines a systematic approach for the design of NbS aimed at reducing pollution and improving ecological health in the coastal systems of the Ria Formosa Lagoon in southern Portugal. This methodology primarily functions as a crucial reference for formulating NbS to mitigate environmental pollution in Ria Formosa, while also being applicable to other coastal and wetland ecosystems.

1.3. Conceptual Models of Marine Ecosystems and Mitigation of Marine Pollution

The conceptual models of marine ecosystems give an idea about the functioning and structure of the ecosystem. These models integrate diverse data from physical, ecological, as well as social settings to elucidate natural-social associations, draw comparisons for governance initiatives, and also establish tradeoffs (Zador et al., 2017).

Pollution of the marine environment is one of the important threats to both marine communities and people, including industrial and municipal wastewater (Butnariu, 2022b). To minimize further impacts on marine ecosystems, mitigation strategies have been developed. The efforts should be concentrated on tracing pollution sources, calculating their influences, and comprehending ocean features to provide an efficient defense (Chitrakar et al., 2019). Conceptual models can help in understanding the effects of specific marine pollution and ways to avoid it (Harvey et al., 2016).

The conceptual models of existing environmental management applied reveal the consequences of anthropogenic stress on marine habitats with diminishing diversity and quality of life (Kennish et al., 2022). They emphasize the need to tackle poor water quality from the land-based activities that cause coastal degradation (Kennish et al., 2022). They also stress the importance of considering the effects of these pollutants on the health of coastal populations, such as

infections, lack of food, and food poisoning or related diseases. The common causes of poor health among people living in inland coastal systems should be addressed through integrated watershed management approaches (Kennish et al., 2022). These models act as a basis for a holistic approach to environmental management aimed at attaining nature and people's sustainability development objectives of coastal communities. They also highlight the importance of cooperation, cuts across sectors, and the land-sea interface for successful management.

It has been recognized worldwide that the Integrated Coastal Zone Management (ICZM) framework is one of the best management approaches for managing coastal areas in an integrated and comprehensive manner (Shi et al., 2019). Nevertheless, implementing ICZM still proves difficult for many regions, including islands' states, because of different pressures like tourism, urbanization, and climatic changes (Arefipour et al., 2022). In some instances, ICZM strategies are neglected while coastal communities fail to be involved, thereby leading to improper use of resources and the susceptibility of coastal ecosystems (Shi et al., 2019). Tailor-made designs and specific approaches should be used to tackle the site-specific ecological and social elements in the management of coastal sites (Das, 2022a).

The PSR (Pressures, States, and Responses) framework can also be modified to be used in the adjacent coastal regions in determining the pressure ecosystem and state of the environment, as well as a solution for these problems. The PSR model uses a combination of objective and perceptual variables as measures of quantifying the effect of tourism in an urban area (Bruna et al., 2023). Song et al. used the pressure-state-response framework to examine the declines in Chinese populations of *Suaeda salsa* inside a China wetland reserve.

The DPSIR Framework (Drivers-Pressures-State-Impact-Responses) (Figure 1) is an instrument for analyzing environmental problems related to sustainable development (Patrício et al.). The basic aims of its approach are (i) to be able to provide relevant information on the different elements of the DPSIR sequence, (ii) to clarify how they are connected and related to each other, and (iii) to estimate the effectiveness of responses. The DPSIR framework provides helpful insights into the relationships between the origins and consequences of environmental problems and, at the same time, helps to understand their dynamics by addressing the links between DPSIR elements. This integrative approach presupposes a substantial understanding of the underlying causal relationships between human activities and the resultant impacts on ecosystems, coastal economies and communities, and human response mechanisms. Nevertheless, the integrative nature of the framework leads to its wide use, especially by the European Environmental Agency, in selecting indicators for evaluating the implementation of EU environmental policies. The DPSIR framework has rapidly become popular among researchers and policymakers alike as a conceptual framework for structuring and communicating relevant environmental policy research (Patrício et al.). For this reason, it has been successfully implemented in different kinds of coastal management issues, and its contribution to highlighting the dynamic characteristics of ecosystems and socio-economical changes has been validated (Turner et al. 1998). A presumed strength of the DPSIR framework lies in its simplicity in capturing key relationships between factors in society and the environment. While simple in concept, the framework is flexible enough to be conceptually valid over a range of spatial scales (Turner et al., 1998). Consequently, it can be used as a communication tool between scientists from different disciplines as well as between researchers, on the one hand, and policymakers and stakeholders on the other.

All these frameworks share the distinction between (i) forces that act on the environment, (ii) changes that, as a consequence, take place in the environment, and (iii) the societal reaction to those changes. The DPSIR framework follows the same general model as previous frameworks but diverges in the sense that it distinguishes more steps in the process (Patrício et al.). So, while there are some differences between these frameworks in terms of terminology and the degree of detail, they are all based on the causal chain concept.

1.4. Study Area: A systematic review of pollution pressure in Ria Formosa

The Ria Formosa Lagoon, an ecologically important coastal system recognized as a Ramsar-listed wetland and a Natura 2000 site, comprises a barrier island complex that includes tidal flats, salt marshes, seagrass, and shoal areas of substantial biological, ecological, and socio-economic significance (Newton & Mudge, 2003). The surface area is 100 km², with barrier islands comprising Ilha de Farol, Ilha da Barreta (also known as Ilha Deserta), Ilha da Culatra, Ilha da Armona, and Ilha de Tavira, which safeguard the coastline from the Atlantic Ocean (Rosa et al., 2022).

This area stretches from the Ancão Peninsula in the west to Manta Rota in the east, covering approximately 60 kilometers of coastline, interspersed with tidal inlets that enable the free exchange between the lagoon and the ocean (Jacob et al., 2016) The lagoon, with an average depth of 0.5 to 2 meters, is notably influenced by a diurnal tidal cycle, consisting of two high tides and two low tides, with an average elevation of approximately 2.8 meters (Cravo et al., 2020). This cycle is crucial for hydrodynamic processes and sediment transport, affecting habitat formation and the transfer of wastewater, nutrients, and organisms from the lagoon to neighboring marine ecosystems (Cravo et al., 2020).

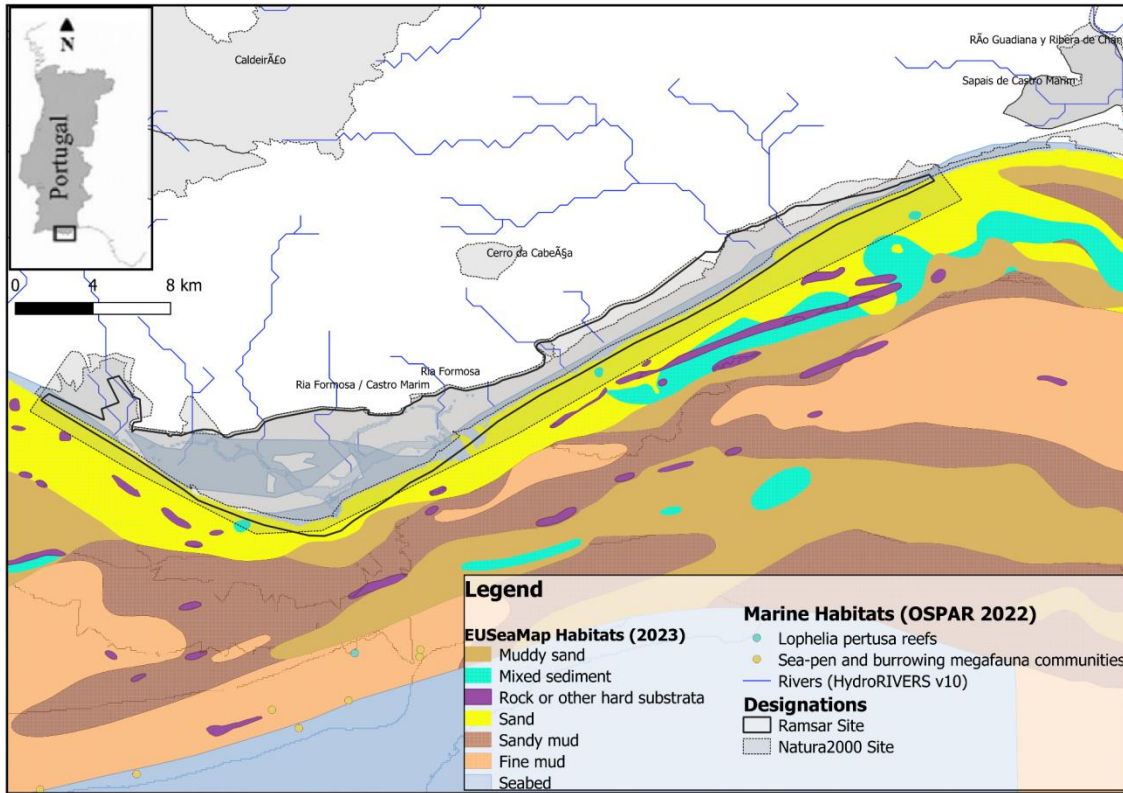


Figure 1.1. The varied habitats of the Ria Formosa Lagoon as delineated and classified according to the EUSeaMap (2023) data. The map delineates the extensive classification of marine habitats, rivers, and the limits of the principal designations of Ria Formosa (Ramsar and Natura 2000).

Due to Ria Formosa's geographic position in the Mediterranean and Marine Atlantic biogeographical regions, the lagoon's substrate exhibits the influence of both marine and terrestrial environments, thereby showcasing a diverse array of biotypes and species.

The region reportedly encompasses a minimum of 19 habitat types as outlined in the Habitats Directive and safeguards at least 121 species as specified in the Nature Directives (Eunis-PTZPE0017). The lagoon's varied ecosystems exemplify its complex environmental and cultural conditions (EUNIS Habitat Type Hierarchical View, n.d.). Consequently, employing a structured classification system such as EUNIS was pertinent for standardizing, classifying, and delineating the various habitats observed in Ria Formosa before analysing the effects of pollution and nature's role in its mitigation. The coastal and marine ecosystems of

the Ria Formosa lagoon were delineated and characterized utilizing the EUNIS classification system. A supplementary table (Table 1.1) delineates the diverse habitats and their respective extents.

The complex network of barrier islands, tidal flats, salt marshes, seagrass meadows, and sublittoral zones offers essential ecosystem services, such as pollutant cycling, carbon sequestration, water filtration, sediment stabilization, water flow regulation, biodiversity, and support for various fish, bird, and invertebrate species. The habitats are vital to the local economy, supporting fisheries, aquaculture, tourism, and recreational activities. The region holds various designations to safeguard its rich biodiversity and ecological heritage, as illustrated in Table 1.1 below.

Table 1.1: Designations assigned to Ria Formosa

Designation	Code	Directive	Year	Ref
RAMSAR wetland of world-wide interest	site no. 212	Nature Reserve	Nov 1980	<a href="https://r
is.ram
sar.org/
ris/212">https://r is.ram sar.org/ ris/212
Natural Park	N.A	<u>Birds Directive</u>	1987	https:// www.ba ixaterra cehoste l.pt/en/ri a- formosa - natural- park
Natura 2000 site	code PTZPE0017	<u>Birds Directive</u>	<u>March 1988</u>	https://e unis.ee a.europ a.eu/sit es/PTZ PE0017
Important bird area (IBA)	N.A	<u>Birds Directive</u>	2002	https://d atazone .birdlife. org/site/ factshe et/ria- formosa -(faro- lagoon) -iba- portugal
Special Protection Area	555540891	EC Directive	1988	https:// www.pr otected planet.n et/5555 40891

Designation	Code	Directive	Year	Ref
One of the 7 Natural Wonders of Portugal	N.A	<u>Birds Directive</u>	2010	https://sanlorenzogolfcourse.com/news-and-events/ria-formosa-voted-one-of-the-7-natural-wonders-of-portugal

Nevertheless, the region endures considerable anthropogenic pressures, encompassing historical modifications such as the damming of waterways, illustrated by the western Ancao Basin; the consolidation of inlets, particularly the principal Faro channel inlet at Farol; the reclamation of salt marshes for salt extraction and aquaculture; and extensive infrastructure projects, including the international airport of Faro, sewage treatment plants, and construction on the dunes (Newton et al., 2022).

Despite extensive examination of the system's hydrology and anthropogenic impacts (Newton et al., 2022), a comprehensive investigation of the region's ecological attributes and its vulnerability to pollution from diverse sources, such as agricultural runoff, urban wastewater, and plastic debris, is imperative before implementing suitable management strategies, including NbS. This gap is substantial because water quality impairments profoundly affect all aspects of an ecosystem's integrity, undermining its ecological functions more than any other stressor.

Consequently, acknowledging the diverse pressures on coastal ecosystems, including pollution, NbS have been recognized as an effective strategy for rehabilitating and restoring the ecological integrity of lagoon's habitats. NbS can improve the restoration of critical habitats, including seagrass meadows and salt marshes, thereby strengthening lagoon resilience to pollution, enhancing water quality, promoting carbon sequestration, regulating flooding, and preserving biodiversity (Cohen-Sacham et al., 2016). Nonetheless, despite the considerable potential of NbS, there are presently no established frameworks to promote the implementation and expansion of these interventions. This thesis aims to address this deficiency by developing a framework tailored to the unique environmental and socio-economic conditions of the Ria Formosa.

1.5. Study outline

This thesis comprises three consecutive chapters. Chapter 1 encompasses the introduction, detailing the study objectives. Chapter 2 addresses the different methods used. Chapter 3 systematically delineates the results and findings of this study, commencing with an evaluation of habitat classification in Ria Formosa utilising the EUNIS classification system. The EUNIS habitat classification provides a framework for comprehending the ecological resources that underpin the region's ecosystem services. The thesis subsequently elucidates the bioremediation services provided by the habitats and their vulnerabilities to pollution, employing the MarESA framework. The prior habitat classification, which encompasses key habitats such as tidal flats, littoral sandbanks, seagrass meadows, and salt marshes, establishes an ecological foundation for evaluating their potential for bioremediation services and their vulnerability to pollution pressures through the Marine Evidence-based Sensitivity Assessment (MarESA) framework.

This evaluation reveals the capacity of these ecosystems to mitigate pollution and their resilience to various pollutants. The formulation of effective NbS interventions depends on comprehension. Ultimately, it presents a framework for the

development and implementation of nature-based solutions for pollution mitigation in Ria Formosa. The NbS pollution-mitigation framework emphasises strategies designed to prevent nutrient enrichment, heavy metal contamination, and organic pollution. This framework integrates global standards, particularly the IUCN Global Standard for NbS, to guide the development and implementation of NbS interventions that positively affect the ecological health of the lagoon and the well-being of its dependent population. Chapter 4, which is the conclusion, encapsulates the study and offers a concise summary of the prior chapters.

2. Methodology

2.1. Systematic review

A systematic review was conducted to consolidate findings from both published and grey literature to determine the current habitat configuration in Ria Formosa, the services it offers, and the trends and impacts of pollution in the lagoon. Data identified, collected, and analysed from multiple databases, including Google Scholar, Web of Science, and general Google searches, to perform a critical and comprehensive review of the existing literature.

The methodology employed to identify pertinent literature used primary search terms such as "Ria Formosa," supplemented by additional keywords including "pollutants," "habitat degradation," "ecosystem services," "ecological impact," "pollution trends," and "conservation strategies." Boolean operators, such as "AND" and "OR," were employed to integrate Ria Formosa Lagoon with supplementary search terms to broaden the scope of the research. No restrictions were imposed on the publication year, thus encompassing both significant early studies and the most recent advancements in the subjects.

The selected papers were chosen based on criteria that, in addition to the key terms, include empirical data and/or theoretical insights related to pollution and the lagoon's ecology. They were also selected based on the titles, abstracts, and

relevant keywords. Titles underwent additional screening, and full texts that satisfied the search criteria were retained.

The following study categories were considered ineligible for inclusion: i) studies unrelated to the specific study area; ii) studies exhibiting inadequate methodological quality; and iii) studies that were not fully accessible. This methodology enabled the eradication of confounding research outcomes, concentrating solely on the highest-quality studies conducted.

A separate comprehensive literature review was conducted focusing on Ria Formosa's ecological attributes, with an emphasis on habitat classification and distribution. This enabled the identification of key sources, including peer-reviewed articles, technical reports, and regional surveys that document the lagoon's ecological characteristics.

Following the selection of literature and the compilation of data, the subjects were meticulously categorized into specific classifications pertaining to Ria Formosa. These classifications encompassed habitats, ecosystem services, types of pollutants, their sources and pathways, temporal variations, ecological impacts, and strategies for mitigation. A data extraction form was employed to create a standardized record. This form captured details such as authors, publication year, study objectives, methodologies, principal findings, and conclusions.

The qualitative synthesis method was applied to draw conclusions and discern similarities, trends, and gaps in the current literature. The review was executed in a sequential manner, highlighting the significance of ecosystem value, the adverse effects of pollutants on that value, and management strategies to mitigate pollution impacts in Ria Formosa.

2.2. Evaluation of the Ria Formosa ecological attributes

2.2.1. Habitat Classification Using EUNIS and Dataset Compilation

- i. EUNIS Habitat Classification System:

- Access the European Nature Information System (EUNIS) website to obtain habitat classification codes relevant to the Ria Formosa area.
- Download a preliminary habitat reference table and filter data using the Natura 2000 code PTZPE0017, which corresponds specifically to the Ria Formosa Special Protection Area.
- ii. EUR Habitat Codes: Ensure alignment with EUR28 habitat codes, derived from the EUR15 classification adopted by the Habitats Committee on October 4, 1999. Include updates for habitat types from the 2002 amendments applicable to accession countries.
- iii. Integration of Additional Habitats: Supplement the list with habitats identified in the EUNIS and RAMSAR classification maps or from other reliable GIS datasets and studies.

2.2.2. Data Sources:

- datasets were extracted from the European Marine Observation and Data Network (EMODnet), including:
 - EUSeaMap 2021: A detailed seabed habitat map for Europe.
 - EMODnet RAMSAR: Data layers specific to wetlands of international importance.
 - EMODnetSBH RAMSAR and EUNIS survey maps: Habitat surveys aligning with EUNIS classifications.
 - OSPAR Threatened Habitats: Data concerning the prevalence of declining habitats.
- Where GIS layers were unavailable, existing maps and habitat distributions, particularly those on key habitats like seagrass meadows.

2.2.3. Data Extraction and Preprocessing in QGIS

- i. Quantum GIS (QGIS) Software version 3.05 was utilized for spatial analysis and mapping. Ensure the software and required plugins are installed and operational.
- ii. Importing Shapefiles:
 - Shapefiles were downloaded from the EMODnet portal and other data sources.
 - The files were imported into QGIS and clipped to the Ria Formosa boundary layer, obtained from the Ramsar Information System.
- iii. Boundary Layer Validation: Ensure the Ramsar boundary layer accurately represents the Ria Formosa area.
- iv. Attribute Table Analysis:
 - Attribute tables were examined within QGIS to determine habitat extents and relevant data fields, such as habitat type, area, and ecological descriptors were extracted.

5. Data Integration and Alignment

- Uniformity in Classification: Habitat classifications were harmonized across the EUNIS, RAMSAR, and Natura 2000 frameworks to reduce inconsistencies. This may involve:
 - Cross-referencing habitat codes and definitions between systems.
 - Addressing uncertainties through the engagement of supplementary resources or consultations with ecological specialists.
- Universal Asset Matrix: A comprehensive table (e.g., Table 1, Annex 1) was developed that integrates habitat data from all classification systems. It also incorporated habitat types, classification codes, area, and their ecological significance.

6. Analysis and Visualization

- The spatial extents of habitats were calculated using QGIS, which also generated summary statistics for each habitat type.
- Mapping: High-resolution habitat maps were created to illustrate the spatial distribution of habitats within Ria Formosa. Mapping: Efforts were implemented to guarantee that maps are visually coherent and include suitable legends, scale bars, and annotations.
- Supplementary Data: The ecological context derived from literature was incorporated into the maps and tables, emphasizing critical attributes including biodiversity hotspots, ecosystem services, and conservation priorities.

7. Final Outputs

- Tables and Figures: The habitat data was systematically organized into comprehensive tables and figures for incorporation into the thesis.
- The maps and data summarized and delineated the ecological characteristics of the study area. This involves emphasizing the connections among habitats, ecosystem services, and the importance of conservation.
- The thesis appendix includes methodological notes that outline the processes, tools, and data sources utilized, thereby improving reproducibility.

2.3. Assessing habitat services and sensitivity

To clarify the bioremediation roles of wetlands and marine ecosystems, as well as their sensitivity to various pressures, the Marine Evidence-based Sensitivity Assessment (MarESA) framework was used. Specifically, the Universal Asset Service Matrix (UaSM) and the Universal Asset-Sensitivity Matrix (UaSM) were employed.

The UaSM was used to obtain a localised assessment of pollution-remediation service delivery across the diverse ecosystems in the Ria Formosa, supplemented by literature sources. In this study, the UaSM was adopted into the Universal Asset Bioremediation Matrix (UaBM) to emphasize the significance of natural ecosystems in nutrient regulation, heavy metal extraction, carbon sequestration, and sediment stabilization.

To contextualize the UaBM within the Ria Formosa, the Ria Formosa Asset Bioremediation Matrix (RFaBM) was created. This matrix focuses exclusively on the specific bioremediation services provided by the lagoon's habitats, as referenced in scholarly literature. These regulatory services are essential for maintaining water quality and are critical for the provision of additional ecosystem services such as aquaculture, food security, tourism, biodiversity, and shoreline protection. The importance of these services is underscored by the lagoon's role in tourism, shellfish aquaculture, and fishing—both for sustenance and leisure—particularly in the eastern lagoon between Olhão and Tavira (Erzini et al., 2022).

Additionally, the MarESA Universal Asset Sensitivity Matrix was employed to evaluate the influence and extent of pollution pressures on natural resources. This matrix encompasses pressures such as nutrient enrichment, heavy metals, organic pollution, turbidity, wastewater discharge, and dredging (sedimentation).

To emphasize ecosystem pressures specifically related to pollution, a variant called the Universal Asset-Pollution Sensitivity Matrix was developed. Consequently, the Ria Formosa Asset-Pollution Sensitivity Matrix (RFaPSM) was created, focusing on pollution-related pressures identified in the Ria Formosa according to literature sources (Table 3.2). The RFaPSM uses the universal pressure matrix and highlights local sensitivities that reflect the lagoon's distinct ecological and socio-economic conditions.

The bioremediation potential of Ria Formosa's habitats and their vulnerabilities to pollution were evaluated using the MarESA framework through a systematic multi-step approach:

1. Creating a Universal Asset-Service Matrix (UaSM)

- Selection of Habitats: All habitats present in the Ria Formosa ecosystem were identified by consulting habitat distribution maps, biodiversity studies, and ecological assessments specific to the region.
- Utilizing the MarESA UaSM Tool: The MarESA Universal Asset-Service Matrix tool was accessed, and habitat-specific data were input to extract relevant ecosystem service (ES) information. Each habitat was assigned ES scores based on the standardized UaSM criteria.
- Habitat-Ecosystem Service Cross-Reference: The matrix was supplemented with data extracted from peer-reviewed literature and regional studies to ensure the relevance and accuracy of service provision levels for Ria Formosa. Service provision levels (High, Medium, Low) were adjusted as necessary based on expert consensus and context-specific details.

2. Determining Service Provision Levels and Confidence

- Cross-Correlation: The ecosystem service (ES) data derived from UaSM were compared with the Ria Formosa-specific ecosystem services documented in academic literature and technical reports. To analyze the correlation of various classification systems, Microsoft Excel was used, incorporating EUNIS data available on the European Environmental Agency website.
- Scoring: Service provision levels were assigned using the UaSM scoring system (High, Medium, Low). A confidence level assessment was incorporated, informed by the quality of data sources, publication dates, and the robustness of the underlying methodologies.

3. Sensitivity Analysis

- Using MarESA Sensitivity Analysis Tools: The MarESA sensitivity assessment resources were accessed, and a table summarizing the universal asset-sensitivity matrix was extracted, focusing on parameters relevant to pollution pressures.
- Filtering for Pollution-Related Pressures: The sensitivity table was narrowed to include only pressures associated with pollution, such as nutrient enrichment, heavy metals, organic pollutants, turbidity, and sedimentation from dredging.
- Regional Contextualization: The matrix was refined to account for unique pressures observed in Ria Formosa. This sensitivity analysis was tailored by integrating EMODnet pressure data and region-specific studies.

4. Creating Habitat and Pollution Parameter Tables

- Mapping Habitats and Pollutants: A comprehensive table was created linking Ria Formosa habitats to specific pollution parameters, leveraging both the literature and EMODnet datasets.
- Assigning Sensitivity Levels: Each habitat's sensitivity was evaluated based on its capacity for pollutant filtration, resistance to turbidity, and bioaccumulation potential. Sensitivity scores (High, Medium, Low) were assigned using MarESA methodologies.
- Confidence Level Assessment: Confidence levels in sensitivity assignments were assessed based on the timeliness of data, with older publications assigned lower confidence levels.

5. Visualization and Interpretation

- **Color-Coding for Sensitivity:** A red-yellow-green scheme was used to represent high, medium, and low pollution sensitivity levels, respectively. The thresholds for these levels were defined based on contextual evidence from local studies, standards set by the MarESA framework, and the ecological characteristics of Ria Formosa.
- **Visual Representation:** The color scheme was implemented into tables and diagrams to facilitate clear communication of findings.

6. Creating Custom Frameworks

- **Ria Formosa Bioremediation Matrix (RFaBM):** A localized version of the UaSM was derived, focusing on bioremediation services. Contributions to nutrient regulation, heavy metal removal, carbon sequestration, and sediment stabilization were highlighted, emphasizing their significance for water quality and related services.
- **Ria Formosa Pollution Sensitivity Matrix (RFaPSM):** A pollution-specific iteration of the UaSM was developed. Regional sensitivities and pollution pressures were incorporated to provide a focused assessment of the lagoon's vulnerability to anthropogenic impacts.

2.4. Development of a Nature-based solution (NbS) framework for pollution remediation

Building upon the findings from the previous methods, a framework for implementing pollution-related nature-based solutions (NbS) in Ria Formosa was developed to mitigate pollution impacts on vital habitats. This conceptual strategy aimed to address marine pollution issues by leveraging NbS and is based on a comprehensive understanding of the interactions among natural assets (habitats), ecosystem services, pollution pressures, and ecosystem sensitivities. It consists of three levels: Metrics for Identifying Pollution-Related Nature-Based Solutions, Criteria Definition for Effective Nature-based Solutions According to IUCN and NbS Identification Framework for Ria Formosa.

The conceptual model developed under this context comprised the following steps:

1. Identification of natural assets (habitats) comprising the Ria Formosa ecosystem, including seagrass meadows, salt marshes, tidal mudflats, and littoral sandbanks.
2. Identification of the ecosystem services provided by these habitats, particularly those related to pollution mitigation, such as nutrient cycling, sediment stabilization, water filtration, and carbon sequestration.
3. Identification of pollution-related stressors: significant impediments to these services encompass nutrient enrichment (eutrophication), heavy metal contamination, organic pollution, microplastic pollution, and anthropogenic effects (dredging and wastewater discharge).

3. Results and Discussions

3.1. Evaluation of the Ria Formosa ecological attributes of using the European Nature Information System (EUNIS) Habitat Classification System

This sub-section provides an overview of the ecological context of the Ria Formosa Lagoon, emphasizing the classification of its diverse habitats, referred to as ecosystem assets, in accordance with the European Nature Information System (EUNIS) classification system. Subsequently, a detailed description of the EUNIS habitat types present in the lagoon is provided, encompassing tidal flats, salt marsh, seagrass meadow, and sublittoral sandbank, supplemented by maps and tables. The interconnections between these habitats and their ecological roles within the lagoon are also highlighted.

The objective is to facilitate further examination into how natural habitats in Ria Formosa mitigate pollution and to assess their vulnerabilities to pollution as a significant stressor in modern marine and coastal ecosystems. Therefore, the prospective value of these habitats for the advancement of NbS focused on pollution mitigation relies on a comprehensive understanding of their ecological contexts and current conditions, such as their spatial extents and ecosystem services. It is imperative to categorize the diverse differentiated habitats within the Ria Formosa Lagoon utilizing recognized classification systems, such as EUNIS.

The application of the EUNIS and Ramsar classification systems provides a dual framework for a clearer comprehension of the ecological complexity of the Ria Formosa Lagoon. EUNIS classifies specific habitat types and their ecological roles, whereas the Ramsar system focuses on wetlands to promote global biodiversity and ecological functions. The application and implementation of both systems in documenting the Ria Formosa Lagoon's habitats guarantee comprehensive descriptions and recordings of their features for subsequent analysis and as a prerequisite for potential protection and restoration efforts.

Consequently, it was imperative to align these classification systems for consistency within the European framework, as both systems provide crucial methodologies for the identification and improvement of habitat protection and management.



Figure 3.1: Conceptual diagrams of EUNIS and Ramsar classification systems for the Ria Formosa lagoon

3.1.1. Habitat classification of Ria Formosa using EUNIS and Ramsar classification systems

Figure 3.2. shows a comprehensive map of all Ria Formosa habitats classified using EUNIS and Ramsar systems. The findings indicate overarching habitat categories (level 1) and subdivisions based on physical characteristics such as salinity, depth, and sediment type (levels 2 and 3). Estuaries, fully saline coastal lagoons, and brackish coastal lagoons typical of Ria Formosa, are categorized as X01, X02, and X03, respectively. The sub-category known as Estuarine coarse sediment shores is classified as A2.12. The various biotypes in Ria Formosa are classified into two main categories: terrestrial wetland habitats and marine habitats.

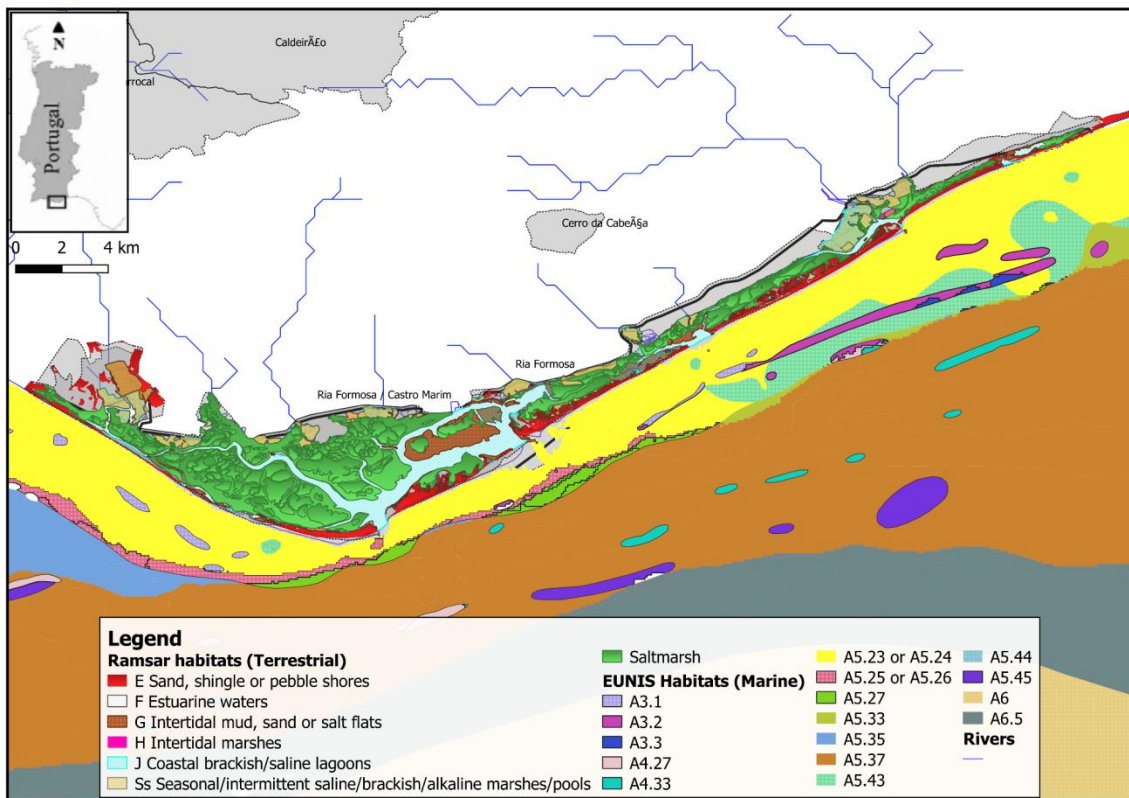


Figure 3.2: A comprehensive map of all habitats in the Ria Formosa, utilizing both EUNIS and RAMSAR classifications.

3.1. 2. Marine habitats (A5)

Various habitat categories were delineated from the EMODnet EUSeaMap data, primarily consisting of substrates and hard substrata, including A3 (infralittoral rock and other hard substrata), A4 (circalittoral rock and other hard substrata), A5 (sublittoral substrate), and A6 (deep sea bed), as shown in Figure 3.3.

The EMODnet EUNIS Survey mapping layers augment the hard substrate categories with the following notable subcategories: A5.23 and A5.24 (Infralittoral fine sand with *Ervilia castanea* and *Bathyporeia spp./[Ophiura spp.]* in infralittoral fine sand, and Infralittoral muddy sand) located on the West coast, A5.25 (Circalittoral fine sand with *Ervilia castanea* and *Nemertini/[Ophiura texturata]* and hermit crab communities in circalittoral fine sand), A5.26 (circalittoral muddy sand with *Calyptraea chinensis*), and A5.27 (deep circalittoral sand with *Diogenes pugilator*, *Amphiura filiformis*, and *Prionospio malmgreni*).

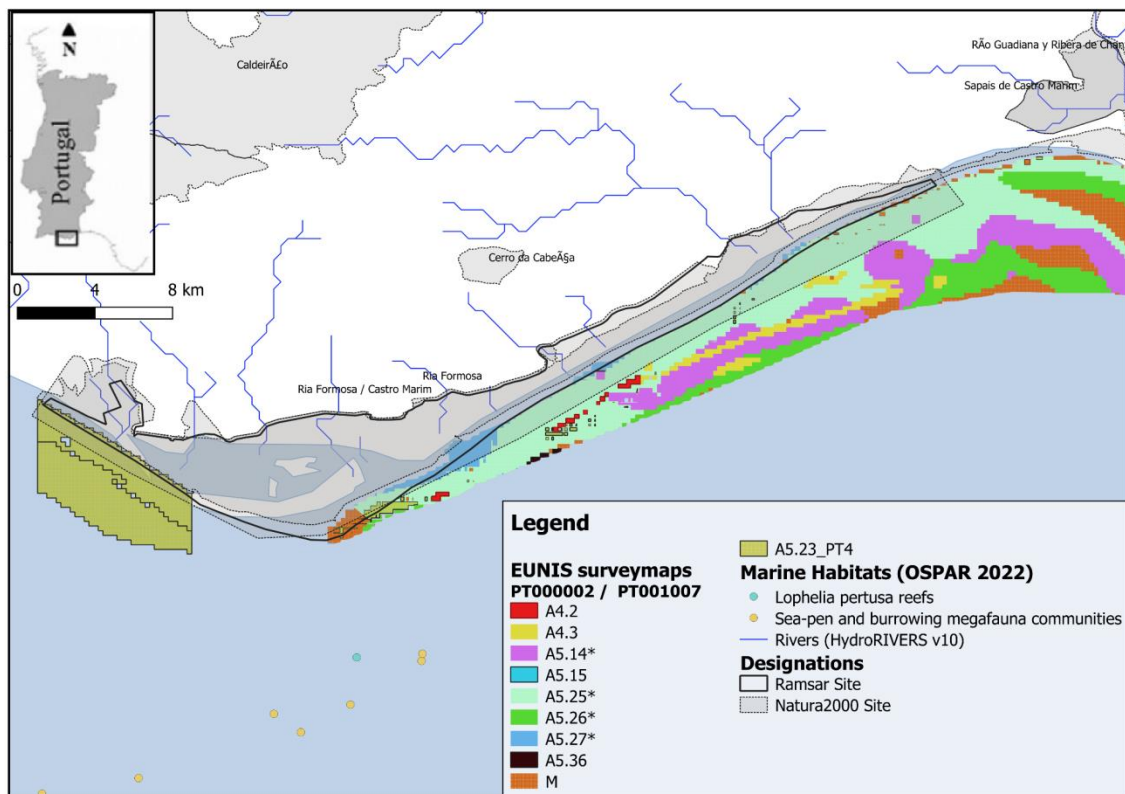


Figure 3.3: Comprehensive map of marine habitats derived from EMODnet EUSeaMap data, emphasizing substrates and hard substrata

Certain habitat types from the EUSeaMap and EUNIS habitat survey maps may be amalgamated due to their descriptions of analogous habitats as follows: 5.14/5.15/5.43 (Circalittoral coarse sediment characterized by a homogeneous macrofaunal community and Deep Circalittoral coarse sediment); 5.23/5.24 (Infralittoral fine sand and Infralittoral muddy sand); 5.26/5.27 (Circalittoral muddy sand containing *Calyptraea chinensis* and Deep Circalittoral sand inhabited by *Diogenes pugilator*, *Amphiura filiformis*, and *Prionospio malmgreni*).

3.1.2.1. Sublittoral Sandbanks (EUNIS Code A5.2)

The EUNIS code A5.2 encompasses sublittoral sandbanks within the aquatic physical environment of Ria Formosa Lagoon. These are shallow sandbanks that form in water depths of less than 20 meters, influenced by tidal currents, wave action, and sediment transport.

The fine-grained sandbanks in the sublittoral zone serve as crucial habitats for the marine community, providing foraging and sheltering areas for demersal fish and invertebrates.

They significantly influence sedimentation processes in the lagoon, stabilize coastal areas, and mitigate erosion of the neighbouring tidal flats and salt marsh regions (Beermann et al., 2023).

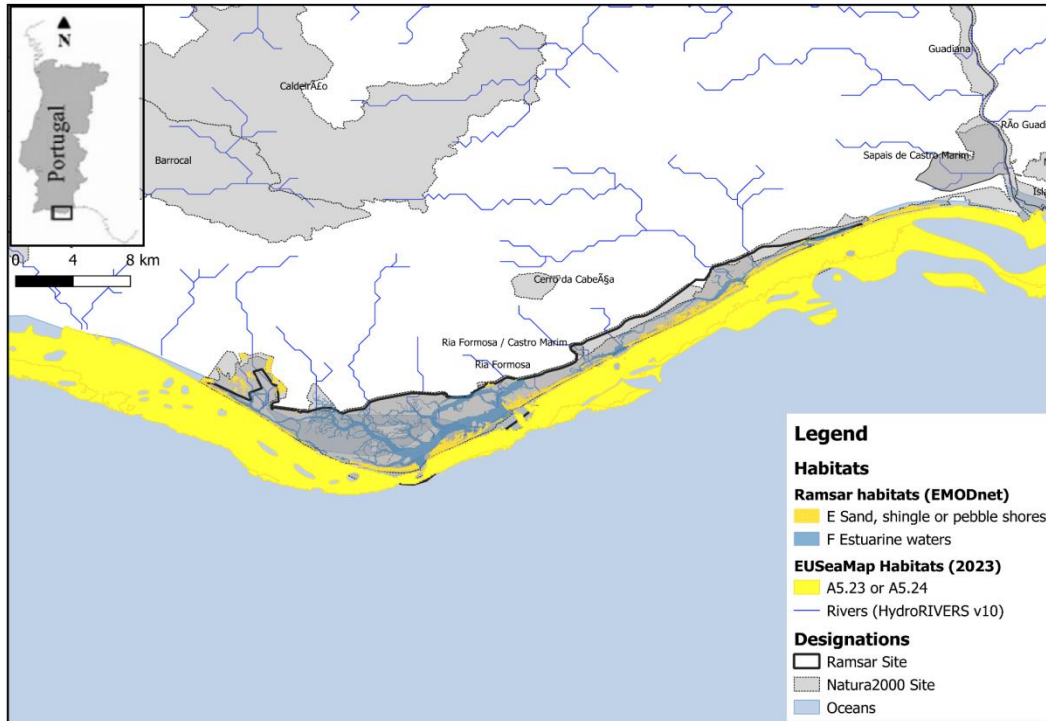


Figure 3.4: Sublittoral sandbanks in the underwater ecosystem of Ria Formosa lagoon.

The sandbanks in Ria Formosa are high-energy systems undergoing hydro-dynamic changes due to natural processes, essential for preserving the lagoon's geomorphological stability, and continuously provide sand critical for the benthos, thereby supporting biological production in the lagoon (Sprung, 1994). (Figure 3.5). They also provide habitat for crustaceans, including shrimp (*Penaeus kerathurus*) and bivalves such as clams (*Ruditapes decussatus*) and cockles (*Cerastoderma edule*) (Sprung, 1994). These species possess significant forage value in the local fisheries, which are crucial for the region's socio-economic factors (Cozzolino et al., 2021).

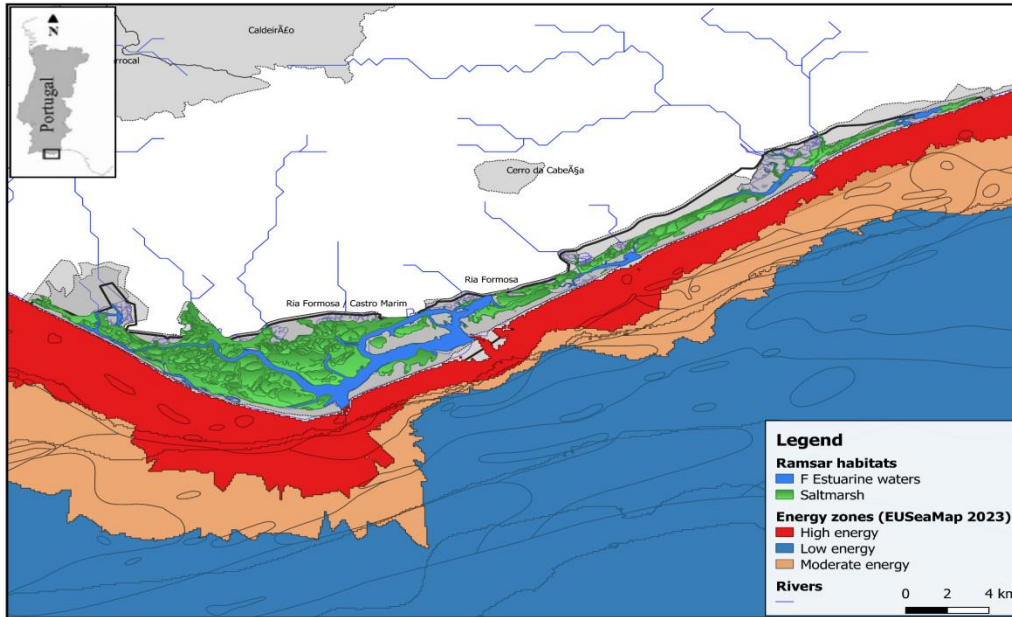


Figure 3.5: Energy zonation of sandbanks in Ria Formosa

3.1.2.2. Terrestrial wetland biotypes

This category describes habitats that fall on the landward side of the lagoon/estuary. These include sandy and shingle coastlines, along with subcategories delineated from the RAMSAR habitat survey data, such as tidal flats, salt marshes, seagrass, and sublittoral sands (Sprung, 1994).

3.1.2.3. Sand and shingle shores (B1/B2)

Advancing inland, habitats characterized by sand and shingle (B1/B2) encompass an area of 3483.03 hectares situated between the terrestrial wetland ecosystems and the high-energy, dynamic subtidal zones (A5.2) of Ria Formosa (Figure 3.6).

The sand-covered shorelines connecting the coastal lagoon to the ocean are dynamic regions continuously modified by wind and wave activity. They comprise gently inclined beaches and beach ridges, created by sands transported by waves, longshore drift, and storm surges, along with dunes, formed by aeolian deposits, occasionally reshaped by waves (eunis habitats). These habitats form the first level

of coastal defense against wave action. They yield to the tidal flats of Ria Formosa, which enhance wave energy dissipation, thereby mitigating extensive flooding and rapid erosion.

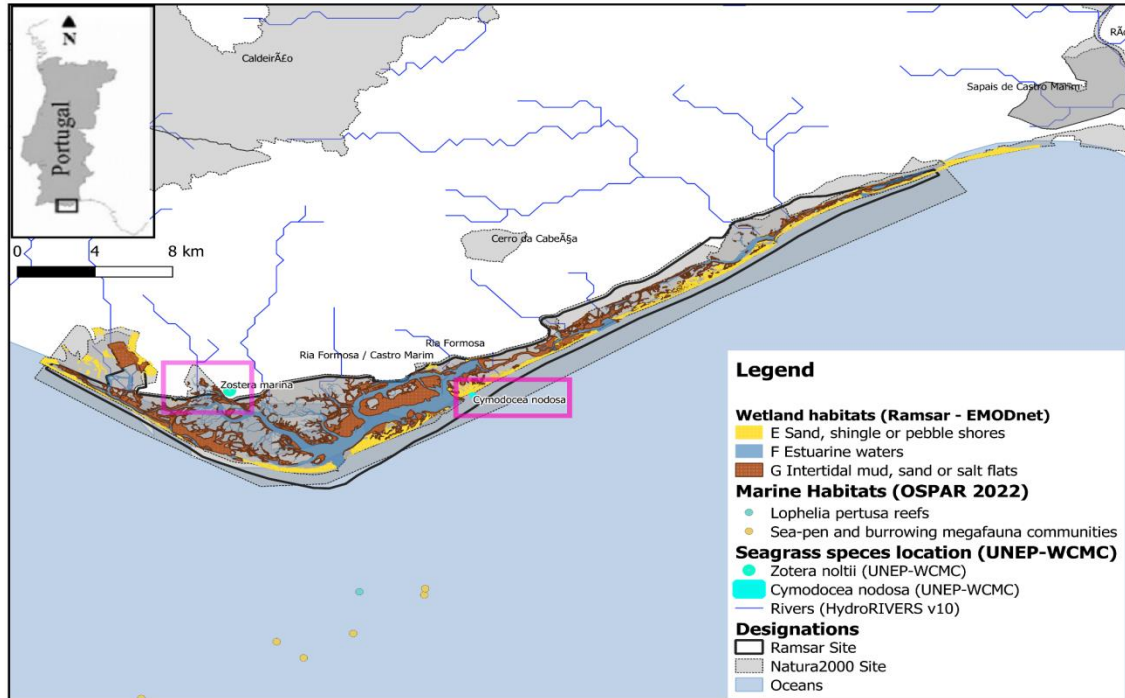


Figure 3.6: Sand and shingle-dominated habitats between terrestrial wetlands and high-energy subtidal zones of Ria Formosa

3.1.2.4. Seasonal/ intermittent saline/ brackish/ alkaline marshes/ pools (Ss/C1.66)

This habitat category encompasses nearly the entire Ria Formosa lagoon, spanning an area of 13,693.49 hectares out of a total of 16,000 hectares (Figure 3.7). It denotes the superficial, transient saline and brackish waters, in which communities may establish, typically forming two strata. The predominant species in seasonal saline habitats include *Ranunculus trichophyllus*, *Najas minor*, *Najas marina*, and *Ceratophyllum demersum* (Eunis habitats 519).

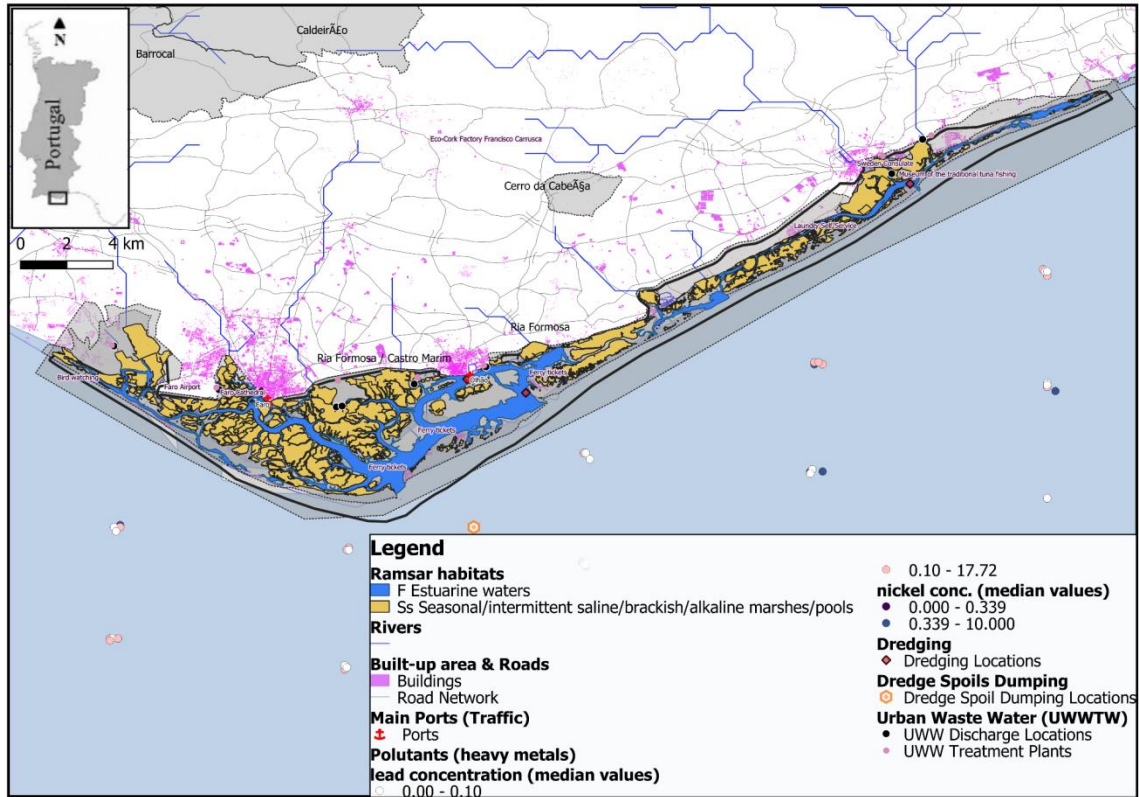


Figure 3.7: Dynamic seasonal marshes and pools: saline, brackish, and alkaline zones of Ria Formosa

3.1.2.5. Intertidal Sediment Habitats: Tidal Flats (EUNIS Code A2.3)

Figure 3.8 shows intertidal sediment habitats. The intertidal zones of the Ria Formosa encompass tidal flats, which are essential components of this zone and are classified by EUNIS as "intertidal soft sediments or intertidal mud, sand, or salt flats" (A2.3) (EUNIS Habitat Type Hierarchical View, marine, 2022, terrestrial 2021.). These comprise fine particulate sediment, predominantly within the silt and clay fraction (particle size less than 0.063 mm in diameter), although sandy mud may encompass up to 40% sand (primarily very fine and fine sand). This habitat comprises extensive mudflats spanning approximately 2957.55 hectares within the sheltered Ria Formosa Lagoon, sustaining high densities of benthic species and avifauna.

During low tide, these areas are revealed, while during high tide, they submerge, creating abundant habitats for various invertebrates. Tidal flats typically comprise mud or sand moulded by tidal currents and runoff from neighbouring land (Wang et al., 2019). The mudflats of Ria Formosa are rich in organic matter, which increases their productivity for benthic organisms such as polychaete worms and molluscs (Sprung, 1994). In the lagoon ecosystem, these organisms serve as sustenance for wading birds, such as the Eurasian oystercatcher (*Haematopus ostralegus*) and the grey plover (*Pluvialis squatarola*) (Brito et al., 2010). The feeding zones for juvenile mullets and seabass are essential in these flats, serving as critical nursery habitats.

The sediment composition enhances nutrient cycling, thereby sustaining the lagoon's water quality. Tidal flats exhibit a pronounced response to pollution resulting from surplus nutrients derived from agriculture and domestic waste. Eutrophication may arise from this condition, resulting in detrimental algal blooms and hypoxia that adversely affect biodiversity and the functionality of these habitats (Newton et al., 2003). The restoration and conservation of tidal flats in Ria Formosa are essential to nature-based solutions (NbS) aimed at preserving biodiversity and enhancing ecosystem resilience.

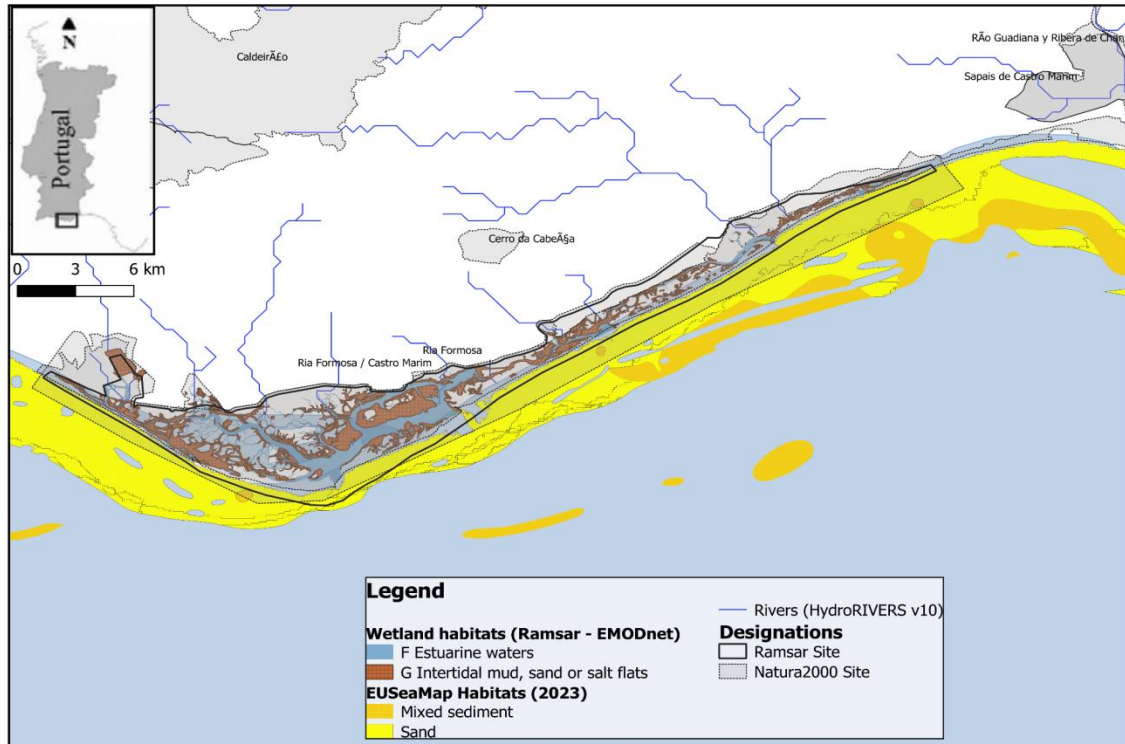
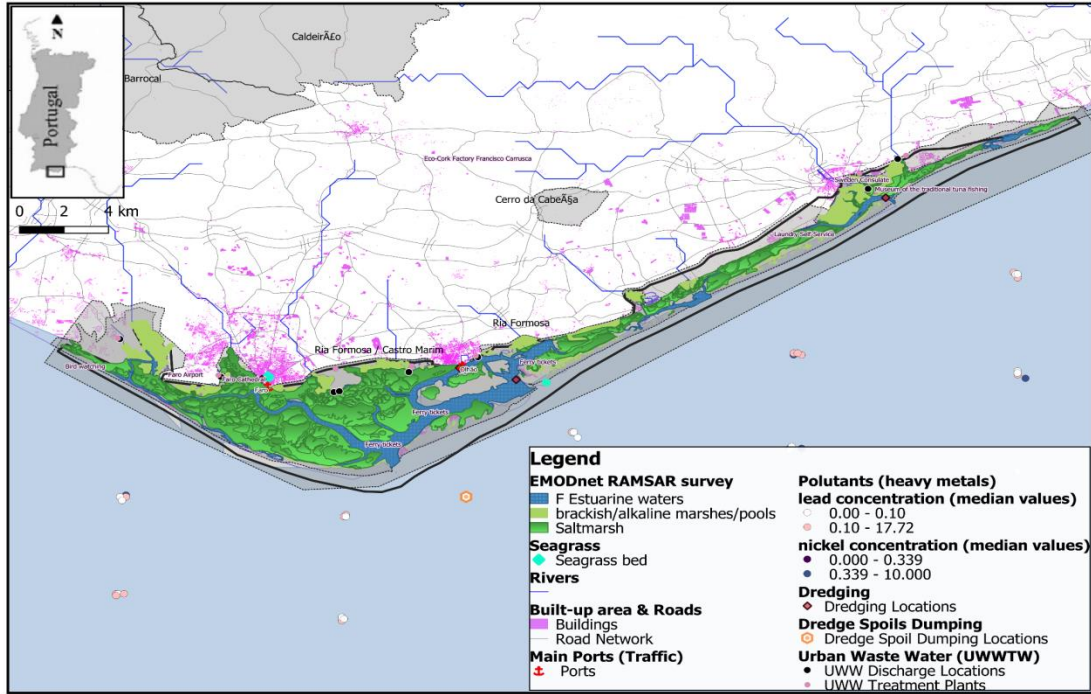


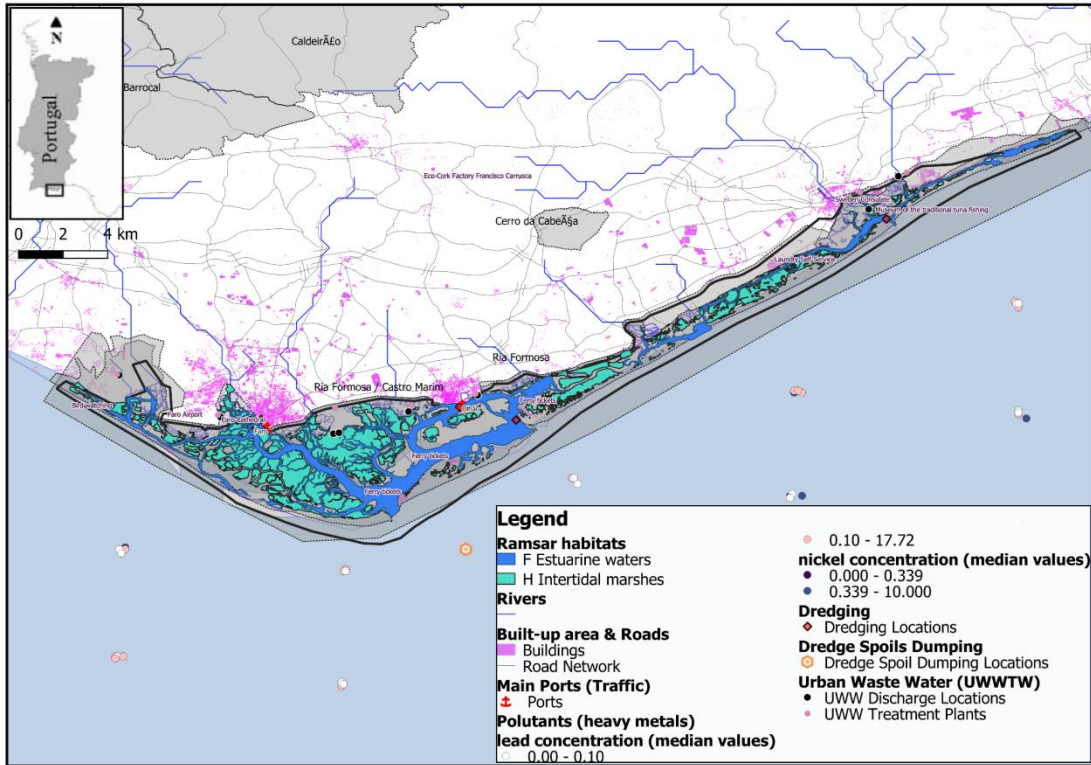
Figure 3.8: Intertidal sediment habitats: tidal flats of mix sediment and sand.

3.1.2.6. Salt Marshes (EUNIS Code A2.53)

Salt marshes (A2.53) constitute a significant characteristic of the Ria Formosa Lagoon. Based on the UNEP-WCMC data, this habitat covers an area of 8827.57 ha (Figure 3.9). Inertial marshes encompass 3589.88 hectares, according to RAMSAR habitat survey data, featuring predominant halophytic vegetation (A2.53) (EUNIS Habitat Type Hierarchical View, marine, 2022, terrestrial, 2021.). The predominant species in these marshes thrive in saline environments, and their composition is influenced by the extent and duration of tidal flooding. The Ria Formosa is home to four principal species: *Spartina maritima*, *Salicornia ramosissima*, *Sarcocornia fruticosa*, and *Juncus maritimus*. These plants withstand and flourish in high-salinity water while aiding in sediment stabilization through their extensive roots (Manuela et al., 2015).



a)



b)

Figure 3.9: Distribution of Salt Marsh Habitats in Ria Formosa showing the UNEP-WCMC data (2010) (a) and EMODnetata (2023) (b).

Figures 3.9 (a and b) both represent salt marsh habitats in Ria Formosa. Nonetheless, Figure 3.9a is an antiquated dataset from 2010, supplied by UNEP-WCMC. The data reveals that the saltmarsh of Ria Formosa covered an area of 8827.57 km² (Table 3.1). Conversely, Figure 3.9b illustrates the Ramsar Classification System Wetland Type 'H-Intertidal Marshes,' as delineated by CCMAR in 2023, encompassing an area of 3589.88 km². The inconsistency between the two datasets may indicate a significant decrease in salt marsh area of roughly 5237.69 km² over the 13-year period since 2010. The discrepancy may also arise from differences in research methodologies, thus requiring additional examination.

3.1.2.7. Seagrass Meadows (EUNIS Code A5.545, A5.53 and A2.61)

Seagrass meadows are essential underwater ecosystems due to their structure and significance in sustaining crucial marine biodiversity. *Zostera noltii* is predominantly located in lower estuaries and protected coastal muddy sands of lagoons. *Z. noltii* establishes dense beds with leaves reaching lengths of up to 20 cm, predominantly in the intertidal zone, though it may also be found in extremely shallow subtidal areas on mud/sand substrates of diverse consistency. The seagrass *Cymodocea nodosa* inhabits soft substrates composed of well-sorted fine sands (Eunis habitats 2236).

Zostera marina establishes dense beds with elongated leaves reaching up to 1 meter in length, inhabiting sheltered bays and lagoons from the lower intertidal zone to approximately 4 meters in depth, predominantly on sandy substrates and sandy mud, occasionally interspersed with gravel (Ospar_zostera_definition.pdf). Estimates of seagrass coverage in Ria Formosa indicate *Z. marina* at 5.1 hectares and *C. nodosa* at 91.26 hectares, respectively.

The predominant seagrass species in Ria Formosa (Figure 3.9) is *Z. noltii*, which occupies an estimated 45% (1304 ha) of the intertidal zone, contributing to a total intertidal area of 2886 ha (Cunha et al., 2009). *Z. noltii* and *C. nodosa* constitute some of the most biodiverse and productive ecosystems (Cunha & Duarte, 2007) in shallow subtidal zones of Ria Formosa, creating a continuous bed that provides shelter, sustenance, and breeding grounds for various marine organisms, commercially significant fish, and other marine invertebrates (Erzini et al., 2022).

3.1.3. Ria Formosa habitats overview

Table 3.1. summarises the attribute data of wetland habitats in Ria Formosa, showing their extent. The habitat extents were calculated in QGIS using the RAMSAR and EUNIS habitat survey maps. The extents of seagrass were obtained from the existing literature. The correlation of various classification systems was conducted on Microsoft Excel, using EUNIS data accessible on the European Environmental Agency's website.

This sub-section has outlined and assessed the primary coastal and marine habitats in Ria Formosa, classifying them according to the EUNIS and Ramsar systems to understand the ecological complexities of the lagoon. It emphasizes that various datasets, both historical and contemporary, were combined to produce the habitat maps utilizing diverse survey methodologies. This indicates that certain habitats illustrated may not accurately reflect current extents. Moreover, diverse classification systems were employed by the different data providers. This issue was tackled by cross-correlating EUNIS and RAMSAR classification codes (to be inserted as an annex). Integrating these systems establishes a robust foundation for characterizing and understanding the varied habitats within the lagoon, as well as for assessing future changes.

Additionally, this framework facilitates a clearer understanding of how these ecosystems enhance biodiversity and regulate environmental processes. Using

this framework, the next step of the present work was evaluating the ecosystem services of the Ria Formosa Lagoon.

Overall, the classification of habitats in the Ria Formosa Lagoon underscores significant habitat characteristics and facilitates a rapid evaluation of their ecological functions, such as supporting biodiversity and enhancing the coastal ecosystem's resilience to disturbances. Therefore, identifying and preserving the EUNIS biotope classes of the lagoon sustains and amplifies the provision of ecosystem services from the site for enzymatic processes while actively bolstering the unity of adjacent human communities.

Table 3.1: Attribute data of wetland habitats in Ria Formosa showing their extent.

Habitat Name	EUNIS code	Survey Method	End date	Data provider / reference	Area, ha (Total inter-tidal area, ha)
<i>Zostera marina</i>	A5.5331	Aerial photography, on-site groundtruthing surveys, photo-interpretation and statistical analysis	31/12/2007	Cunha et al. (2006) (https://www.researchgate.net/publication/29047287_Estimation_of_available_seagrass_meadow_area_in_Portugal_for_transplanting_p)	5.0
<i>Zostera noltii</i>	A2.6111	Spatial analysis Stakeholder analysis	31/12/2010	Helena et al. (2012), sciencedirect)	1304.0 (2886.0)
<i>Cymodocea nodosa</i>	A5.53132	Aerial photography, on-site groundtruthing surveys,	31/12/2007	A. H. Cunha, J. Assis, & E. A. Serrão (https://www.researchgate.net/publication/29047287_Estimation_of_available_seagrass_meadow_area_in_Portugal_for_transpla)	91.3

Habitat Name	EUNIS code	Survey Method	End date	Data provider / reference	Area, ha (Total inter-tidal area, ha)
		photo-interpretation and statistical analysis		nting_purposes/figures?lo=1)	
Sand, shingle or pebble shores	B2	Ramsar Classification System for Wetland Type	15-May-2023	CCMAR	3483.0
Estuarine waters	X01	Ramsar Classification System for Wetland Type	16-May-2023	CCMAR	2667.6
Habitat Name	EUNIS code	Survey Method	End date	Data provider / reference	Area, ha (Total inter-tidal area, ha)
Intertidal mud, sand or salt flats	A2.2	Ramsar Classification System for Wetland Type	17-May-2023	CCMAR	2957.5
Intertidal marshes	A2.5	Ramsar Classification System for Wetland Type	18-May-2023	CCMAR	3589.9
Coastal brackish / saline lagoons	X02 / X30	Ramsar Classification System for Wetland Type	19-May-2023	CCMAR	10357.7
Seasonal / intermittent saline/brackish/alkaline marshes / pools	Ss	Ramsar Classification System for Wetland Type	20-May-2023	CCMAR	13693.5
Saltmarsh	A2.5	Remote sensing, ground-truth	2010	UNEP-WCMC	8827.6

3.2. Evaluation of the bioremediation services delivered by key habitats in Ria Formosa and their sensitivity to pollution based on the MarESA Framework

This section examines the capability of habitats in Ria Formosa, as categorized using the EUNIS system, to perform pollution bioremediation functions and assesses their vulnerability to diverse pollutants. It addresses the ecosystem services related to pollution as a foundation for utilizing natural components to devise solutions for pollution remediation. This indicates an assessment of habitat resilience, demonstrating their ability to provide sustainable nature-based solutions to address pollution.

In an ecological context, resilience denotes the ability of ecological systems to withstand shocks or disturbances resulting from anthropogenic or natural events (Dey et al., 2024). It is crucial to understand the extent to which current ecosystems naturally remove pollutants from the environment and how different types of pollutants in turn impact them as a prerequisite for developing frameworks and models that enable the implementation of NbS for pollution bioremediation.

Initially, various asset-service and asset-sensitivity frameworks were examined to assess habitat resilience to diverse stressors. These integrated tools elucidate the role of marine habitats in supporting ecosystem functions and their vulnerability to environmental stressors, including the Marine Evidence-based Sensitivity Assessment, Marine Sensitivity Assessments, Feature Activity Sensitivity Tool (FeAST), Habitat Resilience Tool-CaBa-Catchment Based Approach, Habitat Evaluation and Assessment Tools (HEAT), Habitat and Biodiversity Assessment Tool (HBAT) (, and an expert-led consensus (Delphi) approach to develop a sensitivity matrix.

The Marine Evidence-based Sensitivity Assessment (MarESA) was ultimately considered the most suitable for this work. MarESA consists of two frameworks: The Universal Asset-Service Matrix (UaSM) and the Habitat Sensitivity Matrix.

The latter denotes an evidence-based approach for evaluating the delivery of ecosystem services by marine and coastal habitats, utilizing various habitat classification frameworks such as the Common International Classification of Ecosystem Services (CICES), Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), and the Economics of Ecosystems and Biodiversity (TEEB), alongside the susceptibility of these habitats and species to multiple pressures. Sensitivity refers to the degree to which a habitat can be adversely affected by different stressors, dependent on its biological characteristics. The sensitivity assessment directs management actions by identifying areas of low resilience and delineating conservation strategies (Dey et al., 2024)

3.2.1. The MarESA Universal Asset Service and Sensitivity Matrix

A generic asset-service matrix and the universal asset sensitivity matrix were created, under this work, to evaluate the bioremediation service provision of habitats in Ria Formosa and their susceptibility to pollution. The matrix correlates essential habitat types with potential pollution parameters and evaluates their sensitivity using a three-tier scale: highly sensitive, moderately sensitive, and low sensitivity. A universal asset-bioremediation matrix (UaBM, Table 3.2) was initially developed by refining the UaSM for pollution services. The primary service identified was the decomposition of waste or pollutants (CICES 2.1.1.1) (or waste breakdown and detoxification of water and sediments, as per the original ES). The UaBM was subsequently filtered to delineate the primary habitats present in the Ria Formosa Lagoon, along with the ecosystem services they provide, the extent

of service delivery, the specific regions where these services are most prominent, and the associated confidence level (Annex 2, Table 2).

The table indicates that, despite their low confidence, the habitats exhibited a high level of bioremediation service provision for sedimentary habitats such as mudflat, moderate for marine/terrestrial vegetation, e.g., seagrass, saltmarsh, and mussel beds, and low for rocky littoral habitats.

Table 3.2. Universal Asset-Bioremediation Matrix (UaBM) derived from the UaSM

Service: Decomposing wastes or polluting substances (CICES 2.1.1.1) (or Waste breakdown & detoxification of water and sediments, according to the original ES)			
Habitat (EUNIS 2007)	Supply Level	confidence	Confidence Type
A2.3: Littoral mud	High	Low	Inherited
A2.31: Polychaete/bivalve-dominated mid-estuarine mud shores	High	Low	Inherited
A2.311: [<i>Nephtys hombergii</i>], [<i>Macoma balthica</i>] and [<i>Streblospio shrubsolii</i>] in littoral sandy mud	High	Low	Inherited
A2.312: [<i>Hediste diversicolor</i>] and [<i>Macoma balthica</i>] in littoral sandy mud	High	Low	Inherited
A2.313: [<i>Hediste diversicolor</i>], [<i>Macoma balthica</i>] and [<i>Scrobicularia plana</i>] in littoral sandy mud	High	Low	Inherited
A2.32: Polychaete/oligochaete-dominated upper estuarine mud shores	High	Low	Inherited
A2.321: [<i>Nephtys hombergii</i>] and [<i>Streblospio shrubsolii</i>] in littoral mud	High	Low	Inherited
A2.322—[<i>Hediste diversicolor</i>] in littoral mud	High	Low	Inherited
A2.3221: [<i>Hediste diversicolor</i>] and [<i>Streblospio shrubsolii</i>] in littoral sandy mud	High	Low	Inherited
A2.3222: [<i>Hediste diversicolor</i>] and [<i>Corophium volutator</i>] in littoral mud	High	Low	Inherited
A2.3223: [<i>Hediste diversicolor</i>] and oligochaetes in littoral mud	High	Low	Inherited
A2.323: [<i>Tubificoides benedii</i>] and other oligochaetes in littoral mud	High	Low	Inherited
A5.361: Seapens and burrowing megafauna in circalittoral fine mud	High	Low	Inherited

Service: Decomposing wastes or polluting substances (CICES 2.1.1.1) (or Waste breakdown & detoxification of water and sediments, according to the original ES)

A5.3611: Seapens, including <i>Funiculina quadrangularis</i>], and burrowing megafauna in undisturbed circalittoral fine mud	High	Low	Inherited
A5.362: Burrowing megafauna and [<i>Maxmuelleria lankesteri</i>] in circalittoral mud	High	Low	Inherited
A2.6111: [<i>Zostera noltii</i>] beds in littoral muddy sand	Medium	Low	Inherited
A3.361: [<i>Mytilus edulis</i>] beds on reduced salinity infralittoral rock	Medium	Low	Inherited
A5.434: [<i>Limaria hians</i>] beds in tide-swept sublittoral muddy mixed sediment	Medium	Low	Inherited
A5.5331: [<i>Zostera marina</i>]/[<i>angustifolia</i>] beds on lower shore or infralittoral clean or muddy sand	Medium	Low	Inherited
A5.5343—[<i>Ruppia maritima</i>] in reduced salinity infralittoral muddy sand	Medium	Low	Inherited
A4.2111: [<i>Caryophyllia smithii</i>], [<i>Swiftia pallida</i>] and [<i>Alcyonium glomeratum</i>] on wave-sheltered circalittoral rock	Low	Low	Inherited
A4.2112: [<i>Caryophyllia smithii</i>], [<i>Swiftia pallida</i>] and large solitary ascidians on exposed or moderately exposed circalittoral rock	Low	Low	Inherited
A4.211: [<i>Caryophyllia smithii</i>] and [<i>Swiftia pallida</i>] on circalittoral rock	Low	Low	Inherited

Subsequently, the vulnerability of habitats to pollution is evaluated using the universal asset-sensitivity matrix to formulate the Universal Asset-Pollution Sensitivity Matrix (UaPSM). The Ria Formosa specific Asset-Pollution Sensitivity Matrix (RFaPSM) was developed and subsequently compared with sensitivity data for the area obtained from literature and other databases, along with their corresponding confidence levels (Table 3.3).




The conclusive database of sensitivity assessment, coupled with the confidence levels based on data age, provides pertinent information for enhancing management strategies to mitigate pollution impacts on the Ria Formosa Lagoon

ecosystem. This is included as an annex to be appended to this thesis (Annexe 3, Table 3).

Table 3.3: The Ria Formosa Asset-Pollution Sensitivity Matrix (RFaPSM).

Pollution Pressure	Intertidal Mud	Salt Marshes	Seagrass Meadows	Sublittoral Sandbanks
Nutrient Enrichment (Eutrophication)	High sensitivity	Moderate sensitivity	High sensitivity	Low sensitivity
Sediment Contamination (Heavy Metals: Cadmium, Lead, Nickel)	High sensitivity	High sensitivity	Moderate sensitivity	Low sensitivity
Organic Pollution	High sensitivity	Moderate sensitivity	Moderate sensitivity	Moderate sensitivity
Hydrocarbon Pollution	Moderate sensitivity	Moderate sensitivity	High sensitivity	Low sensitivity
Microplastic Pollution	High sensitivity	Moderate sensitivity	High sensitivity	Low sensitivity
Turbidity	High sensitivity	Moderate sensitivity	High sensitivity	Low sensitivity

Key:

-  = High sensitivity
-  = moderate sensitivity
-  = Low sensitivity

3.2.2. Analysis of Universal and Ria Formosa Asset Service and Sensitivity Matrices

3.2.2.1. Tidal flats (TF: A2.3)

Tidal flats and sublittoral sandbanks provide essential ecosystem services, including nutrients cycling, sediment stabilization, and water filtration. Tidal flats are crucial for nutrient cycling, facilitating the decomposition of organic matter and the recycling of nutrients within the ecosystem. Hence, their high level of bioremediation service delivery. Their ability to stabilize sediments also maintains the structural integrity of the lagoon, alleviating the impacts of erosion (Kim et al., 2020). However, the UaPM demonstrates considerable susceptibility of tidal flats to nutrient and organic contamination. The extensive mud and sand flats of Ria Formosa experience heightened nutrient enrichment due to wastewater treatment and industrial discharges (A. Cravo et al., 2022; A. Newton et al., 2022). Thus, nutrient enrichment, especially in the lagoon's eastern region, due to anthropogenic influences like agricultural runoff and urban wastewater (A. Cravo et al., 2022), jeopardizes the lagoon's integrity by causing harmful algal blooms and eutrophication that hinder fisheries and diminish water quality. Tidal flats also exhibit considerable susceptibility to organic pollution from aquaculture runoff (Kumar et al., 2020), marked vulnerability to sediment contamination from heavy metal accumulation (Manuela et al., 2015), moderate sensitivity to hydrocarbon pollution due to its enduring effects (Kumar et al., 2020), and increased sensitivity to microplastic pollution as they retain microplastics due to diminished water flow (Cozzolino et al., 2021). Furthermore, they demonstrate significant sensitivity to turbidity resulting from increased dredging associated with coastal development, which hinders their ability to deliver vital ecosystem services, such as sediment stabilization and habitat provision for benthic fauna (Jacob et al., 2020).

3.2.2.2. Sublittoral sandbanks (Ss: A5.2)

The UaBM acknowledged Ss as crucial for sediment stabilization and particularly important for the sustenance of benthic organisms. In Ria Formosa (RFaBM), designated sandbank areas adjacent to Armona and Culatra islands provide

essential regulating services by alleviating coastal erosion and stabilizing sediments, thereby protecting nearby seagrass meadows and tidal flats from further degradation due to sedimentation (Gamito, 2008). Dredging activities near the sandbanks of Armona and Culatra islands represent the principal pressures impacting SS habitats (Newton et al., 2022). These pressures reduce the structural integrity of sublittoral sandbank habitats for benthic organisms and their resilience to shore displacement (Duarte et al., 2007). Sublittoral sandbanks, as per UaPSM, exhibit minimal sensitivity to organic pollution and nutrient enrichment, as well as low sensitivity to turbidity and sediment contamination, owing to their intrinsic sediment mobility capabilities. Nonetheless, this pattern diverges in Ria Formosa (RFaPSM). Table 3.3 indicates that littoral sandbanks exhibit minimal sensitivity to nutrient enrichment due to the difficulty of nutrient accumulation in sandy sediments (Brito et al., 2010). Littoral sandbanks demonstrate minimal sensitivity to turbidity due to the dynamic sediment transport in these areas. The table indicates a low sensitivity level for hydrocarbon pollution, as hydrocarbons are less prone to accumulation in sandy environments. Similarly, there is a low sensitivity for microplastic pollution due to the reduced accumulation of littoral sandbanks resulting from sediment movements. Organic pollution exhibits moderate sensitivity as it affects benthic organisms less severely than vegetated habitats (Kumar et al., 2020). Concerning sediment contamination, they are less affected due to the negligible accumulation of heavy metals.

3.2.2.3. Salt marshes (SM: A2.53)

The UaBM acknowledges that salt marshes are characterized by their roles in flood mitigation, protecting inland areas from storm surges, and enhancing biodiversity. In the Ria Formosa (RFaBM), salt marshes, especially adjacent to the Faro inlet, are essential for flood mitigation and water purification, in addition to providing provisional and supporting services such as salt extraction and biodiversity conservation. Supplementary cultural services emerge from the use of these marshes for tourism and birdwatching, particularly in Ria Formosa (Carrasco et al., 2021). Consequently, their regulatory ecosystem services, such as bioremediation

and carbon sequestration, are vital for the sustainability of ecosystem-wide advantages (Carrasco et al., 2021).

Salt marshes in Ria Formosa are vital for nutrient cycling, sediment stabilization, carbon sequestration, and water filtration services. These ecosystems function as barriers, enabling the retention of sediments and organic matter that safeguard interior regions from flooding and coastal erosion, while the lagoon exhibits a notable ability for self-restoration in reaction to rising sea levels and storm surges (Manuela et al., 2015). Furthermore, salt marshes attenuate pollutants from runoff and enhance water quality, while nutrient cycling is crucial for sustaining lagoon ecosystems. Moreover, it is crucial for sediment stabilization, where sediments are contained, and for alleviating climate change impacts by sequestering atmospheric carbon and storing it in plant biomass or sediments, a process known as carbon sequestration (Martins et al., 2021). However, these habitats are increasingly threatened by agricultural pollution and land reclamation. The ongoing threat to salt marshes is intensified by continuous invasions, particularly *Spartina anglica*, which displaces native species and profoundly disrupts the ecological balance of salt marshes (Manuela et al., 2015).

Table 3.3 shows that salt marshes exhibit a moderate sensitivity to nutrient enrichment, attributable to their capacity to retain nutrients without prompt degradation (Carrasco et al., 2021). Salt marshes demonstrate moderate sensitivity to organic pollutants, as their effects are less pronounced than those in mudflats due to the propensity of pollutants to be sequestered in sediments, thereby reducing their aqueous impact (Kumar et al., 2020). On the other hand, salt marshes have a moderate sensitivity level to hydrocarbons because they bioaccumulate and remain impactful over time (Kumar et al., 2020). Salt marshes are also moderately sensitive to microplastic levels due to their reduced exposure to floating debris, although they still retain some (Cozzolino et al., 2021). These habitats are also moderately sensitive to turbidity because they are affected by

nearby disturbances and are highly sensitive to sediment contamination due to the accumulation of heavy metals in sediment and vegetation (Manuela et al., 2015).

3.2.2.4. Seagrass meadows (SG: A5.53, A2.61)

The UaBM contends that seagrass meadows are vital for provisioning services such as fisheries and regulating services associated with carbon sequestration and erosion mitigation, especially because they serve as fish nursery habitats. In Ria Formosa (RFaBM), seagrasses function as vital nurseries for specific fish species, such as seabass and seabream (Erzini et al., 2022). Furthermore, their regulatory roles, especially in carbon sequestration, are vital in the sub-tidal regions of the lagoons, where they aid in mitigating climate change. These meadows are essential for maintaining biological diversity, thus requiring their preservation. Regarding bioremediation, seagrass meadows in Ria Formosa are essential for nutrient cycling, sediment stabilization, carbon sequestration, and water filtration in the lagoon's bioremediation efforts. These meadows promote the preservation of water quality and the recycling of vital nutrients for marine trophic systems. Moreover, the rise in turbidity is mitigated, and shorelines are safeguarded from erosion due to seagrass's ability to stabilize sediment in retained regions. Moreover, seagrass meadows sequester carbon in their biomass and sediments, serving as carbon sinks and contributing to climate change mitigation. Martins (2017) reports that the median carbon storage value is 0.50% for seagrass (*Z. noltei*) and 0.23% for salt marshes (*S. maritima*). This indicates that the organic carbon storage capacity per unit area in coastal vegetated habitats (*Z. noltei* and *S. maritima*) was approximately twice that of the clam farm. Their ability to filter water is crucial for maintaining the lagoon's purification and the overall vitality of the aquatic ecosystem. According to the UaPSM, SG meadows exhibit moderate sensitivity to nutrient enrichment and hydrocarbon contamination while displaying low sensitivity to turbidity.

Conversely, the RFaPSM indicates that SG exhibits significant sensitivity to nutrient enrichment, owing to its susceptibility to nutrient overload from wastewater discharges and agricultural runoff. Seagrass exhibits moderate sensitivity to

sediment contaminants, such as heavy metals including cadmium, lead, and nickel, due to its filtering capability and high accumulation capacity, rendering it less impacted than salt marshes. Organic pollutants, while influencing the clarity and oxygen levels of the Ria Formosa, exhibit a moderate sensitivity level in seagrass relative to mudflats, as they are often sequestered in sediments, thereby diminishing their impact in the water column. Seagrass meadows exhibit significant sensitivity to hydrocarbon pollution from maritime activities, road runoff, or localized inputs of petroleum-derived hydrocarbons (Kumar et al., 2020). Seagrass exhibits a high sensitivity to microplastic pollution due to the ingestion of microplastic particles by marine organisms (Cunha et al., 2009). Finally, seagrass exhibits high sensitivity to turbidity, as it impacts light availability and photosynthesis due to elevated sediment loads from dredging and coastal development, illustrated in figures 3.14 and 3.15, as well as effluents from wastewater treatment facilities or industrial sources, depicted in figures 3.17, 3.18, and 3.19.

3.3. Evidence-Based Analysis of Drivers, Pressures, State, Impact, and Responses (DPSIR) to Pollution-Related Stressors in Ria Formosa

This analysis performed in this section employs the Asset-Service Framework to evaluate pollution-induced stressors impacting critical ecosystems in the Ria Formosa Lagoon, such as seagrass meadows, tidal flats, and salt marshes. The MarESA framework was applied to quantify the sensitivity of these habitats to environmental pressures. This section will evaluate the extent of the impact of pressures including nutrient enrichment, sedimentation, and heavy metal contamination, along with associated drivers such as population growth, tourism, and dredging activities, utilizing a combination of data from EMODnet and published literature.

The DPSIR framework was used to structure the analysis, emphasizing the interaction among drivers, pressures, and responses to stressors (Figure 3.10). The evaluation underscores the essential habitats that deliver critical ecosystem services, including carbon sequestration and flood mitigation, as well as those

most vulnerable to pollution. Driving force is defined herein as the social, economic, and cultural attributes characterizing the dynamics of change, while pressure is defined as the immediate impacts emanating from the driving forces and impacting the environment. The state is described as the current condition of the environment as a result of the pressures, while the impact is described as the effects of change on the state of the environment on the ecosystems. The response is the measures put into practice to mitigate adverse effects on the environment and to look for ways to conserve the environment.

This analysis aids in decision-making regarding nature-based solutions (NbS) and other management strategies intended to conserve and restore this ecosystem, ensuring its resilience and the continuous provision of essential services.

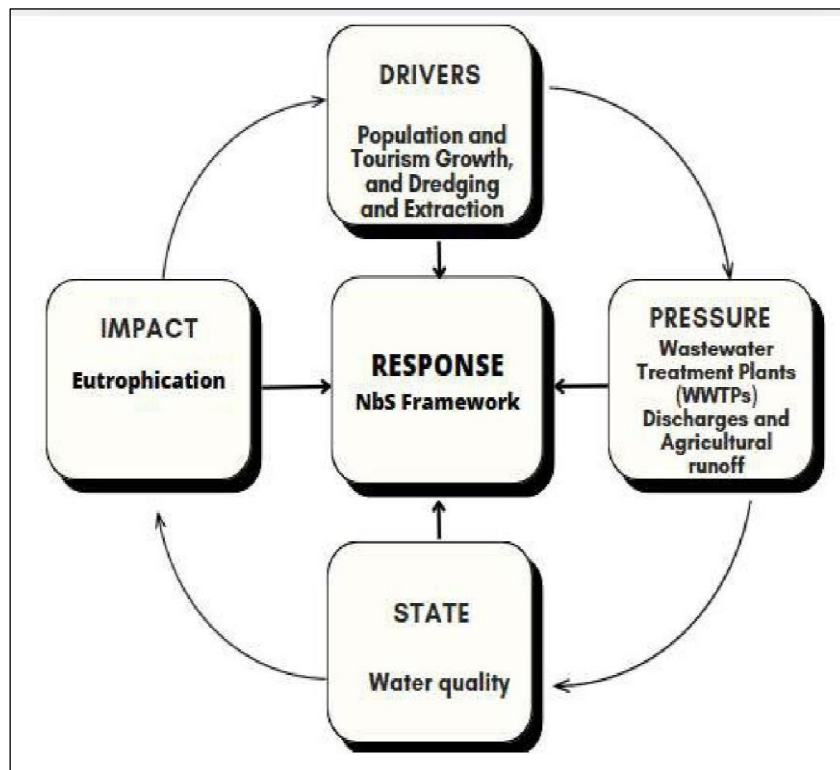


Figure 3.10: DPSIR framework adapted to Ria Formosa.

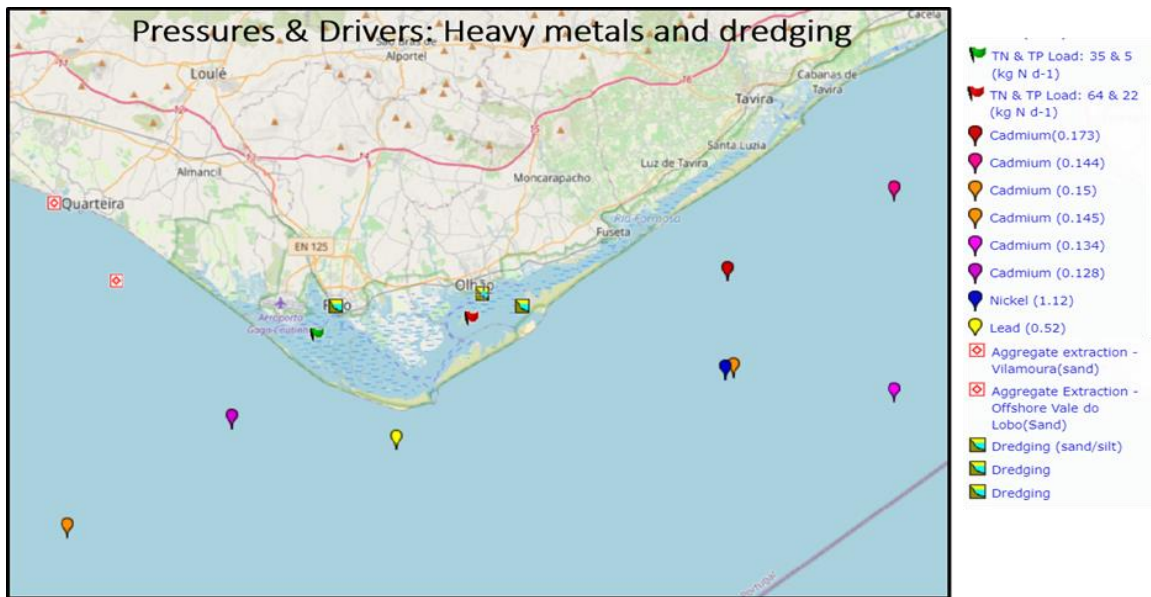


Figure 3.11: A visual flow of Driving Forces and Pressures shaping the Ria Formosa: Heavy metal contamination and dredging areas in Ria Formosa. This map was generated using the GPS Visualizer online tool, designed for the creation of customized maps and profiles from GPS data.

The map (Figure 3.11) illustrates areas contaminated by heavy metals (cadmium, nickel, and lead) and dredging activities, providing a clearer understanding of pollution sources and their drivers. It also illustrates various pollutants contaminating offshore waters through distinct cadmium markers and designated regions for aggregate extraction and dredging. The map also highlights locations with increased nitrogen and phosphorus concentrations, which could contribute to water quality issues.

According to Figure 3.11, dredging has been generally conducted in the Faro and Olhao areas, and in Armona and Culatra Islands, where nutrient and chemical pollution were generally found to be greatest due to waste water discharge and most likely agricultural runoff. This implies that the disturbance of the tidal flat sediments is partly responsible for the spread of chemical pollution in the lagoon, in addition to excessive sedimentation that is detrimental to blue carbon habitats, water quality, and biodiversity. Moreover, although aggregate sand extraction occurs in an area slightly west of Ria Formosa, sediment release, current, and wave action may transport the loose material into the lagoon area. Finally, it can

be seen that heavy metals are exclusively sampled offshore, while only lead was sampled close to the lagoon's southward tip, which is approximate to the location of the dredge spoil dump site (see Figure 3.22). This underscores the need for heavy metal sampling within the lagoon, especially in the sandy and mixed sediment habitats.

3.3.1. Drivers

The primary factors influencing environmental change include economic development, population growth, agriculture, and mass production. These socio-economic factors stimulate the environmental processes linked to ecosystem degradation.

3.3.1.1. Population Growth

In the Algarve, population growth, especially in urban centres such as Faro and Olhão, has significantly increased pressure on the Ria Formosa ecosystems (Algarve - Censos 2021 (Resultados Preliminares) | CCDR Algarve, n.d.). Figure 3.12 depicts a decrease in population growth in 2015, followed by an increase from 2016 to 2022, which contributed to an increase in pressures on the Ria Formosa lagoon. Numerous studies suggest that recent stressors in Ria Formosa correlate with population growth in the Algarve, rising from approximately 395,000 in the 2001 census to 467,000 in the 2021 census (Instituto Nacional de Estatística portal accessed on 30/08/2022).

The discharge of wastewater has escalated due to urban expansion and intensified land use driven by the growing demand for housing, services, and infrastructure. Even the discharge of treated wastewater can result in eutrophication and algal blooms, causing ecosystem imbalances in the Ria Formosa and negatively affecting the water quality necessary for maintaining the lagoon's biodiversity. This directly impacts the lagoon's ability to support essential economic activities, including fisheries and aquaculture (Cravo et al., 2022).

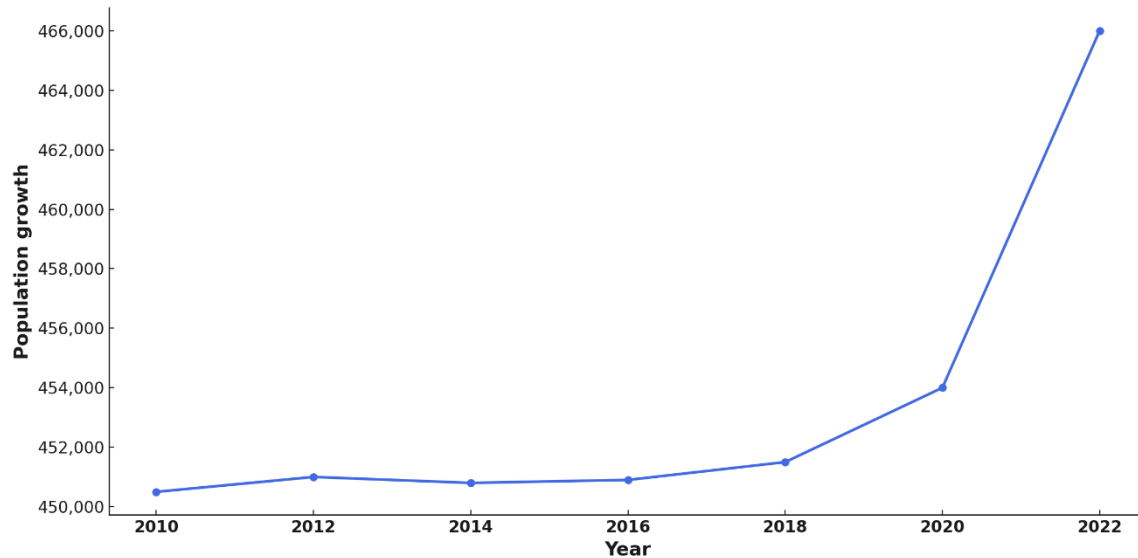


Figure 3.12: Trends in population growth across the Algarve (2011–2021). Data source: *Instituto Nacional de Estatística* (INE, Portugal).

3.3.1.2. Tourism

Tourism growth in the last decades in the Algarve has actively contributed to the deterioration of habitats in the Ria Formosa Lagoon (de Noronha Vaz et al., 2012). Figure 3.13 illustrates a significant surge in tourism growth in the Algarve, despite a decline in tourist visits attributed to COVID-19 travel restrictions, as indicated by the dips in the graph.

The growth of the tourism sector signifies that the region is one of the nation's most favoured tourist destinations, drawing millions of visitors annually, particularly to the coastal area, where the lagoon is used for recreational activities including boating, fishing, and sunbathing (de Noronha Vaz et al., 2012). This has resulted in the establishment of tourist infrastructure, encompassing the construction of resorts, marinas, and associated facilities. The expansion required dredging to ensure adequate waterway depth, leading to heightened turbidity and negatively impacting seagrass meadows, essential for carbon sequestration, water filtration, and fish nurseries. Furthermore, the increase in tourism has exacerbated boating

activities, negatively impacting these habitats, as many are physically harmed and polluted by boat emissions (de Noronha Vaz et al., 2012).

The expansion of tourism in the area underscores the necessity of effective tourist management in conjunction with NbS to adequately tackle pollution.

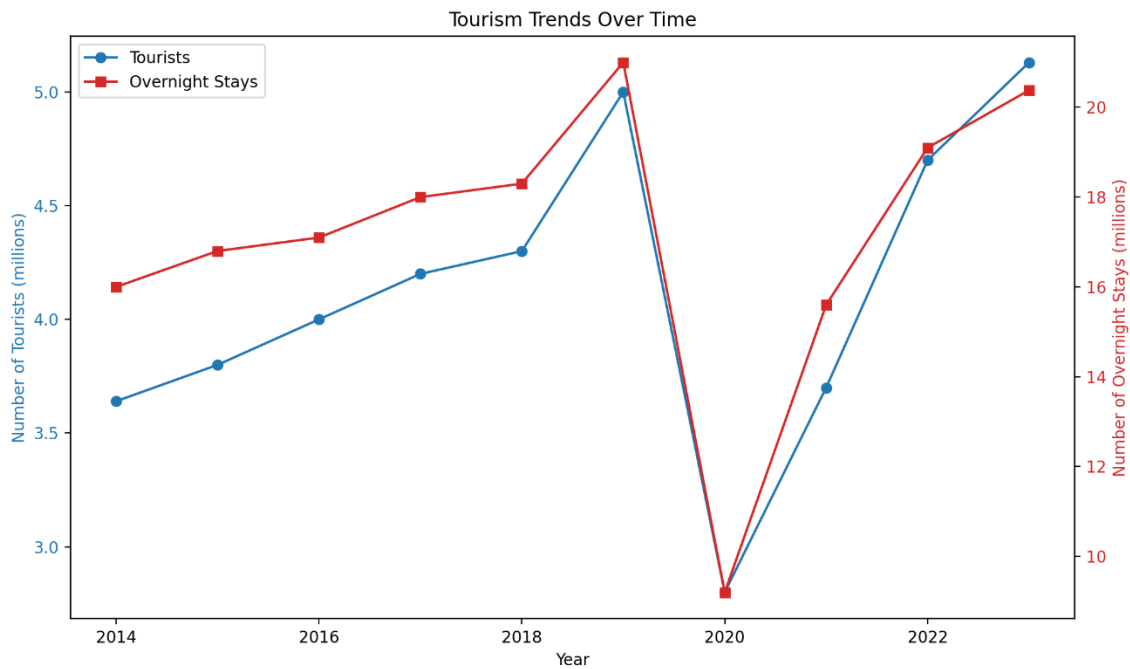


Figure 3.13: Tourist influx and overnight stays in Algarve, Portugal (2014-2023). (Data source: <https://www.statista.com/statistics/1155156/number-of-tourists-in-the-algarve-portugal/>)

3.3.1.3. Dredging and sand extraction

Dredging and sand extraction pose substantial and immediate risks to the sublittoral sandbanks in Ria Formosa. Figure 3.14 indicates that substantial sediment extraction from the Ria Formosa likely occurred, with approximately 520000 m³ of sediment removed in 2000 and 691800m³ in 2015.

Figure 3.15 illustrates that 99% of the sediment extracted in 2015 comprised sand, while the remaining 1% consisted of silt. Dredging may partially contribute to habitat destruction, adversely affecting marine life through heightened water

turbidity, diminished water quality, alterations in coastal dynamics, and the release of pollutants and carbon sequestered in sediments (Erfemeijer et al.).

These activities are driven by the need for infrastructure development to support the increasing local population and the expansion of tourism.

Dredging operations alter sediment composition and depth, affecting specific species dependent on particular substrate types for feeding and reproduction due to the disruption of these substrates (Wilber et al., 2001) Furthermore, the extraction of sand can intensify erosion by reducing the lagoon's ability to function as a barrier against severe storms and saltwater encroachment.

The ecological effects of dredging necessitate the implementation of restrictions on dredging and initiating a sand replenishment program. These measures are essential for preserving the ecological balance and stability of sublittoral sandbanks in Ria Formosa (Wilber et al., 2001).

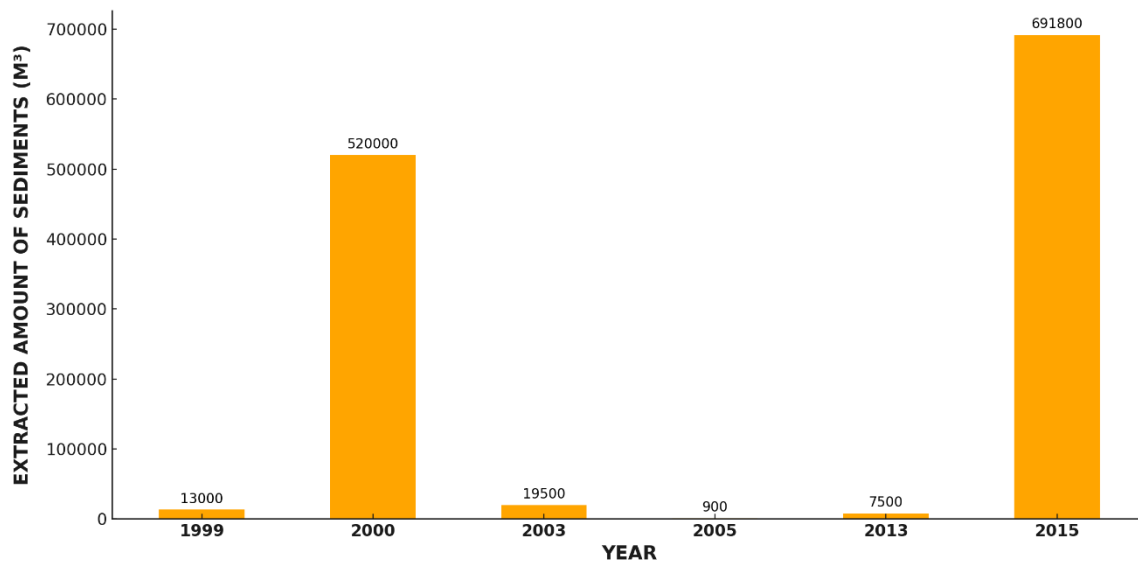


Figure 3.14: Temporal sediment extraction (m³). Trends in Armona and Culatra islands.(Data source: EModnet)

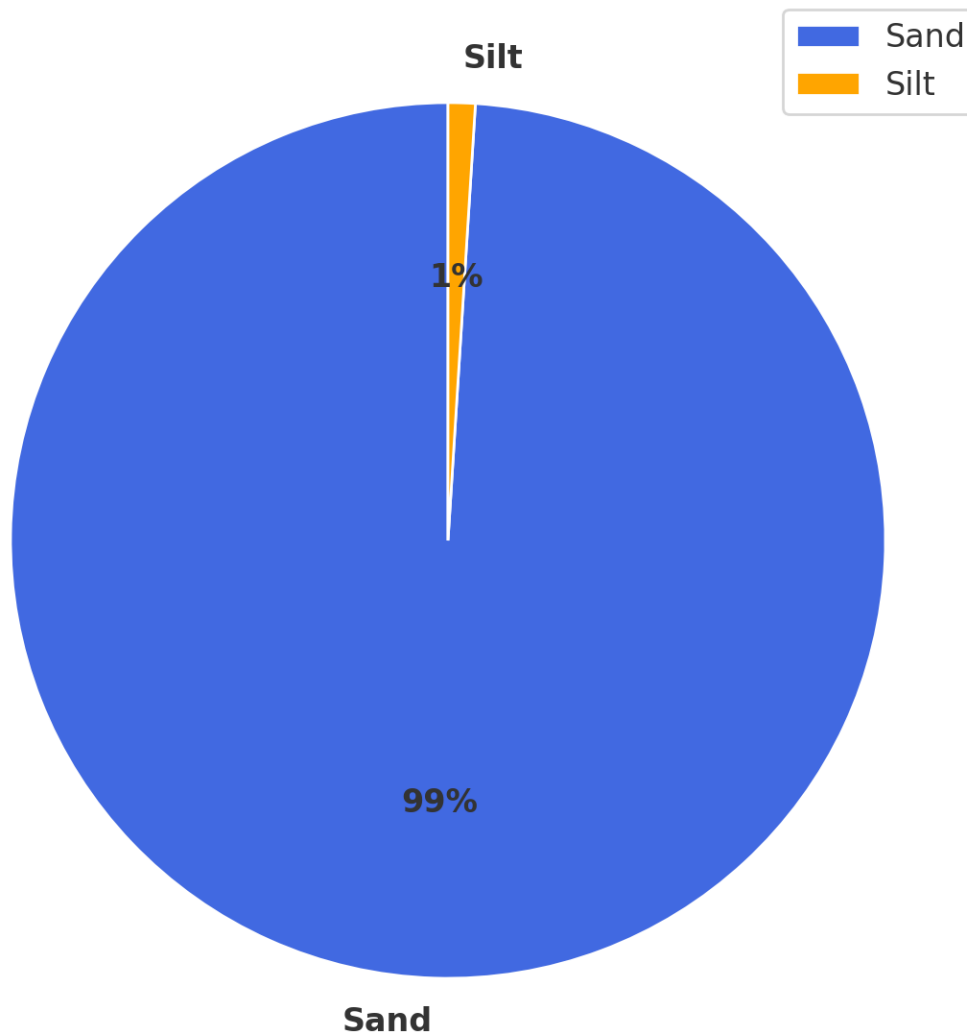


Figure 3.15: Sand and silt extraction from dredging activities (2015). (Data source: EModnet)

The pressures arising from the aforementioned principal drivers include accelerated erosion, storm surges, overtopping (Carrasco et al., 2021; Domingues et al., 2023), climate change (Brito et al., 2012b; Rodrigues et al., 2021), flooding and sea level rise (Lopes et al., 2022), sewage issues (Cravo et al., 2022a), eutrophication and hypoxia (Cravo et al., 2020), pharmaceutical contamination (Cravo et al., 2022b), and chemical pollution (Manuela et al., 2015).

Escalating threats, notably from pollution and habitat degradation, are persistently undermining the lagoon's capacity to provide vital ecosystem services (Newton et al., 2022; Erzini et al., 2022).

In Ria Formosa, human activities continue to impose considerable stress on the lagoon's ecosystems through nutrient enrichment, heavy metal contamination, organic pollution, and microplastic pollution, particularly from wastewater discharges, road runoff, and agricultural runoff, leading to habitat degradation, as discussed further in the present work.

3.3.2. Pressures

Pollution diminishes Ria Formosa's ability to deliver vital services, including nutrient cycling, carbon sequestration, coastal sediment stabilization, and water filtration. The key pollution types addressed in the present work include waste water discharge, nutrient enrichment, heavy metal contamination, and organic pollution.

3.3.2.1. Wastewater discharge

Effluents from wastewater treatment plants (WWTP) significantly affect the water quality of the Ria Formosa Lagoon. The population served by each plant correlates directly with the volume of effluent discharged, highlighting the strain on the lagoon's ecosystem. Figure 3.16 shows the wastewater discharge points in Ria Formosa based on EMODnet data. The map presented in figure 3.16, was generated using the GPS Visualizer online tool, designed for the creation of customized maps and profiles from GPS data.



Figure 3.16: Distribution of Wastewater Discharge Locations from Treatment Facilities in Ria Formosa.

The major wastewater treatment facilities located in Faro and Olhão discharged large quantities of effluents between 2023 and 2024, including high concentrations of nutrients, sewage, and organic matter into the lagoon (Aqua do Algarve, 2023).

Figure 3.17 juxtaposes the population served with the volume of effluent discharge (in cubic meters) across various locations and their corresponding Wastewater Treatment Plants (WWTP): Faro/Olhao, Almargem, Faro Noroeste, Quinta do Lago, Olhão Nascente, and Vale de Lobo. The Faro/Olhão WWTP processes the highest effluent discharge, totalling 520,517 m³.

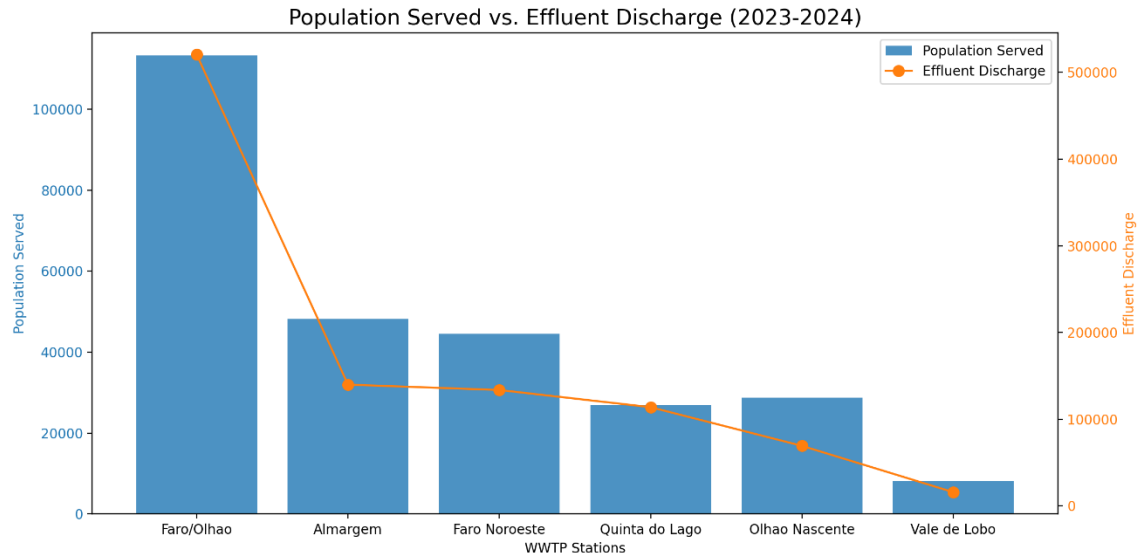


Figure 3.17: WWTP Effluent Discharges and Population Coverage in Faro and Olhão (2023-2024, Ria Formosa). Data source: Águas do Algarve, S.A.

3.3.2.2. Nutrient-enrichment

The Ria Formosa Lagoon is facing escalating pressures from nutrient enrichment (eutrophication), sedimentation, and toxic contaminants such as cadmium, lead, and nickel; organic pollution; and microplastic pollution, all intensified by anthropogenic activities including dredging, population growth, and tourism expansion in the Algarve region (Cravo et al. 2022). These pressures are progressively diminishing the ecological value of the lagoon's habitats and their ability to provide sufficient ecosystem services. Nutrient enrichment leading to eutrophication fosters algal blooms in seagrass meadows, forming a layer of algae that obstructs light and hinders photosynthesis, ultimately causing habitat loss (Cravo et al., 2022; Newton et al., 2022). Nutrient enrichment diminishes light availability, thereby reducing the lagoon's photosynthetic capacity, which impairs its ability to sequester carbon and filter water through seagrass meadows, ultimately degrading water quality (Newton et al., 2022). Tidal flats, like other ecosystems, experience detrimental impacts from organic pollution and nutrient overload, leading to increased macroalgal growth.

The hypoxic conditions produced by macroalgae substantially affect benthic organisms, essential for nutrient cycling and sediment stability (Kumar et al., 2020).

Figure 3.18 shows total nitrogen in Faro is 35 kg N d⁻¹, whereas in Olhão it is 64 kg N d⁻¹. Total phosphorus in Faro is 5 kg Pd⁻¹, while in Olhão it is 22 kg Pd⁻¹.

Figure 3.19 shows the nutrient discharges of Ria Formosa, indicating an increase in total nitrogen to 16.27 mg/L and a decrease in total phosphorus to 4.35 mg/L for both Faro and Olhão. The increase in total nitrogen primarily results from agricultural runoff and wastewater discharges, which introduce significant amounts of nitrogen into the lagoon (Cravo et al. 2022). The reduction in total phosphorus may suggest either improved wastewater treatment entering the lagoon or the lagoon's augmented capacity to sequester phosphorus within its sediments. However, an imbalance in nitrogen and phosphorus ratios can disrupt nutrient cycling, thereby intensifying the effects of nitrogen enrichment.

This leads to algal blooms that primarily block sunlight and reduce oxygen levels, thereby threatening the survival of ecosystems like salt marshes and seagrass meadows.

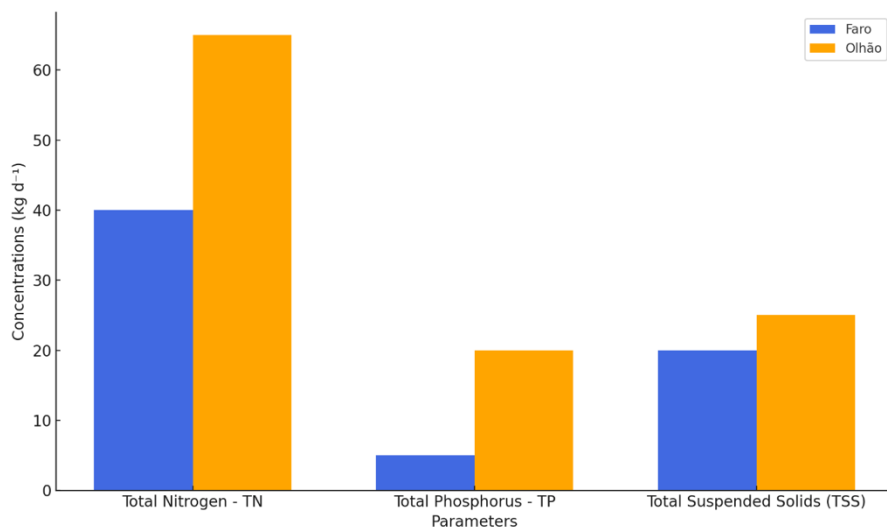


Figure 3.18: Total nitrogen, phosphorus, and suspended solids discharge from the Ria Formosa wastewater plants (2018-2019) Data source: Cravo et al. (2022)

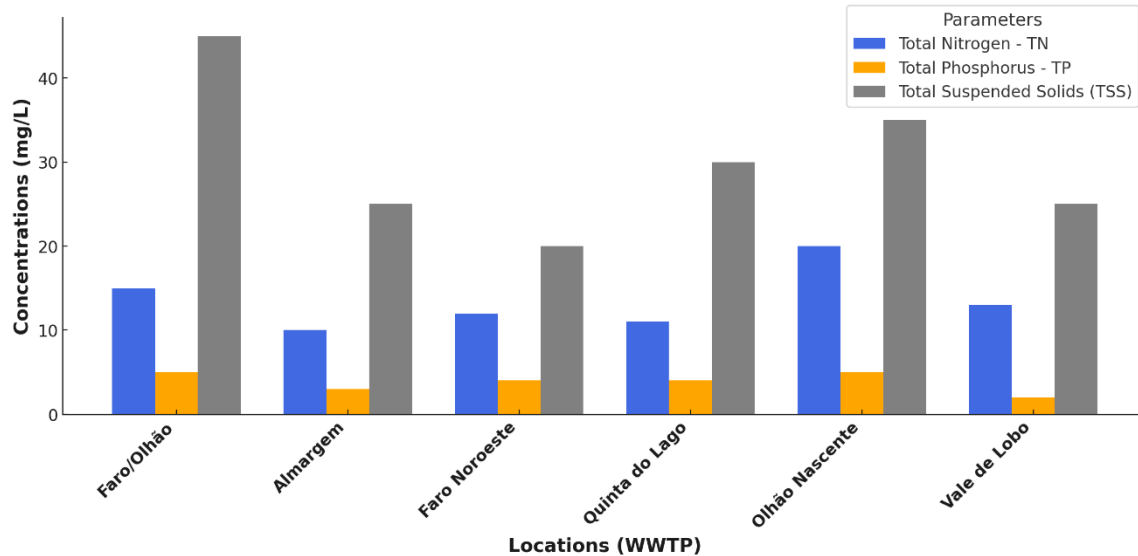


Figure 3.19: Total nitrogen, phosphorus, and suspended solids discharged from the Ria Formosa wastewater plants (2023-2024). Data source: Águas do Algarve (2024). Data provided by the company

3.3.2.3. Sediment contamination and Heavy metals

Salt marshes, recognized for their critical roles in sediment stabilization and water purification, are threatened by pollution from sediments and hazardous contaminants. The discharge of industrial effluents and agricultural runoff introduces heavy metals, such as cadmium, lead, and nickel, into the lagoon, where they accumulate in the sediment and vegetation of the salt marshes. These contaminants negatively affect the plant's physical structures and functions by promoting invasive species such as *Spartina anglica*, which out compete native flora, and they also exert lasting effects on species dependent on these habitats for reproduction and nourishment (Manuela et al., 2015). The graph below depicts the increased levels of heavy metals, such as nickel, lead, and cadmium, in the Ria Formosa area (Figure 3.20). Nickel exhibits the most substantial concentration, with a median value of 0.86 ($\mu\text{g/L}$), followed by lead at a median value of 0.52 ($\mu\text{g/L}$) and cadmium at a median value of 0.173 ($\mu\text{g/L}$). Dredging and the discharge of industrial effluent disrupt the lagoon and introduce deleterious substances into the water, resulting in elevated concentrations of heavy metals.

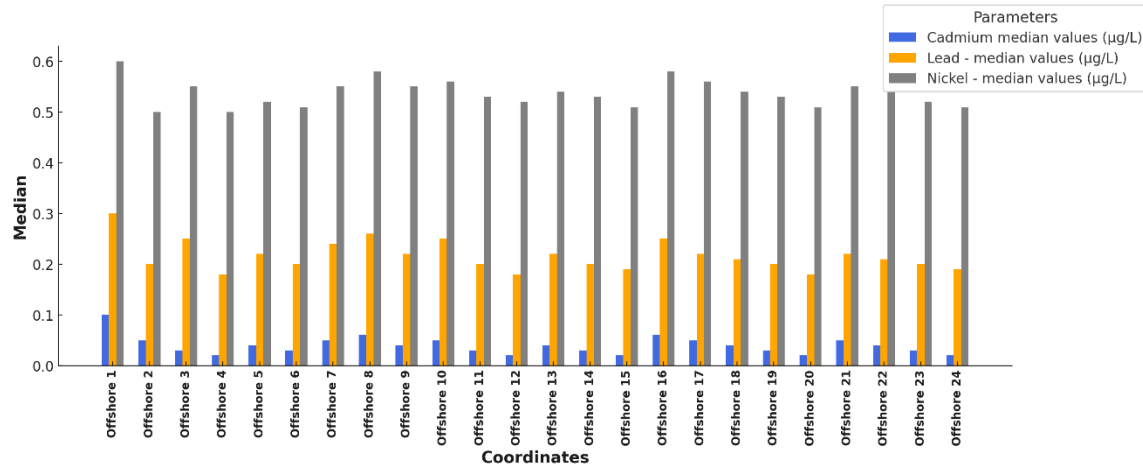


Figure 3.20: Heavy metal concentration trends in Ria Formosa: Correlations with pollution drivers, 2023 (See Fig. 3.20) (Data source: EModnet)

To make effective decisions concerning heavy metal pollution management, it is however important to understand the threshold levels of these pollutants on vegetative habitats such as seagrass, saltmarsh, biogenic reefs such as mussel and oyster beds, and on biodiversity.

3.3.2.4. Microplastic pollution

The increase in tourism and plastic waste generation has enhanced microplastic pollution in the Ria Formosa Lagoon (Vital et al., 2021). Small plastic particles (microplastics) less than 5 mm in size infiltrate aquatic ecosystems and are ingested into marine organisms. This ingestion causes physical stress, reduced reproductive success, and poor growth rates (Cozzolino et al., 2021). The microplastic accumulation disrupts lagoon food chains and compromises ecosystem services in marine organisms.

In recent research, microplastic content has recently been quantified in the soft tissues within three commercially important bivalve species: *Ruditapes decussatus*, *Polititapes* spp., and *Cerastoderma edule* collected from intertidal

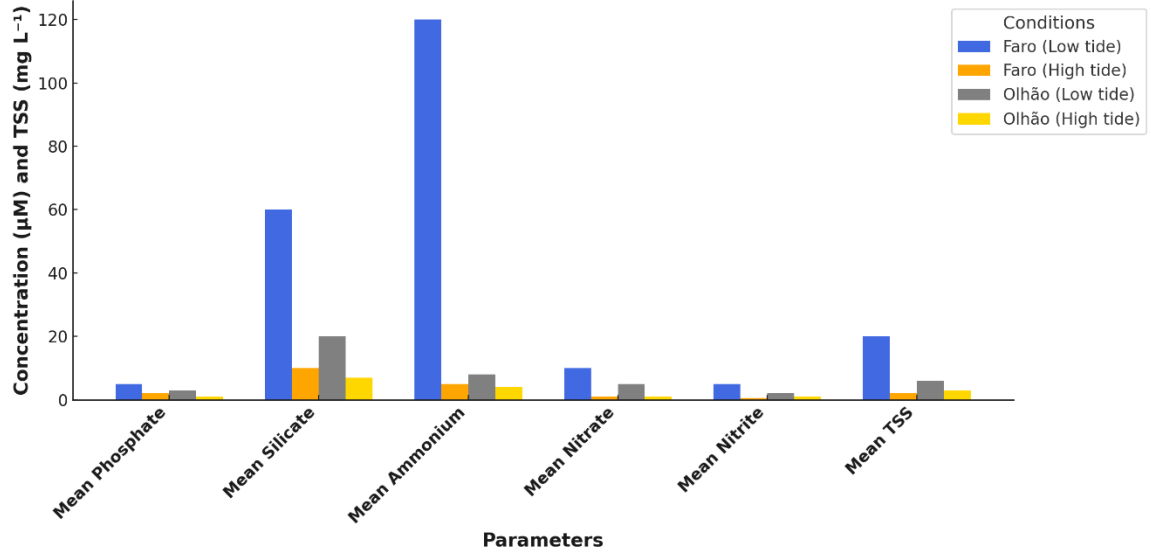
zones of the lagoon. Analysis showed also similar amounts of contamination from 10.4 ± 10.4 to 18.4 ± 21.9 microplastic particles per gram of wet weight (WW) (Cozzolino et al., 2021). The extent of microplastic contamination at this level indicates the widespread nature of microplastics in the Ria Formosa ecosystem.

The presence of microplastics in bivalves has wider impacts, not only on marine ecosystems but also on human health, based on both commercial harvesting and consumption of these species.

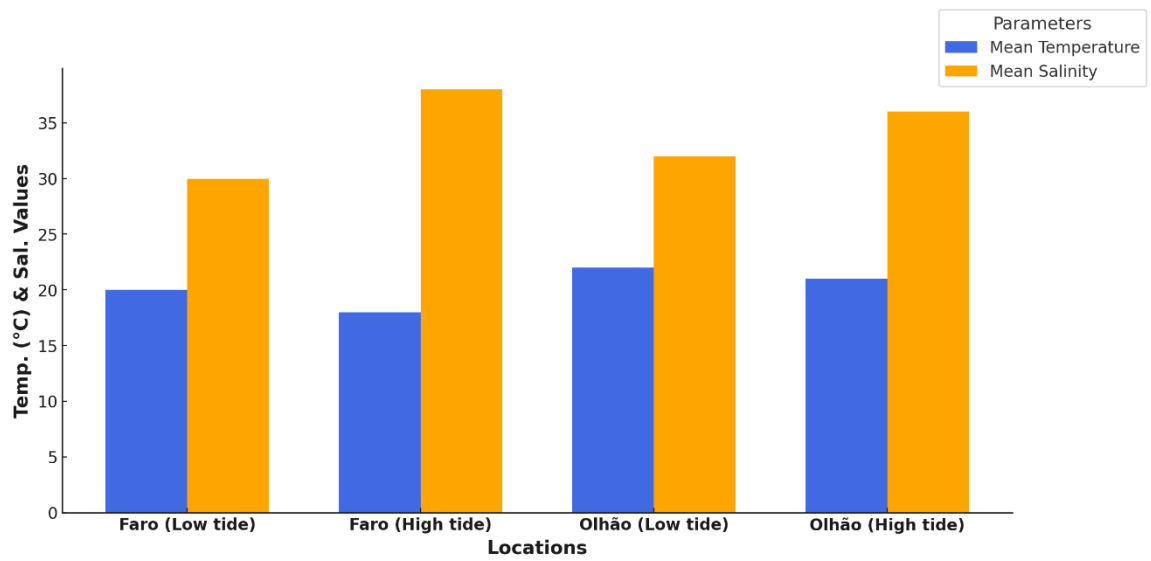
3.3.3. State and Impact

The water quality parameters in Faro and Olhão are compared in Figure 3.21 (a, b, c, d), illustrating significant differences in nitrogen, temperature, salinity, dissolved oxygen, pH, and chlorophyll-a concentration at both high and low tides. At low tide in Faro, ammonium and silicate concentrations are significantly elevated compared to Olhão, suggesting potential local sources like wastewater discharge, which is less evident in Olhão.

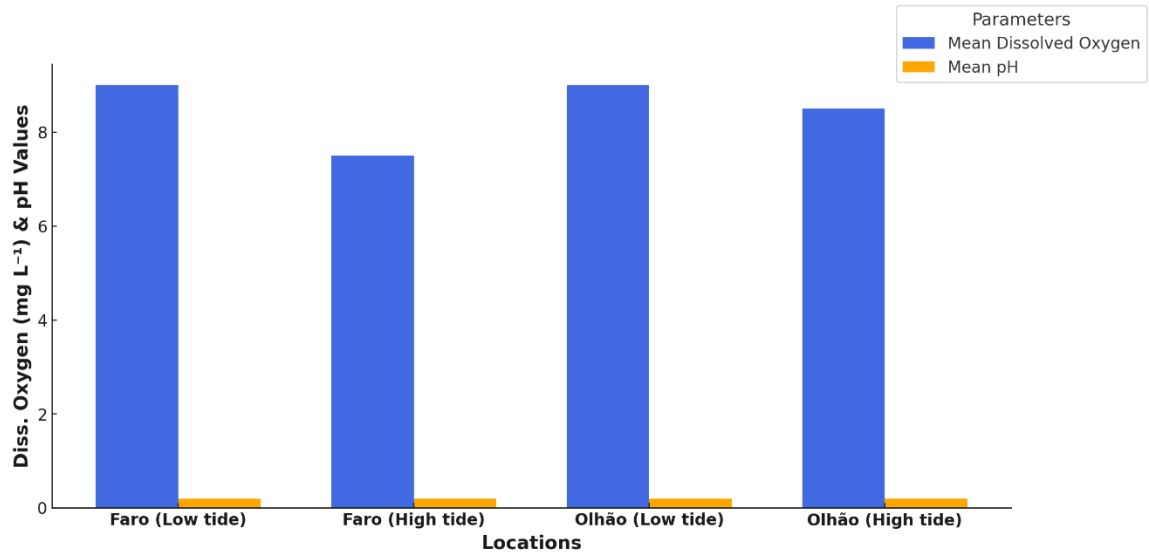
At both locations, salinity increases during high tide with a mean value of 36.7 due to the significant influx of seawater that dilutes freshwater inputs. Dissolved oxygen concentrations are heightened during low tide with a mean value of 8.9 mg L^{-1} in Faro and 7.9 mg L^{-1} in Olhão, presumably due to increased mixing or freshwater input, whereas pH levels remain consistently stable across all conditions with a mean value of 0.1-0.2. Elevated chlorophyll-a concentration beyond the Faro tidal limit at low tide with a mean value of $3.3 \text{ } \mu\text{g L}^{-1}$ which signifies enhanced phytoplankton productivity due to nutrient availability. The graphs illustrate the impact of tidal variations and local human activities on nutrient dynamics, biological productivity, and water quality in the Ria Formosa, indicating increased variability and nutrient enrichment in Faro relative to Olhão with mean values of $10.7 \text{ } \mu\text{M}$ for phosphate, $70.8 \text{ } \mu\text{M}$ for silicate, $115.5 \text{ } \mu\text{M}$ for ammonium, $14.1 \text{ } \mu\text{M}$ for nitrate, $10 \text{ } \mu\text{M}$ for nitrite, and 24 mg L^{-1} for total suspended solids.



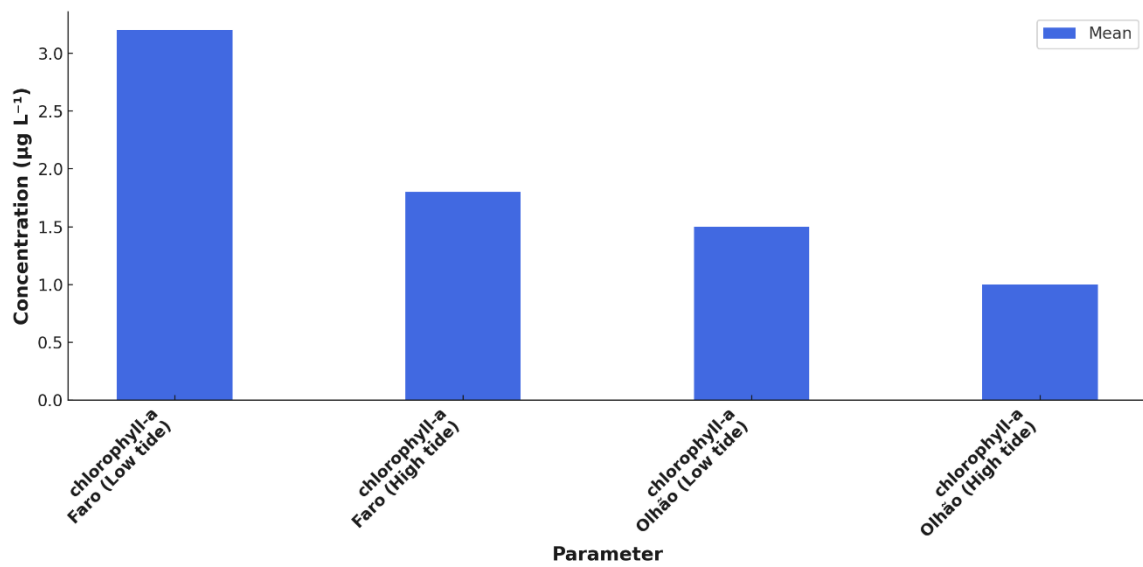
a)



b)



c)



d)

Figure 3.21: Comprehensive Water Quality Analysis of Chemical, Physical, Nutrient, and Biological Parameters (2018-2019): a) Nutrients & TSS; b) temperature & salinity; c) pH & Dissolved O₂; d) Chl-a. Data source: Cravo et al. (2022).

The high concentration of Chl-a in Faro at low tide indicates that this area is relatively more eutrophic. It also highlights the fact that flushing and mixing are key processes that modulate chemical concentration in water and sediments within the lagoon.

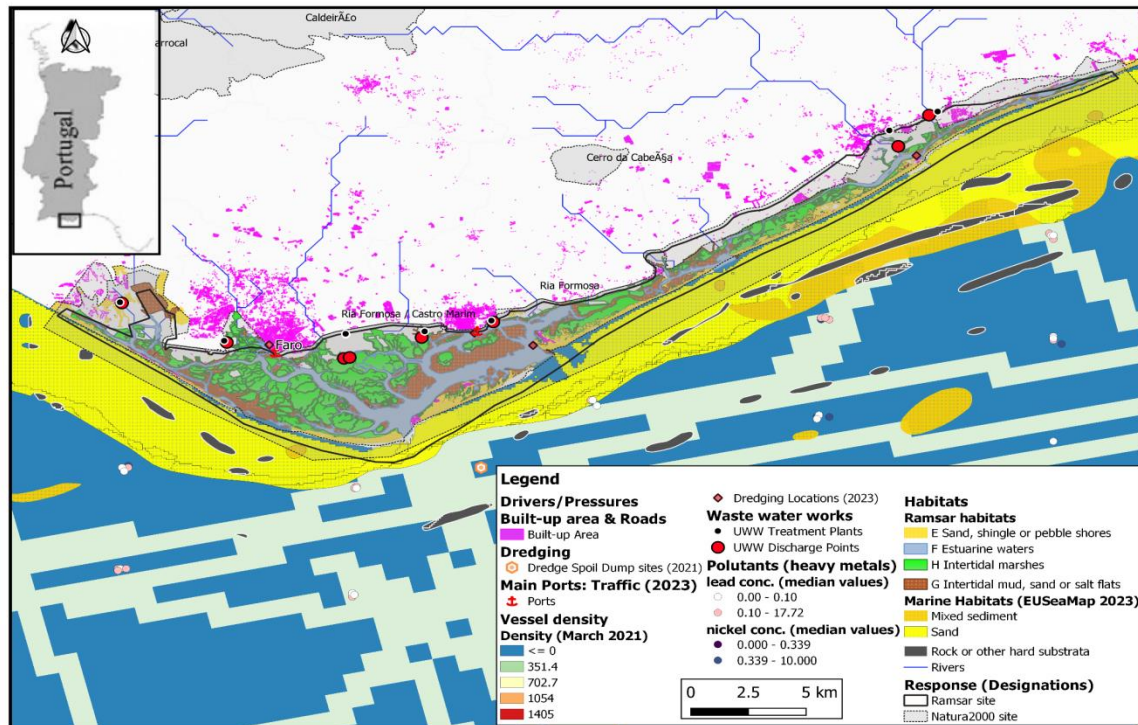


Figure 3.22: The spatial distribution of key pressures and their drivers in Ria Formosa. The data files used to create this map were obtained from EMODnet.
<https://emodnet.ec.europa.eu/geoviewer/>

The map highlights the citing of wastewater facilities within the vital habitats, including salt marsh and seagrass. It also shows the major urban areas, Faro and Olhão, and the location of their ports and dredging activities, which constitute the primary sources of diverse pressures in the Ria Formosa lagoon, a valuable Ramsar and Natura2000 site. The chronic and acute stressors and shocks uncovered in this work necessitate immediate interventions, including the regulation of agricultural drainage and the improvement of effluent disposal, as well as additional strategies to mitigate the effects of pollutants on lagoon ecosystems, such as the enhancement of natural circulation.

Nature-based solutions (NbS), including the restoration of seagrass meadows, salt marshes, and wetlands, can enhance the capacity of natural systems to filter and absorb excess nitrogen, thereby mitigating nutrient overload and restoring the water quality and ecological balance of degraded lagoons. To maintain the ecological integrity of tidal flats and sub-littoral sandbanks and the general health of lagoons, it is imperative to develop a framework to increase the comprehension of the role of NbS in pollution remediation. This could serve as a support tool for policies that restrict detrimental activities such as dredging while encouraging sustainable practices such as nature enhancement and restoration.

3.3.4. Response

3.3.4.1. Metrics for Identifying Pollution-Related Nature-Based Solutions

Before validating the effectiveness of NbS in Ria Formosa, specific metrics concerning pollution remediation must be utilized. These indicators facilitate the evaluation of the effectiveness of NbS in mitigating pollution and delivering ecosystem services:

- Sensitivity and resilience to pollution: regarding habitats' ability to endure and recuperate from heavy metal contamination and other pollutants.
- Number of ecosystem services (ES) related to pollution bioremediation: The quantity of services provided by each habitat, encompassing water filtration and sediment stabilization services.
- Types of pollutants remediated: The capacity of a NbS to address various pollutants, including eutrophication, heavy metals, and organic contaminants.
- Annual pollutant capture: The volume of pollutants removed or processed by NbS annually.
- Net carbon sequestration and air purification rate: The habitat's ability to sequester carbon while simultaneously removing pollutants.
- Net nutrient bio-remediation rate: The rate at which the ecosystem sequesters nutrients and stabilizes sediment.

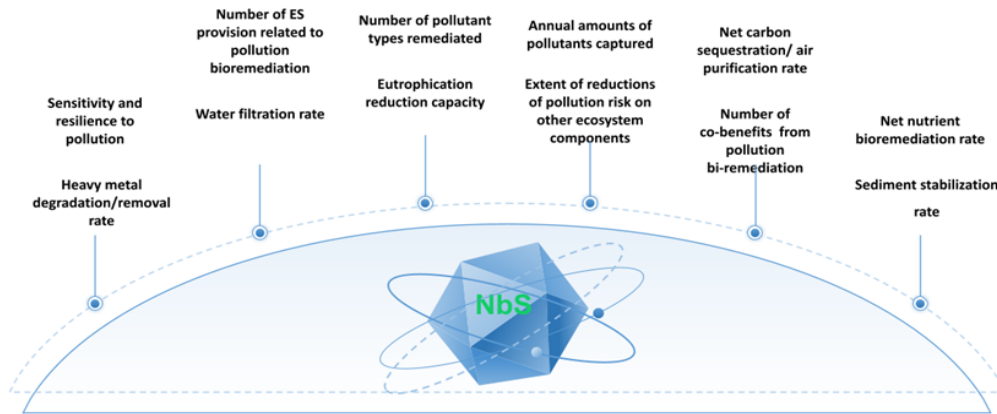


Figure 3.23: Essential Metrics for Identifying and Evaluating the Effects of Pollution-Related Nature-Based Solutions

3.3.4.2. Criteria Definition for Effective Nature-based Solutions According to IUCN

The IUCN has established criteria to ensure that NbS projects are designed and implemented to generate both ecological and societal benefits (IUCN Global Standard for Nature-Based Solutions, 2024). The criteria pertinent to mitigating pollution in Ria Formosa are delineated below:

- Nature-positive outcome: NbS should conserve, restore, and utilize ecosystems sustainably to meet societal demands. Restoration of seagrass and salt marshes in Ria Formosa can simultaneously address pollution-related challenges and improve water quality and fisheries.
- Transparency: Nature-based Solutions (NbS) should be transparent and stakeholder-inclusive throughout their entire lifecycle. Nature-based solutions (NbS) that engage local stakeholders, such as fishing communities, tourism operators, and conservationists, are formulated in accordance with community requirements and ecological sustainability.
- Governance: Nature-based Solutions (NbS) must be governed and managed adaptively. The NbS in Ria Formosa requires adaptive management informed by monitoring data and ecological changes.

- **Co-benefits:** NbS should generate societal advantages while managing trade-offs. Dredging or land reclamation is constrained by NbS, yet the enduring benefits of enhanced water quality, biodiversity preservation, and climate change mitigation are believed to surpass these immediate drawbacks.
- **Planning and implementation:** NbS should be planned and implemented at a landscape/seascape scale. The complete lagoon system must be unified to attain significant pollution reduction and enhance ecosystem resilience in Ria Formosa.
- **Integration of policies:** NbS must be incorporated into policies and regulatory frameworks. To ensure that NbS are long-lasting and effective in managing pollution, recognition of NbS in local and national environmental policy is ensured. Furthermore, NbS should pursue synergies with alternative interventions, including augmentation with traditional pollution mitigation strategies, such as enhanced wastewater treatment, to optimize water quality and ecosystem health outcomes.

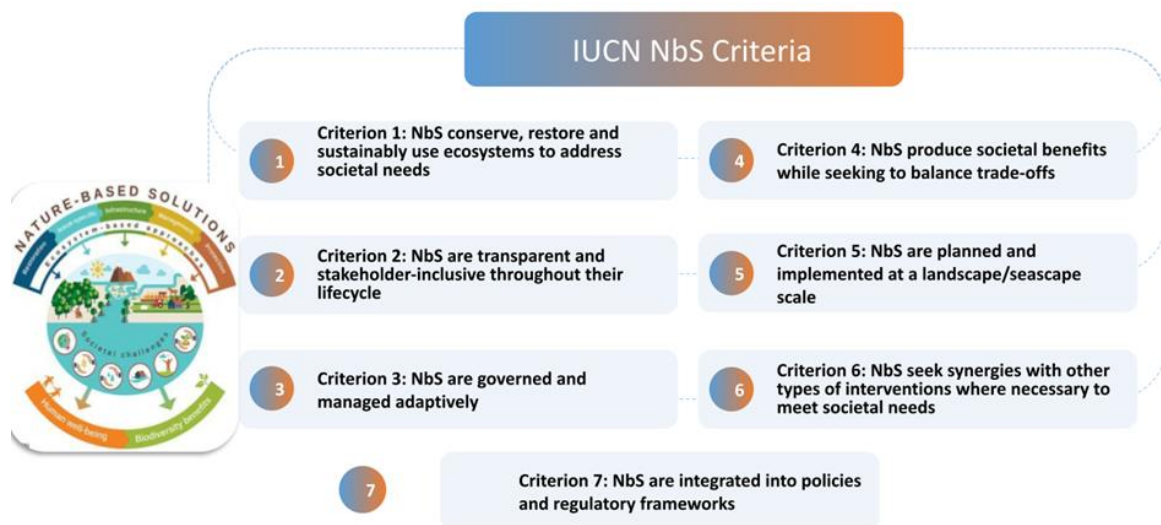


Figure 3.24: Key Criteria for Effective Nature-based Solutions (NbS) as Defined by IUCN

https://iucn.org/sites/default/files/content/documents/2021/nbs_from_concept_definition_to_global_standard_emmanuelle_cohen-shacham.pdf

3.3.4.3. NbS Identification Framework for Ria Formosa

The NbS Identification Framework utilizes the preceding three levels to formulate a conceptual model for the identification and implementation of NbS. It depends significantly on the effective illustration of the interactions among habitats, services, pressures, and sensitivity, subsequently adhering to IUCN criteria.

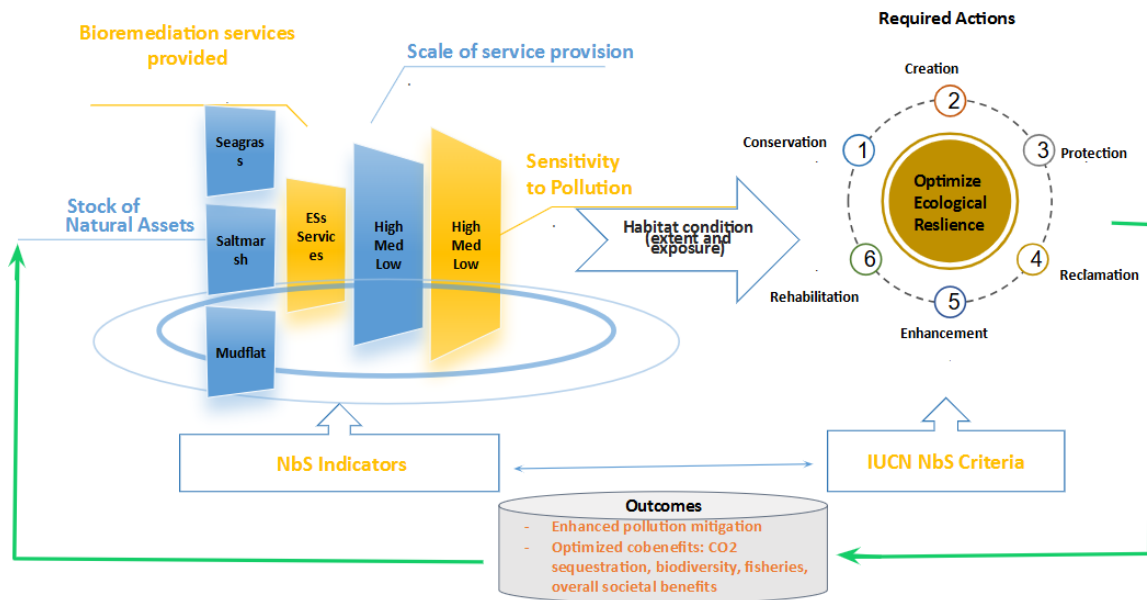


Figure 3.25: Integrated Conceptual NbS Framework for Ria Formosa: A Holistic Approach

NbS criteria are provided by IUCN, accessed via: https://iucn.org/sites/default/files/content/documents/2021/nbs_from_concept_definition_to_global_standard_emmanuelle_cohen-shacham.pdf

3.3.4.4. Application of the Framework to Ria Formosa

The subsequent structure was established to emphasize the implementation of the framework in Ria Formosa and to identify the most pertinent NbS that effectively mitigate pollution in the lagoon while offering additional co-benefits to both nature and humanity.

The steps include:

- Identifying the pertinent types of pollution
- The identification of habitats that offer bioremediation services.
- The evaluation of the degree of habitat sensitivity
- The assessment of habitat conditions
- The identification of pertinent actions necessary to improve service delivery, such as the establishment of new habitats, restoration, protection, and rehabilitation.
- Evaluation of the suitability of the identified NbS based on the IUCN NbS criteria to assess their suitability and feasibility.
- The results of optimizing NbS encompass improved pollution mitigation along with various advantages, such as increased carbon sequestration, enhanced biodiversity, and maximized societal benefits. The strategies implemented would significantly enhance the stock of natural assets, thereby fostering ecological sustainability and resilience.

3.3.4.5. Ranking the NbS Based on Bioremediation Performance and Confidence Levels

The subsequent results were derived from the implementation of the aforementioned steps: habitats were chosen for their bioremediation functions and subsequently ranked based on one of two criteria: performance and data reliability. Confidences are classified as high, medium, or low based on the quantity and relevance of the research data available to support the performance of each habitat.

- Salt marshes are essential for sediment stabilization, carbon sequestration, and water filtration. Salt marshes are essential for alleviating nutrient pollution from agricultural runoff and urban wastewater, making them crucial for the lagoon's resilience. Salt marshes demonstrate high efficacy in sediment stabilization and water purification, as corroborated by various literature reviews (Duarte et al., 2021; Martins, n.d.).
- Seagrass meadows provide significant nutrient cycling, sediment stabilization, carbon sequestration, and water filtration. Their bioremediation capability makes them essential for maintaining water quality, managing nutrients, and controlling erosion. Seagrass meadows predominantly offer bioremediation services with considerable certainty due to their efficient nutrient uptake, carbon sequestration, and sediment stabilization, as documented in the literature (Erzini et al., 2022).
- Tidal flats serve as transient nutrient reservoirs and sediment traps, providing structural integrity to the lagoon and acting as a habitat for various benthic organisms. Tidal flats exhibit moderate performance due to their significant contributions to nutrient cycling and sediment stabilization; however, they are constrained by limited data and a reduced capacity for carbon storage (Erzini et al., 2022).
- Sublittoral sandbanks moderately stabilize sediment volumes and marginally filter aquatic environments, thus mitigating coastal erosion. Sublittoral sandbanks are of lesser significance and rank due to limited data availability and their reduced carbon retention (Arnaud-Fassetta et al., 2006).

These habitats are fundamental to the provision of bioremediation services in Ria Formosa, significantly contributing to pollution reduction and the enhancement of natural ecosystem integrity.

The October edition of the "Our Future Water" newsletter emphasizes the necessity of integrating NbS to address pollution and enhance climate resilience with efficient coastal water management strategies (Brears, 2024). Efficient coastal water management would mitigate pollution, while nature-based solutions such as wetland restoration enhance water quality, thereby preserving ecosystems and promoting long-term sustainability (Brears, 2024).

Diverse management strategies have been implemented in Ria Formosa Lagoon to enhance water quality and foster ecosystem resilience. Since 1989, the installation and enhancement of Urban Wastewater Treatment Plants (UWWT) have markedly reduced nutrient loads, especially nitrogen and phosphorus (Newton et al., 2022). The Water Framework Directive (WFD) requires consistent water quality monitoring and spatial modeling to evaluate the lagoon's condition; unlawful sewage discharges are managed in the municipalities of Faro and Olhão. Furthermore, advancements have been achieved in improving nutrient cycling, sediment stabilization, and the conservation and restoration of seagrass beds and salt marshes. Moreover, pharmaceutical and heavy metal pollutants are monitored; nonetheless, they persist in presenting difficulties. Strategies are being developed to mitigate the impacts of heightened drought frequency and maintain the lagoon's water quality (Newton et al., 2022).

This thesis examines ecosystem-based management strategies utilizing nature-based solutions (NbS) to enhance current pollution remediation initiatives in the Ria Formosa lagoon, located in the Algarve region of southern Portugal.

The NbS framework has identified, evaluated, and prioritized habitats based on their capacity for bioremediation services and their susceptibility to pollution. This information is essential for the efficient identification and execution of NbS. A significant observation is that high-performance habitats, in relation to bioremediation services, demonstrate low resilience to pollution.

As a result, the regulatory functions and co-benefits offered by various biotypes, including seagrass meadows and salt marshes, would be undermined by

heightened nutrient enrichment, organic pollution, turbidity, heavy metal contamination, and plastic pollution, impairing their effectiveness in pollutant bioremediation. In this context, specific management interventions, such as restoration, are essential.

To precisely evaluate these actions, a distinction was initially made between two categories of NbS providers. These are high-priority nature-based solutions (HPNbS) and low-priority nature-based solutions (LPNbS). HPNbS habitats are crucial for delivering significant bioremediation services necessary for pollution mitigation in Ria Formosa, yet they are also highly susceptible to pollution. These encompass seagrass meadows and salt marshes. Tidal flats may be included in the list due to their significance in nutrient cycling and sediment stabilization, as well as their susceptibility to organic pollution, sediment contamination, and structural degradation. The restoration and preservation of these habitats must be prioritized, alongside mitigating the pollution sources in the lagoon. Conversely, LPNbS habitats such as sublittoral sandbanks and various rocky environments, although crucial for ecosystem functionality, exhibit diminished bioremediation capacity and reduced sensitivity to pollution. However, regions with elevated pollutant concentrations in these habitats must be safeguarded from activities like dredging and aggregate extraction that could discharge contaminants into the water column, subsequently allowing them to be transported into the lagoon through tidal action. Furthermore, these habitats provide coastal defense and the sediment necessary for replenishing tidal flats, thereby justifying a degree of protection.

In light of the aforementioned information, the subsequent actions have been proposed to improve the implementation of NbS in Ria Formosa:

- Enhancing the Enforcement of Environmental Protection Regulations: Implement more rigorous pollution control measures to limit nutrient inputs from agricultural runoff, urban waste discharge, and industrial activities before initiating habitat restoration efforts. These measures aim to reduce

the pollutant load in water, including restrictions on fertilizer application, enhancements in wastewater treatment plant standards, and regulations on dredging and construction activities that cause sedimentation and turbidity (Nature-based Solutions Research Policy, 2023).

- Stringent pollution control measures: This may include the creation of buffer zones around agricultural areas, the development of constructed wetlands, and the utilization of phytoremediation techniques to reduce pollutant infiltration in sensitive ecosystems, such as seagrass meadows. Implementing effective strategies to mitigate pollution before it affects natural ecosystems can strengthen the resilience of these habitats prior to extensive restoration efforts (Nature-based Solutions Research Policy, 2023).
- Habitat restoration: evidence indicates a decline in seagrass and salt marshes in Ria Formosa (Guimarães et al., 2012). This indicates a decline in the provision of bioremediation services by these habitats due to the reduced area. Consequently, restoration measures are essential. Before this, evaluations of habitat restoration potential are crucial to identify regions requiring restoration, alongside pollution mitigation strategies. Evaluations of salt marsh habitat extent in comparison to a historical benchmark are necessary to ascertain restoration potential.
- Reassess wastewater discharge sites: The Eastern Olhão region, distinguished by more robust hydrodynamics and a higher wastewater load relative to the northwest Faro area (approximately two to four times the total nitrogen and phosphorus), demonstrated a negligible effect from effluent discharge concerning wastewater contamination. Subpar water quality was observed in the low-load, insufficiently flushed area. Locating wastewater discharge sites in Ria Formosa within high-energy sandbank habitats would effectively mitigate wastewater pollution.

- Reduce heavy metal contamination and dredging: Heavy metal data has predominantly been assessed for offshore locations, including cadmium, lead, and nickel. The results demonstrate increased concentrations at various stations primarily linked to EUNIS A4, A5, and A6 habitats. However, according to MarESA, these regions are also classified as less vulnerable to pollution. Nevertheless, despite the distance from the Ria Formosa lagoon, the benthos may be impacted.
- Additionally, dredging, prevalent in the lagoon, has the potential to resuspend contaminated sediments from the sand and mudflats into the water column, affecting seagrass and saltmarsh ecosystems. Consequently, effective management strategies that focus on minimizing turbidity resulting from dredging activities and controlling nutrient inputs to aquatic ecosystems will be crucial for preserving the bioremediation capacity of these habitats. Salt marshes will benefit from efficient wastewater and nutrients management, as these practices will limit invasive species that often thrive due to nutrient enrichment from agricultural runoff.

3.3.4.6. Integrating Nature-based Solutions (NbS) into the regional environmental management strategy for pollution mitigation and ecological resilience.

All previously discussed efforts should form a crucial part of a thorough coastal zone and pollution management system, enhanced by public education, outreach, and legislative actions designed to reduce pollutant entry into coastal waters via stormwater and sewage systems. This strategy should encourage environmentally sustainable practices in communities to reduce their ecological footprint and safeguard coastal ecosystems, resulting in substantial co-benefits for climate, biodiversity, and the blue economy.

This aligns with the EU Commission's ongoing policy dialogues and outreach initiatives at both EU and global levels aimed at fostering engagement, building a comprehensive knowledge base, and promoting the widespread adoption of nature-based solutions (EU, 2024). This research on NbS could therefore bolster

Ria Formosa's initiatives under the UN Decade on Ecosystem Restoration, facilitate the attainment of the SDGs and the Rio Conventions, and promote the execution of NbS as outlined in the recent UNEA resolution 'Nature-based Solutions for Sustainable Development'. This strategy tackles the interconnected crises of biodiversity loss, climate change, and pollution, resulting in significant benefits for adaptation and disaster risk reduction (G7, 2022) while improving the delivery of diverse ecosystem services (EU, 2023).

4. Conclusion

4.1. Summary of Key Findings

Nature-based solutions (NbS) are increasingly recognized as effective strategies for hazard mitigation, pollution management, enhancing ecosystem resilience, and delivering enduring benefits to both the environment and society (Cohen-Sacham et al., 2016). They have been acknowledged as crucial for tackling environmental challenges, including pollution, especially in relation to the UN Ocean Decade for Sustainable Development. Therefore, states must develop Nature-based Solutions strategies to address diverse marine and coastal challenges, tailored to their specific environmental contexts. This thesis utilizes a systematic approach to create a conceptual framework and strategy for the development and implementation of Nature-based Solutions in Ria Formosa.

This study utilized the MarESA methodology to perform a comprehensive assessment of ecosystem service provision by critical habitats in Ria Formosa, along with their vulnerability and sensitivity to pollution. The distribution of habitats, including tidal flats, seagrass beds, salt marshes, and sublittoral sandbanks, is intricate and exhibits significant heterogeneity while preserving stability across both intra-annual and inter-annual intervals, thereby promoting considerable species diversity and ecosystem services (Duarte et al., 2007). The rehabilitation of seagrass meadows and salt marshes can enhance the lagoon's water quality, thus benefiting species residing in both sublittoral sandbanks and tidal flats. The lagoon provides various ecosystem services, especially when specific species encounter extinction or substantial population declines due to changes in environmental conditions. The interrelation of tidal flats, seagrass meadows, and salt marshes augments the resilience and stability of these ecosystems against environmental changes.

Tidal flats promote the growth of seagrass meadows by improving water clarity, whereas salt marshes support both ecosystems through sediment retention. The interconnections require comprehensive management strategies that tackle the combined effects of population growth, tourism, and pollution in the area (Ribeiro et al., 2007). The adverse impacts of dredging, nutrient enrichment from untreated sewage, and increased tourism hinder the long-term conservation strategy for Ria Formosa. Therefore, Nature-based Solutions (NbS) should be employed to protect and improve the lagoon ecosystem services for future generations. Nature-based Solutions (NbS), including habitat restoration, could enhance habitat conditions, thereby strengthening the overall resilience of the lagoon system (Inácio et al., 2023) to sustain essential ecosystem services.

Seagrass meadows and tidal flats are sensitive biotopes that respond negatively to increased nutrient influx, organic pollution, and heightened water turbidity. Consequently, seagrass protection and conservation should be prioritized to optimize their ecosystem functions in pollution mitigation.

Salt marshes and sublittoral sandbanks exhibit moderate sensitivity, underscoring their ecological importance in fostering biodiversity and mitigating pollution. Restoring and conserving coastal wetland ecosystems, such as peatlands, seagrass, and saltmarsh, enables water utilities to augment carbon sequestration, enhance water quality, and secure the long-term vitality of natural water sources. This strategy alleviates the effects of climate change and enhances the resilience of water management systems. A crucial component, in conjunction with the advancement of Nature-based Solutions (NbS), is the incorporation of NbS into the implementation of nationally determined contributions (NDCs), long-term strategies (LTSs), national adaptation plans (NAPs), National Biodiversity Strategies and Action Plans (NBSAPs), and other strategic frameworks, while underscoring the imperative of collaboration among diverse stakeholders for sustainable development. The ministers underscored the necessity of social and environmental safeguards as essential components of Nature-based Solutions (NbS) and pledged to enhance resource mobilization for NbS, both domestically

and internationally, in accordance with their commitment to the Nature Compact (G7, 2022). This corresponds with the current EU NbS policy objectives, which include: integrating nature-based solutions into research and innovation, policy, and practice at the EU, Member State, and global levels; enhancing and expanding the European research and innovation community focused on nature-based solutions; demonstrating the efficacy of nature-based solutions and establishing a robust evidence base regarding their socio-economic cost-effectiveness and long-term sustainability; promoting the development, adoption, and scaling of locally adapted nature-based solutions through co-creation, co-governance, and citizen engagement; improving financial mechanisms, including access to funding, to expedite the market adoption of nature-based solutions; and refining the regulatory environment for nature-based solutions by incorporating sustainability and nature-based solutions into educational curricula at all levels. The European Commission funds research and innovation initiatives concerning Nature-based Solutions (NbS) that seek to mitigate climate change and biodiversity decline, improve ecosystem health, and create employment through the Horizon 2020 and Horizon Europe programs (EU, 2023). The deployment of nature-based solutions throughout various landscapes is deemed essential for fulfilling the primary objectives of significant EU policy priorities, notably the EU Biodiversity Strategy for 2030 and the EU Adaptation Strategy, to enhance biodiversity and bolster climate resilience in Europe, thereby furthering the European Green Deal.

4.2. Future Perspectives

This foundational study provides a conceptual framework for understanding the adoption of Nature-based Solutions in the context of pollution mitigation and the enhancement of coastal ecosystem resilience. However, given that the environment is consistently exposed to emerging threats, immediate actions are necessary to advance this from a mere framework to a more statistically sound and applicable modeling tool for environmental managers. This NbS-pollution

mitigation mechanism would be refined to address new and emerging threats effectively. Two key areas are proposed for future work:

i. Addressing Marine Pollution from PFAS Contaminants: Another important area of further research is the inclusion of pollution by persistent chemicals, namely PFAS (per- and poly-fluoroalkyl substances), into the current NbS framework. PFAS are referred to as "forever chemicals" because of their persistent nature and pose significant risks to both the environment and human health. Recent research indicates that PFAS contamination in marine environments is primarily influenced by sewage discharges, highlighting the need for focused mitigation strategies. Research conducted in Langstone Harbour, UK, indicated a significant rise in PFAS concentrations following sewage application. Notably, certain compounds, including perfluorobutanoic acid (PFBA), were found to be accumulating in seaweed at concerning levels. The findings indicate that macroalgae may act as a reservoir for PFAS, potentially leading to trophic transfer risks and disruptions within marine ecosystems. Strategies for integrating PFAS mitigation into NbS initiatives should emphasize the restoration of seaweed beds and the enhancement of their contaminant filtration capabilities through biotechnological approaches, such as selective breeding. Improved monitoring and regulation of sewage discharges and identification of safer alternatives to PFAS in consumer products would also be required. It would also include enhancing its supervision of sewer outlets and effluence as well as searching for satisfactory chemicals to eliminate PFAS in consumer products. In addition, cross-sectorial actions with stakeholders such as industry and government agencies would be fundamental in the implementation of preventive procedures and phase-out of PFAS.

ii. Saltmarsh Carbon Sequestration for Emissions Compensation: The incorporation of carbon sequestration via saltmarsh restoration within the NbS framework represents a significant opportunity for future exploration. The development of the Saltmarsh Code presents an opportunity to create a new revenue stream, as it can be utilized to enhance restoration efforts through a

voluntary standard for the verification and sale of carbon sequestered by restored saltmarshes. The Saltmarsh Code enables stakeholders to measure carbon capture and trade saltmarsh carbon credits as a mechanism for offsetting their emissions. This initiative emphasizes carbon sequestration while also providing considerable social and environmental benefits for the future. These factors encompass enhanced biodiversity, greater protection against flood risks, and improved water quality. The potential for future expansion of the NbS framework to include various financial mechanisms could enhance public involvement and investment in restoration initiatives, extending beyond the current participants. The establishment of a monitoring, reporting, and verification (MRV) protocol is essential to confirm that saltmarsh restoration achieves its intended ecological and carbon sequestration benefits, while also ensuring their long-term sustainability. Receiving feedback and input from a variety of stakeholders regarding issue refinement and the integration of this approach is crucial for developing comprehensive coastal resilience strategies.

The incorporation of the subsequent elements in upcoming projects—tackling PFAS pollution, improving carbon sequestration, and safeguarding biodiversity through the restoration and protection of saltmarshes, seagrasses, and shellfish—could greatly enhance the NbS framework, resulting in a more thorough, equitable, multifunctional, and sustainable approach to coastal ecosystem management.

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Annexes:

Annex 1 & 2: Universal Asset Matrix and Universal and Ria Formosa Asset Bioremediation Matrix (UaBM and RFaBM) tables

<https://docs.google.com/spreadsheets/d/1U6nM5L-zjUHgrIfvj9QWt9K0wIf3X7q/edit?gid=1985819237#gid=1985819237>

Annex 3: Ria Formosa Asset-Pollution Sensitivity Matrix (RFaPSM)

Pollution Pressure	Intertidal Mud	Salt Marshes	Seagrass Meadows	Sublittoral Sandbanks	Confidence Level	Reason
Nutrient Enrichment					Strong evidence from recent studies (A. Cravo et al.,2022, A. Newton et al., 2022).	Vulnerability to Nutrient overloading in seagrass meadows and intertidal mudflats is well-documented as causing eutrophication, particularly from agricultural runoff and wastewater discharges (A. Cravo et al.,2022, A. Newton et

						al., 2022). Salt marshes have moderate tolerance due to nutrient retention without immediate degradation (Sousa et al., 2017, A.R. Carrasco, 2021). Sandbanks are less affected as nutrients do not accumulate easily in sandy sediments (Brito et al., 2010).
Sediment Contamination (Heavy Metal: Cadmium, Lead, Nickel)					Strong evidence from recent studies (Silva et al., 2015).	Salt marshes and intertidal mud accumulate heavy metals in vegetation and sediment.

						At the same time, seagrass meadows have a high ability to filter but have a high capacity for accumulation, and they are less affected than salt marshes (Silva et al., 2015). Sandbanks are less affected due to the low accumulation of heavy metals (Silva et al., 2015).
Organic Pollution					Strong evidence from recent studies (Kumar et al., 2020)	Organic pollution can disrupt seagrass and salt marsh ecosystems by affecting clarity and oxygen levels but is

						less impactful compared to mudflats as they tend to be trapped in sediments, reducing waterborne impact, but their effects on sublittoral sandbanks are less severe due to less impact on benthic life than on vegetated habitats. Aquaculture runoff causes significant effects on mudflats (Kumar et al., 2020)
Hydrocarbon Pollution					Strong evidence from	Seagrass meadows are highly sensitive to hydrocarbo

					<p>recent studies (Kumar et al., 2020)</p>	<p>ns from maritime activities, road runoff, or localized petroleum-derived hydrocarbon inputs (Kumar et al., 2020). Sandbanks have low sensitivity as hydrocarbons disperse/are less likely to accumulate in sandy environments (Barreira et al., 2007).</p> <p>Salt marshes and mud absorb hydrocarbons but remain impactful over time (Kumar et al., 2020).</p>
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Microplastic Pollution					Recent data on microplastics is emerging but still developing (Cozzolino et al., 2021).	Microplastic accumulation is significant in seagrass meadows due to ingestion by marine life (Cunha et al.), and intertidal mud retains microplastics due to low water flow. Sandbanks experience less due to sediment movement (Cozzolino et al., 2021). Salt marshes are less affected by floating debris, but retain some (Cozzolino et al., 2021).
Turbidity					Strong evidence from	High turbidity in seagrass

					<p>recent studies (Jacob et al., 2020, Sebastiá-Frasquet et al., 2019).</p>	<p>meadows and intertidal mud affects light availability and photosynthesis due to the increased sediment load from dredging and coastal development. At the same time, sandbanks are generally more tolerant of turbidity due to the dynamic nature of sediment movement in these environments.</p> <p>(Jacob et al., 2020, Sebastiá-Frasquet et al., 2019). Salt marshes</p>
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