NATURE-BASED SOLUTIONS FOR FLOOD RISK REDUCTION

A Review and Guidance for Coastal Protection

Scientific Report from DCE – Danish Centre for Environment and Energy no. 623 2024

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Abstract: This report provides a comprehensive review of Nature-Based Solutions (NbS) for flood risk reduction in coastal areas. By evaluating the effectiveness, costs, and co-benefits of NbS, the report identifies critical gaps in existing research, particularly in the context of Danish coastal ecosystems. The literature review, including over 100 academic papers, reveals a lack of standardized frameworks for assessing the long-term performance and economic viability of NbS. In the report, a holistic research agenda is suggested that integrates ecological, economic, and social dimensions to support NbS's decision-making in coastal protection strategies. The findings underscore the need for further studies focused on cost-benefit analysis, valuation, and scenario-based modelling to enhance the understanding and application of NbS in addressing coastal flood risks.

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Preface

Flooding, exacerbated by climate change and intensified land use, poses a growing challenge for communities worldwide. Traditional infrastructure, while effective, often comes with significant environmental and economic costs. In contrast, Nature-Based Solutions (NbS) have emerged as sustainable alternatives that work with natural processes to mitigate flood risks, offering both environmental resilience and societal benefits. This report, "Nature-Based Solutions for Flood Risk Reduction: A Comprehensive Review and Guidance for Coastal Protection," explores the potential of NbS in addressing flood risks in both coastal areas.

The primary objectives of this report are to map and describe different types of NbS relevant to flood risk reduction, evaluate their effectiveness in various contexts based on existing literature, and assess the costs associated with their implementation. Additionally, the report identifies the co-benefits of NbS, such as enhanced biodiversity, improved water quality, and recreational value.

The research underpinning this report involved an extensive review of more than 100 academic papers and grey literature reports, complemented by further analysis under the EU Horizon project, Invest4Nature. Surprisingly, we found a significant gap in the literature, with minimal research dedicated specifically to the valuation and application of NbS for coastal flood protection in a Danish context. This underscores the need for further basic research in the field and the development of standardized methodologies for evaluating and presenting the economic and environmental benefits of NbS.

This report was financed by a contract with the Ministry of Environment, managed by Aarhus University's Institute of Environmental Sciences and the Institute for Food and Resource Economics. The projects were commissioned by the Coastal Directory. We hope that this report will contribute to filling this knowledge gap and serve as a valuable resource for policymakers, urban planners, and environmental practitioners. By advancing the understanding and application of NbS, we aim to support more resilient and sustainable approaches to flood risk management in the face of climate change.

Sammenfatning

Denne rapport præsenterer en omfattende gennemgang af naturbaserede løsninger (NbS) til reduktion af oversvømmelsesrisiko i kystområder, med fokus på deres effektivitet, omkostninger og merværdi. Kystområder står over for stigende trusler fra klimaforandringer, stigende havniveauer og øget arealanvendelse, hvilket gør NbS til et bæredygtigt og fleksibelt alternativ eller supplement til håndtering af oversvømmelsesrisici, samtidig med at de giver yderligere miljømæssige og samfundsmæssige fordele. Formålet med denne gennemgang var at udfylde videnshuller, særligt med fokus på danske kystøkosystemer.

Undersøgelsen bygger på en grundig gennemgang af over 100 akademiske artikler samt supplerende studier fra EU Horizon-projektet Invest4Nature. På trods af den voksende interesse for NbS fremhæver rapporten en betydelig mangel på standardiserede rammer for at vurdere den økonomiske bæredygtighed af NbS i en dansk kontekst. Mange studier fokuserer på de miljømæssige aspekter, men undlader ofte at tage socioøkonomiske dimensioner i betragtning, herunder omkostningseffektivitet og bredere økonomiske fordele som kulstoflagring, biodiversitetsfremme og rekreative muligheder.

Gennemgangen understreger NbS' effektivitet, herunder brugen af saltmarsker, ålegræsenge, østersrev og strandfodring, til at reducere oversvømmelsesrisici, mindske erosion og forbedre kystområders modstandsdygtighed. Dog påpeger rapporten, at disse fordele er kontekstafhængige og kan variere baseret på lokale miljøforhold som sedimentdynamik og bølgeenergi. Dette understreger behovet for kontekstspecifikke studier, især i danske kystområder, for at sikre, at de foreslåede løsninger er relevante og effektive lokalt.

En central anbefaling i rapporten er udviklingen af en holistisk forskningsdagsorden, der integrerer økologiske, økonomiske og sociale dimensioner. Denne tværfaglige tilgang er afgørende for at opnå en dybere forståelse af, hvordan NbS fungerer under forskellige miljømæssige, sociale og økonomiske forhold. Forskningsdagsordenen foreslår inddragelse af cost-benefit-analyser, vurdering af økosystemtjenester og scenariebaseret modellering for at vurdere NbS' langsigtede bæredygtighed og tilpasningsevne under fremtidige klimaforhold.

Afslutningsvis understreger rapporten behovet for yderligere forskning med fokus på udvikling af standardiserede rammer, gennemførelse af cost-benefit-analyser og anvendelse af scenariebaseret modellering. Disse tiltag er afgørende for at fremme forståelsen og anvendelsen af NbS som en bæredygtig tilgang til håndtering af oversvømmelsesrisici i kystområder, med særlig vægt på danske forhold.

Summary

This report offers a comprehensive review of Nature-based Solutions (NbS) for flood risk reduction in coastal areas, examining their effectiveness, costs, and co-benefits. Coastal areas face increasing threats from climate change, rising sea levels, and intensified land use, making NbS a sustainable and adaptive alternative or supplement for managing flood risks while delivering additional environmental and societal benefits. The purpose of the review were to bridge knowledge gaps, especially in the context of Danish coastal ecosystems.

The research involved a thorough literature review of over 100 academic papers, supplemented by further studies conducted under the EU Horizon project, Invest4Nature. Despite the growing interest in NbS, the report identifies a significant lack of standardized frameworks for evaluating their economic viability relevant to a Danish context. Many studies focus on environmental effectiveness but fall short in addressing socio-economic dimensions, including the cost-effectiveness and broader economic benefits of NbS, such as carbon sequestration, biodiversity enhancement, and recreational opportunities.

The review highlights the effectiveness of various NbS, including salt marshes, seagrass meadows, oyster reefs, and beach nourishment, in mitigating flood risks, reducing erosion, and enhancing coastal resilience. However, it stresses that these benefits are context-dependent and may vary based on local environmental conditions, such as sediment dynamics and wave energy. This variability underscores the need for context-specific studies, particularly in Danish coastal areas, to ensure that the solutions proposed are locally applicable and effective.

A key recommendation of the report is the development of a holistic research agenda that integrates ecological, economic, and social dimensions. This interdisciplinary approach is essential for providing a nuanced understanding of how NbS perform under different environmental, social, and economic conditions. The agenda proposes the inclusion of cost-benefit analyses, valuation of ecosystem services, and scenario-based modeling to evaluate the long-term sustainability and adaptability of NbS under changing climate conditions.

In conclusion, the report underscores the need for further research focused on developing standardized frameworks, conducting cost-benefit analyses, and applying scenario-based modeling. These efforts are crucial for advancing the understanding and application of NbS as a viable and sustainable approach to managing flood risks in coastal areas, with particular attention to the Danish context.

1 Introduction

Flooding represents an escalating threat to both urban and rural areas due to the impacts of climate change and intensified land use. Nature-based solutions (NbS) offer sustainable alternatives to traditional infrastructure by leveraging and mimicking natural processes to mitigate flood risks from both coastal and riverine systems. This project aims to compile and analyse data on various types of NbS, their effectiveness, implementation costs, and associated societal co-benefits.

While conducting a comprehensive literature review, which included over 100 papers, supplemented by an additional 14 studies under the EU Horizon project "Invest4Nature," we found a significant gap in relevant information that can be related to a Danish context – se Chapter 4 for further elaboration on the matter.

This suggests that the literature on NbS for flood reduction, particularly in coastal contexts, is underdeveloped. The lack of robust studies in this field highlights the pressing need for foundational research into the valuation of NbS in coastal protection and flood prevention.

Additionally, there is an urgent requirement for a standardized structure or design for how these values are estimated and reported. Such efforts would enhance the understanding and integration of NbS into effective flood protection strategies. We therefore propose such a design thus laying the grounds for a future with well-developed robust valuation estimates of NbS related to the coast.

The structure of this report is designed to guide the reader through the key concepts, findings, and recommendations regarding NbS for flood risk reduction. Chapter 2 provides an overview of NbS, detailing their definitions, types, and relevance to flood risk management. In Chapter 3, we describe the methodology used in our extensive review of the literature, highlighting the search parameters and selection criteria. Chapter 4 presents the results of the literature review, offering insights into the current research landscape and identifying gaps in the valuation and application of NbS for coastal flood protection.

Building on these findings, Chapter 5 proposes a research agenda and a framework for designing future studies, including suggestions for economic valuation methodologies and implementation strategies. Finally, Chapter 6 offers a critical discussion of the findings and their implications for policymakers and practitioners.

2 Nature-based Solutions

There is no single, universally accepted definition of Nature-based Solutions (NbS), and different organizations emphasize distinct aspects of the concept. Three key definitions come from the European Commission, the International Union for Conservation of Nature (IUCN), and the United Nations Environment Assembly (UNEA).

According to the European Commission, NbS "aim to help societies address a variety of environmental, social, and economic challenges in sustainable ways. They are actions inspired by, supported by, or copied from nature; both using and enhancing existing solutions to challenges, as well as exploring novel solutions, for example, mimicking how non-human organisms and communities cope with environmental extremes" (European Commission, 2015, p. 24).

The IUCN defines NbS as "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges (e.g., climate change, food and water security, or natural disasters) effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits" (Cohen-Shacham et al., 2016, p. xii).

Similarly, UNEA describes NbS as "actions to protect, conserve, restore, sustainably use, and manage natural or modified terrestrial, freshwater, coastal, and marine ecosystems, which address social, economic, and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience, and biodiversity benefits" (UNEA, 2022).

Although these definitions differ slightly, they share several common elements:

1. **Addressing societal challenges:** All three definitions emphasize that NbS are designed to tackle societal challenges such as climate change, biodiversity loss, and socio-economic issues. This highlights that NbS serve multiple purposes—environmental protection and human well-being.
2. **Sustainability and adaptive management:** Sustainability is a central theme across all definitions. NbS are presented as long-term, adaptable approaches that align with environmental sustainability. The European Commission (EC) and IUCN stress "sustainable management" and "adaptive solutions," while UNEA emphasizes "sustainable use and management."
3. **Incorporating natural and modified ecosystems:** Each definition underscores the importance of both natural and modified ecosystems. The EC refers to solutions "inspired by, supported by, or copied from nature," while IUCN and UNEA specifically mention protecting, restoring, and managing both natural and modified ecosystems to deliver benefits.
4. **Human well-being and biodiversity benefits:** Enhancing human well-being and biodiversity are key outcomes in all definitions. NbS are seen as interventions that generate co-benefits for people (e.g., improving livelihoods, providing ecosystem services) and nature (e.g., conserving biodiversity, enhancing ecosystem resilience).

5. **Holistic approach to challenges:** All definitions emphasize that NbS adopt a holistic approach by addressing interconnected environmental, social, and economic challenges. The EC highlights NbS as solutions to a variety of challenges, while IUCN and UNEA stress the simultaneous contributions to human well-being, ecosystem services, and biodiversity.
6. **Innovation and learning from nature:** The EC particularly focuses on the innovative aspect of NbS, noting that some involve "novel solutions" that mimic natural processes. This emphasis on learning from nature's adaptations to environmental extremes adds a creative dimension to NbS design.

In summary, NbS address societal challenges through the protection, restoration, and sustainable management of both natural and modified ecosystems, with the overarching goal of supporting human well-being and biodiversity simultaneously.

2.1 The typology of Nature-based Solutions

Eggermont et al. (2015) identify three broad typologies of NbS, which may overlap or complement each other (see Figure 1). These typologies reflect varying levels of human intervention, ranging from minimal to extensive. The three categories are as follows:

1. **Protection and conservation of high-quality or critical ecosystems:** This typology focuses on preserving healthy, intact ecosystems and managing them sustainably to maintain their ecological integrity and functions.
2. **Modification and restoration of degraded ecosystems:** This approach involves human intervention to enhance or restore ecosystems that have been degraded. It aims to improve the ecological health and resilience of these systems.
3. **Creation of entirely novel ecosystems:** In this category, ecosystems are either transformed or newly established to meet specific human and environmental needs, often in areas where natural ecosystems no longer exist or are unable to recover on their own.

These typologies represent a spectrum of interventions, from conserving existing ecosystems to creating new ones, offering flexible solutions for addressing various environmental and societal challenges.

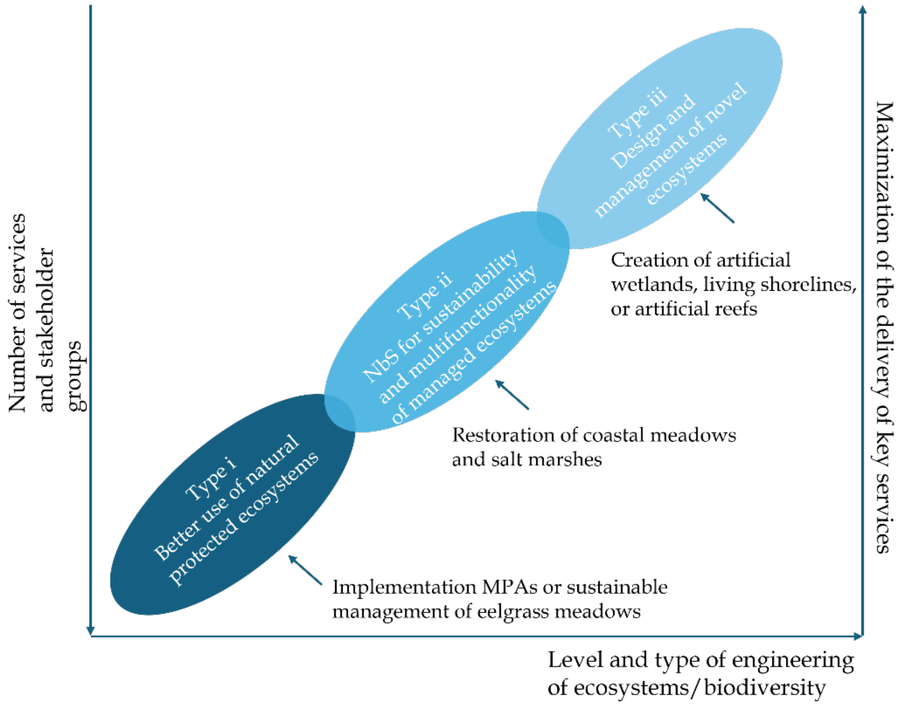

Figure 1 Typology of NbS. Source: Based on Eggermont et al. (2015, p. 245).

These typologies offer a practical framework for implementing NbS, reflecting the diverse ways in which NbS can address societal challenges. At one end of the spectrum, minimal intervention involves protecting and sustainably managing healthy ecosystems. In a Danish coastal context, this could include establishing Marine Protected Areas (MPAs), such as in the Kattegat, or sustainably managing eelgrass beds in Danish waters. Protecting vital ecosystems like eelgrass meadows can enhance biodiversity, improve water quality, and increase carbon storage. MPAs safeguard these ecosystems from overfishing, habitat destruction, and pollution, ensuring long-term benefits for marine biodiversity and supporting local fisheries.

As we move toward more intensive interventions, restoration and rehabilitation come into play, aiming to recover degraded ecosystems and their services. An example is the restoration of coastal meadows and salt marshes along the Danish Wadden Sea coast. These ecosystems, often degraded by agriculture and urban development, are now being restored to enhance biodiversity, strengthen flood defences, and provide critical habitats for migratory birds. Such restoration efforts can mitigate the impacts of rising sea levels, improve coastal resilience, and support nature-based tourism in Denmark.

At the other extreme, entirely novel ecosystems can be introduced to address societal challenges where natural ecosystems have been heavily altered or lost. For instance, the creation of artificial wetlands and living shorelines along Denmark's urbanized coastlines, such as in Greater Copenhagen or Aarhus, can provide flood protection, improve water quality, and create new habitats. These artificial ecosystems—constructed wetlands near harbours or living shorelines using natural materials like plants and shells—serve as natural defences against storm surges and coastal erosion while promoting biodiversity and urban resilience (Smith et al., 2018; Firth et al., 2013; Browne & Chapman, 2011). However, the effectiveness of these nature-based solutions is context-dependent and may require large expanses to significantly reduce storm surge (Saleh & Weinstein, 2016).

Additionally, artificial reefs, often built from natural or recycled materials, can be constructed to create new marine habitats and enhance coastal protection. These structures provide habitats for marine species where natural reefs are absent and act as barriers, reducing wave energy and protecting against coastal erosion (Seaman, 2019; Harris et al., 1996).

2.2 Overview over possible coastal NbS and associated benefits

Coastal NbS offer nature-inspired approaches to mitigate the unique environmental, social, and economic challenges faced by coastal areas. Grounded in the protection, restoration, and creation of ecosystems, these solutions support biodiversity and deliver a variety of ecosystem services. The following provides an overview of key coastal NbS actions and their benefits, illustrating how these interventions can simultaneously enhance human well-being and promote environmental sustainability (Table 1; see also Lozano et al., 2023).

The protection and conservation of existing ecosystems, such as barrier islands, seagrass meadows, salt marshes, and coral reefs, deliver critical ecosystem services. These ecosystems act as natural buffers, protecting coastlines from erosion and storm surges. For example, coral and oyster reefs dissipate wave energy, reducing the impact of storms, while coastal vegetation stabilizes sediments, helping to prevent coastal erosion (see Ferrario et al., 2014; Gracia et al., 2018; Morris et al., 2018). In addition to their protective functions, these conserved ecosystems support biodiversity by providing habitats for marine species, enhancing fisheries, and contributing to food security (see Gilby et al., 2018).

Where ecosystems have been degraded, modification and restoration efforts, such as managed realignment and the rehabilitation of coastal habitats (e.g., dunes, wetlands, and seagrass meadows), are essential. These interventions offer a range of benefits. Managed realignment improves nutrient retention, water regulation, and carbon sequestration while also promoting recreational and nature-based tourism opportunities, which support local economies (see MacDonald et al., 2020). Additionally, restoring coastal habitats like wetlands and seagrasses reduces wind speed, increases carbon storage, and lessens the impact of waves during strong storms, providing critical protection against extreme weather events. These restored habitats also serve as nursery grounds for marine species, enhance water filtration, and boost species richness and overall biodiversity (see Chen et al., 2022; Hynes et al., 2021; Renaud et al., 2013).

Near-shore morphological enhancements, such as beach nourishment, dune reconstruction, and cliff stabilization, mitigate shoreline retreat, reduce coastal erosion and flood risks, and stabilize sediments. These interventions help prevent habitat and nutrient loss, ultimately contributing to the reduction of coastal storm risks and the preservation of coastal ecosystems and communities (see Bridges et al., 2015; Charbonnel et al., 2011; Taal et al., 2016).

Table 1 Overview of coastal NbS and potential benefits. Source: Modified version of Lozano et al. (2023, p. 18).

NbS type		Specific action	Benefits and services
i)	Protection/-conservation of ecosystems	Protection of barrier islands, sea grass (seafloor vegetation), salt marshes, coral & oyster reefs, and coastal vegetation	Lozano et al. (2023) identified various benefits of coastal NbS: i) they diminish the effects of coastal erosion and hazards. (Morris et al., 2018); ii) vegetation and natural barriers support erosion control by retaining sediments (Gracia et al., 2018); iii) reefs made of coral and oysters diffuse wave energy, offering protection (Ferrario et al., 2014); and iv) preservation of fish habitats (higher biomass and food security) and carbon sequestration
ii)	Modification of ecosystems	Managed realignment of coastal areas	Increased nutrient retention, water regulation, carbon sequestration as well as recreational and eco-tourism potential, reduced coastal erosion (MacDonald et al., 2020)
		Restoration of coastal habitats in transitional waters, e.g., dunes, seagrasses, wetlands, saltmarshes, oyster & reef species	Decreased wind speed, improved carbon storage and sequestration, wave attenuation during strong storms (Renaud et al., 2013), nursery habitats, water filtering, species richness, and biodiversity (Chen et al., 2022; Hynes et al., 2021).
		Near-shore enhancement of coastal morphology, e.g., restoration of barrier islands, beach nourishment, dune reconstruction, cliff stabilization	Mitigation of shoreline retreat, erosion and flooding, sediment stabilization, coastal storm risk reduction, reduced habitat and nutrient loss (Bridges et al., 2015; Charbonnel et al., 2011; Taal et al., 2016).
iii)	Creation of new ecosystems	Engineered hybrid solutions: Natural solutions combined with built structures, such as, green dikes, wooded fences and vegetated levees, which are combined with structural dikes	Improved resilience against climate-related risks including storm surges, coastal erosion, and landslides, as well as an increase in biodiversity.

In areas where natural ecosystems are absent or severely degraded, the creation of novel ecosystems through engineered hybrid solutions becomes highly relevant. These approaches, such as green dikes and vegetated levees, combine natural elements with structural defences to enhance coastal resilience. By integrating built infrastructure with natural systems, hybrid solutions provide improved protection against storm surges, coastal erosion, and landslides, while simultaneously boosting biodiversity and delivering ecosystem services that traditional grey infrastructure alone cannot offer (see, e.g., Morris et al., 2018).

While NbS can mitigate coastal floods and erosion, concerns exist regarding their environmental impacts (Inácio et al., 2020). Implementation of marine NbS remains limited, but is expected to increase as they are incorporated into policies and research programs (Riisager-Simonsen et al., 2022). Assessing NbS effectiveness requires a comprehensive set of ecosystem service indicators, encompassing biodiversity, environmental, and socioeconomic dimensions (Murillas-Maza et al., 2023). However, the outcomes of NbS interventions can be context-dependent, with varying effects observed in different locations (O'Shaughnessy et al., 2021). Further research is needed to address knowledge gaps and improve the design and implementation of marine NbS (O'Leary et al., 2023).

3 Review description

This section outlines the methodology used for the literature review, which provided the foundation for gathering evidence and insights on the implementation of Nature-based Solution (NbS). The primary goal of the review was to identify relevant case studies and explore the broader academic discourse surrounding NbS in various contexts. The process involved screening multiple databases, using tailored search queries, and evaluating abstracts and full texts based on predefined inclusion criteria.

To identify pertinent case studies on NbS, a comprehensive review was conducted across seven key databases, focusing on NbS and the economic valuation of ecosystems. The selected databases were deemed relevant for the literature search and provided a robust source of academic and empirical studies.

- Ecosystem Services Valuation Database (ESVD)
- Bluevalue (database of valuation studies for ecosystem services)
- OPPLA (EU Repository of NbS)
- weADAPT (Global platform for knowledge exchange on climate adaptation)
- Natural Water Retention Measures (NWRM)
- The European Climate Adaptation Platform (ClimateADAPT)
- Bottom-Up Climate Adaptation Strategies Towards a Sustainable Europe (BASE)

Although some databases, such as the ESVD, contain a substantial number of case studies (over 10,000 in total), the number of Danish case studies was relatively limited, as shown in the second column of Table 2. For example, while the ESVD lists 14 Danish case studies, none met the minimum relevance criteria for this project, which focused on NbS in coastal ecosystems related to flood risk mitigation. This trend was consistent across all databases, with none of the Danish case studies ultimately qualifying for further analysis.

Table 2 Overview of databases screened for relevant Danish case studies. (Databases last accessed: 20.09.2024).

Database	No. of case studies	No. of Danish case studies	No. of relevant case studies
ESVD	10874	14	0
Bluevalue	1279	0	0
OPPLA	542	11	0
weADAPT	849	1	0
NWRM	188	1	0
ClimateADAPT	137	3	0
BASE	24	3	0

To supplement the database review, a set of tailored search queries was applied in Google Scholar. Google Scholar was chosen over traditional academic databases like Web of Science and Scopus to capture potentially valuable grey literature, including reports and other non-peer-reviewed materials that could offer insights into the practical aspects of NbS planning and implementation.

The initial search yielded a large number of studies, especially when focusing on broader NbS topics without geographical limitations. To refine the results and ensure relevance to the project, the search was narrowed to Danish case studies. The findings for beach nourishment in Denmark are summarized in Table 3 below.

Table 3 Example of Google Scholar Search Results for Beach Nourishment.

Search string	Nr. of publications
"nature based solutions" "denmark" "cost"	3,980
"beach nourishment" "denmark" "cost"	1,320
"beach nourishment" "denmark" "cost" "valuation"	260

Each search queries were designed to capture studies relevant to different types of NbS, with a specific focus on Danish contexts and the cost-benefit aspects of NbS. The search strings for the four considered NbS (beach nourishment, cliff stabilisation, barrier islands and salt marshes) are summarised in Table 4.

Table 4 Google Scholar Search Strings.

Search string
"beach nourishment" "denmark" "cost*" "benefit*" "nature-based solutions"
"cliff stabilisation" "denmark" "cost*" "benefit*" "nature-based solutions"
"barrier islands" "denmark" "cost*" "benefit*" "nature-based solutions"
"salt marshes" "denmark" "cost*" "benefit*" "nature-based solutions"

Studies were first screened at the abstract level based on four key criteria: the environmental issue (flood risk), the type of solution (NbS), the geographical focus (Denmark), and the type of assessment ((socio-)economic). If all criteria were met, the study proceeded to full-text assessment (see also for Figure 2).

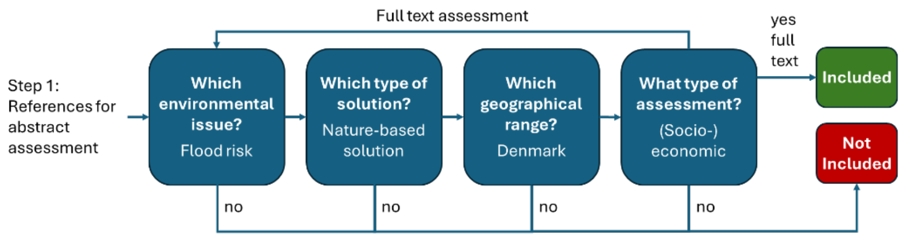

Figure 2 Decision flowchart based on four criteria used during abstract and full text assessment. Source: Based on Heckwolf et al. (2021).

On this basis, the identified and selected literature was systematically recorded and categorized according to several key variables, allowing for a detailed and structured analysis of relevant studies. The extraction categories included are:

- Reference number
- Study (bibliographic information, e.g., author names, publication year, title and source details)
- Type (e.g., journal article, report, etc.)
- URL/DOI
- Relevance (to the review focus)
- Comments
- NbS definition / reference (ether a definition of NbS was provided, and if so, which definition it referred to e.g. IUCN, European Commission)
- NbS typology (categorization of NbS according to Eggermont et al. (2015))

- Location (geographical focus of the study)
- Type of NbS (e.g., beach nourishment, salt marshes)
- Method (methodology used in the study)
- Main findings (summary of key outcomes of the study)
- Effectiveness (performance of the NbS)
- Costs
  - Establishment costs
  - Cost unit
  - Maintenance costs
  - Maintenance interval
  - Monitoring costs
  - Financing costs
  - Opportunity cost
  - Indirect costs
- Cost of technical solution
  - Type of grey infrastructure
  - Establishment costs
  - Cost unit
  - Maintenance costs
  - Maintenance Interval
- Co-benefits
  - Recreational
  - Water Quality
  - Biodiversity
  - Other

4 Results

A total of 150 documents were initially screened during the review process, 37 of which were identified as duplicates due to the use of different search strings. This left 113 documents for further screening (see Table 5 and the supplementary Table). None of these were fully relevant as they did not focus specifically on Danish case studies. However, 12 studies were deemed partly relevant because they aligned with Nature-based Solutions (NbS) for flood protection in coastal ecosystems, albeit in different geographical areas or with limited socio-economic assessments. These studies provided insights into the cost-effectiveness, overall effectiveness, and co-benefits of NbS. However, caution is advised when interpreting these findings due to the differences in geographical context and focus.

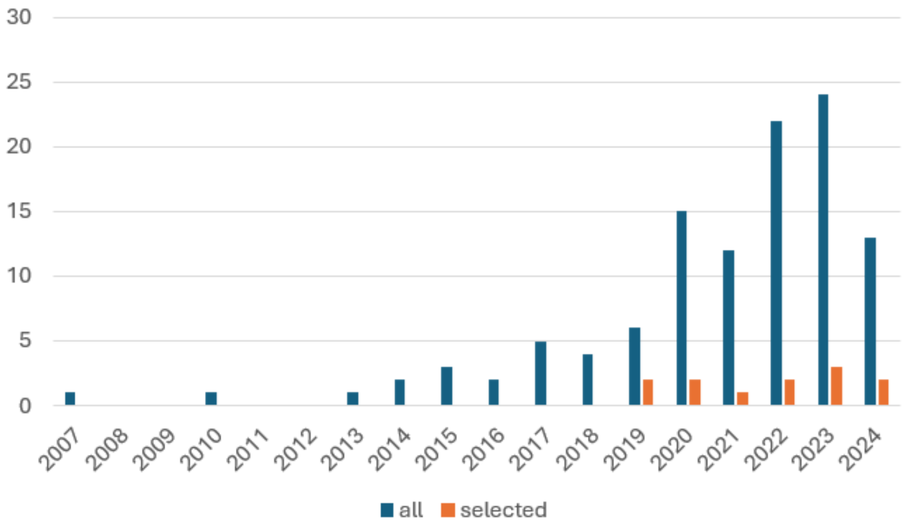

Figure 3 Bar chart showing the distribution of publication years for all studies screened and the included studies.

As illustrated in Figure 3, the studies span from 2007 to 2024, indicating a growing interest in the application of NbS for coastal protection over recent years. Most of the relevant studies were published in 2022 and 2023, reflecting the increasing focus on NbS in academic literature.

Table 5 Overview of screened documents.

Nr.	Study	Type
1	van der Meulen, F., IJff, S. and van Zetten, R. (2023), Nature-based solutions for coastal adaptation management, concepts and scope, an overview. Nordic Journal of Botany, 2023: e03290.	Article (peer-reviewed)
2	Wolf, B. (2024). Coastal Nature-based Solution: a proposal for the Italian context starting from the Danish case study (Master's Thesis, Politecnico di Torino).	Thesis (Master)
3	Borner, Johan Singharat, 2020. Climate adaptation for coastal zones : benefits and tradeoffs in a southern Swedish case. Second cycle, A2E. Alnarp: SLU, Dept. Of Landscape Architecture, Planning and Management	Online publication
4	Vuik, V., Borsje, B. W., Willemsen, P. W., & Jonkman, S. N. (2019). Salt marshes for flood risk reduction: Quantifying long-term effectiveness and life-cycle costs. Ocean & coastal management, 171, 96-110.	Article (peer-reviewed)
5	Nordh D., Goodfellow B.W., Hollander J., Danielsson P. 2022, A review of environmental aspects of beach nourishment, Literature Study, Swedish geotechnical institute, SGI, Linköping, 2022-09-22.	Report
6	Sánchez-Arcilla, A., Cáceres, I., Roux, X. L., Hinkel, J., Schuerch, M., Nicholls, R. J., Otero, d. M., Staneva, J., de Vries, M., Pernice, U., Briere, C., Caiola, N., Gracia, V., Ibáñez, C., & Torresan, S. (2022). Barriers and enablers for upscaling coastal restoration. Nature-Based Solutions, 2, 100032.	Article (peer-reviewed)
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112	Tyllianakis, E., Fronkova, L., Posen, P., Luisetti, T., & Mangi, S. C. (2020). Mapping ecosystem services for marine planning: A UK case study. Resources, 9(4), 40.	Article (peer-reviewed)
113	Hérivaux, C., Rey-Valette, H., Rulleau, B., Agenais, A.-L., Grisel, M., Kuhfuss, L., Maton, L., & Vinchon, C. (2018). Benefits of adapting to sea level rise: The importance of ecosystem services in the French Mediterranean sandy coastline. Regional Environmental Change, 18, 1815–1828.	Article (peer-reviewed)

The 12 selected studies spanned coastal environments in the Netherlands, Italy, Portugal, the UK, Norway, Sweden, and Ireland. These studies covered a range of NbS types, including salt marshes, seagrass meadows, oyster reefs, beach nourishment, seaweed cultivation, and kelp forest restoration. The primary focus of the studies was on coastal erosion and flood protection, though some studies also addressed biodiversity and water quality co-benefits.

Key NbS types included (see also Figure 4):

- Salt marshes (Rendón et al., 2022; Tyllianakis et al., 2020; Vuik et al., 2019)
- Seagrass meadows (Sierra et al., 2023; Unguendoli et al., 2023)
- Oyster and shellfish reefs (Cobacho, 2019; Hynes et al., 2022)
- Beach nourishment (Lorenzoni et al., 2024; Pais-Barbosa et al., 2023)

- Kelp forest restoration(Hynes et al., 2021)
- Seaweed cultivation (Hasselström et al., 2020)
- arrier islands and hybrid structures (Vieira et al., 2024)

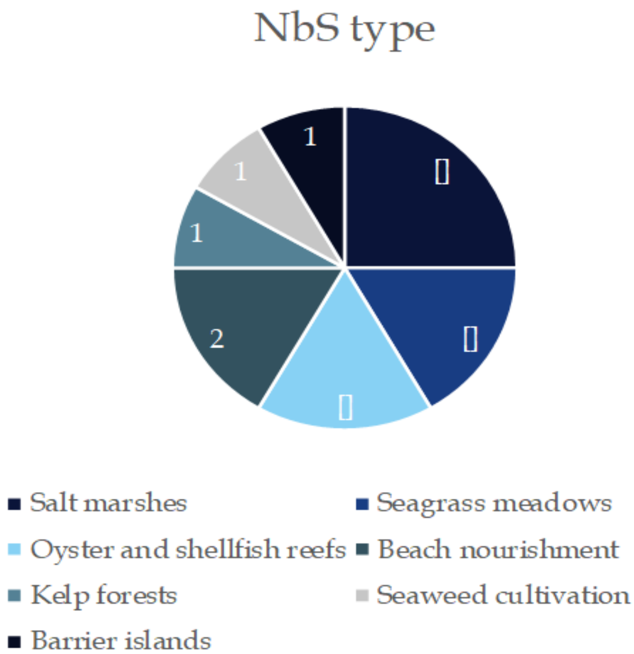

Figure 4 Pie chart depicting the distribution of NbS types across the selected studies.

The methods used across these studies ranged from probabilistic modelling, cost-benefit analysis (CBA), to discrete choice experiments (DCE), and participatory workshops. Many studies used ecological or hydro-morphodynamic models to assess the effectiveness of NbS under different environmental conditions, especially for reducing coastal erosion and mitigating flood risks. Hydro-morphodynamic models are specialized tools that simulate the interactions between water flow, sediment movement, and landforms along coastlines and rivers. These models help scientists understand how natural features like beaches, dunes, and riverbanks will evolve over time in response to changes in water movement, wave action, and sediment deposition. By combining physical and environmental data, hydro-morphodynamic models can predict how coastal and riverine areas will respond to extreme weather events or long-term changes, like rising sea levels or increased storm frequency. This information is essential for evaluating how NbS might protect these areas by stabilizing sediments or slowing down water flow

4.1 Key findings from the literature review

The individual studies provided a range of insights into the effectiveness, costs, and benefits of NbS. Key findings include:

1. Vuik et al. (2019): Salt marsh construction was found to reduce the probability of dike failure by a factor of 2.8. The cost of constructing a foreshore with a high zone was significantly lower (€1.5–3.9M) compared to dike heightening (€5.4–14.9M).
2. Unguendoli et al. (2023): Seagrass meadows reduced wave heights by 49–89%, and artificial dunes attenuated flooded areas by 51-75%. These NbS approaches also offered co-benefits, including habitat development and biodiversity enhancement.

3. Lorenzoni et al. (2024): Public perceptions of beach nourishment (sandscaping) in the UK's first sandscaping scheme indicated strong support for the approach, particularly due to relief from flood and erosion anxiety, though expectations for long-term success were tempered by concerns over future maintenance costs.
4. Sierra et al. (2023): Transplanted seagrass meadows reduced wave heights by an average of 10.5%, with reductions as high as 36.1% in certain areas, demonstrating the potential for seagrass to mitigate coastal erosion in medium to low-energy environments.
5. Pais-Barbosa et al. (2023): The cost-benefit analysis of beach nourishment in Portugal found that the benefit-cost ratio varied between 0.66 and 2.09, depending on sediment volumes and assumptions about future climate scenarios.
6. Vieira et al. (2024): Hybrid NbS structures such as barrier islands and submerged structures were highly effective in reducing erosion and reversing longitudinal drift, while also promoting sediment accumulation.
7. Cobacho (2019): Shellfish reefs in the Wadden Sea were found to contribute to coastal protection by stabilizing sediments and reducing erosion. However, their effectiveness was influenced by future climate scenarios, with potential reductions in their long-term sustainability.
8. Hynes et al. (2022): Oyster reef restoration provided a significantly higher benefit-cost ratio (19.27) compared to traditional grey infrastructure (1.34), underscoring the economic and environmental viability of NbS in specific cases.
9. Hynes et al. (2021): The choice experiment conducted in Norway revealed a strong public willingness to pay for kelp forest restoration, particularly for biodiversity improvements, with WTP ranging from €23.11–26.94 per person per year for high biodiversity.
10. Hasselström et al. (2020): Seaweed cultivation in Sweden demonstrated significant potential for nutrient sequestration and economic profitability, although there were concerns about the potential negative impacts on recreational activities due to commercial seaweed use.
11. Rendón et al. (2022): Public preferences for saltmarsh expansion in Wales showed higher WTP for saltmarshes with high vegetation (€0.17–0.29 per household per year) compared to traditional defence structures (note that original values were converted from GBP to EUR and adjusted for inflation).
12. Tyllianakis et al. (2020): Saltmarsh conservation in Southwest England showed notable ecosystem service benefits, particularly carbon sequestration valued between €23176–27298 (note that original values were converted from GBP to EUR and adjusted for inflation).

Synthesizing the findings from the 12 case studies reveals three consistent themes:

- NbS can be more cost-effective than traditional grey infrastructure, particularly in terms of long-term sustainability and co-benefits. Studies on oyster reefs (Hynes et al., 2022) and salt marshes (Vuik et al., 2019) demonstrated clear economic advantages over dike heightening or revetments.
- Biodiversity and ecosystem services such as nutrient sequestration, carbon storage, and recreational benefits are significant co-benefits of NbS, as highlighted in studies on kelp forest restoration (Hynes et al., 2021), seaweed farming (Hasselström et al., 2020), and saltmarsh expansion (Rendón et al., 2022).

- The effectiveness of NbS is highly context-dependent, with environmental conditions such as wave energy, sediment dynamics, and climate scenarios playing a crucial role in determining success. For instance, seagrass meadows were more effective in low-energy environments (Sierra et al., 2023), while barrier islands excelled in reversing longitudinal drift (Vieira et al., 2024).

However, several potential issues regarding the assessment's risk of bias can be identified:

- Geographical limitations: Several studies, such as those by Hynes et al. (2022); Hynes et al. (2021) and Cobacho (2019), focused on regions outside Denmark, such as Norway, Ireland, and the Wadden Sea. These regional biases may limit the applicability of findings to Danish coastal contexts.
- Modeling assumptions: Many studies relied on numerical simulations (e.g., Delft3D, XBeach models), which introduced biases based on the parameters and assumptions made. For example, Vieira et al. (2024) used hydro-morphodynamic modeling to simulate the effects of hybrid structures like barrier islands, which may not account for all local ecological dynamics.
- Socio-economic data gaps: Studies like Cobacho (2019) and Sierra et al. (2023) focused heavily on environmental effectiveness without comprehensive socio-economic analysis, which limits the understanding of local perception and acceptance, broader impacts and of the long-term viability of NbS.
- Changes in environmental conditions: For example, the high cost-effectiveness of oyster reefs and salt marshes may not fully account for potential maintenance costs or changing environmental conditions.

These biases affect the generalizability and robustness of the findings, particularly when attempting to apply them to different geographical or social contexts. As a result, the overall certainty of evidence across the reviewed studies is only moderate. While most studies employed robust modeling techniques and consistently demonstrated the effectiveness of NbS, the lack of detailed socio-economic assessments and regional biases in many studies diminish the overall confidence in the findings.

Nevertheless, the consistent identification of co-benefits, such as biodiversity enhancement and ecosystem service provision, strengthens the case for using NbS over traditional grey infrastructure. To leverage these co-benefits effectively, it is essential to quantify them in ways that facilitate direct comparison with the costs and benefits of alternative solutions. One approach is to measure co-benefits using indicators tied to their ecological, social, or economic impact, such as habitat restoration area, carbon sequestration rates, recreational value, or public health improvements. Translating these metrics into monetary terms can further enhance their comparability across different contexts and facilitate cost-benefit analyses. Techniques such as contingent valuation, choice experiments, hedonic pricing, and avoided cost methods can be employed to estimate the economic value of these benefits, aligning them on the same scale as financial costs (TEEB, 2010).

Despite the potential of these methods, there remains a critical challenge: the lack of standardized frameworks or methodologies for measuring and valuing the effectiveness and economic viability of NbS. This variability in approaches complicates the comparison of results across studies and geographic contexts, potentially hindering broader uptake of NbS. Developing universally accepted guidelines for quantifying and valuing co-benefits could support more robust and comparable evaluations, thereby strengthening the case for nature-based solutions in coastal and marine environments

5 A proposal for a research agenda and estimates design structure

A holistic and interdisciplinary approach is crucial for advancing research on Nature-based Solutions (NbS) in coastal protection. Future assessments of coastal NbS for flood risk management must extend beyond evaluating their effectiveness in mitigating flood risks to include their broader environmental, social, and economic impacts.

Despite their potential, the widespread adoption of NbS faces several challenges. Predicting their long-term effectiveness remains difficult, and standardized methods for evaluating benefits are still lacking. Additionally, the absence of comprehensive data complicates efforts to conduct reliable cost-benefit analyses, particularly when comparing NbS with traditional engineering solutions.

To address these challenges, it is vital to develop standardized assessment frameworks and compile comprehensive datasets that facilitate meaningful comparisons between NbS and grey infrastructure (Moraes et al., 2022; Morris et al., 2018; Narayan et al., 2016; Temmerman et al., 2013).

To fully realize the potential of NbS, research must integrate multiple disciplines—including ecology, economics, social sciences, and engineering. This interdisciplinary approach will allow future studies to provide a more nuanced understanding of how NbS function across different contexts and under varying environmental, social, and economic conditions. Expanding the scope in this way ensures that NbS not only address flood risks but also contribute to broader societal and environmental goals, such as biodiversity conservation, climate resilience, and public health enhancement and access to recreational services.

5.1 The effectiveness in a Danish context

The effectiveness of NbS in mitigating flood risks must remain a key research focus, particularly in the Danish context, where unique coastal conditions like sediment dynamics and wave energy differ from other countries. While studies in Europe, the UK, and the U.S. show NbS can reduce erosion and flood risks, future research should prioritize Danish environments to ensure local relevance. Numerical modeling and scenario-based simulations will be essential for understanding how well NbS perform in these specific conditions.

In this context, the ability of different NbS to adapt to climate change, particularly rising sea levels and extreme weather events, should be a key area of investigation. For example, while salt marshes and seagrass meadows can absorb wave energy and stabilize coastlines, their long-term sustainability may hinge on their capacity to accumulate sediment and maintain structural integrity over time.

5.2 The costs

There is a need for more comprehensive cost assessments. Establishment cost, maintenance cost, and the maintenance interval are direct costs that need careful evaluation. However, other critical cost dimensions should also be considered, including monitoring costs, financing costs, opportunity costs, and indirect costs. In many cases, NbS may provide long-term cost savings compared to traditional grey infrastructure, but understanding the full range of costs involved is essential for making informed decisions.

5.3 The co-benefits

In addition to evaluating the direct flood mitigation benefits of NbS, it is equally important to quantify their broader co-benefits. These co-benefits, which go beyond flood risk reduction, may include:

- Recreational opportunities: NbS often enhance coastal landscapes, creating new spaces for public recreation and tourism. This includes opportunities for hiking, birdwatching, and water-based activities, which can generate local economic benefits.
- Water quality improvements: Wetlands, oyster reefs, and other NbS can naturally filter pollutants from the water, improving overall water quality and contributing to healthy marine ecosystems.
- Biodiversity gains: By restoring and/or creating natural habitats, NbS can support increased biodiversity in coastal areas. For instance, salt marshes, seagrass meadows and reefs provide critical habitats for marine and bird species.
- Carbon sequestration: Certain NbS, such as salt marshes and seagrass meadows, act as carbon sinks and contribute to broader climate mitigation goals.

Quantifying these co-benefits is crucial for capturing the full value that NbS provide. Studies based on stated or revealed preferences can offer valuable insights into how much the public values these benefits. For example, eliciting preferences and measuring willingness-to-pay (WTP) can help assess the societal value of biodiversity conservation or enhanced recreational opportunities (e.g., Bartkowski et al., 2022; Panduro, 2024). By incorporating these co-benefits into cost-benefit analyses, we can achieve a more comprehensive economic valuation of NbS. Including the economic value of co-benefits is likely to shift the evaluation in favor of NbS when compared to traditional grey infrastructure solutions.

5.4 Scenario-based estimates

Developing a comprehensive scenario-based modeling framework is important for evaluating the long-term effectiveness and cost-efficiency of NbS. Scenario-based modeling will play a key role in predicting how NbS perform under different environmental, social, and economic conditions, allowing for a thorough evaluation of their adaptability. Key scenarios to consider include:

1. **Sea-level rise:** Models should be used to simulate the effects of various levels of sea-level rise on NbS, evaluating how resilient they are in the face of changes to coastal topography and water dynamics. Understanding how salt marshes, seagrass meadows, and oyster reefs can mitigate flooding under potentially extreme sea-level rise scenarios is crucial for long-term planning.
2. **Storm frequency and intensity:** As climate change intensifies, the frequency and severity of storms are expected to increase. Research should

simulate the ability of NbS to withstand these extreme weather events, particularly in terms of their wave attenuation capabilities and erosion protection. These models will help assess whether NbS alone can provide sufficient protection.

3. **Sediment dynamics:** Some NbS rely on sediment deposition to maintain their structure and function. Changes in sediment availability, driven by both natural processes and human activity, may significantly impact the effectiveness of these NbS. Future research should evaluate how shifts in sediment transport affect the stability and performance of salt marshes and other NbS that depend on sediment accumulation.
4. **Changes in biodiversity and ecosystem health:** Estimates should consider how NbS will interact with evolving marine ecosystems, particularly under conditions of warming seas and shifting species distributions. This will help evaluate the long-term sustainability of NbS and their ability to continue providing ecosystem services like carbon sequestration and habitat provision.
5. **Land use change and future landscape usage:** Scenario-based analyses should account for potential shifts in land use patterns, such as changes in urban development, agricultural expansion, or conservation priorities. Understanding how future landscape usage may affect the implementation and performance of NbS is critical, especially in terms of balancing competing demands for space, protecting ecosystems, and ensuring sustainable development.

5.5 Future research agenda

A future research agenda for NbS in coastal protection must prioritize their effectiveness in flood risk mitigation, comprehensive cost evaluations, and the quantification of co-benefits.

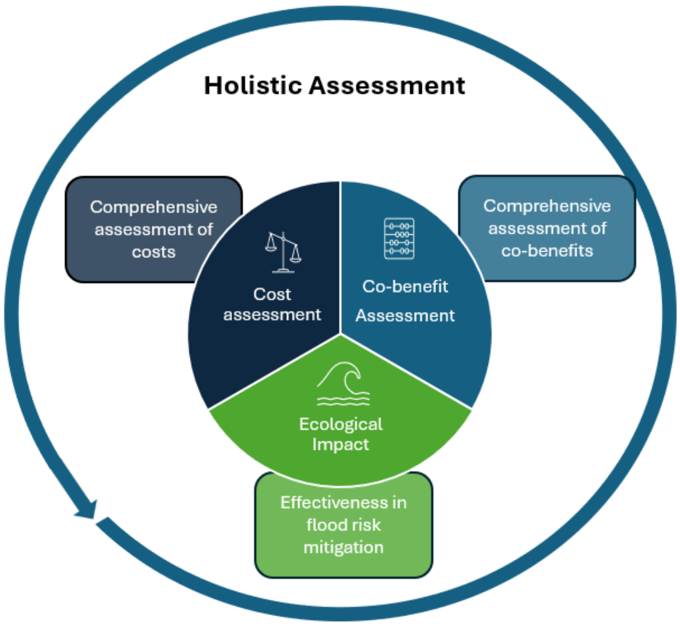

Figure 5 Visualize the need focus point of a new research agenda for NbS apply for coastal flood protection and mitigation.

Cost-benefit analysis (CBA) should be a central part of these evaluations, fully accounting for implementation, maintenance, and opportunity costs, while also considering broader economic benefits such as increased tourism, enhanced recreational opportunities, and ecosystem services like carbon sequestration and improved water quality. Many of these values have yet to be fully assessed, highlighting the need for more valuation studies on the benefits provided by NbS. Scenario-based assessments will be essential for evaluating NbS performance under changing environmental, social, and economic conditions. Future research should take a holistic approach to ensure that NbS are both environmentally sustainable and economically viable.

To effectively assess the long-term viability and benefits of NbS, a structured framework is essential. The diagram below outlines the key considerations that must be addressed in this process. At its core, the framework begins by recognizing the **societal challenges** driving the demand for NbS, particularly in the context of **climate change**, **biodiversity loss**, and **public welfare**. These issues require solutions that not only address immediate environmental risks but also provide broader societal and economic benefits.

Given the dynamic nature of **environmental, social, and economic conditions**, NbS must be adaptable to future changes. Assessing how NbS perform over time is crucial, especially as conditions evolve due to climate variability, shifting land use patterns, and changing socio-economic factors. A key question, therefore, is the **long-term effectiveness** of NbS. To explore this, the diagram highlights two critical approaches: **scenario-based modeling**, which helps predict how NbS will perform under various future scenarios, and **context-specific case studies** that compare NbS to grey infrastructure, providing insights into their relative effectiveness, cost-efficiency, adaptability in specific local settings and long-term monitoring.

Finally, the framework emphasizes the need for **continuous assessment**. Ongoing monitoring of NbS, both in terms of their physical performance (e.g., erosion reduction, wave attenuation) and their socio-economic impacts (e.g., tourism, public acceptance), is vital to ensure they remain effective over time. This adaptive management approach allows for the necessary flexibility in modifying NbS strategies as conditions change, ensuring their sustainability and resilience in the long term.

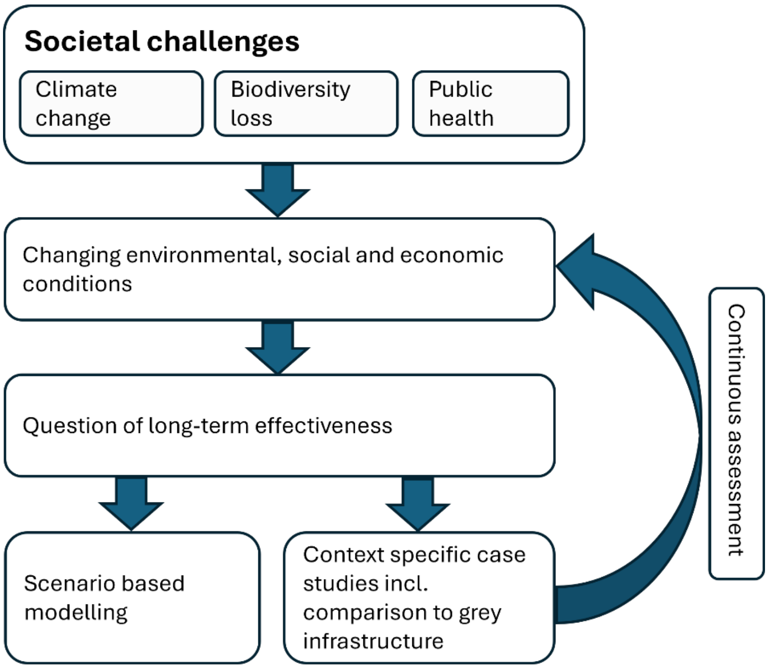

Figure 6 Provide a process diagram for question that need to be answered in an appropriate assessment tool.

6 Discussion

In this report, we conducted a comprehensive literature review of the costs and benefits of Nature-Based Solutions (NbS) related to coastal protection and flood mitigation. Despite the growing interest in NbS, we found a notable gap in the existing literature. There is limited well-developed research specifically addressing the economic evaluation of NbS in these contexts. This highlights an urgent need for standardized frameworks to assess both the effectiveness and the economic viability of NbS compared to traditional grey infrastructure.

A standardized approach should allow for more consistent and comparable results across studies, enabling decision-makers to better understand the trade-offs involved. We propose a holistic approach to future research, integrating environmental, social, and economic dimensions to provide a more comprehensive understanding of the benefits and costs of NbS, and to support their broader implementation in coastal protection strategies.

To address the gaps identified in this report, we recommend developing a targeted research agenda that the Ministry of Environment can fund and support. This agenda would focus on the following key areas:

1. **Standardization of Assessment Frameworks**: Research should prioritize the creation of standardized frameworks for evaluating NbS, particularly in terms of cost-effectiveness and long-term performance. These frameworks would allow for better comparisons across projects and regions, supporting evidence-based policymaking and investment decisions.
2. **Context-Specific Case Studies**: The Ministry could fund localized case studies in Danish coastal areas, examining the specific environmental, social, and economic conditions in which NbS operate. These studies should compare NbS with grey infrastructure solutions, highlighting the relative benefits and challenges of both.
3. **Comprehensive Cost-Benefit Analyses**: There is a pressing need for more robust cost-benefit analyses of NbS. These studies should not only evaluate direct implementation and maintenance costs but also quantify co-benefits, such as biodiversity enhancement, carbon sequestration, and recreational opportunities. Such analyses would provide a clearer picture of the full economic value of NbS.
4. **Long-Term Monitoring and Adaptive Management**: Ongoing funding should support the development of long-term monitoring programs that track the performance of NbS over time. This would include both physical indicators, such as flood risk reduction and coastal erosion mitigation, and socio-economic impacts, such as public acceptance and tourism growth. An adaptive management framework would ensure that NbS can be adjusted as conditions change, maximizing their effectiveness and sustainability.
5. **Scenario-Based Modeling**: Funding should also support the use of scenario-based modeling to evaluate how NbS will perform under future environmental, social, and economic conditions. These models could be instrumental in predicting how NbS will respond to challenges such as rising sea levels, more frequent extreme weather events, and changes in land use.
6. **Public and Stakeholder Engagement**: Research should explore public and stakeholder preferences for NbS compared to traditional infrastructure. Willingness-to-pay (WTP) studies and participatory planning processes

could help policymakers better understand public perceptions and ensure that NbS implementation aligns with societal needs and expectations.

By funding research in these areas, funders can play a critical role in advancing the understanding and application of NbS. This research agenda will not only address the gaps in current knowledge but also provide the tools needed for effective, sustainable, and economically viable NbS implementation in coastal protection strategies across Denmark.

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NATURE-BASED SOLUTIONS FOR FLOOD RISK REDUCTION

This report provides a comprehensive review of Nature-Based Solutions (NbS) for flood risk reduction in coastal areas. By evaluating the effectiveness, costs, and co-benefits of NbS, the report identifies critical gaps in existing research, particularly in the context of Danish coastal ecosystems. The literature review, including over 100 academic papers, reveals a lack of standardized frameworks for assessing the long-term performance and economic viability of NbS. In the report, a holistic research agenda is suggested that integrates ecological, economic, and social dimensions to support NbS's decision-making in coastal protection strategies. The findings underscore the need for further studies focused on cost-benefit analysis, valuation, and scenario-based modelling to enhance the understanding and application of NbS in addressing coastal flood risks.

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