COMMISSION FOR ENVIRONMENTAL COOPERATION

Nature-based Solutions to Address Flood Risks in Coastal Communities

Retrofitting Existing Infrastructure

Report Series:

Co-Benefits

Monitoring Efficacy

Monitoring Efficacy: Proposed Methodology and Indicators

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Abstract

North America boasts an extensive portfolio of coastal flood-risk management (FrM) infrastructure. Much of this infrastructure is nearing or past its design life and was not designed to accommodate the effects of climate change, nor was it constructed with a comprehensive understanding of the broader social, cultural, and environmental impacts. Retrofitting existing infrastructure using nature-based solutions (NBS) provides an opportunity to improve the performance or integrity of FrM systems while providing numerous additional social, economic, and environmental co-benefits.

This document supports the uptake of NBS in coastal communities across Canada, Mexico, and the United States by providing decision makers with practical information and guidance related to retrofitting existing FrM infrastructure using NBS. Types of potential NBS are summarized and compared, for ease of reference, though different conditions in the three countries may impact the feasibility of retrofitting or the type of NBS used. A framework for scoping (i.e., identifying and evaluating) retrofitting opportunities and options is outlined. Administrative considerations (i.e., scoping, roles and responsibilities, communications and engagement, financing, regulations, and timing) and technical considerations (i.e., engineering, environmental, social, and economic, as well as monitoring and adaptive management) are discussed. Incentives to retrofit are outlined and a list of potential opportunities to help fill gaps and overcome barriers related to retrofitting is provided as a key takeaway for decision makers. Case studies are included throughout this document to provide real-world context and emphasize key concepts.

Executive Summary

Many coastal urban and peri-urban communities throughout Canada, Mexico and the United States rely on heavily engineered or ‘gray’ structures, including dikes/levees, seawalls/bulkheads, rock armouring, and breakwaters, to provide a certain degree of protection from flooding and erosion hazards. These structures can be prone to rapid (catastrophic) failure and often interrupt natural dynamic processes, resulting in unintended consequences and natural system degradation, and negatively impacting post-event recovery and system resilience. For example, conventional gray coastal protection measures, such as seawalls, can have negative consequences for coastal biodiversity and can increase erosion of adjacent coastlines that are not protected by seawalls. Coastal flood and erosion risks are projected to escalate in the coming century due to climate change and increasing coastal populations. Projected flood risks and the unintended impacts of gray approaches have created a need to update and retrofit gray infrastructure to improve flood-risk management (FrM). With much of the existing gray coastal FrM infrastructure in North America exceeding or nearing the end of its service life, there is an opportunity to consider the role of nature-based solutions (NBS) alongside or instead of these conventional approaches to coastal protection. NBS can be adapted to retrofit existing FrM systems to increase protection, mitigate damages, extend the life of an existing FrM structure, and increase the climate resilience of FrM structures and communities. There are multiple benefits of utilizing NBS to retrofit existing conventional coastal structures, including (but not limited to):

- increased coastal protection and longevity of FrM benefits;
- enhanced environment and biodiversity;
- social benefits from recreation, green space, and improved health; and
- economic benefits from employment and tourism.

Although there are numerous benefits associated with NBS retrofits, there are many barriers to their broader uptake for FrM. Barriers can be categorized into the following broad groups:

- **social/attitudinal** (e.g., perception that NBS do not provide the same level of protection and performance as gray structural approaches);
- **technical** (e.g., lack of technical guidance, trained professionals, or pilot/demonstration projects in diverse settings);
- **environmental** (e.g., seasonal and long-term variability of natural systems, and resilience to disturbances);
- **institutional** (e.g., lack of funding, regulatory issues); and
- **lack of data** (e.g., on performance and co-benefits in varied regions, particularly in comparison to conventional, gray FrM approaches).

This document provides guidance, evidence, and tools to support decision makers in the broader implementation of NBS through retrofitting existing gray FrM infrastructure to address coastal flood risks in communities. Specifically, it is intended to assist decision makers in all stages of a project, from conceptualization through to design and operation. This document does not provide in-depth technical guidance, nor does it provide an exhaustive review of the rapidly growing body of literature on NBS.

<u>NBS Retrofitting Options</u>
Retrofitting involves replacing, modifying, or enhancing existing infrastructure with new features and systems. NBS options for retrofitting FrM infrastructure exist on a spectrum from gray to green. The NBS retrofit should generally move infrastructure towards the green end of the spectrum by enhancing its contribution to natural system function or reducing negative impacts on the system.

NBS options for retrofitting may be broken into the following six broad categories:

- beaches and dunes;
- wetlands (e.g., marshes, tidal flats, and mangroves);
- islands;
- terrestrial coastal vegetation (e.g., coastal forests and woody areas);
- submerged features (e.g., reefs, kelp forests and submerged vegetation); and
- hybrid features (i.e., solutions that combine natural or nature-based features with gray infrastructure).

Notably, when adopting a system-level approach to FrM (as advocated for in this document), the majority of FrM systems will inherently be categorized as hybrid solutions, as they will involve combinations of approaches varying across many different reaches of shoreline. Hybrid solutions may be achieved through a range of strategies, including through modification of existing infrastructure to include natural or nature-based features (e.g., adding habitat-enhancing tiles to an existing seawall), or through complete replacement of existing infrastructure with new hybrid solutions.

These six categories of NBS retrofits are discussed in detail within this synthesis document. FrM benefits and co-benefits frequently associated with each category of NBS are described. Relative costs for each type of NBS retrofit are provided for various phases within the NBS development cycle (i.e., planning and design, construction, and operations and maintenance).

<u>Identification, Prioritization and Evaluation of Retrofitting Opportunities</u>
As part of this document, a simple two-step framework was developed to assist decision makers in identifying, prioritizing, and evaluating retrofitting opportunities as part of broader (system-based) flood risk strategy development processes. The first step of the framework is identification, which may be divided into five iterative parts:

Step 1: Identifying NBS Retrofitting Opportunities

- **Step 1.1 Create an Inventory of Existing FrM Assets**
  This step focuses on creating an inventory of all existing coastal flood protection assets within a given system (e.g., seawalls, dikes/levees).
- **Step 1.2 Define an Engagement Strategy**
  An engagement strategy should be developed and carried out through all remaining stages of the process. This step is vital in determining stakeholders and rightsholders who will provide insight on coastal defense needs, priorities, and options.
- **Step 1.3 Evaluate FrM Needs and Strategy**
  As part of this step, the need for FrM should be evaluated within the coastline and system of interest. A risk assessment is recommended to identify and prioritize risk management strategies.
- **Step 1.4 Assess Site and Asset Suitability**
  This step involves a high-level assessment of the suitability of assets and sites for a NBS retrofit. The goal is to determine if it would be feasible to replace or modify the existing structures with NBS at the location of interest.
- **Step 1.5 Prioritize Opportunities**
  The desired outcome of this step is to determine which sites and assets identified in Step 1.4 should be prioritized for NBS implementation.

Step 2. Evaluate Retrofitting Options

The second step of the framework involves the evaluation of retrofitting options, including NBS, hybrid, conventional, and 'do-nothing' approaches. The framework for determining the most suitable retrofitting option for the project involves comparing different options, such as through multi-criteria analysis. This includes assessing the FrM benefits and other co-benefits, along with the specific needs and constraints of the project. Co-benefits evaluation follows a three-step process, which is briefly described in this document, and described in detail in the associated *Co-Benefits* guidance document. The outcome of the second phase is to identify the best option (following a multi-criteria analysis approach) for coastal flood management and to maximize project-specific co-benefits.

<u>Administrative and Technical Considerations for Retrofitting</u>

When considering retrofitting using NBS, decision makers should pay attention to various administrative and technical considerations. Administrative considerations discussed in this document include scoping, roles and responsibilities, communications and engagement, funding, regulations and timing. Technical considerations discussed in this synthesis are grouped into engineering, environmental, social, economic and monitoring and adaptive management considerations.

<u>Incentives for Retrofitting with NBS</u>

There are multiple types of incentives that exist for retrofitting gray infrastructure with NBS, as opposed to direct (like for like) replacement or purely structural upgrades. In addition to the direct positive impacts from co-benefits, incentives may arise through the government, private sector, non-governmental organizations (NGOs) and community organizations:

- **Inherent** incentives arise through the provision of multiple co-benefits which may not be realized through conventional, gray approaches. Incentives also arise from the potential for NBS to adapt to changing coastal hazards and the opportunity that they provide to shift to an adaptive management approach. Existing infrastructure in need of repair or replacement also provides the opportunity to learn lessons from past approaches (includes failed approaches) and to rebuild stronger following damaging events.
- **Government** incentives typically include financial, policy, program, or regulatory incentives, including those stemming from government joining international agreements.

- **NGO or community-based organization** incentives are typically provided through advocacy, working to increase political will and motivation for NBS projects, technical support, funding or issuing certifications.
- **Private organizations** typically provide incentives through financing and funding of research to help fill knowledge gaps.

<u>Opportunities and Future Directions</u>
To help alleviate known data gaps and barriers, a list of potential opportunities and future directions that may be taken by decision makers are outlined. Key opportunities are briefly summarized below:

- develop regional funding streams for NBS retrofit pilot projects and projects with a high degree of innovation;
- develop a NBS community of practice with experts spanning multiple disciplines and across multiple regions;
- develop funding streams and policy that support adaptive management approaches;
- implement pilot projects involving NBS retrofits and novel NBS, and publish findings publicly;
- provide policy initiatives and incentives for retrofits using NBS;
- encourage and highlight case-studies comparing NBS to structural shore protection measures;
- encourage and highlight case-studies with long-term results;
- establish additional networks to host and share standard monitoring data required for NBS design and make data publicly available;
- establish evidence-based national or international standards and certifications for NBS design, which enhance legitimacy and provide direction;
- simplify permitting processes for NBS construction, monitoring and adaptive management;
- support and publish research involving NBS retrofits and novel NBS; and
- collect and present success stories and lessons learned from failed efforts of retrofitting conventional FrM systems with NBS to serve as examples.

Preface

The Commission for Environmental Cooperation (CEC) is a trilateral organization that facilitates cooperation between Canada, Mexico and the United States to conserve, protect and enhance the North American environment. In 2021, the CEC initiated a project to help guide the broader implementation of nature-based solutions (NBS) for coastal flood-risk management (FrM) in North American communities. The initiative may be broadly partitioned into three phases, as follows:

1. **An intersectoral workshop series** to lay the foundation for a North American community of practice, convene practitioners to scope needs and opportunities, and identify barriers to implementation of NBS.
2. **A set of guidance documents** to address knowledge gaps and further develop opportunities identified during the workshop series, and guide best practices related to implementing NBS.
3. **Webinars** to improve the uptake and usage of the guidance documents.

As part of the first phase of the project, DHI Water and Environment Inc. (DHI) was engaged to develop and host the workshop series. The workshop series consisted of seven sessions held over a five-week period in May and June 2022. The sessions were focused on the following topics:

- 1A and 1B: Nature-based Solutions Co-Benefits
- 2A and 2B: Retrofitting Existing Infrastructure Using Nature-based Solutions
- 3A and 3B: Monitoring Efficacy of Nature-based Solutions
- 4: Summary Workshop

The workshop series saw the participation of 95 specialists, spanning a range of academia, private industry, government, and non-governmental organizations (NGOs) from across North America. Group activities were included in the workshop series to build community, develop ideas, solicit feedback, and identify gaps and opportunities. Group activities included discussions of six different case studies, four sets of collaborative online activities and two interactive question series. The participation and idea development from participants with diverse backgrounds and experiences provided a strong foundation for building both a community of practice and guidance documents on NBS in North America.

The second phase of the project involved addressing knowledge gaps identified in the workshop series through the development and publication of a comprehensive set of guidance documents on NBS within an urban and peri-urban North American context. This document forms part of a series of guidance documents that are intended to be referenced as a whole. The guidance documents include:

- Co-Benefits
- Retrofitting Existing Infrastructure (this document)
- Monitoring Efficacy
- Monitoring Efficacy: Proposed Methodology and Indicators

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1 Introduction

Much of North America's population is concentrated in coastal communities that are subject to coastal flood-related hazards (DHI, 2022a). Significant flood-risk management (FrM) infrastructure already exists to reduce the exposure of these areas to coastal flood hazards. However, coastal flood risks are projected to intensify due to increasing population densities in urban areas and the effects of climate change (Diez et al., 2011; Ford et al., 2018; Ghanbari et al., 2021; Kim et al., 2021; OECD, 2021). There is a pressing need and opportunity to retrofit many existing and aging FrM infrastructure in North America over the coming decades to manage these increasing risks, while simultaneously unlocking a suite of co-benefits.

Existing FrM infrastructure relies largely upon conventional, structural methods, such as dikes and seawalls. Such conventional methods have a long history of application, and are well represented in scientific literature, guidelines, and standards (i.e., the Coastal Engineering Manual, USACE, 2002). Because of their long history of use and extensive literature on design and performance, there is generally an underlying trust that these techniques perform as intended. However, structural systems are prone to catastrophic failure and are often designed with little redundancy, potentially leading to sudden inundation and catastrophic impacts (Bridges et al., 2021, 180). In addition, these systems were often designed without comprehensive understanding of the broader social, cultural and environmental impacts, potential co-benefits, or increasing risks associated with climate change.

Projected increases in flood risks, aging infrastructure, a greater awareness of unintended impacts of gray FrM approaches, and the potential to obtain co-benefits, present an opportunity to adopt more holistic approaches to FrM. Nature-based Solutions (NBS) rely on the use of natural or nature-based materials and processes to provide FrM, while also providing social, environmental, and economic co-benefits. However, the usage of NBS as part of FrM systems is less well established in practice and sometimes viewed with skepticism (e.g., Anderson et al., 2022; Raška et al 2022). Definitive design guidance and standards are still being developed for North American applications, but significant advancements have recently been realized (e.g., Bridges et al., 2021; Doswald et al., 2021, Vouk et al., 2021). Despite the perception that NBS are more novel and less well understood than structural methods, natural systems—such as beaches/dunes, marshes, reefs, and islands – have always provided FrM services to coastal communities. There is immense potential for these types of natural features to be adapted, mimicked, or combined with existing structures to retrofit existing shore protection systems and better mitigate challenges associated with natural hazards, such as sea-level rise and increased storm frequency, while providing significant co-benefits.

Retrofitting existing FrM systems with NBS involves replacing, modifying, or enhancing existing gray—also known as conventional, structural, or gray—infrastructure with natural or nature-based features and processes. Throughout this document, the term 'retrofitting' will be used in the context of improving the performance and diversifying the benefits of coastal defense systems using NBS.

This document aims to support the uptake of NBS in coastal urban areas of North America by providing decision makers with practical information and guidance related to retrofitting existing infrastructure systems with NBS and by addressing several previously identified data gaps and barriers. This document forms part of a series developed by DHI Water and Environment Inc. (DHI) on behalf of the Commission for Environmental Cooperation (CEC), which are intended to be referenced as a whole, and are outlined as follows:

- Co-Benefits
- Retrofitting Existing Infrastructure (this document)
- Monitoring Efficacy
- Monitoring Efficacy: Proposed Methodology and Indicators

1.1 Objectives and Scope

An intersectoral workshop series was hosted by DHI in spring 2022 as part of a CEC project to support the broader implementation of NBS for coastal FrM in North American communities (DHI, 2022b). The workshop series consisted of seven sessions, with 95 specialists from Canada, Mexico, and the United States. Two of the sessions focused specifically on retrofitting existing infrastructure systems using NBS. During these sessions, attendees participated in idea generation and identification of data gaps, barriers and opportunities related to retrofitting.

This document addresses knowledge gaps identified in the workshop series, synthesizes existing information, and provides practical guidance to identify, plan and implement retrofitting opportunities using NBS to address flood risks in coastal communities. It is part of a comprehensive set of guidance documents which are intended to support decision makers (e.g., Indigenous leaders, land use planners, government representatives, and infrastructure asset owners or managers), in implementing NBS for coastal flood-risk management across North America.

More specifically, this document aims to:

- Contextualize existing differences that may influence retrofitting initiatives and highlight opportunities for retrofitting within the North American environment;
- Provide a roadmap to demonstrate the value proposition of retrofitting;
- Provide a comprehensive summary of options that may be available for NBS retrofitting and, where possible, provide examples of costs and cost-comparisons;
- Develop strategies for decision-makers to identify retrofitting opportunities, options and costs;
- Summarize key administrative considerations for retrofitting, including roles and responsibilities, financing and regulations;
- Summarize key technical considerations for retrofitting;
- Discuss incentives for retrofitting infrastructure using NBS as an alternative alongside, or in combination with gray techniques;
- Provide case studies related to retrofitting using NBS; and
- Where possible, address gaps and barriers identified during the previous intersectoral workshop series.

This document is intended to provide guidance, evidence, and tools to support decision makers in the broader implementation of NBS to address coastal flood risks in communities across North America. The guidance provided herein is intended to assist decision makers in all stages of the project process, from conceptualization through design and operation. The document does not provide in-depth technical guidance, nor does it provide an exhaustive review of the rapidly growing body of literature on NBS.

For further reading material and key documents on retrofitting using NBS, the reader is referred to section 1.4.

1.2 The Value of Retrofitting

North America boasts an extensive portfolio of coastal FrM infrastructure. Much of this infrastructure is nearing or past its design life and was not designed to accommodate the effects of climate change or was constructed without fully considering social and environmental impacts. NBS provide an excellent opportunity to learn from past mistakes and 'build back better'[1] (United Nations, 2015). NBS can improve the performance or integrity of FrM systems by replacing, retrofitting, or upgrading existing gray infrastructure, while providing numerous additional co-benefits which can address multiple societal challenges, and provide an opportunity to restore degraded habitats. Potential benefits of retrofitting existing FrM infrastructure using NBS are provided in Box 1.

Box 1. Benefits of retrofitting existing FrM infrastructure using NBS

Improved Flood or Erosion Risk Management

Reinforce or Repair Existing Aging Infrastructure

Improved Residual Performance
(i.e., resilience)

Enhanced Climate Change Adaptation

Compliance with Project Requirements
(e.g., funding requirements)

Opportunity for Indigenous and Community Partnerships

Advance and Apply New Knowledge
(e.g., research and guidance development)

Improved Public Buy-In

Environmental Co-Benefits
(e.g., habitat restoration)

Social Co-Benefits
(e.g., improved access to green space)

Economic Co-Benefits
(e.g., decreased life cycle costs)

Location Specific Solutions

The primary benefit of retrofitting existing coastal FrM infrastructure using NBS is to improve or provide flood or erosion risk management function. This may be done by replacing existing gray infrastructure, or by reinforcing or repairing existing, aging, or underperforming gray infrastructure. When properly conceived and in the right settings, NBS often become more established and effective over time, providing improved flood or erosion risk management function over the life of the project (e.g., Sutton-Grier et al., 2015). Ultimately, this reduces risk to people, property, livelihoods, culturally or socially important lands and environmental sensitive areas.

By definition, NBS are scalable, flexible, adaptable, and resilient to climate change (Osborne, 2022). Because NBS often have the ability to self-adapt, they have residual performance (i.e., resilience) following a storm event and are also able to adapt to a changing climate. Under the right circumstances, NBS are often able to grow to keep pace with sea-level rise (Sutton-Grier et al., 2015). These abilities are significant up-sides of NBS in comparison to gray, static infrastructure and provide an opportunity to learn from past mistakes made with gray infrastructure, while increasing resilience and adopting an adaptive management approach.

In addition, the co-benefits provided by NBS are often undervalued in comparison to conventional, 'gray' approaches (e.g., conventional approaches generally focus on engineering function and capital and maintenance costs for the project, and do not include consideration of co-benefits such as improved access to foraging grounds, carbon sequestration, etc.). Retrofitting gray infrastructure systems with NBS allows for the incorporation of environmental, social, and economic co-benefits

[1] "Build Back Better" is one of the four Priorities for Action in the Sendai Framework.

that have significant value to local communities, project stakeholders, and rightsholders. Notably, NBS may be able to reduce life-cycle costs (i.e., an economic co-benefit) of the FrM project through adaptive management and the ability of some NBS to keep pace with sea-level rise. Additional potential co-benefits associated with NBS are outlined in the *Co-Benefits* companion document. Retrofitted projects involving NBS may also leverage these co-benefits to obtain funding and improve public buy-in for the project.

Retrofitting initiatives may be completed as part of a larger project or FrM strategy to help meet regulatory or funding requirements, by creating additional habitat or providing social services. By creating additional habitat, offsetting/compensation schemes associated with gray infrastructure may also be avoided.

1.3 Existing Data Gaps and Barriers to Retrofitting

A summary of the findings from the CEC NBS workshop series (DHI 2022b) regarding data and knowledge gaps, and barriers to retrofitting existing infrastructure with NBS, is provided in this section. Environmental barriers include seasonal and long-term variability of natural systems, and the lag time for NBS to establish, which can contribute to uncertainty and hesitance among the public, institutions, and the project team. In addition, there is some uncertainty around the impacts of climate change, particularly on rates of sea-level rise at longer time horizons and effects on storm intensity and frequency.

Box 2 provides a summary of the barriers identified during the CEC workshop series.

Public and institutional trust in existing techniques and distrust towards NBS appears to be a significant barrier to retrofitting using NBS. This seems to stem from a tendency to trust and default to the status quo, and uncertainty that natural or nature-based measures are able to provide the same level of protection as gray approaches, an issue that has also been identified in Anderson et al. (2022), Raška et al. (2022), Cado van der Lely (2021). There is also a tendency to discuss NBS as though all techniques have the same costs and benefits—this may result in the false impression that if one NBS performs poorly, all other NBS will perform similarly poorly. Communicating the nuances and potential benefits of NBS through case studies and by discussing each type of NBS independently may help to improve public buy-in and understanding.

The *International Guidelines on Natural and Nature-based Features for Flood Risk Management* (Bridges et al., 2021) provides a comprehensive overview of NBS options and design considerations. However, experts at the workshop indicated that there is still a need for specific and detailed technical guidance, rooted in research, and spanning a wide range of NBS, development types (i.e., retrofitting or new construction) and regions. The need for technical guidance is underlaid by the fact that understanding of some NBS is still in its infancy, with research and pilot projects underway or outstanding. In addition, trained personnel (spanning many disciplines) are required for NBS design and implementation. Notably, there is a need to involve qualified professionals from multiple disciplines, which poses logistical and budgetary difficulties, particularly during the early phases of a project (DHI, 2022a). Additional training, technical guidance documents, and up-to-date case studies (which highlight both successes and failures) are needed to support knowledge development for personnel. For further reading, many of these needs and barriers are discussed in a Canadian context in Vouk et al. (2021).

Project designers at the workshop series also noted that that NBS often function better on a larger scale than many conventional, gray solutions. NBS are dynamic, having capacity to adapt to disturbances and often to self-repair. However, their size in relation to coastal processes will impact how successfully they can absorb hazards (i.e., a small constructed marsh system may be completely eroded by a large storm, whereas a larger marsh may experience some localized damage and be able to self-repair) (Wilson, 2021). This does not necessarily mean that NBS must be large, capital-intensive projects; phased approaches can be applied to leverage the cumulative benefits of multiple, smaller interventions. In addition, exposure of a site to high winds, waves, currents, or storm surges may limit the applicability of some NBS. For this reason, an easy-to-use options appraisal framework for NBS is required to support decision making and balance different design objectives (Osborne, 2022), prior to committing to a design approach.

Environmental barriers include seasonal and long-term variability of natural systems, and the lag time for NBS to establish, which can contribute to uncertainty and hesitance among the public, institutions, and the project team. In addition, there is some uncertainty around the impacts of climate change, particularly on rates of sea-level rise at longer time horizons and effects on storm intensity and frequency.

Box 2. Barriers to retrofitting using NBS

Source: Adapted from barriers identified as part of the intersectoral workshop series on NBS hosted by DHI on behalf of the CEC in spring 2022.

Type of Barrier	Focus (this report)
Social / Attitudinal	
• Trust in or defaulting to the status quo	○
• Perception that NBS do not provide the same level of protection as conventional approaches	✓
• Perception that all NBS options perform similarly	✓
• Lack of knowledge on potential co-benefits of retrofitted projects	✓
Technical	
• Lack of definitive technical guidance, covering all potential NBS options	○
• Need for expert involvement across many disciplines (e.g., social science experts)	○
• Lack of trained and qualified professionals, particularly at a local level	○
• Lack of training/education on NBS design and implementation	✓
• Lack of up-to-date and useable case studies and inventories (demonstrating both successful and unsuccessful outcomes)	✓
• Need for an options appraisal framework	✓
• Adaptive management challenging to manage long term	○
• Design constraints due to physical space/property limitations	✓
• Design constraints due to coastal processes and hazards	○
Environmental	
• Seasonal and long-term variability of natural systems	○
• Uncertainty in the effects of climate change	○
• Lag-time for natural systems to establish	○
Institutional	
• Lack of funding for NBS projects and retrofits	○
• Lack of policy incentives or legal obligations	○
• Focus on short-term horizons as part of existing programs	✓
• Regulatory hurdles which impose constraints on the type of solution and implementation timing	○
• Conflict between jurisdictional or agency requirements	○
• Corruption	○
• Lack of political will	✓
• Lack of strategic planning / piecemeal approach to planning	○
• Lack of visibility and promotion of NBS in legislation and policies	○
• Lack of institutional regulations and market instruments	○

Experts also indicated that institutional barriers pose a significant challenge to retrofitting existing systems using NBS. Institutional barriers included a lack of policy incentives and legal obligations, lack of political will, corruption, conflict between jurisdictional and agency requirements, regulatory hurdles and focus on short-term results. Many of these barriers have resulted in a notable lack of strategic and systems-wide planning, resulting in a piecemeal and reactive approach to flood protection. Institutional barriers are amplified further by a lack of funding available to support NBS projects, and particularly the operational phases of the projects, which involve long-term monitoring and adaptive management (DHI, 2022c). Many decision makers and funders are unaware of the potential benefits of NBS or do not put significant value on social and environmental benefits and are consequently hesitant to fund these projects (Brill et al., 2021).

This document aims to directly fill several of these data gaps and overcome barriers where possible (as identified in Environmental barriers include seasonal and long-term variability of natural systems, and the lag time for NBS to establish, which can contribute to uncertainty and hesitance among the public, institutions, and the project team. In addition, there is some uncertainty around the impacts of climate change, particularly on rates of sea-level rise at longer time horizons and effects on storm intensity and frequency.

Box 2), or, where not possible, to identify methods to address them through further initiatives (see section 7). Barriers that are a focus of this document include social/attitudinal, technical, and institutional barriers which may bay be (in part) alleviated through additional data availability, knowledge, or guidance. Barriers that require additional action to be taken by decision-makers (such as the establishment of funding sources) have not been addressed.

For greater detail on specific barriers to development of NBS, please refer to Vouk et al. (2021) and Raška et al. (2022). Additional data gaps and barriers related to co-benefits of NBS and monitoring NBS are outlined in the associated *Co-Benefits* and *Monitoring Efficacy* guidance documents.

1.4 Further Reading

Numerous guidance documents were reviewed and referenced in preparing this synthesis. These documents—as well as the CEC's workshop series on NBS—served as the foundation for development of guidance, processes and considerations outlined in this synthesis. Key guidance documents are listed below and may provide the reader with further information and technical guidance.

- *Nature-Based Solutions for Coastal Highway Resilience: An Implementation Guide*, US Department of Transportation Federal Highway Administration (US Federal Highway Administration 2019)
- *Practical Guide to Implementing Green-Gray Infrastructure,* Conservation International (Green-Gray Community of Practice 2020)
- *Increasing Infrastructure Resilience with Nature-Based Solutions (NBS): A 12-Step Technical Guidance Document for Project Developers*, Inter-American Development Bank (IDB 2020)
- *International Guidelines on Natural and Nature-Based Features for Flood Risk Management*, United States Army Corps of Engineers (Bridges et al., 2021)
- *Nature-Based Solutions for Coastal and Riverine Flood and Erosion Risk Management*, Canadian Standards Association and National Research Council of Canada (Vouk et al., 2021)

2 Options for Retrofitting with NBS

This section outlines the intent of retrofitting and briefly characterizes the broad range of NBS options that may be adopted to meet project-specific retrofitting needs and constraints. A high-level cost-comparison is provided for each broad category of NBS. Case studies are included in this section to provide real-world examples of NBS projects.

2.1 The NBS Spectrum

When discussing retrofitting, it is useful to consider that all coastal protection infrastructure, as with retrofitting projects, exist on a spectrum. This spectrum is often referred to as 'gray to green' (Figure 1). 'Gray' coastal FrM options include concrete seawalls, tide gates, and breakwaters, amongst others. NBS (including retrofits) may exist across the 'gray' to 'green' spectrum. More natural (i.e., green) solutions do not rely upon gray features, are typically dynamic, and provide numerous co-benefits. 'Green' solutions may include NBS such as beaches, wetlands, and oyster reefs, for example. NBS may introduce gray features to help mitigate various project or site constraints, or a retrofit project may retain some of the existing gray features. These hybrid solutions (e.g., beach and headland systems, or marshes with rock sills), fall somewhere within the two ends of the 'gray to green' spectrum.

NBS retrofitting projects will therefore fall broadly within the following three strategies:

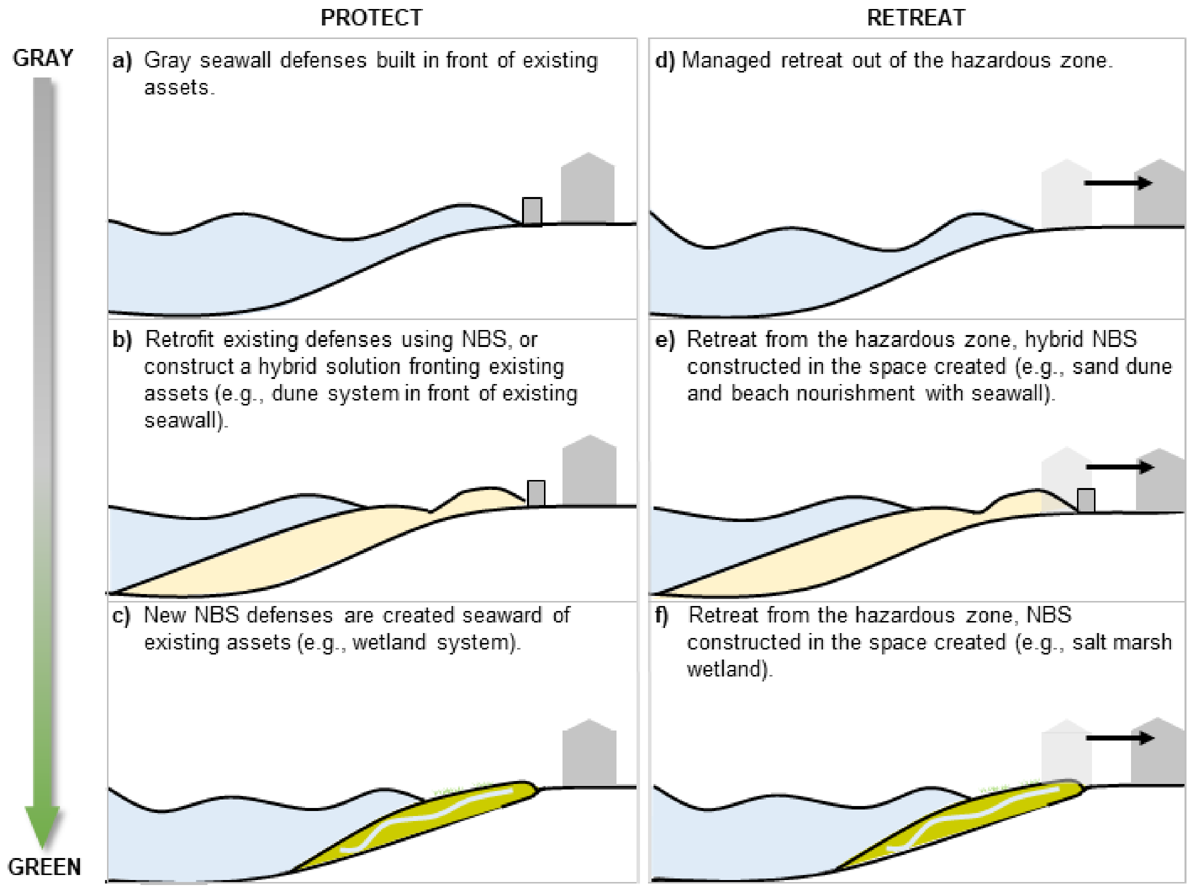
1. **A complete return to natural processes** – where the existing gray infrastructure is decommissioned and a NBS (not including hybrid solutions) is implemented in its place.
2. **A partial return to natural processes using new hybrid features** – where existing infrastructure is removed or updated, and both new, hybrid NBS are implemented.
3. **A partial return to natural processes resulting in hybrid features** – where a NBS is applied to, implemented in front of, or constructed in combination with existing gray infrastructure (which remains in place), creating a hybrid feature.

In the following sections, we provide details on the different NBS options for retrofitting, which can be adopted under any of these three retrofitting strategies. Hybrid solutions draw upon knowledge and information discussed in the sections relating to other NBS options and are discussed in a dedicated section.

2.2 Coastal Hazard Risk Management Strategies

The Protect, Avoid, Retreat and Accommodate framework is frequently used to characterize the management of and adaptation to coastal hazard risk (e.g., Doberstein et al., 2019). Conventional and NBS strategies both fit into the 'protect' and 'retreat' strategies as either hybrid or standalone options, some examples of which are provided in **Error! Reference source not found.**1**Error! Reference source not found.**. 'Avoid' strategies seek to prevent development in hazardous zones, while 'accommodate' adapts existing land-use and buildings to reduce the effects of hazards. While both of these strategies are valuable hazard management options, they do not fit within the context of retrofitting existing FrM infrastructure with NBS.

Figure 1. Protect and retreat coastal management strategies across the NBS spectrum



To be effective, NBS should be identified, developed, and deployed as part of a broad FrM strategy, following system-based principles (deViers et al., 2021), that accept that some flooding is inevitable, especially in an uncertain future, and aim to manage the risk of hazards (Sayers et al., 2013). Different approaches should be considered on a systems-based scale, and different strategies can be deployed in tandem, appropriate to site-specific conditions.

'Protect' strategies involve the implementation of measures to protect existing land use, property or infrastructure from flooding and erosion. 'Protect' strategies are often applied to defend land or infrastructure that has significant economic or cultural value and significance, which cannot be relocated out of the flood risk zone. Specific 'protect' strategies include 'advance the line' and 'hold the line' approaches (e.g., Simm, 2021). 'Advance the line' maintains existing built assets in the same location and new defenses are constructed, or existing defenses are upgraded, seaward of the threatened assets (Figure 1 a–c). There is potential for NBS retrofitting projects to be incorporated into an 'advance the line strategy', through the development of natural systems such as marshes or beaches in front of existing gray infrastructure. Space and property limitations often pose constraints on whether 'advance the line' NBS options are feasible. 'Hold the line' also fits within 'protect' strategies, where current FrM is improved upon and the existing coastline remains the same. This could involve for example, raising the height of structures and/or restoring existing degraded habitat.

Retreat options (Figure 1 d–f) (also referred to as rollback or managed realignment) involve either abandoning existing built assets (including FrM infrastructure) and land use in hazardous areas, relocating assets out of the hazardous zone, and moving defense infrastructure further back from the coast. Retreat may be applied where the means to sustain other strategies do not exist, or where infrastructure can be relocated (i.e., there is adequate space to do so, and relocation is economically feasible, or where land use does not have significant economic or cultural value). Relocating existing gray infrastructure may also be beneficial for reducing incidence of coastal squeeze and the resulting loss of coastal intertidal habitats in front of sea defences due to erosion. In many cases, retreat alone (without any additional interventions) may be sufficient to mitigate coastal hazards and can be considered a NBS since this strategy allows for floodplain habitat to recover and should be given proactive consideration (Saunders-Hastings et al., 2020) (Figure 1d). Retreat strategies can also facilitate the implementation of NBS retrofits by creating additional space seaward of the built assets for NBS. Suitable available space for relocating existing infrastructure away from the coastal hazard is often limited and costly; however, this can be offset by the equivalent capital cost of coastal defense infrastructure that would have been developed under other strategies.

2.3 Retrofitting Intent

Retrofitting involves replacing, modifying, or enhancing existing infrastructure with new features and systems. Decision makers may choose to retrofit existing, aging or underperforming gray infrastructure systems or components of those systems with NBS rather than developing further gray defenses. Retrofitting with NBS therefore provides an excellent opportunity to improve the performance or integrity of FrM systems, while simultaneously providing numerous additional benefits. Environmental, social, and economic co-benefits provided by NBS provide significant incentives for retrofitting existing FrM infrastructure using NBS. Additional benefits are discussed in detail in section 1.2.

Opportunities for retrofitting existing gray FrM infrastructure with NBS are present throughout the life cycle of coastal defense assets, including when considering new construction, repair, modification, and replacement of existing gray features. Retrofitting with NBS is particularly relevant when the current system is nearing the end of its useful life, when the existing system no longer provides adequate mitigation of current hazards, or as a preventative measure in the face of increasing future hazards. Additional discussion on the timing of retrofitting is provided in section 4.6.

The following sections outline potential NBS options for retrofitting existing FrM systems. Notably, FrM retrofits may require a combination of both gray and green features (also known as hybrid features, section 2.10), thereby falling within the gray-green spectrum (e.g., Figure 1). For example, artificial coral reefs may be constructed using concrete foundations, and groynes or sand fences may be incorporated into a beach system. Each project will require a unique solution, falling into a different portion of gray-green spectrum and within the Protect, Avoid, Retreat and Accommodate paradigm. Despite this, **the intent of retrofitting should be to move FrM systems toward the green end of the NBS spectrum, through incremental upgrades to the overall system, by applying as natural an approach as is reasonably and technically feasible, while maximizing co-benefits.**

2.4 Overview of Retrofitting Options

There are a range of NBS options that may be used to retrofit existing FrM infrastructure and mitigate coastal hazards. An overview of the different types of NBS available for retrofitting existing infrastructure is given in this section. As there are many different retrofitting options (depending on the location, coastal context, and existing gray and habitat features), this section is intended to provide an overview of potential options that can be adapted to meet project-specific needs. For detailed design guidance and further case studies refer to Suedel et al. (2021).

It is possible that various NBS may be combined and implemented in tandem to better suit the project needs. NBS may also include gray components (such as groynes or rock sills) or be constructed as part of existing FrM systems that include conventional coastal engineering strategies nearby (such as seawalls and dikes), creating hybrid systems (section 2.10). In addition, NBS options may be implemented in conjunction with various hazard management strategies, including Retreat (see section 2.2). Projects may range in scale, from small, private developments to large, neighborhood or regional scale projects. Selection of suitable NBS retrofitting options has to consider project-specific needs, including both administrative (e.g., financing constraints) and technical considerations (e.g., coastal processes), which are discussed further in sections 4 and 5, respectively.

NBS options for retrofitting may be broken into the following six broad categories:

- beaches and sand dunes;
- wetlands (including marshes and tidal flats, and mangroves);
- islands;
- terrestrial coastal vegetation;
- submerged features (including reefs, kelp forests and submerged vegetation); and
- hybrid features.

FrM benefits provided by each of the six broad NBS options are briefly summarized in Figure 2. Every NBS project will be different, and benefits provided by the NBS will be site-specific. Figure 2 is therefore intended to provide a high-level indication of benefits that may be associated with each type of NBS retrofit. There is also the possibility to deploy different types of NBS in tandem (e.g., islands with marshes, Gailani et al., 2021), which will maximize benefits from different types of NBS.

Figure 2. Summary of flood-risk management benefits provided by retrofitting options

	Beaches & Dunes	Wetlands & Tidal Flats	Islands	Terrestrial Vegetation	Submerged Features	Hybrid Features
Reduced maximum still water flood levels	○	?	?	○	○	?
Reduced wave effects (i.e., overtopping)	✓	✓	✓	✓	?	?
Reduced or diverted flood water velocities	?	?	?	?	?	?
Shorter flood duration	?	?	○	?	○	?
Residual performance following flood events	✓	✓	✓	✓	✓	✓
Resilience or contingencies for failure of FRM defenses	?	✓	✓	✓	✓	?
Erosion protection	✓	✓	✓	✓	?	?
Improved sediment supply or retention	✓	✓	✓	✓	?	?

LEGEND
○ Benefit not provided
? Benefit sometimes provided, depending on design specifics
✓ Benefit provided

Most of the potential NBS options mitigate FrM impacts through wave, flood water, current and storm surge attenuation or transformation. Wave attenuation is the reduction in wave height and energy that occurs when waves experience friction as they pass over the seafloor and through vegetation. The reduction in wave height and energy reduces the potential for both erosion and wave-induced flooding (i.e., over-topping). NBS attenuate flood waters by providing storage and improving drainage, reducing the height and duration of flooding. Storm surge attenuation is the reduction in storm surge levels through attenuation of energy over large distances. Due to the range of different hybrid systems falling within the gray-green spectrum, many of the benefits in Figure 2 have been indicated as possible, but not certain. Hybrid features that fall towards the green end of the spectrum could potentially provide as many benefits as a true NBS.

The six NBS options for retrofitting are described in sections 2.4–2.10 (including discussion of potential co-benefits). A qualitative comparison of design, construction, and maintenance costs for each option is also provided in section 2.11.

2.5 Beaches and Dunes

Retrofits involving beach and sand dune NBS focus on preserving and enhancing existing beaches and dunes, or developing new systems, through either artificial nourishment of sediments, encouraging natural depositional processes or a combination of both approaches. Beaches and dunes dissipate wave energy, providing protection against wave-induced flooding and erosion (Lodder et al., 2021). In addition to the direct benefits of mitigating coastal hazards, they may also bring a host of environmental, social, and economic co-benefits. The co-benefits provided by a NBS project involving beaches or dunes will be project-specific; however, co-benefits that are typically associated with these types of projects are outlined in Box 3. A more complete list of potential co-benefits associated with NBS is provided in the *Co-Benefits* guidance document. Proposed monitoring methodology and performance metrics for beaches and dune systems are also provided in the *Monitoring Efficacy: Proposed Methodology and Indicators* document.

Box 3. Examples of typical co-benefits provided by NBS involving beaches and dunes

Environmental	Social	Economic
✓ Terrestrial and aquatic habitat availability and quality ✓ Refuge and forage areas ✓ Water cycling	✓ Broader recreation and gathering spaces ✓ Improved esthetics	✓ Increased tourism ✓ Reduced costs to adjacent infrastructure (flood losses) ✓ Ecotourism opportunities

Beach nourishments and sand dunes are discussed in detail in sections 2.5.1 and 2.5.2, respectively. Key takeaways related to beach nourishments and dune systems are summarized in Box 4.

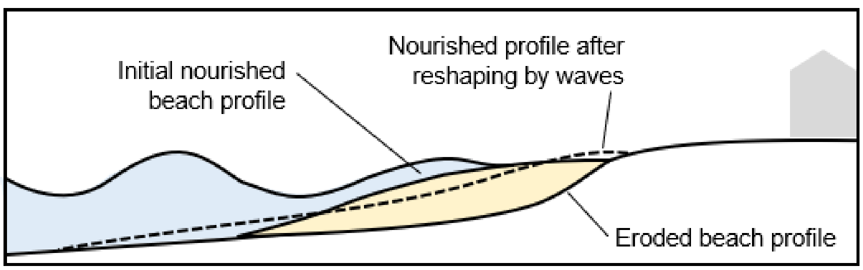
Box 4. Key takeaways related to beach nourishments and sand dunes

- Sand dunes and beach nourishments are dynamic, constantly changing systems that can provide protection from erosion and flooding, provide new habitat and improved recreation and tourism benefits.
- NBS involving sand dunes and beach nourishments are achieved through sediment deposition, native vegetation planting and removal of invasive species.
- It is important that appropriate selection of vegetation species is made for sand dune plantings and to avoid negatively impacting existing habitats through nourishment.
- A wide enough beach for sediment transport and sufficient development space available for dune growth are required. Significant technical design guidance is already available.
- It is important to understand local coastal dynamics. Adaptive management should be expected.
- Strong controls over public access and trampling of dune vegetation and structure will be required to maintain dune systems and habitat.

2.5.1 Beach Nourishment

Beach nourishment involves adding sediment (which may include sand, gravel, pebbles, or cobble) material to the beach, shoreface, channel bank or outer delta (Figure 3) and has become one of the preferred coastal hazard mitigation measures in North America. Beach nourishment has been applied in several cases, one of the most notable examples being in Miami, United States, where the Miami-Dade County Beach Erosion Control project has been ongoing since 1975 (MD County, 2010). Detailed guidance on methods and techniques for beach nourishment can be found in Dean (2002) and Dean and Dalrymple (2010). The aim of beach nourishment is to rebalance the sediment budget in favor of accumulation over erosion, often attempting to offset nearby activities which have previously cut-off the sediment supply and increasing the stability of the system (Lodder et al., 2021). Sediment is either directly applied to the beach or sand dune system (either at once or through a phased approach), or a "sand engine" approach is taken where deposited sediment is placed such that it will be transported along the beach by longshore drift (e.g., de Schipper et al., 2016). Although erosion may still occur (particularly for areas with sediment deficits), the beach is often widened and elevated, providing a buffer against erosional forces. Beaches with a range of substrates (including sandy, rocky and cobble beaches) may benefit from beach nourishment (Lodder et al., 2021).

Figure 3. Conceptual sketch of a beach nourishment to reduce erosion



The fate of deposited sediment will be highly site-specific, and an understanding of the hydrodynamics and sediment transport regime of the area is typically necessary to estimate sand budgets and predict the long-term behaviour of the project (Wilmink et al., 2017). The type, size and distribution of sediment material used in nourishment is also critically important and will vary project to project. Inappropriately sized material may enhance erosion, negatively impact the ecological values of the site and impact public usage. For example, beach nourishment in the Hel Peninsula in Poland was unsuccessful as the fine-grained material dredged from a nearby bay and deposited on the beach was eroded away (Hanley et al., 2014). In this case, a more appropriate material would have been coarse sand from the open sea, which was similar to the native beach sands (Hanley et al., 2014). Even with appropriately-sized material, replenishment of emplaced sediment should be expected (de Schipper et al., 2016) and accounted for in the planning (e.g., to ensure appropriate resources are available) and adaptive management of the project. Case Study 1 provides an example of a successful beach nourishment project in Cancún, Mexico, which followed an adaptive management approach following construction. See section 5.5 for additional information on adaptive management.

Sediment accumulation or increased residency time can be encouraged by implementing hybrid approaches, using built features such as groins, submerged or emergent headlands, and sand fences to enhance accumulation of sediment through modifications of nearshore hydrodynamics and thereby sediment transport patterns. Green approaches, such as vegetation planting and seagrass meadow enhancement, may also help to reduce erosion and promote accretion (Chen et al., 2022). Beach nourishment projects incorporating such accumulation strategies (such as vegetation planting or combining seagrass meadows with sediment deposition) have seen greater longevity and success in sand accumulation and erosion reduction of deposited material (Chen et al., 2022)

It is also important that ecological impacts be considered when planning beach projects. Extracting nourishment sediment from the borrow location can disrupt animals and habitats of the area. Also, existing habitat, vegetation and animals present on the beach being nourished may also be impacted (e.g., Peterson and Bishop 2005). For instance, beach nourishments in turtle nesting areas may impact nesting and hatching success, which is potentially related to changes in sediment grain size and colour (Brock et al., 2009). So-called "mega-nourishments" are often driven by trade-offs in system recovery time post-nourishment for a single, large nourishment in comparison to multiple, frequent nourishments (Lodder et al., 2021).

Because beach nourishments are a popular means of shore protection globally, there is significant technical design guidance available. For example, the reader may refer to the *International guidelines on natural and nature-based features for flood risk management* (Bridges et al., 2021) or the *Coastal Engineering Manual* (USACE 2002) for technical design guidance. Site-specific technical constraints that typically need to be considered to ensure the success of a beach nourishment project include the following (Lodder et al., 2021):

- sediment availability;
- sediment size and gradation;
- beach slope;
- profile height;
- sediment volume;
- beach width;
- control structures (such as groins);
- habitat types; and
- wave regime.

As described in section 5.1, some systems will fall outside of standard technical guidelines and limits of empirical equations, requiring the use of numerical or physical models, or pilot projects to inform, refine, or prove the design (World Wildlife Fund 2016). For beach nourishment projects, geomorphic numerical models such as LITPACK, GenCADE, XBeach, XBeach-G, MIKE 21/3 ST/SM (Sediment transport/shoreline morphology), and Delft3D are commonly used to inform the stability of beach nourishments during discrete storm events and over the long-term, to assess the impact of human activities (such as dredging), and to inform the potential need for future maintenance works. See section 5.0 for more information on design considerations.

Case Study 1. Beach nourishment in Cancún

Beach nourishment in Cancún:
Successful beach stabilization following erosion

Cancún, Quintana Roo, Mexico

Cancún's beaches are prone to erosion from wave action, which has been worsened over the last several decades following a series of hurricanes and storms. In the early 2000s, erosion was further exacerbated by the dense development of hotels and associated removal of natural features, such as mangroves and dunes along the coast, which further facilitated sediment loss. Due to the economic importance of tourism to the area, efforts have been made to re-establish the beaches and protect them from erosion.

Beach nourishment was first undertaken on Cancún's beaches in 2006, which involved placing 2.7 million m^3 of sand borrowed from two nearby sand banks, costing US$19 million (Martell et al., 2020). This first attempt was shortly followed by Hurricane Dean in 2007, which significantly damaged and eroded the beach, removing much of the deposited nourishment and creating dramatic beach scarps.

Monitoring efforts were conducted throughout 2006 to 2009 to understand the currents, transport and accumulation dynamics along the coast. Following these studies, a second nourishment was completed in 2010 taking this knowledge into account. The second nourishment involved placing 5.2 million m^3 of more compatible sediment on the beach and installing a groin and breakwater to prevent transport of sand seaward (Martell et al., 2020).

After the second nourishment attempt in 2010, the project first appeared unsuccessful as significant erosion occurred, reducing the beach width and forming dramatic beach scarps. However, by 2013, these scarps were modified naturally, in response to wave forcing and tides, and formed a gentle slope with a stable beach width of approximately 30 m. The beach system has remained stable, and as of 2020, no further nourishment has been required. However, the area remains vulnerable to hurricanes, and further renourishment is to be expected following future significant storm events. (Martell et al., 2020).

Figure 4. Satellite imagery of the beach in 2009 before beach nourishment (left) and in 2020 (right), ten years after beach nourishment was completed

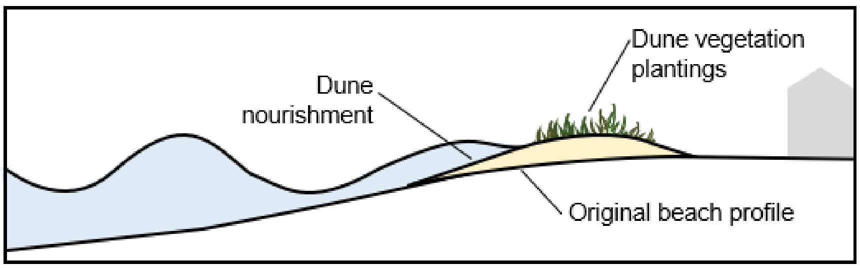
Source: Google Earth, 2022

2.5.2 Sand Dunes

Sand dunes are dynamic systems which exist above the limits of regular wave action. Dunes may grow, reduce in size, reshape, experience seasonal changes, can be naturally or artificially re-nourished and are adaptable to climate change. They provide a physical barrier to inundation and dissipate wave energy, reducing erosion. Dunes are formed by wind- and wave-driven transport of sediment, which is often trapped by vegetation or other roughness elements located on the dune. Sand dunes require an adequate supply of sediment and sufficient wind speeds or waves to drive transport onto the dune crest (Lodder et al., 2021).

Dune restoration or establishment is usually achieved through a combination of sediment nourishment, planting of native vegetation and removal of invasive species to increase dune stability and encourage sediment accumulation (Figure 5). Restricting pedestrian access can also help prevent flattening and loss of dune structure and vegetation (e.g., Šile et al., 2017).

Figure 5. Conceptual sketch of a dune establishment for improved flood protection



Dune creation and restoration will require differing technical approaches depending on site-specific needs. If designed appropriately, dunes can accumulate naturally over time, providing a long term and naturally adaptable coastal defense requiring little additional maintenance (e.g., Maun and Fahselt, 2009). It is important that a multidisciplinary team of experts with an understanding of the local environment is consulted (see sections 4 and 5), and that an adaptive management approach is followed (see section 5.5). Case Study 2 provides an example of a dune restoration project that successfully reduced storm related impacts. Hybrid dune systems are also an option, for example a dune system can be established over an existing seawall or dike, which is buried under the new dune system (e.g., van Loon-Steensma et al., 2014). Further consideration of hybrid features is given in section 2.10.

International guidelines from the United States Army Corps of Engineers provide detailed technical design considerations for sand dunes (Lodder et al., 2021). A summary of general factors to consider in the design of sand dune systems is included below (Lodder et al., 2021):

- Vegetation type, non-native species removal, succession and needs related to vegetation planting, watering, fertilization and adequate salt spray;
- A sandy beach wide enough for wind sediment transport (> 100 m from mean sea-level to dune foot);
- Development space to allow dune growth and evolution; and
- Effects of wave and wind energy on sediment transport, deposition, and erosion.

These design considerations are important for the success of a project, as some dune creation projects have been subject to retreat and erosion. In a study of several dune construction projects, (Morris et al., 2018) found that dunes constructed close to the sea (e.g., following a ‘protect’ style approach) were frequently eroded, while those constructed further inland (e.g., following a ‘retreat’ style approach) grew, even during storm events. Dunes can recover and grow naturally (e.g., Maun and Fahselt, 2009) and although some projects in the study were eroded initially, some of these projects experienced recovery and growth after the initial erosion (Morris et al., 2018).

Case Study 2. Sand Dune restoration in New Jersey

South Cape May Meadows Sand Dune Restoration: Increasing resilience to storms through sand dune restoration

Cape May, New Jersey, United States

Cape May is a small community in New Jersey, United States, prone to flood damage and coastal erosion from coastal storms and hurricanes. Following a series of storms in the late 1990s, local governments held discussions to identify potential solutions to reduce flood risk and damage.

In 2007, a combination of NBS strategies were completed at South Cape May Meadows preserve, including sand dune restoration and beach nourishment to protect the town and improve the coastal habitat. The project required 1.4 million m^3 of sand to restore a 1.6 km long and 5 m high sand dune system, which cost US$15 million in total (Naturally Resilient Communities, 2022a).

The project was a success, providing protection during Hurricane Sandy in 2012, during which the restored dune and beach system successfully prevented flooding of the community. The average flood claim in Cape May following storms was ~US$144,000 prior to the completion of the NBS project (Naturally Resilient Communities, 2022a). Following the completion of the dune and beach system and Hurricane Sandy, flood damage claims were reduced to ~US$4,000. Projected savings resulting from the NBS project over the next 50 years from reduced flood damage claims has been estimated to be US$9.6 million (Naturally Resilient Communities, 2022a).

Figure 6. Completed beach and dune project at South Cape May Meadows

Source: the Nature Conservancy, 2022

In addition to the FrM benefits the project has brought, additional co-benefits have also been seen in an increase in the number of migratory birds using the area for foraging and resting (The Nature Conservancy, 2022). More information can be found at Naturally Resilient Communities (2022a): <nrcsolutions.org/south-cape-may-meadows-cape-may-point-new-jersey/>

2.6 Wetlands

Coastal wetlands include salt, brackish and freshwater marshes, sand and mud tidal flats and mangroves. These coastal wetland ecosystems provide a host of ecosystem services and can help to mitigate coastal hazards such as storm surges, wave overtopping, coastal flooding, and coastal erosion. Wetlands can attenuate flooding through the storage and drainage of flood waters by providing an area for inundation. Semi-submerged wetland vegetation such as mangrove forests also play a key role in reducing erosion and flooding through wave attenuation. Wetland vegetation further mitigates erosion by stabilizing the shoreline and encouraging sediment accumulation (Piercy et al., 2021). In addition to FrM benefits, wetlands provide many co-benefits. Several co-benefits typically associated with wetlands are given in Box 5. However, co-benefits should be evaluated on a project-specific basis. For additional potential co-benefits, refer to the *Co-Benefits* document. Proposed monitoring methodology and performance metrics for wetlands are also provided in the *Monitoring Efficacy: Proposed Methodology and Indicators* document.

Box 5. Examples of typical co-benefits provided by NBS involving wetlands

Environmental	Social	Economic
Aquatic habitat availability and quality	Broader recreation and gathering spaces	Increased tourism
Abundance and diversity of native plant and animal species	Improved esthetics	Reduced costs to adjacent infrastructure (flood losses)
Water storage and quality		Ecotourism opportunities
Carbon sequestration		

Strategies for implementing wetland NBS can range from conserving existing systems to restoring degraded systems and creating new environments. Hybrid systems are often adopted where wetlands are created or restored in front of an existing gray solution such as a dike or seawall (See section 2.10).

As with other NBS types, site-specific considerations need to be assessed in the design and selection of an appropriate wetland solution. Significant design guidance exists for wetlands, particularly in temperate climates. The international guidelines from the United States Army Corps of Engineers provides a comprehensive overview of technical design considerations (Piercy et al., 2021). A summary of general factors to consider include:

- Choosing an appropriate location according to the problem (e.g., inland, non-tidal wetland vs coastal, tidal wetland);
- Site-specific geomorphology such as elevation, shape and tidal creek order (e.g., Odell et al., 2008);
- Coastline and storm characteristics;
- Environmental factors and processes such as hydrology, tides, waves, sediment transport and soil type; and
- Vegetation cover and type, and the need for removal of invasive species.

Marshes and tidal flats are briefly discussed separately in section 2.6.1, and mangroves are discussed separately in section 2.6.2. Key takeaways related to wetland systems are summarized in Box 6.

Box 6. Key takeaways for NBS involving wetlands

- Coastal wetlands include salt, brackish and freshwater marshes, sand and mud tidal flats and mangroves. They offer protection from erosion and flooding, and provide new habitat and improved recreation and tourism benefits, although scale is important in reducing flood risks and to ensure a functioning system.
- Wetland restoration is achieved by promoting natural inundation of land (often through dike and levee breaching) or by raising existing low-lying lands to suitable elevations, sediment deposition, native vegetation planting, and removal of invasive species.
- Salinity, hydrology (e.g., drainage), sediment transport and soil type will all be key factors to consider for successful vegetation establishment.
- Salt marshes generally form in shallow temperate intertidal zones, that are low energy, wave protected and have a continuous sediment supply. Mangroves inhabit salty and brackish water in the tropics and subtropics.
- It is important to understand local coastal dynamics to allow for sediment accumulation and vegetation growth. Adaptive management should be expected.

2.6.1 Marshes and Tidal Flats

Marshes are most common in temperate regions. Coastal and inland marshes include freshwater, saltwater and brackish marshes. Marshes are vegetated areas that exist primarily within the intertidal zone. Marshes are dominated by grasses and rushes, and vegetation types depends on climate, salinity, and drainage, amongst other factors. Tidal flats are non-vegetated inter-tidal components of these systems adjacent to the marsh (Piercy et al., 2021). Salt marshes can provide significant wave attenuation and shoreline stabilization benefits (Shepard et al., 2011; van Loon-Steensma, 2015). Semi- or fully submerged vegetation in marshes helps to trap sediment and reduce wave energy, stabilizing the shore and reducing the size and energy of waves, mitigating erosion as well as wave-induced flooding (e.g., Barbier et al., 2011; Duarte et al., 2013).

Tidal flats play a role in dissipating wave energy and sediment transport by slowing water velocities across the tidal flats and promoting sediment deposition (Piercy et al., 2021). Recent research also suggests that sediment may accumulate on tidal flats through biogenic processes (Readshaw and Williams, 2022). Wetlands also have the potential to be self-sustaining and increase in elevation as sea-level rises through continued natural sediment accumulation (e.g., Kirwan and Megonigal, 2013).

Marshes can also help alleviate flooding through water storage, and facilitate drainage of flood waters, reducing recovery times after flood and surge events (Piercy et al., 2021). As such, it has been found that financial losses related to flooding from major hurricanes in the United States has been significantly reduced in areas where wetlands are present (Costanza et al., 2008). Case Study 3 provides an example of a marsh restoration project developed to mitigate repetitive flooding in a region of Oregon.

Case Study 3. Wetland Restoration in Oregon

The Southern Flow Corridor Flood Reduction and Habitat Restoration Project:
Reducing flood damage through wetland restoration

Tillamook Bay, Oregon
United States

Tillamook County, west of Portland, Oregon, has experienced repetitive seasonal flooding that has damaged property, farmland, the highway, and the rail line (FEMA, 2021). Flood-related losses in Tillamook are estimated to have totaled more than $60 million between 1996 to 2000 (FEMA, 2021). Winter storm surge, heavy rain (NOAA, 2021), fires and deforestation exacerbated flooding as river discharge and sediment content of rivers were higher than normal (FEMA, 2021).

Following repeated seasonal flooding and a significant storm in 2006 (which caused flooding, erosion and landslides), a collaborative effort between 24 community, local, state and federal agencies was made in 2007 to restore the marsh wetland to mitigate flood impacts in Tillamook (Shaw and Dundas, 2021).

Construction began in 2016 after land purchase and easement agreements to acquire the surrounding farmland for inundation had been completed. This involved the removal of 8 km of levees and 15 tide gates, which were replaced with new tide gates positioned further from the sea (Shaw and Dundas, 2021). This opened the area up to inundation and tidal forces allowing for 180 hectares of marsh wetland to re-establish. To further improve the wetland habitat, 18 tidal channels were reconnected to the river.

Figure 7. Restored marsh in Tillamook Bay

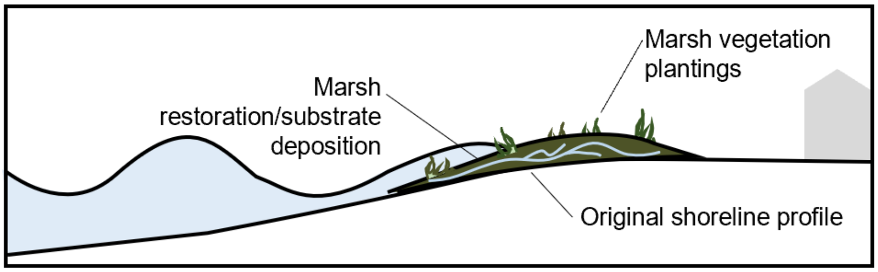
Source: Tillamook Estuaries Partnership, 2021

Modelling has projected significantly reduced flood damages resulting from the marsh restoration (Shaw and Dundas, 2021), resulting in estimated savings of $9.2 million from flood damages over the next 50 years (NOAA, 2021). Additional co-benefits of the project included the creation of 108 jobs, reduced dredging required, increasing water quality and storage of 25,000 tons of blue carbon (Shaw and Dundas, 2021).

Marsh and tidal flat NBS can be implemented by conserving existing, restoring degraded or creating new marshes, making this solution highly compatible with retrofitting activities. There are many different approaches to wetland restoration and creation, which will be specific to the particular project. Salt marshes generally form in shallow intertidal zones that are low energy, wave protected and with continuous sediment supply (Jordan and Fröhle, 2022). Restoration and development of marshes is typically achieved through a combination of:

- Replanting native vegetation and removal of invasive species;
- Sediment deposition;
- Levee or dike breaching to allow inundation of previously protected land;
- Measures to reduce wave action; and
- Encouraging sediment accretion (e.g., van Loon-Steensma and Vellinga, 2013).

Figure 8. Conceptual sketch of a marsh restoration for improved flood protection

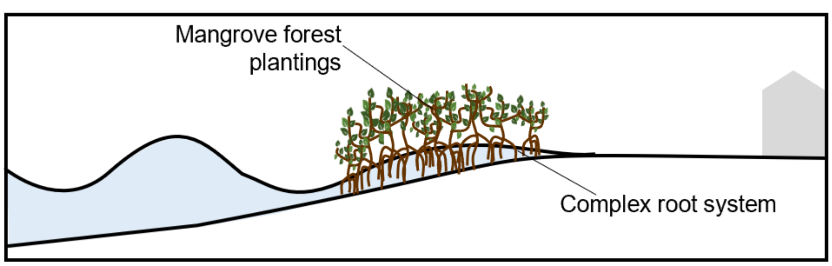


Although marsh systems are frequently used as part of NBS projects and restoration projects in general, designs are very site-specific. Consequently, design often relies on the use of 'analogue' marshes with similar physical characteristics as the study site, to inform the size and length of channels and the elevations and slopes of the marsh surface. The project team will often construct preliminary marsh channels to convey tidal flows and stimulate further natural channel evolution (rather than attempt to predict the final form and character of the marsh channels). Odell et al. (2008) described this design process in detail. Marsh projects also tend to rely heavily on adaptive management to manage uncertainties following construction. Numerical models are sometimes used to confirm hydrodynamics and sediment transport, but physical models are rarely employed. See section 5.0 for more information on design considerations.

2.6.2 Mangroves

Mangroves are shrubs or trees that inhabit salty and brackish water along coasts and estuaries in the tropics and subtropics (Figure 9), limiting their use in North America to Mexico and the southern United States. Under the right conditions, mangroves are expected to recover and adapt to changing climate (Gedan et al., 2011), making them a resilient, naturally persistent, and adaptive choice of coastal defense that will grow and maintain functionality over time with increasing risk. The above-ground root system of mangroves reduces wave energy and traps and stabilizes sediments, reducing erosion (e.g., Gijsman et al., 2021). The ability of mangroves to dissipate wave energy and store water have also been shown to be effective in reducing flooding from storm surges (Montgomery et al., 2019). An example mangrove NBS project is provided in Case Study 4.

Figure 9. Conceptual sketch of a mangrove forest planting for improved flood protection



Successful mangrove creation or restoration requires the following (adapted from Balke et al., 2011):

- Sufficient time without inundation for plants to anchor into the soil and for seeds to germinate;
- Root growth to a depth that allows vegetation to remain in place under wave and current stresses and sediment loss; and
- Appropriate salinity, hydrology, tides, low energy wave environments, sediment transport and soil type.

Similar to marshes, mangrove systems are frequently developed based on established 'analogue' systems with similar physical characteristics as the study site. Provision of appropriate soil nutrients and tidal channels (to support flushing) is critically important. A key consideration to mangrove restoration is also providing protection of saplings from erosion, wave exposure, currents and predation during establishment. Mangrove projects also tend to rely heavily on adaptive management to manage uncertainties following construction. Section 5.0 outlines additional general design considerations for NBS. More specific design guidance for mangroves can be found in Balke et al. (2011) and Teutli-Hernández et al. (2020).

Case Study 4. Mayakoba mangroves expansion

Mayakoba Mangroves Expansion:
Integrating mangroves into the urban area

Playa del Carmen, Quintana Roo, Mexico

Mexico has nearly 1 million ha of mangrove forests along its Gulf, Caribbean and Pacific coasts. Most of these ecosystems are located on the Gulf Coast, in the Yucatán Peninsula, where there is also significant tourism. The coastal area of Quintana Roo, in the Mexican Caribbean, has experienced accelerated growth in recent decades due to tourism development. As a result of the development of tourism infrastructure and urban sprawl, large areas of mangroves have been lost in the Mexican Caribbean (Chávez et al., 2021).

The Mayakoba hotel and golf course development emerged as a response to the high-density tourism developments in the area, proposing environmentally conscious infrastructure to preserve biodiversity (Mayakoba, 2020). The Mayakoba development is located in a degraded mangrove system, which has now been restored and serves as a NBS to coastal flooding in the area.

The 60 ha mangrove restoration involved constructing channels and culverts to improve hydrology and reduce salinity, which encourages natural reestablishment of the mangroves. In addition, reforestation of mangrove vegetation has been completed, which involved planting 15,000 red mangrove propagules. There is ongoing monitoring and maintenance of the restored mangroves, including water quality monitoring, removal of objects that impede water flow, control of aquatic vegetation and sediment removal (Mayakoba, 2020).

Figure 10. An artificial channel in the restored mangrove system

Source: Mayakoba 2020

In addition to the increased coastal protection the restored mangroves have provided to the tourist development, co-benefits of the project include improved water quality and increased biodiversity, particularly in birds, fish, and amphibians, from 35 species to 200 in the area (Mayakoba, 2020).

2.7 Islands

Island development involves the creation of new land separated from the existing shoreline, which can be expensive. This typically involves the provision of a substantial volume of fill materials, and often requires protecting portions of the island edges using gray materials. Islands primarily act to dissipate wave energy, reducing erosion and the severity of storm surges. Islands can be a suitable alternative for locations where there is little space available for other intertidal or land-based solutions. Islands often function as an additional line of defense in front of the coast. Islands frequently feature a combination of the other NBS types, such as beach and dune systems or salt marshes (see Case Study 5 for island-salt marsh project example). Islands, therefore, have the potential to provide a range of FrM benefits and co-benefits.

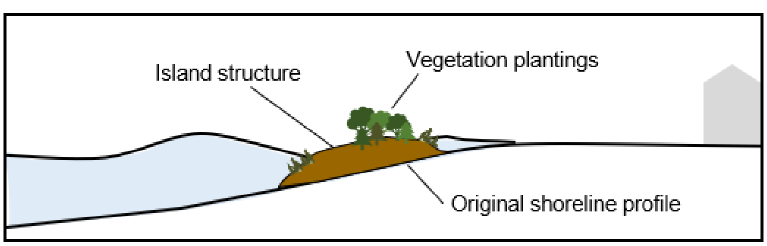
Co-benefits typically associated with islands are provided in Box 7. However, projects may include numerous additional benefits, particularly if islands are combined with other NBS strategies, such as wetlands. Co-benefits should therefore be identified and evaluated on a project-specific basis. The associated *Co-Benefits* guidance document provides a detailed description of potential co-benefits of NBS. Proposed monitoring methodology and performance metrics for NBS involving islands are also provided in the *Monitoring Efficacy: Proposed Methodology and Indicators* document.

Box 7. Examples of typical co-benefits provided by NBS involving islands

Environmental	Social	Economic
Aquatic habitat availability and quality Abundance and diversity of native plant and animal species	Improved esthetics	Increased tourism Reduced costs to adjacent infrastructure (flood losses)

There are three types of islands that can either be created or restored: barrier, deltaic and in-bay or in-lake (Gailani et al., 2021). Barrier islands are long and narrow in shape and situated parallel to the coast. They are typically less than 20 km in length and protect against storm surge, erosion and wave overtopping. In-bay or in-lake islands are similar to barrier islands but are located within a lagoon or bay. Deltaic islands form in river mouths due to sediment deposition, which forms islands between a network of channels.

Figure 11. Conceptual sketch of an island structure for improved flood protection and reduced erosion



For islands to form naturally and remain a feature of the coastline, sufficient wave energy and sediment supply is required, as well as a mildly sloping foreshore (Gailani et al., 2021). In addition, islands are typically only feasible where there is a low to moderate tidal range (e.g., Souris, PEI), which potentially limits their applicability in areas where tidal ranges are exceptionally large, such as in parts of the East Coast of Canada. Islands are dynamic systems, and—without interventions to protect them—they should be expected to continuously be reshaped and eroded by coastal processes. They therefore need to be designed appropriately with consideration of the local coastal dynamics. For example, in Case Study 5, the design of the second phase island project was less successful and suffered erosion and reduced ability to attenuate wave action. Due to their position further offshore of the coastline and their dynamic nature, islands sometimes require a greater degree of design and adaptive management than other NBS options. Careful consideration should also be given regarding the placement of islands, as to not impact existing sub-tidal habitats. In addition, it is important to note that foreshore leases (or other special permitting) may be required for construction.

Design guidance for islands can be found in Gailani et al. (2021). Numerical modeling, physical modeling or pilot projects may be used to inform, refine or prove the design (World Wildlife Fund, 2016). Hydrodynamic, wave and geomorphic numerical modeling tools are also commonly used to refine the layout, slopes, elevations, or material sizing later in the design process (Vouk et al., 2021). Additional technical considerations related to design of NBS in general are provided in section 5.0.

Key takeaways related to islands are summarized in Box 8.

Box 8. Key takeaways for NBS involving islands

- Islands provide protection from erosion and storm surge; and can provide new habitat and potential recreational opportunities.
- Islands are most useful where there is little space available for land-based solutions. Careful consideration should be given to placement, as to avoid negatively impacting existing sub-tidal habitats.
- Islands are often used in combination with other NBS (e.g., salt marsh island).
- For islands to form and remain a feature of the coastline, adequate sediment supply, a low slope and sufficient wave energy to shape sediments is required or alternatively, erosion protection measures (Gailani et al., 2021).
- It is likely that maintenance, monitoring and adaptive management will be required due to the coastal processes these systems are exposed to. It is important to understand and plan around local coastal dynamics to minimize erosion.

Case Study 5. Island creation in Florida

Project Greenshores:
Reducing storm surge impacts and flooding with islands

Pensacola, Florida, United States

Pensacola is located in Northwest Florida on the coast of the Gulf of Mexico. The area is prone to high energy waves and coastal erosion as well as storm surge from hurricanes and tropical storms. Pensacola has been subject to damage to property and public infrastructure and is ranked 8th on the list of worst places for hurricanes in the United States (Naturally Resilient Communities, 2022b).

In response, Project Greenshores is a two-phase coastal habitat restoration program which began in 2003. Phase one involved the creation of five islands in Pensacola Bay using dredged sand and an artificial breakwater. The islands were planted with native vegetation to create wetland marsh habitat (Naturally Resilient Communities, 2022b). The first phase has been a success as the islands have reduced flooding and erosion in Pensacola through wave attenuation. This was particularly evident during 2004 when Hurricane Ivan affected the area. The hurricane caused extensive flood damage and road closures in Pensacola, except for the area behind the Greenshores project, which sustained less damage (Naturally Resilient Communities, 2022b).

After the successful completion of the first phase of the project, the second phase of the project began in 2007. Phase two involved construction of three intertidal marsh islands west of the original project, using material that was routinely dredged from the nearby Escambia River (Florida Department of Environmental Protection, 2021). The islands created in phase two were completely submerged following requests during public consultation to preserve the existing aesthetics of the Bay. This phase was not as successful as the first. Two of the islands have experienced erosion and wave attenuation from the islands was not reduced in comparison to the first phase (NRC, 2022b), most likely as a result of the fully submerged design.

Figure 12. Project site 1 (five marsh islands) and site 2 (three islands, two of which are being eroded)

Source: Google Earth 2022 *Lat 30.41, Long -87.19*

2.8 Terrestrial Vegetation

NBS retrofits involving terrestrial vegetation includes planting native trees, grasses, or shrubbery above the typical high-water mark, within the riparian zone. Placement of terrestrial vegetation in the backshore can provide wave attenuation and wind attenuation during extreme storm events, reduce ice impact, and stabilize sediments from overland flows (Scheres and Schuttrumpf, 2019). Root systems from terrestrial vegetation can help to trap sediments and provide greater shoreline or bank stability (Gray, 1995). Increased weight from vegetation, increased sediment, and improved soil moisture can also add to stability. Terrestrial vegetation may be planted in areas that may currently experience wave-induced flooding or erosion during extreme storm conditions, or as a means to adapt to sea-level rise.

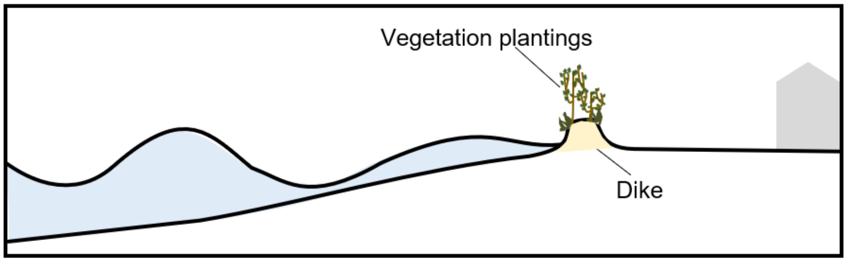
In addition to FrM benefits, terrestrial vegetation can provide co-benefits, such as the provision of habitat for insects and birds. Co-benefits typically associated with terrestrial vegetation NBS are provided in Box 9. For additional potential co-benefits, please refer to the *Co-Benefits* document. Proposed monitoring methodology and performance metrics for NBS involving terrestrial vegetation are also provided in the *Monitoring Efficacy: Proposed Methodology and Indicator* document.

Box 9. Examples of typical co-benefits provided by NBS involving terrestrial vegetation

Environmental	Social	Economic
Terrestrial habitat availability and quality	Improved esthetics	Reduced costs to adjacent infrastructure (flood losses)
Abundance and diversity of native plant and animal species	Foraging, gathering, and traditional usages	
Soil health		
Carbon sequestration		

There is the potential for retrofitting or developing hybrid sea dikes with terrestrial vegetation (Figure 13); however, the efficacy and safety of this approach is debated (Scheres and Schüttrumpf, 2019). Concerns arise around the potential for vegetation induced damage—particularly from woody vegetation—to the dike structure, increased risk of erosion, and additional forces from wind. There are also concerns regarding terrestrial vegetation complicating the ability to maintain and monitor the integrity of the dike. Consequently, local policies may prevent the application of terrestrial vegetation on dikes. For example, in British Columbia, Canada, vegetation on dikes is limited to grass that can be mowed to facilitate dike integrity monitoring (British Columbia, 2022). The United States Army Corps of Engineers guidelines for management of levees and other flood protection structures in the United States (USACE, 2019a) also recommends against the usage of terrestrial vegetation on dikes (although variances may be obtained), and states that terrestrial vegetation may be "periodically cleared" to maintain functionality and accessibility for maintenance. In addition, seasonal die-off of vegetation, particularly in cold-climates, may result in variable FrM performance that must be accounted for in design. Regardless, there may be opportunities to collaborate with diking authorities or other decision makers to determine a suitable inspection and maintenance plan that facilitates the use of terrestrial vegetation.

Figure 13. Conceptual sketch of terrestrial vegetation for improved flood protection and reduced erosion



This type of solution is understood to be cost-effective and compatible with many existing land uses. However, the usage of terrestrial vegetation as flood protection is still in its infancy and design guidance is limited. Research is currently underway to better understand its efficacy (e.g., Kalloe, 2019; Kalloe et al., 2022). For this reason, although numerical modeling may be a useful tool, physical modeling or pilot projects should also be considered to inform, refine, or prove any NBS retrofits relying upon terrestrial vegetation as flood protection. Additional technical considerations related to design of NBS in general are provided in section 5.0.

Key takeaways related to terrestrial are summarized in Box 10.

Box 10. Key takeaways for NBS involving terrestrial vegetation

Terrestrial vegetation provides protection from wind and erosion, as well as waves during high water events. Performance may vary depending on seasonal die-off and growth.

Technical design guidance for terrestrial vegetation NBS for FrM is still in development (e.g., Kalloe, 2019; Kalloe et al., 2022), and this approach should therefore be used with caution. Physical modeling or pilot projects are recommended to better understand FrM benefits.

There is the potential for retrofitting or developing hybrid sea dikes with terrestrial vegetation. However, to facilitate inspection, diking authorities may not allow the solution.

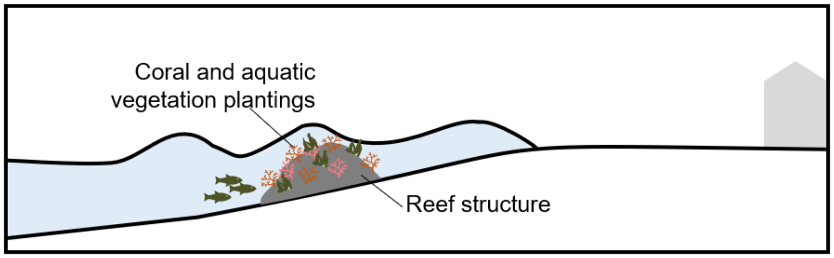
Terrestrial vegetation is compatible with many existing land-uses and could be used in combination with other NBS (e.g., salt marshes).

Terrestrial vegetation is already an important part of many ecosystems, suggesting that existing vegetation may provide secondary FrM benefits.

2.9 Submerged Features

Submerged features – such as coral or oyster reefs, or eelgrass and kelp forests – can dissipate wave energy, reducing erosion and the impact of storm surges (e.g., Lowe et al., 2021) (Figure 14). Submerged aquatic vegetation and created/restored reefs have been used extensively in coastal restoration and coastal protection projects across North America. These features have the potential to provide significant co-benefits while protecting the shoreline from erosion and wave-induced flooding (see Case Study 6 for an example oyster reef with eel grass project that reduced erosion while enhancing biodiversity). Reefs are most feasible and effective in regions with small tidal ranges (Lowe et al., 2021).

Figure 14. Conceptual sketch of a coral reef structure for improved flood protection and reduced erosion



Submerged aquatic vegetation has similar properties as semi-emergent vegetation outlined in section 2.6 (Wetlands). They can serve to attenuate wave energy (helping to prevent flooding and erosion at the coastline) and help stabilize seabed sediments. Reefs, on the other hand, are rigid, submerged structures, with similar properties as some conventional gray solutions such as artificial breakwaters. Artificial breakwaters provide similar FrM benefits to reefs, but fewer co-benefits than a natural reef. Hybrid reef features will exist in the spectrum between these two types of structure. Design of reef NBS benefits from existing knowledge and proven efficacy of these gray structures in reducing erosion and wave energy at the shoreline, as well as from an existing understanding of the effects of natural reef systems on coastal processes. For example, The Mesoamerican Reef in Quintana Roo, Mexico, was estimated to have reduced damage from Hurricane Dean in 2007 by 43% (Reguero et al., 2019). Like many other NBS options, reefs can be self-sustaining, growing over time and maintaining their structure if designed appropriately (Brathwaite et al., 2022). Consequently, reefs may be a suitable adaptation approach to sea-level rise in some areas if the reefs are able to grow at a rate that is in line with local sea-level rise.

In addition to FrM benefits, submerged features can provide numerous co-benefits. Co-benefits typically associated with submerged features are provided in Box 11. A list of additional potential co-benefits associated with NBS is provided in the *Co-Benefits* document. Proposed monitoring methodology and performance metrics for NBS involving submerged features are also provided in the *Monitoring Efficacy: Proposed Methodology and Indicators* document.

Box 11. Examples of typical co-benefits provided by NBS involving submerged features

Environmental	Social	Economic
✓ Aquatic habitat availability and quality	✓ Broader recreation opportunities	✓ Increased tourism
✓ Abundance and diversity of native plant and animal species	✓ Foraging, gathering, and traditional usages	✓ Reduced costs to adjacent infrastructure (flood losses)
		✓ Ecotourism opportunities

Coral and oyster reefs involve the construction of an underlying reef structure which is often artificial, in combination with natural materials such as oyster shells to encourage natural oyster recruitment; they can also be actively planted with corals. Recreating the correct environment for living components to thrive and grow is challenging. Coral reefs in particular are very sensitive to their environment and live in a relatively small range of conditions. They primarily need good water quality (which is often an issue near estuaries and in coastal urban areas), the correct water depth, and hydrodynamic conditions. Because of this, design often relies upon established 'analog' reefs, which exist nearby and have similar site conditions. Materials should generally be similar to those found in the local environment to encourage recruitment and growth (Lowe et al., 2021). However, many practitioners have found success in the use of artificial materials, such as 3D printed concrete reefs (e.g., Levy et al., 2022).

Reefs are subject to a multitude of increasing pressures (e.g., Bryant et al., 1998). Ocean acidification and ocean warming (e.g., Spalding and Brown 2015), are predicted to add stress to coral reefs in particular. In addition, increased coastal development has and will likely continue to increase run-off into coastal and estuarine environments (e.g., Rabalais et al., 2009), introducing pollutants and disrupting nutrient levels required for healthy coral systems, while also promoting harmful algal blooms and eutrophication; fishing of grazers which control algal populations also adds stress to corals (Bryant et al., 1998). All these pressures threaten the functionality of these systems and highlight the importance of creating additional habitat. Monitoring and adaptive management will likely be essential for NBS involving submerged features. Maintenance of submerged features generally requires a team of specialized dive biologists and may therefore be more costly than other options, depending on site-specific conditions and hazards.

Numerical models are used to better understand the FrM benefits of submerged features, and frequently to understand secondary impacts such as changes to currents and sediment transport pathways. The geometry and location of submerged features (particularly reefs) in respect to local coastal dynamics and processes, waves and currents and water quality are key in the design of a successful project. Additional guidance on eelgrass and kelp forest restoration can be found in Beheshti and Ward (2021) and Eger et al. (2022). Additional guidance related to submerged reefs can be found in Baine (2001) and Lowe et al. (2021). See section 5.0 for more information on general design considerations for NBS.

Key takeaways related to submerged features are summarized in Box 12.

Box 12. Key takeaways for NBS involving submerged features

Submerged features can dissipate wave energy, reducing erosion and the impact of storm surges. They can also provide habitat and recreational and tourism benefits.

Coral and oyster reefs involve the construction of an underlying reef structure which is often artificial, in combination with natural materials such as oyster shells to encourage natural oyster recruitment or are actively planted with corals.

Design should be based upon existing local reefs and eelgrass or kelp beds, using materials similar to those found in the local environment, to encourage ecological recruitment and growth (Bridges et al., 2021).

Maintenance of submerged features will require a team of specialized dive biologists and will likely be more costly than other options

Case Study 6. Oyster Reef project in San Francisco Bay

San Francisco Bay Living Shorelines Oyster Reef Project:
Pilot oyster reef project for mitigating coastal erosion

Marin County, California, United States

The San Francisco Bay Living Shorelines Project is a pilot oyster reef restoration project initiated to inform the design of potential future larger scale projects in the area. The project began in 2012, with the aim to reduce erosion and maintain coastal processes while enhancing habitat.

Four 320 m^2 plots were constructed along the San Rafael shoreline, 200 m from shore to assess the efficacy of different types of shoreline treatments in achieving the two goals of reducing erosion and enhancing habitat. These plots included a Pacific oyster plot, eelgrass plot, oyster and eel grass combination plot, and a control (Judge et al., 2017).

Figure 15. Pacific oyster shell assemblages in San Francisco Bay

Source: Judge et al., 2017

The oyster plot combined concrete structures with bags of clean half Pacific oyster shell to encourage recruitment of the native Olympia oyster, as well as other substrates such as reef balls and baycrete, to assess which substate types were most successful. The two other experimental plots included eel grass plantings and a combination of eel gras plantings and oyster reef. The project, including all four plot treatments and subsequent monitoring, cost $2.5 million (Judge et al., 2017) and involved federal, state, academic and commercial partners.

Once constructed, high frequency monitoring was conducted from 2012 to 2017. Monitoring was to continue at a lower frequency post-2017, for a period of five years, with the ambition to continue monitoring into the long-term. The monitoring program measured: wave attenuation, eel grass survival and density, Olympia oyster recruitment, survival and density, invertebrate, fish and bird use, wave energy, and water quality (Judge et al., 2017).

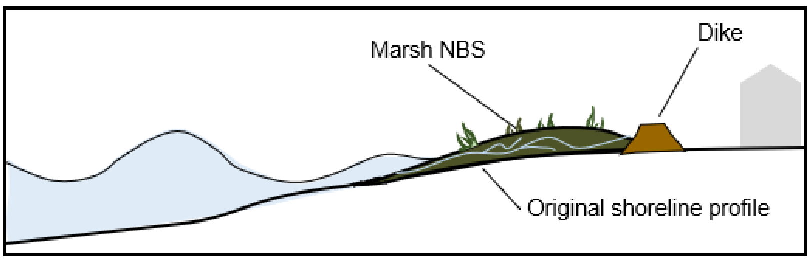
Monitoring revealed that there was successful and rapid (within 5 months) recruitment of oysters at the oyster reef plots, particularly on the shell assemblages. It was found that the combination plot of eel grass and oyster reef achieved the goals of wave attenuation and habitat enhancement better than the other treatments. At this plot there was a greater increase in biodiversity, (including fish, invertebrates, and birds) and a reduction in wave energy of 30% (Judge et al., 2017). The project also raised awareness, support, and interest for NBS projects within the San Francisco Bay area.

One of the key lessons learned from the project was that clean half Pacific oyster shell was the most successful surface for oyster recruitment. Shell mounds became buried in sediment, leading to the recommendation that a concrete base be used to support the valuable oyster shell above the zone of sedimentation. Oyster shells were difficult to acquire, and a partnership between restaurants and shellfish growers was suggested to increase supply (Judge et al., 2017).

2.10 Hybrid Features

All the NBS options previously described can generally be used in conjunction with conventional gray engineering options. These combinations of natural and gray features are referred to as hybrid features (Figure 16). A combination of natural and gray features may be implemented to replace aging infrastructure or where there are no coastal defenses currently in place (e.g., van Loon-Steensma et al., 2014). Hybrid features may be implemented where there is already existing gray infrastructure, providing a transitionary role between gray and green elements. NBS can also be implemented in conjunction with existing gray features, effectively resulting in a new hybrid feature. **Many—or even most—retrofitting projects will not necessarily utilize NBS alone (result in a return to fully natural processes) and will therefore be categorised as hybrid features.**

Figure 16. Conceptual sketch of an example of a hybrid feature, involving a marsh constructed in front of an existing dike system



Hybrid options may be developed at any stage of the coastal defense life cycle (i.e., new construction, maintenance, re-design, or decommissioning). Hybrid approaches often employed for FrM may include the following:

- Marsh with edge protection (e.g., oyster shells or rock);
- Marsh and dike system;
- Beach nourishment and headland system or detached breakwaters;
- Rock groins and beach nourishment;
- Beach nourishments and anchored large woody debris;
- Dune restorations with wooden fencing;
- Revetments with intertidal benches;
- Seawalls with habitat-enhancing tiles;
- Dikes with woody vegetation;
- Islands with edge protection (e.g., rock or sheet piles); and
- Mangrove planting with headland or breakwater system.

Hybrid solutions are often considered when asset managers are trying to improve the co-benefits (e.g., the habitat suitability) associated with existing 'hard' infrastructure, or when there is significant uncertainty surrounding the performance of NBS as they provide a compromise between "proven' static solutions and dynamic NBS. For example, constructing a sub-tidal reef offshore of an existing seawall may improve the performance and longevity of the seawall, while providing habitat for species at risk. Similarly, the incorporation of headlands or groins into a beach nourishment may help to stabilize sediments and provide more assurance that the beach nourishment will remain in place in the long-term. Gray elements may also be introduced as a 'back-up' in the event that the design criteria for dynamic stability of non-structural components of the NBS are exceeded. For example, a revetment may be buried beneath a dune system to prevent catastrophic failure in the event of extreme storm event. In this way, hybrid solutions may provide many of the co-benefits associated with NBS, while often providing a greater level of confidence in the performance and longevity of the project for the project team and stakeholders. Hybrid features also have potential benefit of having a smaller footprint, allowing them to be used in areas where space is too limited for NBS or constrained by regulatory issues (Sutton-Grier et al., 2015). Case Study 7 provides an example of a hybrid beach nourishment project in British Columbia, Canada.

Because of the many potential benefits of hybrid solutions, there is often a tendency to introduce gray elements into otherwise natural systems, even when it is not entirely necessary. This practice limits the potential co-benefits of the project and fails to take advantage of learning and research around the usage of NBS. It may also enable the unintended impacts of gray features to continue, such as increased erosion elsewhere in the system, inhibiting drainage, or trapping flotsam. Eco-engineered features (e.g., gray FrM designed to maintain or enhance ecosystem function, increased seawall roughness and concrete tide pools) fall towards the gray end of the NBS spectrum (e.g., Suedel et al., 2021; O'Shaughnessy et al., 2019; Strain et al., 2018). These options are an improvement on conventional infrastructure and have many benefits, but where there is opportunity to move a project even further along towards the green end of the spectrum, this is greatly encouraged. The intent of retrofitting (as stated in section 2.3) should be to move FrM systems towards the green end of the NBS spectrum by applying as natural of an approach as reasonably and technically feasible while also maximizing co-benefits. Hybrid options that are implemented with a system-level understanding, that maximize benefits of NBS in combination with gray features, where uncertainty, risk, space, or other factors restrict the use of fully green NBS, fit within this intent.

Hybrid approaches have the potential to leverage several perceived benefits of gray features, such as:

- their ability to provide FrM has been proven;
- their design is often relatively simple compared to NBS;
- they can be implemented relatively quickly;
- they are effective as soon as they are built;
- they can incorporate existing or aging infrastructure so that there is no need for its removal (e.g., a dune system established over an existing seawall);
- they may already have societal support; and
- finance may be more easily secured.

Case Study 7. Beach Creek estuary enhancement

Beach Creek Estuary Enhancement:
A hybrid intervention providing multiple benefits

Qualicum Beach, BC, Canada

The Town of Qualicum Beach's waterfront is a central feature for the town, providing significant social and economic benefits through tourism and recreation. The waterfront is characterized by a wide sandy lower-intertidal beach, and a coarse gravel and cobble upper-intertidal beach, typically backed by a concrete seawall. The foreshore is also part of the environmentally important Parksville-Qualicum Wildlife Management Area.

In 2021, the Town enhanced a section of their waterfront by upgrading a section of seawall and revitalizing a salmon-bearing outfall by creating an artificial estuary (ACEC-BC 2021; Qualicum Beach, 2022) (Figure 17). The work included beach nourishment, establishment of a meandering creek bed, and construction of a reinforced coastal spit to shelter the newly constructed estuary from large incident waves. These measures further provided protection of the upland area from wave-induced flooding by breaking incident waves farther offshore (ACEC-BC, 2021; PQB News, 2022). Importantly, rigid, 'hard' elements (e.g., rounded rock spit) were introduced, to work symbiotically with more dynamic 'soft' elements, such that longevity and resiliency of the project could be improved while maximizing environmental and social benefits.

Figure 17. The newly constructed estuary behind the coastal spit (summer 2022)

Source: image provided by J. Wilson

In January 2022, a significant storm (accompanied with high winter tides) battered much of the region. The newly constructed spit and estuary withstood the storm well, with only minor dislodging of rocks (PQB News, 2022) (Figure 18, left). Approximately 100–200 m away, two adjacent sections of concrete seawall failed during the storm event (Figure 18, right).

The project received an Award of Merit from the British Columbia Association of Consulting Engineering Companies (ACEC-BC, 2021).

Figure 18. Photos of the shoreline following the 7 January 2022 storm, (left) along the restored creek estuary, and (right) along an adjacent section of shoreline, at which the seawall failed

Source: images provided by J. Wilson

Due to the wide range of hybrid options and varying spectrum of project types from green to gray, the co-benefits provided by hybrid options will be highly project-specific. Some co-benefits that might be expected from hybrid features are given in Box 13.

Box 13. Co-benefits that might be realized from hybrid systems

Environmental	Social	Economic
Aquatic habitat availability and quality	Broader recreation opportunities	Increased tourism
Abundance and diversity of native plant and animal species	Improved public health	Reduced costs to adjacent infrastructure (flood losses)
Improved soil health		Ecotourism opportunities
Carbon sequestration		

Although there is evidence for many hybrid systems being effective in mitigating coastal hazards (e.g., remote sensing data from Bangladesh showed a hybrid system of dikes and restored mangroves significantly reduced flooding damage from cyclones; Morris et al., 2018), there is limited research on how well hybrid systems perform compare to purely gray or NBS projects. There is also limited design guidance available on the design and selection of hybrid systems (Sutton-Grier et al., 2015). Significant opportunities exist to develop additional technical design guidance on hybrid solutions (See section 7). Section 5.0 provides additional information on technical design considerations for NBS retrofitting in general.

Key takeaways related to hybrid features are summarized in Box 14.

Box 14. Key takeaways for hybrid features

- Hybrid solutions combine NBS features with gray structural features.
- Hybrid options can be implemented when existing gray infrastructure requires maintenance or upgrades, during replacement or re-design of existing gray infrastructure, or at the decommissioning phase of existing coastal defenses.
- FrM benefits and co-benefits of hybrid features will be highly project-specific.
- Hybrid options should be designed with the intent of moving FrM systems towards the ‘green’ end of the NBS spectrum, applying as natural an approach as feasible while also maximizing co-benefits.

2.11 Cost Comparison of NBS Features

The total costs involved in planning, designing, constructing, and managing a NBS retrofit project will be project and site-specific. Costs will depend greatly on the size of the project, existing infrastructure type and condition, type of NBS, environmental conditions, regulatory environment, and public buy-in. Costs should also be expected to vary across North America, due to significant differences in labor costs and material and equipment availability, amongst other variables. In addition, recent years have seen significant unpredictability in costs associated with all phases of the project life cycle, due to global financial crises, the COVID-19 pandemic, natural disasters, climate change, resource availability, and geo-political changes, amongst other factors. Because of the significant variability in project costs between and even within countries, cost-fluctuations over time, and limited availability of cost data in many regions, this section focuses on relative costs of NBS across various project stages, including planning and design, construction, and operations and maintenance. This section is intended to provide a high-level understanding of costs. The actual retrofitting costs incurred will be site-specific, and additional cost analysis should be carried out for specific projects.

Some typical costs that may be incurred at each stage are briefly summarized below (adapted from Bridges et al., 2021, 470):

Planning and Design

- Project management
- Stakeholder engagement
- Scoping and planning activities (including options analysis)
- Early monitoring activities
- Pre-design studies (including hazard assessments)
- Multi-disciplinary design (including design revisions)
- Cost-estimations
- Funding applications
- Licensing, approvals, and permits
- Land purchases

Construction

- Project management
- Stakeholder engagement
- Tender services
- Site preparation
- Construction (materials and placement)
- Material disposal
- Habitat offsetting
- Compliance monitoring
- Record drawings and reports

Operations and Maintenance

- Project management
- Stakeholder engagement
- Monitoring
- Analysis of monitoring data and updates to adaptive management plan
- Adaptive management (repairs)
- Contributions to research and development

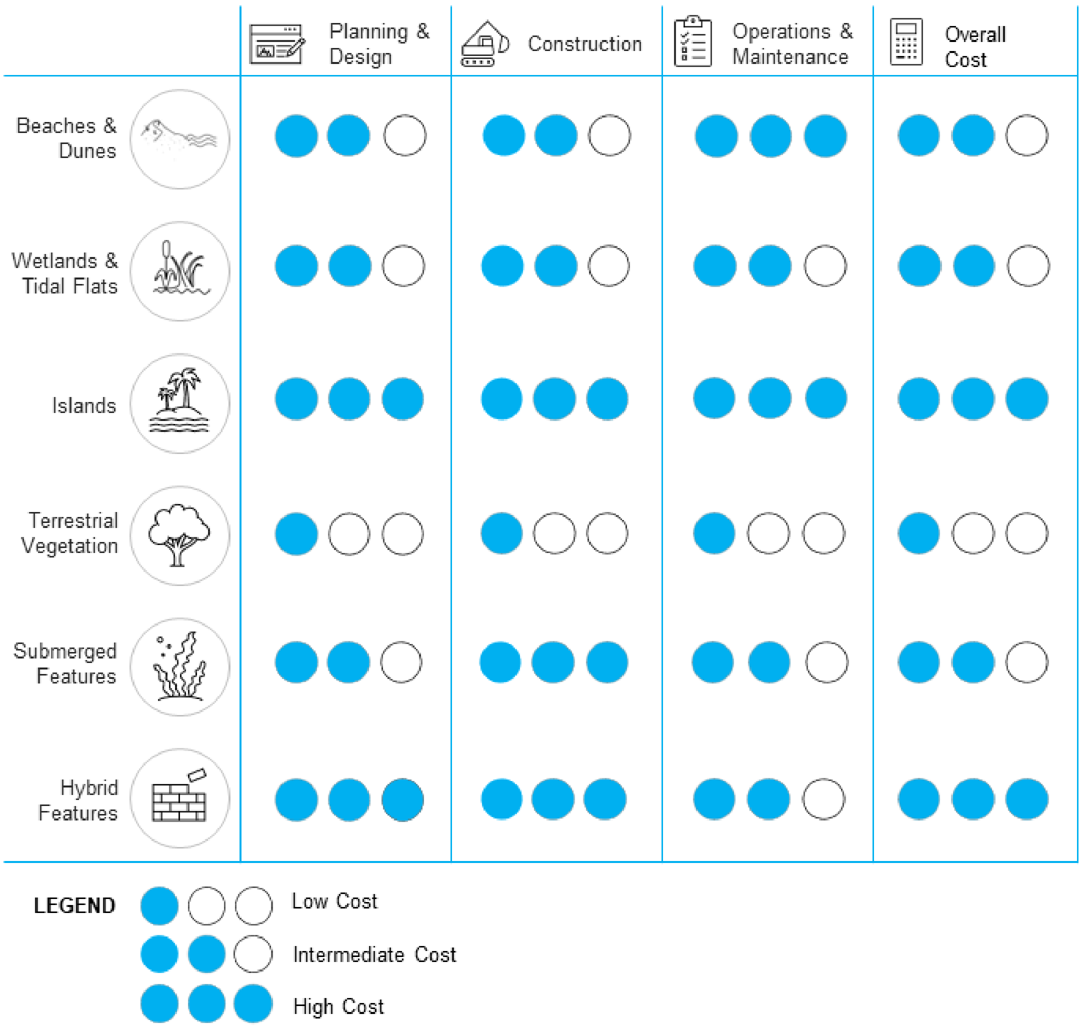
- Decommissioning

Figure 19 summarizes the relative total costs of undertaking various types of NBS, as well as the costs incurred at various stages of the NBS development-cycle, including planning and design, construction, and operations & maintenance. Relative cost estimates provided in Figure 19 are based on available literature and expert knowledge of the type of NBS. Retrofitting will incur other costs such as repair or decommissioning and removal of existing features, which are not considered in the relative cost estimates provided herein. For example, the removal of a seawall and installation of a reef will be significantly more costly than a dike breech and the natural restoration of salt marsh. **Project-specific cost analysis based on local markets, regulations, and site-specific considerations is always recommended.**

Relative cost ratings in Figure 19 were developed in collaboration with a panel of expert advisors from DHI who participated in an internal workshop in November 2022 on retrofitting options, costs and barriers, and opportunities. Experts noted that costs should be expected to vary significantly depending on project-specific requirements, design details and construction complexity. For example, construction of an island will cost significantly more in deep-waters than in shallow-waters, even if all other factors remain the same. Construction of a beach dune system several meters high will require more beach fill and be more expensive to construct than a small dune nourishment. For all NBS types, it is also more cost-effective to conserve or restore an existing system, than to create a new one. It is generally more cost-effective to construct projects on-land than off-shore or underwater. Complex projects with many interconnected elements should also be expected to be more expensive during all project phases.

Projects that benefitted from the lessons learned from similar past projects and are properly designed (in consideration of the coastal hazards) may require minimal maintenance and repair. In contrast, projects that are designed poorly or are novel in nature (either due to using a new technique or implementing an established technique in a new setting) may require greater maintenance during the operations phase of the project. Decision makers should therefore ensure that budgets are available for the long-term adaptive management, maintenance, and monitoring of a NBS, and that the budget is commensurate with the complexity, uncertainty, risk, and value that has been added by the project.

Figure 19. Relative costs of project development stages for different NBS types



Costs should also be expected to vary across North America, particularly in the construction and adaptive management phases, due to significant differences in labor costs and availability in Canada, Mexico, and the United States. Notably, in Canada and the United States, the planning and design phase is generally less costly than construction, with planning and design fees often being on the order of 10–20% of the construction cost. In Mexico, however, lower labour costs may result in reduced planning, design, and construction costs. There is significant uncertainty surrounding operational and maintenance costs associated with NBS.

When considering NBS options, expected costs should be balanced and compared against the benefits provided over the full life cycle of the project. Benefits may come from the damage reduction caused by coastal hazards, and from the social, environmental, and economic co-benefits. Costs should also be balanced against potential savings. The upfront cost of a NBS system can reduce costs of maintenance or improvement of FrM features elsewhere, particularly for reefs and islands, which can reduce the need for shoreline protection. Section 5.4 further discusses economic considerations related to NBS retrofitting, including the importance of evaluating NBS across the full life cycle. Strategies for evaluating NBS options are included in section 3 and discussed further in the *Co-Benefits* document.

Cost considerations specific to the six types of NBS are briefly discussed further below.

Beaches and Dunes

The estimated overall cost of beach and dune projects (including retrofits) relative to other NBS options is intermediate. Planning and design costs are often relatively low, since beach nourishments may rely on established design principles and often receive good public support. The presence and condition of an existing beach will play a significant role in determining costs, as it will always be less costly to restore a degraded beach or dune system.

The largest costs will stem from construction and post construction maintenance. Beach and dune systems are often installed in high-energy environments, making them vulnerable to storm induced erosion. Maintenance and operations will depend greatly on the success of the project in balancing the sediment budget and the frequency and severity of storm events. Re-nourishment as part of operations and maintenance should be expected for most projects. Maintenance costs may be lower if erosion is minimal. Morphological studies during the planning and design stage of the project, as well as continued monitoring and adaptive management, will help inform the need for re-nourishment. Construction and maintenance costs will vary further depending on the volume, origin and type of material used and associated transport costs. Sand dredged during harbor maintenance can sometimes be a relatively inexpensive by-product of local, routine activities (Aerts, 2018), given that it meets quality standards and regulations (e.g., low concentrations of heavy metals and hydrocarbons).

Wetlands

The relative costs for retrofitting involving wetlands (during all stages of development) are estimated to be intermediate relative to other types of NBS. The cost of restoring an existing degraded habitat is generally expected to be much less than virgin development.

As with all NBS, the planning and design stages will require input from a multi-disciplinary team including biologists, engineers, and coastal experts. However, designs generally rely on nearby, established 'analogues' with similar physical characteristics as the study site. Consequently, wetland planning, and design may be less complex and costly than island and hybrid features, for example, and more so than terrestrial vegetation. Because of this, design and planning costs are often low to intermediate.

Wetland construction and adaptative management costs will vary significantly depending on the type of wetland being developed and its suitability for the environment. Mangroves are the cheapest wetland option by hectare to develop, whereas costs associated with salt marshes are approximately twice those of mangroves (Bridges et al., 2021). Wetland projects tend to rely heavily on adaptive management to manage uncertainties following construction; however, maintenance costs associated with management are typically low.

Islands

Islands can be the most complex and costly option, both overall and across all project development stages. These costs can be reduced if an existing degraded or relic island is restored.

Islands are frequently placed in high-energy environments to help protect the coastline; these environments are typically also capable of eroding and degrading their structure (unless a hybrid approach is taken). As a result, islands require careful planning involving a team of multi-disciplinary experts to ensure the project's success. Significant complexities may arise through the permitting and approvals process. For example, islands may require the purchase of additional land or leasing of the foreshore. Construction of new islands may also impact navigation, coastal processes, and existing habitats, thereby requiring additional permits and approvals. Additional planning costs may also be involved if islands are to incorporate other NBS types such as beaches or marshes.

Construction costs are generally higher than most other options, with the exception of submerged features. Construction costs arise from the significant time required and the fill volume needed to create the island and develop a stable structure. In addition, construction logistics are complicated due to offshore construction (often requires working from a barge, away from land), as well as the need to place material below the high tide mark.

Costs during the operations phase are also relatively high, due to the need for careful monitoring, the high likelihood of repair and maintenance, and the complexity of undertaking maintenance offshore. As a result of high operational and maintenance costs, most islands will incorporate gray shore protection, which increases costs and moves the project away from the green end of the NBS spectrum.

Terrestrial Vegetation

Terrestrial vegetation (e.g., trees, grasses, and shrubs) are typically one of the simplest and least costly NBS options overall.

Terrestrial vegetation may be planted and integrated into existing land uses, requiring minimal planning and design costs. However, because understanding of their FrM performance is still limited by a lack of research and pilot projects, numerical or physical modeling may be required to prove their FrM efficacy.

Construction may require finding a local nursery to grow native tree species, manual planting of saplings, and care for young starts or saplings post-construction. This type of construction will be cost-effective in regions with low-labour costs. Adaptive management will be more intensive in the years directly following construction, when starts and saplings are vulnerable to storm events, drought, and other seasonal and climate-related effects. Regardless, these types of projects have relatively low complexity, and therefore the relative costs of planning, construction and maintenance are low compared to other options.

Submerged Features

Costs of submerged features can be intermediate to high relative to other NBS options. However, a reef restoration project can be completed relatively efficiently and therefore be less costly than virgin development. Costs will also vary significantly depending on the type of feature developed. For example, coral reefs are a more expensive option than oyster beds and eelgrass meadows (Narayan et al., 2016).

As with all NBS, the planning and design stages will require input from a multi-disciplinary team including biologists, engineers, and coastal experts. Similar to wetlands, designs (particularly for eelgrass and kelp meadows) often rely on nearby, established ‘analogues’ with common physical characteristics to the study site. Reef design frequently relies upon established precedence for submerged breakwaters. Because of this, design and planning costs are often intermediate. It should be noted that in some cases, significant complexities in design and planning may arise through the permitting and approvals process. As such, careful consideration should be given to navigation, impact to existing habitats, and public approval during the scoping and planning stages of the NBS development cycle.

Due to the complexity involved in constructing underwater and offshore works, submerged features typically have relatively high construction costs.

These systems are often relatively self-sustaining, reducing the risk of high maintenance and operational costs. Despite this, monitoring and adaptive management should be conducted. If maintenance is required, costs are generally high. For example, there is the possibility for low frequency and high damage storm events to impact coral reefs, resulting in the need for rapid and costly response from a qualified dive team to repair. Coral reefs are also sensitive to water quality, nutrient levels and require high stocks of grazing fish, in areas where these conditions are not met, reefs will require greater maintenance or even may not survive. In Mexico, coral reefs are vulnerable to sargassum seaweed (Chávez et al., 2020), which could increase maintenance costs associated with removing this seaweed from the reefs. If these features are developed in areas prone to hurricanes, such as the Gulf of Mexico, there may be higher associated maintenance costs to consider. Construction and maintenance costs will vary further depending on the volume, origin, and type of material used, and the associated transport and placement costs.

Hybrid Features

Because hybrid NBS vary significantly, there is limited reliable data available on the costs for planning and design, construction, and operations. Costs will vary significantly according to the combination of features chosen, the site setting, and other project-specific factors. For example, towards the gray end of the hybrid spectrum, habitat features may be added to existing infrastructure (e.g., seawall textures, concrete tide pools), providing simple low-cost improvements (e.g., Suedel et al., 2021). Projects closer to the green end of the spectrum, which require more significant work to amend or replace existing structures (e.g., a beach system with minimal structures such as headlands and groynes) will be more costly. It is important to consider and balance the relative costs of the options available with the potential benefits, as greater co-benefits are typically realized from projects closer to the green end of the scale.

Hybrid features may appear to be more straightforward to implement, as they are closer in similarity to conventional 'tried and tested' gray methods. However, the addition of multiple types of features may increase the complexity in design, construction, and operations relative to both a conventional gray solution and NBS. As with all NBS, the planning and design stages will also require input from a multi-disciplinary team including biologists, engineers, and coastal experts. Projects that have significant precedence and are properly designed (in consideration of the coastal hazards) may require minimal maintenance and repair. In contrast, projects that are designed poorly or are novel in nature (either due to using a new technique or implementing an established technique in a new setting) may require greater maintenance and adaptive management. Numerical modeling, physical modeling, or pilot projects may help to better understand the limitations and future costs related to novel, hybrid solutions. Regardless, monitoring, and adaptive management should both be expected and budgeted for early in the NBS development cycle.

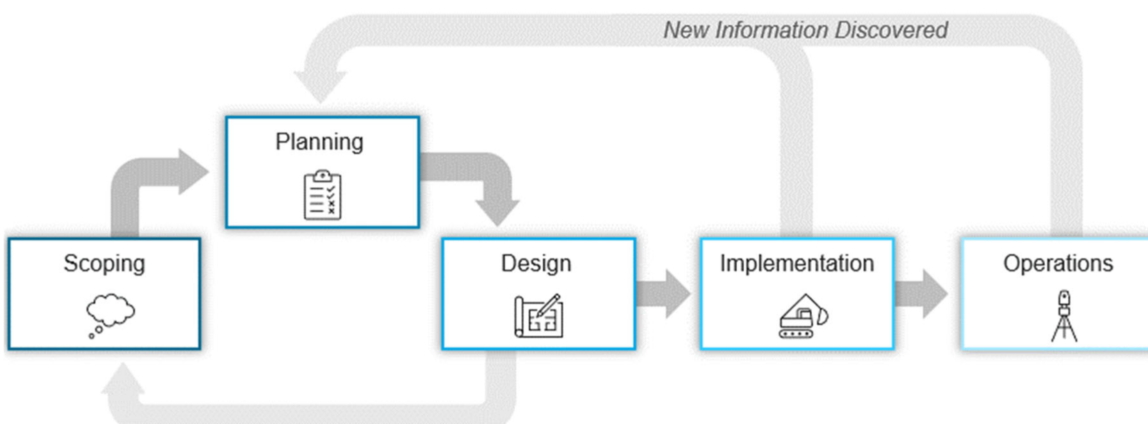
3 Scoping Retrofitting Opportunities and Options

The decision to retrofit using NBS may be driven by several factors including the numerous benefits NBS can provide. This section explores the process for identifying retrofitting opportunities and discusses tools and techniques for evaluating potential retrofitting options, taking these benefits into account. This framework represents a comprehensive set of best practices for scoping retrofitting opportunities and options; however, it is recognized that project constraints and resource limitations frequently exist that may limit the framework's direct application for some projects. Decision makers may scale the level of effort dedicated to this process, such that it is commensurate with stakeholder needs, project risks, and resource availability. In certain cases, it may be appropriate to fund several studies to inform decisions and have a multi-disciplinary group of experts participate in an interactive process over many years. In other cases, where resources are limited, a knowledgeable professional may use the framework to guide a simple decision-making process and engage outside experts and stakeholders on an as-needed basis only.

3.1 Project Phases for Implementing NBS

The framework for the development of a NBS project encompasses five main phases: scoping, planning, design, implementation, and operations (Figure 20) (Bridges et al., 2021). These phases are iterative and cyclical. The cyclical process allows for the adaptive management of existing FrM systems as they are continuously re-assessed, and for the project team to scope and implement retrofits or changes at any point in the project life cycle. A diverse team of experts will be needed to implement a NBS project; roles and responsibilities are discussed in section 4.2.

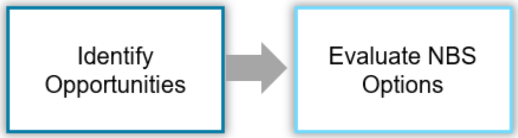
Figure 20. Framework for development of a NBS project



Source: adapted from Bridges et al., 2021
Note: Dark gray arrows are primary pathways and light gray arrows are secondary (iterative) pathways.

When considering retrofitting, decision makers should carefully consider how to identify potential opportunities and how to evaluate potential NBS options (Figure 21). These two stages are part of the scoping phase of the implementation process, and form the backbone for the future planning, design, implementation, and operations phases of work.

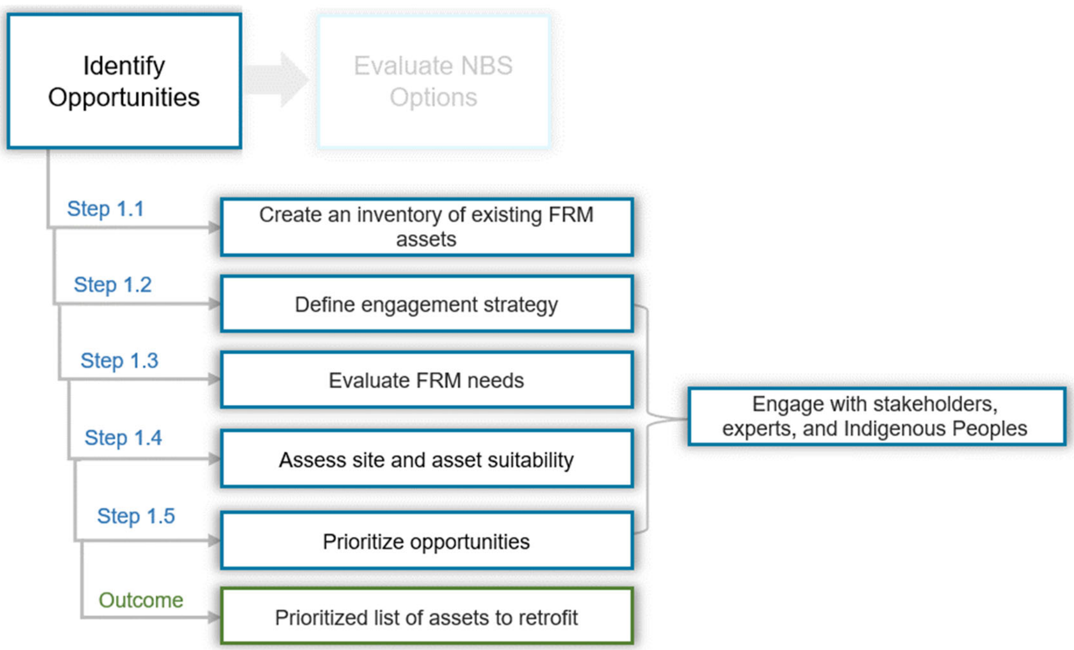
Figure 21. Conceptual framework for scoping retrofitting opportunities and options



3.2 Identification of Retrofitting Opportunities

Identifying opportunities for retrofitting existing infrastructure is the first step in developing a NBS project. Once opportunities for projects have been identified, a process to prioritize these opportunities will need to be carried out to allow decision makers to select assets for NBS retrofitting. Figure 22 outlines a five-step framework to guide decision makers in identifying and prioritizing FrM assets for NBS retrofitting. This framework is further described in the following sub-sections. Following this identification step, an evaluation of different coastal FrM options, including NBS, is then carried out (Step 2, see section 3.3).

Figure 22. Conceptual framework for identifying NBS opportunities



3.2.1 Step 1.1: Create an Inventory of Existing FrM Assets

The first step in identifying opportunities for retrofitting with NBS is to create an inventory (e.g., a list or database) of existing coastal defense assets (e.g., seawalls, revetments, dikes, dunes, etc.) within the region of interest to the decision maker. Considering all the assets and locations that may need FrM will allow for a systems-based approach (e.g., de Vries et al., 2021) and creation of a broad FrM strategy, rather than treating each site or asset in isolation. This inventory should include pertinent details, such as their purpose, location, length, age, remaining life, and condition of each asset. The inventory will provide the starting point for assessing the need and feasibility of NBS. From here the following steps can be applied to refine the inventory to a list of priority sites that could be retrofitted.

Result: List of existing FrM assets created

3.2.2 Step 1.2: Define an Engagement Strategy

Consultation with the local community, stakeholders, permitting/approval agencies, and Indigenous Peoples will provide valuable input on needs, values, and concerns, so that FrM needs and opportunities may be evaluated and prioritized. In addition, engagement provides an opportunity for education on coastal FrM needs and options (including NBS), as well as relationship building. Engagement is an important activity that should be carried out throughout the identification, prioritization, and evaluation processes. An engagement strategy should be developed early in the identification process. Defining an engagement strategy is complex and should be completed by professionals with the necessary expertise. It is vital that the strategy consider who should be involved (i.e., stakeholders), when they should be involved and with what frequency engagement should take place, and how (i.e., in what form) engagement should be implemented (see Box 15). See section 4.3 for more information on engagement.

Result: Engagement plan developed

Refer to the *Co-Benefits* document, sections 3.3.2 and 3.3.6, and the *International Guidelines on Natural and Nature-Based Features for Flood Risk Management* (Bridges et al., 2021), for more detailed guidance on engagement.

Box 15. Key questions to consider when developing an engagement strategy

Who should be involved?	What form will engagement take?
When will engagement be carried out?	What are the objectives? What information do you wish to receive/provide?
At what frequency will engagement take place?	How will feedback be incorporated into the project?

3.2.3 Step 1.3: Evaluate FrM Needs and Strategy

Step 1.3 involves evaluating the current FrM infrastructure with the aim of identifying locations and assets where increased FrM is needed. For each asset, any gap that exists between the coastal hazard exposure and hazard mitigation should be identified. These gaps in flood risk mitigation may arise where current infrastructure is no longer providing adequate protection against flooding or erosion, the infrastructure is not expected to meet future needs as the climate changes, the condition of the asset has (or is expected to) decline, repairs are required, or it has reached the end of its serviceable life. These gaps may be viewed as opportunities to improve existing coastal FrM using a wide range of potential options (including NBS) and these options should be evaluated in the context of the system and overarching FrM strategy.

Risk assessment may be conducted to evaluate FrM needs and strategy by assessing the coastal hazards and vulnerabilities. It is best practice to follow a holistic, systems-based approach to risk assessment, considering the risk at an appropriate spatial scale, rather than assessing flood risk within only one jurisdictional area for example (e.g., Nicholls et al., 2005; Narayan et al., 2012; Menéndez et al., 2020).

There are several different approaches and frameworks available for carrying out risk assessments (e.g., Hall et al., 2003; van Alphen et al., 2011 Narayan et al., 2012; Journeay et al., 2015; British Columbia 2020; Murphy et al., 2020), although the overarching goals and elements are similar (Jones et al., 2014)—where risk is typically treated as a product of the probability of a hazard, the vulnerability to the hazard, and the consequences.[2] A detailed step-by-step guide to risk assessment, which is considered an international best practice, is provided by the International Standards Association in ISO 14091 (International Standards Association, 2021). The level of effort involved in completing a risk assessment may vary significantly from project to project, and the method chosen and applied should be commensurate with the needs and scale of the project. In some cases, a high-level, qualitative assessment relying on existing studies and professional judgement may be sufficient. For more complicated projects, the best practices outlined by the International Standards Association (2021) may be followed.

An overview of the main elements of risk assessments are given in this section:

1. Evaluate the current condition of FrM assets;
2. Assess the current and future coastal hazards;
3. Evaluate the ability of existing assets to mitigate coastal hazards; and
4. Complete risk and vulnerability assessment.

Step 1.3.1 Evaluate the current condition of FrM assets

The risk assessment would first involve an evaluation of the current conditions of existing FrM assets, using the list of assets compiled in Step 1.1. This would typically require a condition inspection from qualified professionals and review of historical documents (including historical inspection records, drawings, maintenance reports etc.).

Step 1.3.2 Assess current and future coastal hazards

The next step would involve identifying and assessing the coastal hazards. A form of coastal hazard risk assessment should be carried out by qualified professionals to identify the likelihood and severity of coastal hazards, such as flooding and erosion, which may vary between locations and even across small project sites (e.g., USACE, 2019b). The goal is to understand the existing exposure to coastal hazards, as well as how these hazards might change in the future with climate change. The types of assessment needed would include the evaluation of current and future sea-level, coastal flooding, tides, tidal surge, wind speeds and direction, wave set-up, wave height and effects, sediment transport and coastal erosion (e.g., FEMA, 2016).

Step 1.3.3 Evaluate the ability of existing assets to mitigate coastal hazards

Once the existing and future coastal hazards are understood, an evaluation of the current infrastructure's ability to provide adequate protection should be carried out to identify the need for improved FrM. This would include, at a minimum, assessing the minimum elevations required to reduce wave overtopping or run-up levels to safe levels and comparing them against those necessary to mitigate flooding. Erosion protection capabilities should also be reviewed, along with considerations for structural and geotechnical stability. Key questions to consider are:

- Does the asset provide adequate FrM for current and future coastal hazards?
- What is the risk of failure?
- Does the asset need repair/maintenance?

[2] see Journeay et al. (2015) for a critique of different risk assessment methods

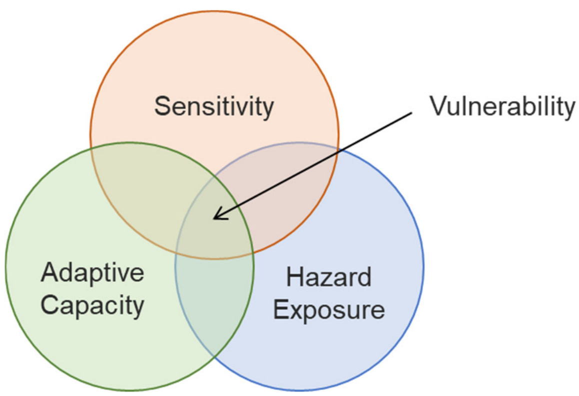
- Is the asset reaching the end of its serviceable life?

Step 1.3.4 Assessment of risk and vulnerability

A risk assessment can then be completed which considers the likelihood and severity of a range of coastal flood hazard events, and the consequences of those events. Evaluation of the vulnerability of the community and natural system to coastal flood hazards is also an essential part of this step (e.g., IPCC, 2007, 2012). A vulnerability assessment takes into consideration the sensitivity (i.e., economic and social importance) of the affected lands, and the adaptive capacity of the system, in addition the coastal flood risks and infrastructure fragility (Figure 23). Adaptive capacity is the ability to overcome and adapt to climate change impacts (Adger, 2006; IPCC, 2022).

Result: FrM needs (i.e., gaps) identified and quantified

Figure 23. Vulnerability as a combination of coastal hazard exposure, adaptive capacity and sensitivity of protected areas to the hazard



Source: IPCC, 2007, 2012

3.2.4 Step 1.4: Assess Site and Asset Suitability for NBS

The technical feasibility of NBS for FrM will be highly dependent on site-specific constraints. This step involves assessing the suitability of sites (as identified in Step 1.3) for NBS implementation. At this stage in the scoping process, it is generally sufficient to rely on expert knowledge on NBS and local site knowledge to understand whether a project may or may not be feasible. Additional studies will be required later in the project to compare co-benefits associated with feasible options, select a preferred option, and undertake detailed design (see section 3.3). As part of this high-level assessment of site suitability for NBS, the project constraints outlined in Box 16 should typically be considered. Additional constraints, such as funding availability (see section 4.4) and regulatory requirements (see section 4.5) may also be considered.

Result: Feasibility level understanding of site suitability (for all assets in the inventory) for NBS implementation

It should be noted that this step focuses primarily on the technical feasibility of NBS options. Social, environmental, and economic co-benefits will be assessed further during the options evaluation phase (see section 3.3).

Box 16. Examples of site conditions, constraints, and opportunities to be considered that affect NBS suitability

Appropriate Location	• Is there sufficient space available for all types of NBS? • Do existing land-uses conflict with some NBS? • Will regulations restrict the project footprint? • Will some NBS require the purchase or lease of new land?
Coastal Hazard Exposure	• Does the site host a large tidal range? • Is the site exposed to regular or severe waves or storm surges? • Are there regular or strong winds?
Existing Sediment Supply	• Has the naturally occurring sediment supply to the system been altered by either natural or anthropogenic influence (i.e., currently in a sediment deficit)? • Is the system dominated by longshore or cross-shore sediment transport? • What are the off-site sources of sediment?
Access Constraints	• How will access be gained during construction? • Will construction require underwater or offshore work? • Will there be access available for long-term monitoring and adaptive management? • Could regular maintenance cause negative impacts to systems?
Existing Natural Features & Ecosystems	• Are there existing natural features (such as sand dunes or wetlands) which could be restored or enhanced? • Are there existing natural features or habitats which may be negatively impacted by new construction activities?
Community Support	• Is there community support for NBS at this site? • Have community members been negatively impacted by past FrM projects in this area? • Is there potential for significant co-benefits to the community?

3.2.5 Step 1.5: Prioritize Opportunities

Once a list of existing FrM assets (and associated details identified in earlier steps) has been compiled, the last step is to prioritize opportunities for retrofitting. The desired outcome of this step is to identify which locations or project sites should be prioritized for retrofitting using NBS, rather than the specific type of NBS to implement. This step draws upon information gained throughout the previous steps of the identification process. Stakeholder engagement at this stage will provide an understanding for community support behind NBS at certain locations. Professionals with expertise in FrM and NBS may also help with this ranking exercise. The ranking exercise could be completed using a simple, high-level comparative assessment, which ranks projects considering vulnerability, potential for NBS and community support for the projects (Box 17).

Result: Refined list of priority existing assets or locations that require greater FrM

Box 17. Categories to consider for ranking or prioritizing NBS projects

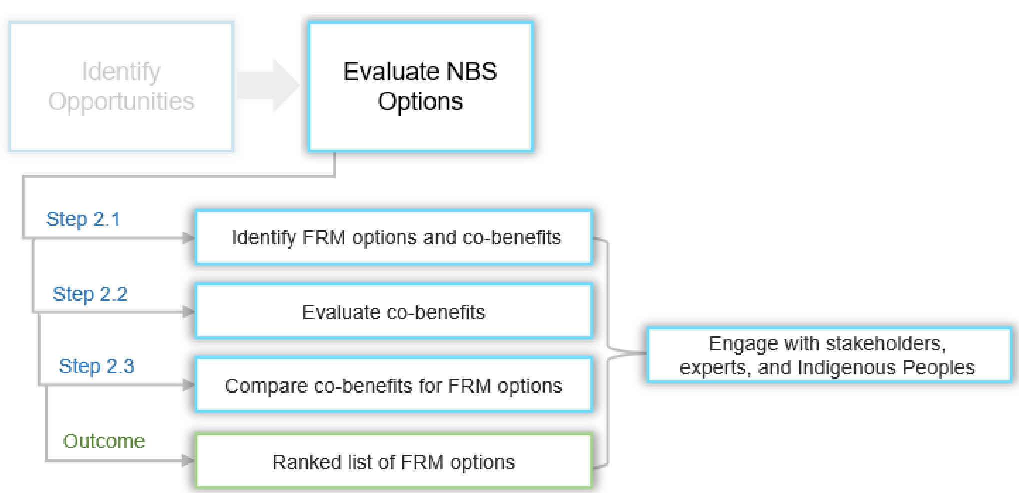
Vulnerability	• Are the current assets near the end of their design life? • Do the current assets meet existing and future FrM needs? • Are the impacts of failure high? • Is there little resilience in the system?
NBS Potential	• Is there significant potential for NBS to be implemented (e.g., are they feasible)? • Is there sufficient space or existing features that could be enhanced? • Are there significant co-benefits that could be gained, relative to those provided by existing FrM system?
Support	• Is there community support for the project? • Is there sufficient expert knowledge, funding, etc. to develop a project?

3.3 Evaluation of Retrofitting Options

Once a list of priority sites for retrofitting has been established using the framework outlined in section 3.2, the next stage is to evaluate the different FrM options available. The goal of this stage is to make an informed decision on the best coastal hazard management option to implement. For a complete understanding of the benefits provided by NBS—and in order to communicate these benefits to stakeholders, rightsholders, and other parties—it is recommended to evaluate NBS options alongside conventional gray alternatives and a do-nothing approach in the context of the overarching FrM strategy. In addition, completing a multi-criteria analysis along with a co-benefit assessment facilitates a comprehensive approach to identifying all potential benefits, while preventing the assertion of non-realistic advantages. This type of analysis is particularly useful in mitigating the potential for—and perception of—greenwashing.

A recommended approach for identifying, comparing, and prioritizing potential FrM options based on the FrM benefits and co-benefits provided by the potential solution is explored in detail in the *Co-Benefits* document, section 3. This framework is summarized in the context of retrofitting in Figure 24 and described further below.

Figure 24. Conceptual framework for FrM option evaluation



3.3.1 Step 2.1 Identify FrM Options and Co-Benefits

The first step will involve identifying potential design options (including NBS, as described in section 2) that could be implemented to meet FrM needs for the locations prioritized in Step 1.5, alongside conventional gray alternatives and a do-nothing approach. It is recommended to consider the feasibility of all potential solutions identified in this step, such that only solutions that are technically and logistically feasible are brought into the next evaluation and comparison steps. Limitations that should be considered include budget, schedule, expertise limitations, construction feasibility, suitability of the environment, physical constraints, and the ability to meet permitting or regulatory constraints. Decision makers may need to consult experts with experience on NBS to develop a short-list of feasible solutions.

It is also necessary to identify broad project timelines (based on previous similar projects and funding requirements, for example), local challenges and goals, and a broad list of potential co-benefits. Identifying and considering co-benefits at this early phase is important, to maximize the project's value and to prevent co-benefits from being an afterthought. It also allows for a more robust comparison and evaluation of the different FrM solutions available, as all benefits (rather than just FrM benefits) associated with the project can be considered and compared against each other. This is particularly important when considering NBS alongside more conventional gray FrM options, which often undervalue co-benefits. Refer to the *Co-Benefits* document, section 3, for additional information on this step in the co-benefits evaluation process.

Engagement with stakeholders, experts and Indigenous Peoples is also critically important at this stage and throughout the rest of the process (as outlined in Step 1.2). Engagement can help identify FrM goals and will likely also highlight important co-benefits that should be prioritized. For example, stakeholders may have expressed a need for improved recreational space, which would potentially lead to ranking a variety of NBS types more highly in comparison to conventional gray options.

Result: A list of potential co-benefits, project constraints, and feasible FrM options for priority sites

3.3.2 Step 2.2 Evaluate Co-benefits

Step 2.2 aims to assign value to potential and desired co-benefits for each retrofitting option short-listed in Step 2.1. Value is not necessarily monetary and can refer to the importance, worth, or usefulness related to a co-benefit (DHI, 2022a). Options can be evaluated and prioritized on the ability to meet project and stakeholder goals, feasibility, uncertainty, benefits and trade-offs, budget, schedule, and expertise limitations. Key steps in this process include the following:

- identifying limitations in the co-benefits valuation methods;
- selecting an appropriate valuation method;
- deciding on performance indicators associated with each co-benefit;
- set a baseline for each co-benefit, serving as a reference level to assess project benefits; and
- carrying out the co-benefits valuation.

Result: A list of valued co-benefits for each retrofitting option

Refer to the associated *Co-Benefits* document, section 3.4, for a detailed description of this step in the co-benefits evaluation process.

3.3.3 Step 2.3 Comparison of Options

Once the potential co-benefits of each potential solution have been identified and valued, for each retrofitting option, a comparison of different design options can be made. There are several tools that could be used to compare the different solutions available, including:

- SWOT Analysis (Strengths, Weaknesses, Opportunities, Threats);
- Cost-benefit analysis;
- Multi-criteria analysis;
- Pugh matrix;
- Root cause analysis;
- Decision tree analysis;
- A/B testing;
- Prototyping;
- User testing; and
- Survey/Questionnaire.

Due to the often intangible nature of some co-benefits and the complexity involved in giving co-benefits a monetary value, we recommend using a multi-criteria analysis to weight and compare co-benefits associated with each FrM option. Co-benefits should be weighted according to their importance and priority to the project team, stakeholders, and rightsholders. Please refer to the *Co-Benefits* document, section 3.5.3, for additional details on multi-criteria analysis.

The comparison phase aims to identify the retrofitting option(s) that best meet project and stakeholder goals through the multi-criteria analysis of expected FrM benefits and co-benefits. The highest scoring options(s) from the analysis will theoretically provide the largest number of benefits, given the project needs. However, the results of the analysis should only be used as a decision-making aid. Careful consideration of project-specific needs, constraints, and trade-offs should still be made when selecting the preferred option. In particular, trade-offs between co-benefits and the provision of co-benefits equitability across stakeholder and rightsholders must also be considered.

The provision of certain benefits (e.g., reduced flood levels) will likely be of particular importance, and more detailed modeling or analysis of several of the best-rated options could be completed at this stage to confirm valuations.

Result: Potential FrM options are scored using a multi-criteria analysis, to facilitate selection of a preferred alternative for retrofitting

4 Administrative Considerations for Retrofitting

This section outlines key administrative considerations to support decision-making related to retrofitting existing infrastructure systems using NBS. This section includes a summary of considerations related to project scoping, roles and responsibilities, financing challenges, regulations, and timing considerations. Technical considerations are summarized separately in section 5.

4.1 Scoping

Scoping of a NBS project is the first phase of the NBS development framework (Figure 20). Scoping generally involves building a clear understanding of the project needs and defining project constraints. Scoping should be carried out as part of a broad FrM strategy that is systems-based, rather than focusing on individual sites. Example of systems-based FrM strategies include the San Francisco Bay Sea-level Rise Adaptation Framework (Point Blue Conservation Science, 2019) and the shoreline management plans for England and Wales (Environment Agency, 2022).

Section 3 provides a detailed step-by-step process on scoping retrofitting opportunities within an existing portfolio of FrM assets and identifying suitable options. Bridges et al. (2021) also provides a comprehensive description of steps and outcomes related to the scoping phase. A summary of potential tasks and considerations related to scoping a retrofitting project are included below:

- Identify and engage project partners, key experts, and stakeholders (see section 4.2).
- Reference previous similar projects, including outcomes of previous engagement activities.
- Collaboratively define the project problem, purpose, needs and goals.
- Define the system (i.e., important physical, environmental, social, and economic processes).
- Begin identifying project constraints (including spatial, temporal, regulatory, governance and financial constraints) and retrofitting opportunities (see section 3.2 and sections 4.2–4.6).
- Begin identifying potential retrofitting options (see section 2).
- Identify potential funding or financing mechanisms (see section 4.4).
- Prepare initial (rough) budget for the project, which should cover costs involved in planning and design, construction, monitoring and adaptive management and maintenance.
- Secure funding to begin early analyses, including assessment of baseline conditions and options evaluation (see section 3.3).

During the scoping stage, it is also important to have a general understanding of the technical considerations (see section 5).

4.2 Roles and Responsibilities

Experts from the CEC workshop (DHI, 2022b) identified governments, local communities, developers, landowners, and private entities as actors that could be responsible for NBS. Overall, governments were identified as having the greatest responsibility. In Canada, Mexico, and the United States, overlapping jurisdictions can make identifying which level of government is responsible for the coastal zone difficult. Various levels of government and nongovernmental actors have authority, responsibility, claims or interests in the coast. Indigenous Peoples, and federal, state, provincial and municipal governments all have jurisdiction in coastal and marine areas, and their interests may not align. Furthermore, many laws, treaties, sovereign rights, and declarations (including the United Nations Declaration on the Rights of Indigenous Peoples) may apply to these areas. It is therefore important for all levels of government to take a share of the responsibility, and act collaboratively to provide a policy and regulatory framework that facilitates implementation of NBS.

Federal governments will likely be responsible for the higher-level responsibilities of creating and managing policy and regulations, funding, and for providing guidance. Federal governments are responsible for the creation and distribution of funding programs to which local governments are eligible applicants (see section 4.4.). Federal governments also have responsibility for certain public infrastructure assets such as highways and military infrastructure which may require FrM. For example, the US federal government is prioritizing retrofitting military bases with NBS (The White House, 2022) and is considering NBS for coastal highway resilience (Federal Highway Administration, 2018). State or provincial government agencies will be responsible for more detailed policies, objectives and regulations that meet the specific needs for their region, while also providing funding. State and provincial governments are also responsible for managing certain types of infrastructure, which may require retrofitting. For example, in Canada, management of highway infrastructure and management of regulated dikes are both provincial responsibilities.

Local governments will also need to set policies and regulations, especially related to land use planning objectives and policies, that will facilitate and encourage NBS (Pathak et al., 2022). It is likely that local governments will take a large share of the responsibility for identifying need, developing project plans, and implementing projects, as it will often be existing coastal assets within their jurisdiction and existing infrastructure portfolio that will be subject to retrofitting. Likewise, coastal Indigenous Peoples will need to consider their coastal infrastructure, FrM needs and policies and the potential for NBS in meeting those needs.

Given the fragmentation in governance and multiple stakeholder interests in the coastal zone, it is particularly important that decision makers work collaboratively with all levels of government, Indigenous Peoples, rightsholders, local communities, organizations (e.g., Conservation Authorities), approval agencies and stakeholders early within the NBS implementation processes, to ensure that the needs of all parties are considered and incorporated. Case Study 8 provides a description of the Living Dike Initiative in British Columbia, Canada, which brings together a roundtable of representatives (including local First Nations, all levels of government, non-profits, academia, and industry experts) to retrofit existing dike infrastructure using salt marshes. Additional discussion on engagement is provided in section 4.3.

Communities and private landowners have a share of the responsibility for identifying needs, engaging, or lobbying governments and local authorities, as well as taking part in the engagement process. Private landowners facing flooding or erosion risks, may wish to consider retrofitting the existing shoreline using NBS to reduce these risks.

Responsibility for design and development of NBS projects will lie with the project team. As with any NBS project, retrofits using NBS will require a multi-disciplinary team of qualified professionals, and often necessitate the inclusion of specialists with local expertise and knowledge (Suedel et al., 2021; World Wildlife Fund, 2016). NBS projects that address coastal FrM are frequently led by coastal engineers, coastal geomorphologists, and marine biologists. However, teams may include technical specialists in meteorology, climate change, hydrogeology, geotechnical engineering, marine structural engineering, and civil engineering, in addition to environmental (see section 5.2), social science (see section 5.3) and economic specialists (see section 5.4).

Case Study 8. The living dike initiative

The Living Dike Initiative:
Using Salt Marshes to Adapt Dike Infrastructure

Boundary Bay, BC, Canada

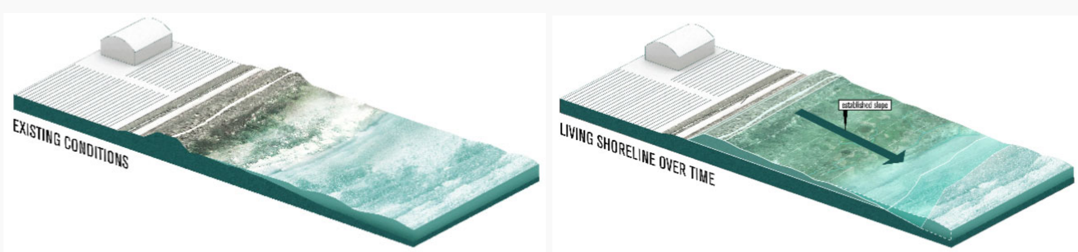
Boundary Bay boasts approximately 400 ha of salt marsh and extensive mud flats (Molnar et al., 2021). It is bordered by approximately 15 km of dikes, which protect nearby low-lying farmlands, communities, and infrastructure from coastal flooding. The existing salt marsh provides important habitat for juvenile salmon and migratory birds and serves to dissipate wave energy on its mild slopes prior to waves reaching the dike. As sea-levels rise, the tidal prism will shift inland, forcing the existing marshlands to migrate and squeezing them up against the dike. This is known as 'coastal squeeze.' The salt marsh will consequently reduce in size, impacting both habitat availability and wave dissipation. The existing dike is not designed to accommodate sea-level rise, nor an increase in wave exposure due to the loss of salt marsh (SNC-Lavalin, 2018).

As a means to adapt to sea-level rise, the City of Surrey, the City of Delta, and the Semiahmoo First Nation partnered together (Molnar et al., 2021) to implement an innovative approach originally outlined by Westcoast Environmental Law and SNC-Lavalin in 2018: The Living Dike Initiative (SNC-Lavalin, 2018; Carlson, 2020). The initiative includes gradually nourishing the existing marsh with fine sediments to raise the marsh in small lifts over a period of many years (Figure 25). The marsh and existing organisms will be able to migrate and adapt to changing conditions, without interruption to ecological services they provide. By expanding and elevating the marsh, the need to raise existing dike infrastructure to adapt to sea-level rise is significantly lessened.

The first stage of the project involves implementing a pilot project to test variants of the Living Dike concept (City of Surrey, 2022). Planning, design and permitting started in 2020. Construction is planned to start in 2023 and finish in 2027. The pilot projects are being developed with technical guidance from a roundtable of representatives, including local First Nations, all levels of government, non-profits, academia, and industry experts. Information obtained from the pilot project will help inform later stages of the pilot and inform adaptation planning in the region.

Funding for the pilot project was obtained from Infrastructure Canada's Disaster Mitigation and Adaptation Fund and the First Nations Emergency Planning Secretariat.

Figure 25. Conceptual illustration of (left) existing conditions and (right) future potential living dike design



Source: Lokman, 2022

4.3 Communications and Engagement

NBS retrofitting projects offer a broad range of engagement opportunities, which should be maximized to improve project outcomes. Engagement for a NBS retrofit project involves communication between the team responsible for delivering the project and any relevant stakeholders and rightsholders. It is important that the engagement process is implemented early in the scoping phase to allow participation in defining existing problems and future needs, and in establishing preferred project alternatives (Bridges et al., 2021). To this end, a resource and engagement plan should be established in the early stages of the project to ensure there are sufficient resources (including funding and expertise) for all engagement and communication activities to occur. Engagement plans should be reassessed frequently to ensure the level and type of engagement still fit the purpose of the project (Bridges et al., 2021). It is important to note that engagement should be inclusive, equitable, accessible, and meaningful to all those who may be directly impacted by or have an interest in the specific project (Bridges et al., 2021; IDB, 2020).

Understanding the level of engagement required (i.e., light, moderate or extensive engagement) at each project phase will help determine specific actions. Light engagement situations can be characterized as projects with low conflict or uncertainty, few decision opportunities and low stakeholder interest. Box 18 provides examples of light engagement within the context of NBS retrofit project phases (adapted from Bridges et al., 2021). Moderate engagement situations can be characterized as projects with relatively low conflict, the need for multiple stakeholders and the need to evaluate trade-offs. Extensive engagement situations can be characterized as projects with high potential of conflict or uncertainty, many stakeholders to be affected (potentially at disproportionate rates) and high level of compromise required (Bridges et al., 2021). It is important to consider the results and feedback from any previous consultation work conducted for similar projects or projects in similar areas in the past. Although thorough engagement is encouraged where appropriate, the level of engagement achieved may also be dependent on time and resource constraints of the project. The United States Army Corps of Engineers *International Guidelines on Natural and Nature-based Features for Flood Risk Management*, Chapter 3 (Bridges et al., 2021), serves as a thorough reference for recommended engagement activities to be completed during NBS projects.

Box 18. Examples of engagement actions through all phases of a NBS retrofit project with light stakeholder engagement required (adapted from Bridges et al., 2021)

Scoping	• Determining overall engagement required • Stakeholder identification • Creation of engagement plan
Planning	• Engagement activities carried out with relevant stakeholders • Acquire feedback on specific activities • Where possible improve detail and quality
Design	• Present final plan with relevant or impacted stakeholder groups • Communicate what and when activities will take place • Communicate who to contact if concerns arise
Implementation	• As new information and data is acquired, engagement plan is to be revisited and adjusted or adapted
Operation	• Engagement to continue through management and monitoring • Ensure affected stakeholders are regularly informed of management, maintenance, and monitoring activities.

Through initial engagement, stakeholders and project members may be able to determine additional opportunities to incorporate multiple benefits through their unique perspectives and goals (Bridges et al., 2021). Introducing a diverse group of stakeholders (e.g., NGOs, local and regional government, local industry, scientists and researchers, landowners, marginalized Indigenous groups, landowners, community members) can also increase the potential for buy-in or funding from motivated groups if they know their investments will be maximized through co-benefits (Brill et al., 2021). Several different communication approaches may be required to engage effectively with a variety of audiences, such that all groups of stakeholders are able to become familiar with project goals and needs.

For more information on stakeholder engagement, please refer to the *Co-Benefits* document*,* section 3.3.

4.4 Funding

Funding for NBS can come from a range of sources, including international financial institutions, governments, NGOs, and private institutions; however, accessing this funding was highlighted as one of the main challenges at the CEC workshop (DHI, 2022b). An overview of the different types of funding and some examples are provided herein. For more details on funding opportunities please refer to the *Monitoring Efficacy* document*,* section 3.3. Additional information on funding opportunities is also detailed in Silva Zuniga et al. (2020) and Pathak et al. (2022). Emerging/new funding opportunities can also be found on the Green Growth Knowledge Platform and Green Finance for Latin America and Caribbean Platform (See Box 19).

Government funding is currently the most common funding source for NBS (UNEP, 2021) and is primarily achieved through federal grants (such as Building Resilient Infrastructure and Communities in the United States and the Nature Smart Climate Solutions Fund in Canada), state grants (such as the Florida Resilient Coastlines Program), and local government loans (Pathak et al., 2022). Local governments are less likely to provide funding due to lower budgets but could explore private partnership options. Other government funding mechanisms may include carbon credits (see section 6.2.2), loans and bonds (e.g., Global Centre on Adaptation, 2021). A brief list of some funding opportunities available through international institutions and federal governments are given in Box 19; this list is not exhaustive and is intended to provide examples of the main funding sources available.

There are two funds available in Mexico which promote flood-risk management: the Disaster Assistance Fund (FONDEN) and the Disaster Prevention Fund (FOPREDEN). The Sectorial Fund for Environmental Research funds initiatives aimed at increasing local resilience to the effects of climate change (OECD, 2021). Despite this, budget allocation for NBS implementation and monitoring is scarce. International development agencies, multilateral banks and the private sector have been instrumental in facilitating NBS initiatives in Mexico. For example, the United Nations Development Programme is working to involve the private sector to develop alternative non-governmental finance mechanisms, recognizing that increasing funding for NBS through the public budget may not be feasible (UNDP BIOFIN, 2021).

Box 19. Examples of international and country-specific funding

International Institutions:

- Green Climate Fund

Canadian Government Funding:

- Nature Smart Climate Solutions Fund
- Disaster Mitigation and Adaptation Fund
- Natural Infrastructure Fund

United States Government Funding:

- Building Resilient Infrastructure and Communities
- National Coastal Resilience Fund

Mexican Government Funding:

- Disaster Assistance Fund (FONDEN)
- Disaster Prevention Fund (FOPREDEN)

Resources

- Restore Your Coast (Resource for finding funding sources for projects in the United States)
- Green Growth Knowledge Platform
- Green Finance for Latin America and the Caribbean
- Climate Funds Update

Private sector financing can provide funding through loans, green bonds and insurance. Case Study 4 in the *Monitoring Efficacy* document provides an example of insurance used to fund monitoring and maintenance of the Mesoamerican Coral Reef in Quintana Roo, Mexico (TNC, 2021). In Canada, new incentives inspired by this Mexican project are in development. The Natural Assets Initiative is partnering with Swiss Re and Insurance Bureau of Canada on a pilot project to develop new insurance solutions for local governments, that would provide compensation for damage to natural assets that provide flooding protection (MNAI, 2023; IBC, 2023). Environmental impact bonds have been successful in partnering investors with municipalities planning environmental projects; for example, the first environmental impact bond in the United States financed the Washington DC Water "Storm water project" (Quantified Ventures, 2022) and could equally be applied to NBS projects.

There are increasingly creative opportunities for funding such as public-private partnerships, a common model of financing which involves collaboration or partnering of public and private sector entities to fund projects (Eyquem, 2021) as well as blended finance (e.g., Earth Security, 2021). As an alternative to the conventional funding and financing options, communities can raise capital for small-scale projects through crowdfunding and community grant programs (Pathak et al., 2022). Developers are also increasingly incorporating NBS into coastal developments to attract private investment.

4.5 Regulations

Various levels of government regulations will be applicable to NBS, as federal, provincial, state, territorial, municipal and Indigenous governments all hold FrM responsibilities (e.g., Vouk et al., 2021; West Coast Environmental Law, 2022). The regulations relevant to NBS at the federal or national level of government frequently fall under broad climate change, climate change adaptation, FrM or infrastructure regulations. NBS are sometimes referred to directly, but specific regulations and goals are not always defined (DHI, 2022b; Rahman et al., 2019). As such, there is opportunity for NBS to be incorporated more thoroughly into the regulatory landscape as they become a more accepted and familiar solution.

Due to the complexity of overlapping jurisdictions and varying regulatory landscape between and within countries, local expert advice will be needed to help navigate the regulatory environment that pertains to retrofitting existing FrM infrastructure with NBS within a specific region.

Policies and regulations specific to NBS are being introduced in North America. The United States has announced a federal NBS policy highlighted in Case Study 9, which sets intentions, goals and solutions for NBS and sets a basis for a regulatory framework. The Bipartisan Infrastructure Law is currently the main regulatory framework supporting NBS in the United States (The White House, 2022), mainly through directing and funding government departments with a responsibility for the coast, such as the National Oceanic and Atmospheric Administration (NOAA, 2022a). The Government of Canada has published a National Adaptation Strategy (2023), which provides a national framework for action for implementing adaptation solutions such as NBS, and an Adaptation Action Plan which will direct future federal programming and investment in this area (Environment Climate Change Canada, 2023).

There is currently a policy and regulatory framework in place in Mexico, however the implementation of this framework is in its early stage (DHI, 2022b). The Ministry of Environment and Natural Resources (*Secretaría de Medio Ambiente y Recursos Naturales*) is most directly involved in NBS planning and implementation across the country (OECD, 2021). NBS were recently included in some of the country's key policies (e.g., the National Water Program and the 2020–2024 Sector Program for the Environment and Natural Resources) (OECD, 2021). Multiple government institutions are involved in the management and development of coastal zones in Mexico, and there are more than 40 laws and regulations applicable to the coastal zone. Some of the federal laws of note that have relevance to NBS are the General Law of National Property (*Ley General de Bienes Nacionales*), General Law of Ecological Balance and Protection of the Environment (*Ley General de Equilibrio Ecológico y Protección al Ambiente*), Wildlife Law (*Ley de Vida Silvestre*), Climate Change Law (*Ley de Cambio Climático*), and Human Settlement Law (*Ley de Asentamientos Humanos*).

Higher-level policies and regulations can set out goals for state or provincial and local levels of government to follow when developing their own regulations, which will be more detailed and specifically tailored to the needs of the region or locality. Provincial and state level regulations in the three countries have significant influence over NBS projects, as requirements set out in these regulations will need to be met in order to obtain construction permits and approvals. State or provincial regulations relevant to NBS can be found in adaptation regulations, disaster management, environmental protection regulations, infrastructure regulations and coastal management plans. For example, the California Coastal Act sets out regulations pertaining to coastal developments in the state (California Coastal Commission, 2023), and in Canada a similar provincial regulation is the Nova Scotia Coastal Protection Act (Nova Scotia, 2021).

On the local level, regulations of relevance to NBS in the three countries are mostly related to land use planning (Pathak et al., 2022), climate change adaptation and environmental policies. Local level environmental and development permitting regulations will have some of the greatest impact on NBS projects. Projects will need to be designed to meet the requirements set out in specific municipal and city building or construction regulations relevant to the coastal area and will need to meet environmental regulations in order to be approved.

Case Study 9. Policy and funding support for NBS from Federal Government

Nature Based Solutions Road Map: United States
Federal funding and regulatory support for NBS in United States

In 2022, the United States government announced the Nature Based Solutions Road Map (White House Council on Environmental Quality, 2022), with the aim of "unlock[ing] the full potential of nature-based solutions to address climate change, nature loss, and inequity" (The White House, 2022). The roadmap sets out to provide both funding and regulatory mechanisms to enable NBS development, while also providing leadership by focusing on retrofitting federal facilities and assets, from which cases studies and guidelines will become available.

Funding is being made available through the Federal Emergency Management Agency Building Resilient Infrastructure and Communities program (FEMA, 2022), and efforts are being made to make applying for funding easier and more accessible. There is an emphasis on providing funding to disadvantaged communities to help them complete a benefit-cost analysis which is required for NBS project permits (The White House, 2022).

From a regulatory perspective, floodplain management requirements from the Federal Emergency Management Agency will now require NBS to be considered "for all projects that have the potential to affect floodplains or wetlands" (The White House, 2022).

The road map also aims to provide guidance on tools for evaluating NBS, with a working group dedicated to developing guidelines for benefit-cost analysis specific to NBS projects.

4.6 Timing

Opportunities for retrofitting existing FrM infrastructure with NBS are present throughout the life cycle of coastal protection assets, including when considering new construction, repair, modification, and replacement of existing gray features. However, the greatest opportunity for retrofitting with NBS will occur when existing FrM infrastructure is nearing the end of its serviceable life or is in need of repairs. Retrofitting using NBS can be considered in the planning phases of maintenance, repair, or replacement to meet increasing and changing FrM and stakeholder needs (Suedel et al., 2021).

Alternatively, retrofitting using NBS may be considered for existing FrM infrastructure that may currently be in good condition (i.e., not in need of repair or replacement), but does not meet current or future FrM needs or fails to provide sufficient environmental, economic, and social co-benefits. In the same vein, areas that were identified as having a low vulnerability during the previous FrM development cycle (see section 3), may now be more vulnerable due to changing climatic conditions and increased population densities near the coastline, for example. These areas may present an opportunity to implement NBS, with retrofitting completed as part of adaptive management activities for existing FrM infrastructure.

The duration of the NBS development cycle (from conceptualization to implementation) will vary significantly based on the complexity of the project, local regulations, engagement activities and other project-specific factors. However, many NBS projects take between one and five years to scope, plan, design, and construct. The performance of NBS often vary over time, with delayed or improving performance as vegetated components take hold and the system adapts in response to environmental factors. Adaptive management and monitoring will be required to ensure the project's success (see section 5 for additional discussion on varying performance related to physical and ecological components of the NBS). Construction can often be completed in one season, but may span several years, particularly if a phased approach is necessary or if intensive adaptive management is required.

Timing of construction will vary based on the local climate, environmental windows of least harm, tidal windows, daylight hours and contractor availability, amongst other factors. Monitoring and adaptive management should extend throughout the project life, which may vary significantly, and is discussed thoroughly in the associated *Monitoring Efficacy* document.

5 Technical Considerations for Retrofitting

The use of a system-based approach is fundamental to NBS. System-based approaches incorporate a broad range of physical (engineering), environmental and social processes and inter-connections—on a range of spatial and temporal scales—into the design and implementation plan (Vouk et al., 2021). Retrofitting initiatives using NBS must take a similar approach, requiring the consideration of numerous technical parameters. Technical considerations may be broadly broken into engineering, ecological, social, and economic design considerations. Long-term monitoring and adaptive management must also be considered at an early stage. This section provides an overview of these key technical considerations.

5.1 Engineering Considerations

NBS retrofits have the potential to provide immense social, environmental, and economic benefits (as described in *Co-Benefits* document) if well designed, implemented, and adaptively managed. The goal of a NBS retrofit will generally be such that it is self-maintaining, with increasing performance over-time (Bridges et al., 2021); however, adaptive management should be expected, particularly during and in the early years following construction. The US Federal Highway Administration (2018) suggests considering the following engineering-related questions to guide scoping and early option development:

- Is it technically feasible?
- Is it reasonable?
- Is it justifiable?
- Is it constructible?

At the design phase of the project (see Figure 20), the design team will need to define the materials, size of placement, elevations, slopes, and construction methodology, amongst other details (Federal Highway Administration, 2018). The design team must also incorporate social, environmental, and economic considerations into the design and adaptive management.

Although some NBS retrofits may be well defined in literature with technical design guidance available, many NBS retrofits will fall outside of standard technical guidelines and limits of empirical equations. Numerical modeling, physical modeling or pilot projects may be required to inform, refine, or prove the design (World Wildlife Fund, 2016). Hydrodynamic, wave and geomorphic numerical modeling tools are commonly used to evaluate the performance of design alternatives or to refine the layout, slopes, elevations, or material sizing for an existing design (Vouk et al., 2021).

Geomorphic modeling tools are particularly helpful to inform the stability of sediment-based systems (e.g., beach nourishments) during discrete storm events and over the long-term, to assess the impact of human activities (such as dredging), and to inform the potential need for maintenance works. However, extensive field data acquisition is required to support model development, calibration, and validation. Physical models are often used for high-risk projects or where numerical models are not well suited for the problem (Vouk et al., 2021, Wilson et al., 2020). Physical models typically require significant time and resources to undertake, with limited facilities available to complete such work across North America. Adaptive management further allows for the design team to learn from monitoring results and refine the design during and following construction to improve performance (see section 5.5).

A more extensive, but non-exhaustive, set of technical questions to guide the engineering aspects of the design are provided below (adapted from Federal Highway Administration, 2018; IDB, 2020; Suedel et al., 2021; Vouk et al., 2021; World Wildlife Fund, 2016):

Spatial and Temporal Scale

- Does the physical scale correspond to the scale of coastal processes?
- Does the physical scale impact navigation or infringe on neighbouring lands?
- Does the design account for both discrete and chronic degradational processes?
- Does the design consider lag-time required to reach full performance?
- What is the design life of structural, gray components?
- What is the uncertainty in future conditions at the site? (i.e., high uncertainty may make NBS more desirable)

Design

- How will sediment supplies be maintained, if not self-sustaining?
- Have changes to the cross-shore profile, crest elevation, and roughness been considered, in response to varying morphological conditions or changes in vegetation or biological growth?
- Have geotechnical and hydrogeological processes been considered?
- How will living components (i.e., vegetation and biological actors) contribute to FrM performance?
- Does the design have the potential to negatively impact existing structures?
- Will the design perform in both present and future potential climate change conditions, given a range of uncertainties?
- Does the design incorporate sufficient redundancy or residual FrM performance considering known processes, uncertainties, and lag-time?
- Are there risks that have not been mitigated?

Construction & Maintenance

- When and where will materials be sourced to facilitate construction and maintenance?
- How will construction or maintenance of existing gray structures be impacted?
- Has 'closure' at the end of the design life been considered?

The *International Guidelines on Natural and Nature-based Features for Flood Risk Management* (Bridges et al., 2021) provides the most comprehensive guidance on NBS design and implementation. The *Nature-based Solutions for Coastal Highway Resilience: An Implementation Guide* (Federal Highway Administration, 2018) provides practical engineering design guidance. The *Practical Guide to Implementing Green-Gray Infrastructure* (Green-Gray Community of Practice, 2020, 107) also provides a list of available engineering design guidance documents for NBS. *Increasing infrastructure resilience with Nature-based Solutions* (IDB, 2020), provides guidance on retrofitting with NBS, specific to Latin America and the Caribbean. Further information on the monitoring component of the maintenance phase is provided in the associated *Monitoring Efficacy* document.

5.2 Environmental Considerations

The provision of environmental co-benefits, such as habitat connectivity, carbon sequestration and improved water quality and air quality, is a fundamental component of NBS projects. Understanding and observing the baseline of the system ecology and biology is therefore vital for NBS retrofit design, implementation, and adaptive management. In particular, this understanding supports the design and adaptive management of the NBS, including the decision of the type of feature(s), material type(s), and location and size. Diversification of features and inclusion of adaptive components can also aid in resiliency of a system, by developing multiple lines of defense from flooding and erosion (Vouk et al., 2021).

Environmental systems are continuously evolving in response to external factors. The influence of climate change and the related impacts will further challenge environmental systems (which may include NBS) resulting in their dynamic adaptation over short, medium, and long-time scales (Bridges et al., 2021). The resiliency of environmental systems is a key factor to long-term functionality, durability, and sustainability of NBS, which must in-turn accommodate the natural behaviour of environmental systems.

There is often a time-lag between implementation of a project and full performance. The time required to fully realize the benefits from a NBS retrofit can be difficult to estimate but should be considered and built into the project timeline (i.e., managed in the design and adaptive management phases of the project), with the understanding that there will be some degree of uncertainty surrounding the time for benefits to be fully realized. This uncertainty can be managed by consulting experts within the design team and through learning from other similar projects implemented elsewhere. In addition, the project team should account for natural variations in the system, which may impact both FrM performance and co-benefit performance. For example, introducing a multi-use reef system may take multiple spawning seasons before anticipated results related to marine biodiversity and increased abundance of fish are seen. Vegetation also has a time lag between implantation and full growth, which may take anywhere from one growing season to multiple years, depending on project-specific circumstances. The *International Guidelines on Natural and Nature-based Features for Flood Risk Management* (Bridges et al., 2021) provides comprehensive guidance on the importance of life-cycle considerations and its relation to changing performance of NBS.

When scoping opportunities and options, there may be multiple methods to achieve the project-goals; trade-offs need to be considered to narrow down the choice. For example, planting fast-growing invasive species may maximize carbon storage capacity, but can cause negative impacts to native vegetation and wildlife (e.g., pollinators, birds, insects, etc.). At minimum, NBS retrofits should never reduce the resiliency of a system, nor should they negatively impact adjacent ecological values (Al-Rajhi, 2020).

A set of technical questions are provided below to help guide the environmental aspects of a NBS retrofit design (adapted from Bridges et al., 2021; Vouk et al., 2021; Pathak et al., 2022):

Design

- Is the primary aim of natural components to provide FrM services or to improve ecological value?
- Will the NBS yield net positive benefits for the environment?
- Are there trade-offs between individual co-benefits?
- Will the NBS provide natural features and processes the space they need to function?
- Does the NBS protect or restore critical natural infrastructure?
- What are the optimal ecological conditions required at a given location?

Climate Change Adaptation

- Will climate change affect natural assets which the NBS will rely on for performance?
- Can living components (i.e., vegetation and biological actors) withstand expected and potential future environmental stressors?
- What parameters are needed to design enhancement features that are sustainable over the project life and are appropriate for predicted climate change effects?

Construction and Adaptative Management

- How will existing living features be impacted by construction?
- How will existing living features be impacted by monitoring and maintenance activities?

The *Co-Benefits* document provides an extensive list of potential environmental co-benefits that may be considered as part of a NBS project. The *Use of Natural and Nature-Based Features for Coastal Resilience* report (Bridges et al., 2015) provides additional guidance on their use for coastal resilience within a changing climate.

5.3 Social Considerations

The vulnerability of communities to flood risks is influenced significantly by the ability of communities to prepare for, respond to, and recover from climate hazards (Arkema et al., 2017). The main factors for social vulnerability to coastal hazards include differences in access to resources (e.g., money and technology), power (e.g., political influence), capacity (e.g., social capacity to respond), and information. These elements contribute to inequalities in disaster response and recovery (Arkema et al., 2017). Social vulnerability is often disproportionality higher for minority and marginalized groups and those in lower income communities with high rates of poverty (Arkema et al., 2017). Areas with incomes gaps may produce different socioeconomic outcomes for a specific project based on the location. For example, when examining replacement costs, a wealthy neighbourhood may receive larger FrM investments in order to protect properties of higher value, even though providing flood protection for a more densely populated or lower-income community may provide greater non-economic benefits (Arkema et al., 2017). It is therefore important to consider the key questions regarding equity, Indigenous Peoples, and access, listed below, within and outside the project team, at the onset of the project.

It is important to consider that minority populations, historically marginalized communities, and populations of lower socio-economic status are often more exposed to climate risks based on their geographic location, access to recourses, economic status, and land ownerships (Pathak et al., 2022). Unless NBS retrofits are developed with equity as a key consideration, socially vulnerable communities will continue to disproportionally face climate hazards and challenges (Pathak et al., 2022). Minority groups, marginalized communities, and peoples with low socio-economic status often also experience limited access to NBS retrofits, which can provide social and health benefits, such as green spaces that improve mental wellbeing, reduce chronic illness, and provide safe places to exercise (Pathak et al., 2022).

Natural assets and improvements can also create challenges for socially vulnerable communities by increasing housing or renting costs and property values, leading to eco-gentrification and displacement. The project design team should take social vulnerabilities and adaptive capacity into account in the planning and design phases of the project, and local authorities should assess proposed designs to ensure the project will not aggravate socioeconomic vulnerabilities or be maladaptive to these communities (Pathak et al., 2022). Stakeholders and rightsholders should be engaged early in the planning process to understand needs, values, and priorities. Trade-offs between co-benefits should be discussed in detail with stakeholders and rightsholders to maximize benefits to those communities and improve public buy-in.

Many socially vulnerable areas coincide with Indigenous communities, who have frequently been marginalized in public and private decision-making (Löfqvist et al., 2022). For Indigenous Peoples across Canada, Mexico and the United States, the act of enhancing climate and biodiversity solutions is not new, but rather an approach they have been taking for centuries (Reed et al., 2022). It is important that Indigenous perspectives and knowledge—often referred to as Traditional Ecological Knowledge—are given at least equal consideration to "Western" knowledge systems in the NBS development process.

In summary, the types and magnitude of social benefits provided by a NBS retrofit should be heavily influenced by the needs, values and priorities of local stakeholders and rightsholders. It is therefore necessary that social considerations are accounted for in NBS retrofit projects. To aid the socially responsible design of NBS with inclusive governance, the International Union for Conservation of Nature and Natural Resources has published the *IUCN Global Standard for Nature-based Solutions* (IUCN, 2020); a set of technical questions are provided below to help guide the social aspects of a NBS design (adapted from Pathak et al., 2022 and Reed et al., 2022):

Equity

- Is the project team considering social and economic vulnerability that considers marginalized communities?
- Are there equity implications related to the NBS retrofit?
- Will this NBS retrofit reduce risk for the target community?
- Are local stakeholders and rightsholders part of the NBS development cycles (including scoping, planning and implementation)?
- Is there fair representation in the decision-making process?
- Is there fair allocation of resources, costs, and benefits?

Indigenous Peoples

- Have local Indigenous groups been part of the NBS development cycles (including scoping, planning and implementation)?
- Does the design incorporate Traditional Ecological Knowledge and Indigenous perspectives?
- Could this project result in or facilitate violence and land dispossession against Indigenous Peoples?

Access

- Do impacted individuals have access to participate in the decision-making process?
- Do impacted individuals have accessible information relevant to the project?
- Are there transportation or accessibility barriers which would prevent marginalized groups from benefiting from the proposed project?

The *Co-Benefits* document provides an extensive list of potential social co-benefits that may be considered as part of a NBS project. The report, *Linking social, ecological, and physical science to advance natural and nature-based protection for coastal communities* (Arkema et al., 2017), provides valuable insight and social metrics to measure social vulnerability to coastal hazards. The *Toward Indigenous visions of nature-based solutions: an exploration into Canadian federal climate policy* report highlights the importance of supporting Indigenous sustainable self-determination to prevent further damage to Indigenous Peoples. Chapter 3 of the *International Guidelines on Natural and Nature-based Features for Flood Risk Management* (Bridges et al., 2021) also provides detailed strategies for stakeholder engagement.

5.4 Economic Considerations

When evaluating options for FrM, there is often a tendency to focus primarily on a direct cost-benefit comparison based solely on FrM performance. Not only does this type of evaluation devalue non-tangible co-benefits, such as equity and inclusion, it also fails to reflect the complete economic impact over the life cycle of the project. Failure to account for all economic impacts related to a project can produce substantial unintended consequences. A framework that includes co-benefits into the valuation of projects is provided in the associated *Co-Benefits* document. Alternatives to cost-benefit analysis may include, but are not limited to, the following:

- Economic value assessment
- Input-output analysis
- Life cycle cost analysis

- Risk analysis
- Social cost benefit analysis

All NBS projects should consider a wide range of economic co-benefits and evaluate the total cost and savings/revenue over the life of the project. Costs can occur at all stages of the NBS development process, including during design, operation, management, construction, monitoring, and adaptive management. Revenue generation is possible, where direct benefits are monetized, through tourism, job creation or carbon off-sets, for example (IDB, 2020). Cost-estimates are typically made during the design phase (Aerts, 2018), however, all costs and savings may not be realized at the same time, since NBS tend to evolve over time (IDB, 2020). Costs and savings may also vary due to changes in socioeconomic fluctuations which may affect labour costs, supply of material and land values (Aerts, 2018). It is therefore important to monitor and evaluate the economic co-benefits from the project as it evolves, and to report those benefits back to project stakeholders.

Direct costs related to NBS retrofits may be broken down into categories including design and construction, operation and management, opportunity, and transaction costs. Design and construction costs are upfront investments, which may include fees related to planning, design, land acquisition, permitting, purchasing of materials and machinery and labour costs (Aerts, 2018; IDB 2020). Operation and management costs occur over the life cycle of the project and include the yearly costs needed to operate, monitor, undertake repairs and replace necessary equipment (Aerts, 2018; IDB, 2020). Opportunity costs are the potential, relative loss of money related to implementing a NBS retrofit as opposed to an alternative option (IDB, 2020). Transactional costs are associated with time, effort, and resources required to facilitate the NBS retrofitting project including the cost of scoping, planning, decision-making, etc. Transactional costs may be high for developers that lack experience with FrM projects and NBS, or for projects that have many false starts, scope changes or re-work and the resources required increasing the level of time and effort needed (IDB, 2020).

Savings, revenue, or value related to direct FrM benefits or co-benefits of a NBS project are often difficult to put into monetary terms, as benefits are often non-economic in nature. However, determining the magnitude of economic benefits provided by a project is often useful and necessary. Valuation methods may be qualitative or quantitative, depending on resources available and desired outcome. It is important to note that valuation methods and indicators need to remain consistent over the life cycle of the project to allow for accurate monitoring, performance tracking, and adaptative management, as well as to communicate benefits to stakeholders. For technical guidance on valuation methods and assessment please see the *Co-Benefits* document.

Understanding the project costs (through all stages of the NBS cycle) and all potential funding sources is also necessary to ensure the feasibility of a NBS project. Development of a funding strategy and estimated costs/savings should occur at the beginning of a project and be adjusted as new information becomes available throughout the project life cycle. Funding opportunities are discussed in detail in section 4.4.

A set of technical questions are provided below to help guide the economic aspects of a NBS design (adapted from Pathak et al., 2022 and IDB, 2020):

Cost

- Is there potential to integrate the NBS retrofit into existing planning processes?
- What is the timeline of incurring costs?
- Does this NBS retrofit offer a lower cost alternative (including installation, monitoring, and maintenance) compared to other options?
- Are there alternative options which are more cost-effective?
- What is the cost of resources including time, effort and knowledge required for the NBS retrofit?

- How much investment is required for upfront costs including capital, planning, permitting, material, machinery, land acquisition, labour, and construction?
- How does the cost of the NBS project compare to alternative coastal flood management strategies, such as gray structures or land-use planning?
- How much long-term investment is needed for the project life cycle including operation, maintenance, monitoring, and equipment?

Value

- Will this project reduce risk or damage and therefore recovery/repair costs?
- How will the benefits of the NBS project be valued and monetized, for example through avoided damages, increased tourism, or improved quality of life?
- What are the long-term benefits of the project?
- How will the NBS project affect the local and regional economy, including employment, income, and trade?
- What data and information are needed to assess the economic impact of the NBS project, and how will it be collected and analyzed?
- How will intangible savings or value be measured and monetized?
- Are economic benefits distributed across stakeholders and rightsholders?
- What cost off-sets will be produced from this project?
- How will the benefits of the NBS project be distributed among different stakeholders, including local residents, businesses, and government agencies?
- What is the timeline for incurring value/revenue/savings?

Funding

- What is the stakeholder engagement strategy?
- What is the funding strategy?
- What are all funding sources (including federal funding and grant opportunities)?
- How will the NBS project be funded and maintained over time?
- Are there synergistic opportunities that are applicable to other stakeholders?

The *Co-Benefits* document provides an extensive list of potential economic co-benefits that may be considered as part of a NBS project. The *Increasing infrastructure resilience with Nature-based Solutions* document (IDB, 2020) provides guidance on economic assessment of NBS and how NBS can deliver increased value to infrastructure projects. The *A Review of Cost Estimates for Flood Adaptation* report (Aerts, 2018) provides information from peer-reviewed literature on construction costs and expenses for operation and maintenance of NBS.

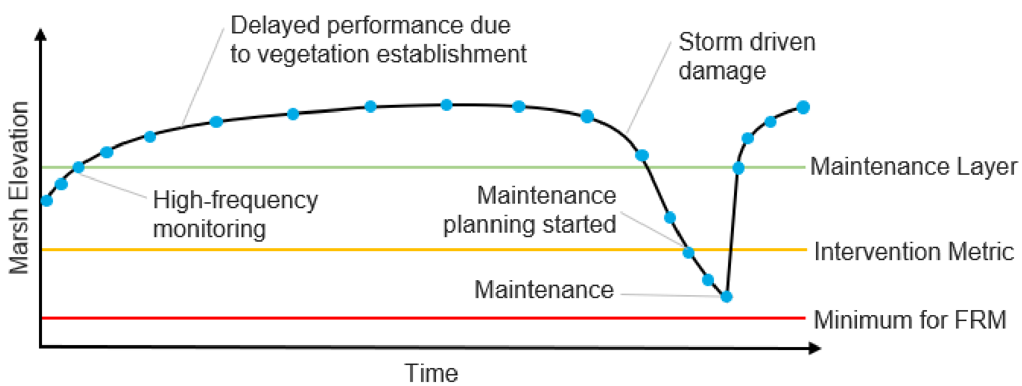
5.5 Monitoring and Adaptive Management Considerations

Adaptive management is built on the principle of addressing and reducing uncertainties in NBS projects in a phased implementation. It acknowledges the dynamic nature of the environment and focuses on the aspects of the project that can be controlled or adapted, increasing flexibility in planning stages and allowing the design to evolve over time (de Looff et al., 2021 and references therein). This is especially important given the uncertain future under climate change (e.g., Cado van der Lely et al., 2021). Monitoring and adaptively managing a NBS retrofit will also help realize FrM benefits and co-benefits over time (Vouk et al., 2021). Monitoring and adaptive management is therefore central to the NBS project cycle.

Introducing monitoring and adaptive management considerations early in the NBS cycle, and continuing it throughout the project, will help achieve optimal results. Considerations for monitoring and adaptive management includes clear identification of project-specific roles, monitoring frequency and duration (i.e., timeline), data collection methodology, compliance with relevant policies or standards, training required to carry out activities, and funding (Vouk et al., 2021).

The monitoring and adaptive management timeline will vary based on the project and specific NBS retrofit being applied. Timelines should be considered from baseline data collection through to operational data collection. As most NBS retrofit projects occur over large timescales, there is a need for regular maintenance to ensure the project is functioning as intended and benefits are achieved (Vouk et al., 2021). There may also be a need for emergency maintenance following a storm event for example, in addition to ongoing regular maintenance. Figure 26 illustrates how monitoring of marsh elevations (for example) could feed into decision making on when to supplement the marsh with additional substrate, and how much substrate to provide. In this example, when monitoring data reveals that the marsh elevation is below the intervention metric, planning is initiated for maintenance activities. Timely feedback between the monitoring program and adaptive management is required to facilitate action by decision makers. Maintenance work should be designed such that the maintenance layer is achieved and the FrM performance is always maintained.

Figure 26. Conceptual model of marsh elevation monitoring data feeding into adaptive management



Source : adapted from de Looff et al., 2021

Performance metrics and indicators, as well as monitoring and analysis methods need to be considered to ensure consistency throughout the project, allowing for an accurate understanding of performance, and to allow for comparison between projects (Pathak et al., 2022). Specific data collection and analysis methods will be determined on a project-specific basis, however quality assurance and quality control measures should always be implemented (e.g., metadata, proper documentation). Additional technical guidance on monitoring and adaptive management is provided in the *Monitoring Efficacy* document and in the *Monitoring Efficacy: Proposed Methodology and Indicators* document.

Frequency and duration of monitoring and adaptive management activities will directly relate to the level of funding needed (Vouk et al., 2021). Funding sources can include international finance institutions, public institutions (e.g., government budgets, grants, non-profits, volunteers), and private sources (e.g., donations) (de Looff et al., 2021; Silva Zuniga et al., 2020). Funding opportunities for NBS retrofitting are discussed in detail in Section 4.4, and funding opportunities specifically related to monitoring are discussed in the *Monitoring Efficacy* document.

A set of technical questions are provided below to help guide considerations related to monitoring and adaptive management (adapted from IDB, 2020, de Looff et al., 2021, and Pathak et al., 2022):

Spatial and Temporal Scale

- When will expected benefits be produced?

- What is the anticipated frequency and duration of monitoring activities?
- What is the spatial scale of monitoring activities?
- Is the timeline of sufficient length to see the outcomes of an action based on the temporal dynamics?
- Is there sufficient time to implement adaptive management?

Resources

- Is adequate funding available for anticipated monitoring and maintenance?
- How will monitoring be funded?
- Are human resources and equipment required for anticipated monitoring available?

Data

- How will specific benefits/actions be measured?
- What indicators will be measured consistently?
- What metrics will be used to determine if the NBS is performing or if adaptation is required?
- How will required data be collected?
- Who will carry out data collection?
- How will data be managed, analyzed, and stored?
- How will results be disseminated to stakeholders and rightsholders?

More in-depth technical guidance on developing and implementing monitoring plans is provided in the *Monitoring Efficacy* document and the *Monitoring Efficacy: Proposed Methodology and Indicators* document. The *Increasing infrastructure resilience with Nature-based Solutions* document (IDB 2020) also provides guidance on monitoring and evaluation plans for NBS. Chapter 7 of the *International Guidelines on Natural and Nature-based Features for Flood Risk Management* (de Looff et al., 2021) provides detailed strategies for the development of an adaptive management plan. The entirety of Bridges et al. (2021) outlines monitoring and adaptive management strategies for specific natural features (e.g., beaches and dunes, islands, reefs).

6 Incentives for Retrofitting with NBS

There are various types of incentives for retrofitting existing FrM infrastructure with NBS (as opposed to gray engineering options). These incentives may be inherent to the project itself, or derived externally from governments, the private sector, NGOs, and community organizations. This section provides an overview of the different types of incentives that currently exist, as well as incentives which could be implemented. Given this diversity of possibilities and the complexity of possible financial support for this type of project in each country, it is recommended to obtain the advice of local experts to help identify the options for acquiring financial support.

6.1 Inherent

The inherent ability of some types of NBS to adapt to changing environmental conditions (including increased regional sea-level rise) and the opportunity that these types of projects present to shift into an adaptive management approach provide an advantage over conventional, gray approaches in the context of future uncertainty (e.g., Cado van der Lely et al., 2021). NBS projects also provide inherent incentives for their development through numerous co-benefits. Although the specific co-benefits provided will vary from project to project, all coastal NBS types referred to in this document (see section 2) will provide direct FrM benefits, and project-specific social, economic, and environmental co-benefits, that may otherwise not be provided by a gray option. Most NBS projects will provide some form of local employment via the planning, design, construction, monitoring, and adaptive management of the development. They may also provide longer-term economic benefits through increased tourism or tax revenue, for example. All NBS projects will feature new or restored habitat of some kind, providing additional ecosystem services associated with this habitat. For example, a NBS involving mangrove development may result in improved water quality, soil health and carbon sequestration. Social benefits will also be realized through the addition of new green and recreational space and the potential for improved public health, amongst other benefits. Further social (and cultural) benefits may be realized through the facilitation of traditional Indigenous land-use and management, such as the restoration of clam gardens. These co-benefits are inherent incentives for retrofitting using NBS. In order to identify and evaluate the specific incentives that may be inherent in a project, refer to the *Co-Benefits* document, section 2.

6.2 Government

Incentives to implement NBS come from all levels of government, from international inter-governmental agreements (such as the 2016 United Nations Framework Convention on Climate Change), to national or federal, state, territorial, or provincial, and local governments. Government incentives at all levels fall into two broad categories discussed below: (1) regulations that incentivize NBS or make NBS permitting less complicated, and (2) financial incentives for projects and research (including through grants and programming). In addition to these two main categories, governments can also incentivize NBS projects by providing guidance and education on benefits and technical design elements. Governments can also develop certification programs designed to recognize private entities for implementing NBS (see section 6.3).

6.2.1 Regulations

For decision makers to implement NBS, regulations need to be considered early in the planning stages of FrM projects, whether they be new constructions or retrofits. Government regulations and policies can incentivize the use of NBS by making consideration for NBS a requirement at the planning stages of a project. For example, in 2016, the Town of Qualicum Beach (British Columbia, Canada) created two sets of evaluation frameworks to help assess waterfront development proposals in a systematic and transparent matter and inform decision-making related to their approval. The framework requires applicants to compare their proposed solution against a 'do nothing' approach (at minimum) and promotes moving towards NBS if the proposed solution has negative engineering, environmental or social impacts relative to the 'do nothing' approach. Additional information on these frameworks is provided in the *Co-Benefits* document, Case Study 6: Qualicum Beach waterfront evaluation frameworks.

During the CEC workshop series (DHI, 2022b), experts also raised that NBS guidance on the permitting and approval process for NBS was lacking. Governments can work together to make acquiring permits and approvals more efficient or streamlined for NBS. Allowing for certain planning exemptions, lower fees, or faster permit application processing times for NBS projects can also act as an incentive for developers (Pathak et al., 2022). They may also remove disincentives which arise from opaque planning requirements by setting clear NBS-specific planning regulations to guide the development of such projects. For example, the Green Shores pilot program (British Columbia, Canada) provides expedited permitting for NBS shoreline projects as well as a detailed checklist for the required surveys and documentation needed for a NBS application (Stewardship Centre for British Columbia, 2022a).

6.2.2 Financial

Experts from the CEC workshop (DHI, 2022b) identified access to funding for NBS projects as a barrier to development. Workshop attendees indicated that the uncertainty surrounding novel solutions (including NBS), a lack of precedents, and the site-specific nature of NBS projects, can make obtaining finance difficult due to a perception of increased risk. Increased risk may also be a disincentive when projects are reliant on private financing, which requires repayment (Raška et al., 2022). Federal and state grants and project funding through programming that provide capital which does not need to be repaid or is repaid at low interest can therefore act as an incentive by alleviating costs and reducing financial risk (e.g., the National Coastal Resilience Fund in the United States, NOAA, 2022b). There is also the opportunity for governments to enter into public-private-partnerships in order to provide funding for NBS. Section 4.4 provides examples and resources for identifying funding sources for NBS.

Other government financial incentives could come from tax incentives and insurance subsidies for private entities which implement projects or provide financial support to NBS. For instance, governments could provide tax incentives to private landowners who develop NBS or restore coastal ecosystems that provide FrM benefits on their land. Private entities could also be incentivized to support or develop NBS projects if they are publicly recognized for doing so, in a way that allows them to better meet corporate social responsibility targets.

Carbon credits can also provide a financial incentive for developing NBS such as mangroves, salt marshes and seagrass meadows, that provide the co-benefit of carbon sequestration. Carbon credits have been issued for the San Crisanto mangrove restoration project in Mexico (refer to Case Study 1 in the *Co-Benefits* document for more details on the project) (Godoy, 2022); and in Canada, carbon credits have been issued by the Province of British Columbia for land-based NBS implemented by the Coastal First Nations Great Bear Initiative (Coastal First Nations, 2010).

6.3 NGO and Community-based

NGOs and community-based organizations can also provide incentives for NBS, through various actions, such as campaigning and leveraging support, providing technical support, or funding, issuing certifications or spearheading projects directly. In Mexico, for example, NGOs have had a major role in the development of NBS, with almost all pilot projects having some NGO involvement (OECD, 2021).

NGOs and community organizations can increase public support by campaigning and raising awareness of NBS and their co-benefits, bringing NBS to the attention of policy and decision makers. Increased public support can lead to greater community engagement and the potential for communities to apply pressure on governments and private industry to consider NBS options for FrM. With increased awareness and added social pressure, NBS can become more of a priority for governments and be brought into policy agendas, catalyzing government funding and regulations required to facilitate NBS projects. NGOs can also incentivize NBS by contributing to these government grant programs, or by setting up grants either independently or in partnership with private entities, to fund NBS projects.

Certifications and awards could be offered by NGOs or governments to recognize private actors who have supported or developed NBS projects. Certifications can help private companies meet corporate social responsibility targets and verify their commitment to environmental issues, which is becoming a growing requirement from clients and stakeholders. For example, in British Columbia, Canada, and Washington State, United States, the Green Shores program assesses shoreline developments against various sustainable design criteria and award points to those projects (Stewardship Centre for British Columbia, 2022b). The Institute for Sustainable Infrastructure also provides a global awards program for infrastructure projects assessed against sustainability, resiliency, and equity criteria within their Envision Framework (Institute for Sustainable Infrastructure, 2022)

Indirectly, NGOs can provide incentives for NBS by supporting projects through collaboration with stakeholders to identify their FrM needs and preferred management options, conducting research and disseminating knowledge on NBS, by offering technical guidance to local actors involved in development, and by leading projects directly. These opportunities for NGOs help to alleviate barriers and remove disincentives related to NBS retrofitting.

6.4 Private

The private sector can help incentivize NBS by providing financing, such as grants, loans, public-private-partnerships, green bonds and insurance products (see section 4.4). In addition to providing direct funding to projects, private actors could provide funding for research on NBS to help fill knowledge gaps that may be acting as a barrier to development of NBS projects. Private entities can also contribute to social pressure on governments to support NBS through lobbying efforts and collaborating with NGOs, community groups and other stakeholders. Where appropriate, private companies with technical expertise could offer to provide guidance to local actors intending to develop NBS projects.

7 Opportunities and Future Directions

Retrofitting existing FrM infrastructure using NBS provides numerous positive benefits, including improved flood protection, improved climate resilience and provision of numerous environmental, social, and economic co-benefits. However, there are several challenges and knowledge gaps that provide barriers to retrofitting, which are outlined in section 1.3. A summary of potential opportunities and initiatives that decision makers may employ to alleviate these barriers are provided in Box 20, based on opportunities identified as part of the CEC workshop series (DHI, 2022b).

Most social (or attitudinal) barriers related to retrofitting existing FrM infrastructure using NBS may be overcome, or at least reduced, by improving communication, engagement, and knowledge-sharing. Improved communication may be achieved by developing sessions, workshops, or seminars on NBS and their potential benefits, ensuring that the format, technical level of detail, and messaging provided is appropriate for the intended audience. Additional initiatives to develop and share knowledge through studies, pilot projects, and case studies will also help to communicate the benefits of NBS to communities. Improved engagement may be achieved by integrating it into a project early in the project life cycle, during the scoping stages.

Technical barriers may be reduced through applied research, the development of additional technical guidance, education and training, case studies and knowledge-sharing. Experts from the CEC workshop (DHI, 2022b) series repeatedly mentioned the need for additional technical guidance on NBS; however, given the novel nature of many NBS, there is a need for additional research and pilot projects to inform the development of this guidance. Case studies also provide an important source of information, but are often located in similar regions, using a small subset of NBS techniques. New case studies should focus on more novel techniques, under-represented regions, negative outcomes, and long-term results. Case studies are also required which compare NBS to conventional infrastructure. Training and knowledge-sharing may be achieved through amending existing academic programs and developing communities of practice to focus on the multi-disciplinary aspects of NBS. There is also a future opportunity for northern regions to learn from approaches employed in southern regions, as ecotypes shift northwards with climate change.

Seasonal and long-term variability of natural environmental systems also pose a significant barrier to retrofitting using NBS. Encouraging and highlighting case studies with long-term monitoring results, may help to reduce this barrier. Establishing additional networks to monitor and disseminate core/standard environmental data (which are required NBS design) in areas with little existing long-term monitoring data will help reduce uncertainties in the understanding of the natural environment. Core monitoring data for NBS are recommended in *Monitoring Efficacy: Proposed Methodology and Indicators*. In addition, developing downscaled climate projections at the regional or local level throughout North America would provide decision makers with useful information to support the case for NBS retrofitting.

Amongst experts polled as part of the CEC's workshop series on NBS (DHI 2022b), a lack of funding and lack of access to funding were repeatedly highlighted as the major barriers to the implementation and long-term management of NBS. In particular, funding is lacking for long-term monitoring, as well as operations and maintenance, which skews funding towards capital-intensive gray solutions. In addition, there appears to be a lack of recognition from funders of the potential co-benefits of NBS that can be achieved with either the same level or slightly higher level of funding required for conventional FrM projects. Developing regional-level funding streams may help to alleviate funding-related barriers to developing pilot projects using novel NBS, retrofitting existing infrastructure, long-term adaptive management of NBS and long-term, broad strategic planning of FrM infrastructure. Funding strategies should take into account regional-specific policies, mechanisms and protocols (Brill et al., 2021).

Governments may further support retrofitting using NBS through developing policy incentives and legislation which mandate the consideration of multiple options, assessment of co-benefits, and further drive investments in NBS. Incentives may also promote decision makers to "build back better" (Vouk et al., 2021) following natural disasters and infrastructure failures. Additional institutional opportunities outlined in Box 20 relate to distributing existing information on the benefits of NBS to government organizations, proving legal protection for the environment or environmental services, and simplifying the permitting process for NBS by creating streamlined pathways.

Box 20. Opportunities and future directions related to retrofitting NBS and the type of barrier that the opportunities address

	Opportunities and Future Directions	Type of Barrier Addressed: Social	Technical	Environ.	Institut.
1.	Host or fund sessions, workshops and seminars on NBS retrofits.	✓	✓	○	✓
2.	Encourage diverse stakeholder engagement (i.e., policy makers, Indigenous Peoples, social groups, etc.) early in project life cycle.	✓	○	○	✓
3.	Develop a NBS community of practice with experts spanning multiple disciplines, across multiple regions.	✓	✓	○	○
4.	Support and publish research on NBS retrofits and novel NBS and develop design guidance.	✓	✓	○	○
5.	Implement pilot projects involving NBS retrofits and novel NBS.	✓	✓	○	○
6.	Encourage and highlight case-studies comparing NBS to conventional, gray infrastructure.	○	✓	○	✓
7.	Encourage and highlight case-studies with long-term results.	○	✓	✓	✓
8.	Include cross-disciplinary training on NBS design and implementation within academic programs/degrees.	○	✓	○	○
9.	Establish additional networks to host and share standard monitoring data (e.g., wave data) required for NBS design, and make data publicly available.	○	✓	✓	✓
10.	Downscale global and national climate projections to a local level, to reduce uncertainty around climate change adaptation.	○	✓	✓	✓
11.	Amend regulatory approvals to require the comparison of multiple options (including a NBS and a 'do-nothing' approach).	✓	○	○	✓
12.	Establish funding streams for regional and local governments to develop strategic management plans for FrM infrastructure.	○	○	○	✓
13.	Develop regional-level funding streams for NBS pilot projects and projects with a high degree of innovation.	○	✓	○	✓
14.	Develop regional-level funding streams for retrofitting projects using NBS.	○	○	○	✓
15.	Distribute existing NBS guidance to government organizations.	○	○	○	✓
16.	Simplify permitting processes (i.e., provide expedited processes) for NBS construction, monitoring and adaptive management.	○	○	○	✓
17.	Resolve conflict between jurisdictional and agency regulations.	✓	○	○	✓
18.	Provide policy incentives (e.g., tax breaks) for retrofits using NBS.	○	○	○	✓
19.	Provide legal protection for the environment or environmental services.	○	○	○	✓

8 Conclusions

The goal of retrofitting using NBS is to transition FrM from gray systems to green systems. This document provides a synthesis of information related to retrofitting with NBS in the context of Flood Risk Management in Canada, Mexico, and the United States. Focus is given to NBS retrofit options, identification of retrofitting opportunities, administrative and technical considerations, incentives for retrofitting with NBS, and opportunities to alleviate information gaps and barriers.

To improve the uptake of NBS, it is necessary for decision markers to first identify opportunities for retrofitting within their portfolio of FrM infrastructure and within the overarching FrM strategy. Identification of opportunities should begin in the early stages of a project and be re-assessed periodically throughout the project life cycle. This document proposes several key steps to support decision makers in identifying opportunities, starting with assessing the existing inventory of FrM assets, planning for stakeholder engagement, identifying FrM needs and gaps, assessing site suitability for NBS and prioritizing specific assets for retrofitting. Once assets are prioritized, retrofitting options involving NBS can be identified and evaluated against gray options and a 'do nothing' approach. It is important to consider the feasibility and uncertainty of potential projects during this step, and to evaluate options in a holistic manner, considering both FrM benefits and environmental, social, and economic co-benefits.

This synthesis also outlines key administrative considerations (i.e., scoping, roles and responsibilities, communication and engagement, funding, regulations, and timing) for retrofitting using NBS. Responsibility for retrofitting falls on and requires collaboration from all levels of government, local communities, and private landowners. Funding is mainly available through government grants, but also increasingly though private finance and public-private partnerships. The regulatory framework for NBS is currently relatively weak but is improving, with proposed policies and regulations in the pipeline throughout North America. Technical considerations (i.e., engineering, environmental, social, economic, monitoring, and adaptive management) will be project specific. Decision makers and the project team should adopt system-based approaches, continuous engagement, and adaptive management throughout the NBS development cycle.

Incentives that already exist or can be introduced to increase the uptake of retrofitting with NBS are outlined. Incentives that are inherent to NBS projects include a wide variety of co-benefits, including environmental (e.g., restored habitats, improved water quality), social (e.g., new green spaces, improved public health) and economic (e.g., increase job opportunities, increased tourism). In addition, incentives can arise from a variety of organizations including government, NGOs, community groups or the private sector. Incentives that currently exist are primarily related to financial and regulatory incentives from the government, such as tax rebates and expedited permitting. However, NGOs, community groups, and the private sector are increasingly incentivising the uptake of NBS through advocacy, provision of funding or technical expertise, and by directly initiating NBS projects.

Finally, there are numerous opportunities to advance NBS by removing barriers and data gaps related to identification and evaluation of retrofitting opportunities. Additional funding streams or opportunities for NBS pilot projects, retrofit identification, evaluation and long-term assessment, monitoring and adaptive management are essential to removing barriers.

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