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Nature-Based Infrastructure for Coastal Flood and Erosion Risk Management

A Canadian Design Guide



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Partners and Contributors























































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List of Acronyms

AAM	Active Adaptive Management
ADCP	Acoustic Doppler Current Profiler
ADV	Acoustic Doppler Velocimeter
AFN	Assembly of First Nations
AM	Adaptive Management
AR	Augmented Reality
BACI	Before-After Control-Impact
CAN-EWLAT	Canadian Extreme Water Level Adaptation Tool
CEC	Commission for Environmental Cooperation
CFAS	Coastal Flood Adaptation Strategy
CHS	Canadian Hydrographic Service
CICES	Common International Classification of Ecosystem Services
CIRNAC	Crown-Indigenous Relations and Northern Affairs Canada
CMA	Coastal Management Area
CSCI	Coastal Sensitivity Change Index
CSI	Coastal Sensitivity Index
CSSP	Canadian Safety and Security Program
Defra	Department for Environment Food & Rural Affairs (UK)
DEM	Digital Elevation Model
DFO	Fisheries and Oceans Canada
DMAF	Disaster Mitigation and Adaptation Fund
DRIPA	Declaration on the Rights of Indigenous Peoples Act (BC)
DRR	Disaster Risk Reduction
ECCC	Environment and Climate Change Canada

ENSO	El Niño-La Niña Southern Oscillation
FERM	Flood and Erosion Risk Management
GLISA	Great Lakes Integrated Sciences and Assessments
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HHWLT	Higher High Water Large Tides
IAP2	International Association for Public Participation
ICZM	Integrated Coastal Zone Management
IDF	Intensity-Duration-Frequency
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
LiDAR	Light Detection and Ranging
LLWLT	Lower Low Water Large Tide
LOMAS	Large Ocean Management Areas
LWD	Large Woody Debris
MDR	Managed Dyke Realignment
MNOC	Métis Nation of Canada
MRFW	Making Room for Wetlands
NAS	Canada’s National Adaptation Strategy
NBI	Nature-Based Infrastructure
NBS	Nature-Based Solution
NBSAP	National Biodiversity Strategy and Action Plan
NGO	Non-Governmental Organization
NNBF	Natural and Nature-Based Features
NOAA	National Oceanic and Atmospheric Administration (U.S.)

NRC	National Research Council Canada
NRCan	Natural Resources Canada
NSDA	Nova Scotia Department of Agriculture
OC	Organic Carbon
OCAP	Ownership, Control, Access, and Possession
OECD	Organisation for Economic Co-operation and Development
PAM	Passive Adaptive Management
PARA	Protect, Accommodate, Retreat, Avoid
RCA	Reference Condition Approach
RCP	Representative Concentration Pathway
REI	Relative Exposure Index
RPAS	Remotely Piloted Aircraft Systems
RSET	Rod Sediment Elevation Table
RSL	Relative Sea-Level
RTK	Real Time Kinematic
SAV	Submerged Aquatic Vegetation
SBAS	Sediment Budget Analysis System
SLR	Sea-Level Rise
SMP	Shoreline Management Plan
SSP	Shared Socio-Economic Pathway
TEK	Traditional Ecological Knowledge
TLP	Thin-Layer Placement
UAV	Unmanned Aerial Vehicle
UNDP	United Nations Development Program
UNDRIP	United Nations Declaration on the Rights of Indigenous Peoples

USACE	United States Army Corps of Engineers
VR	Virtual Reality
WoO	Window of Opportunity

1 Introduction

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1.1 Chapter Key Messages

- This is the first edition of *Nature-Based Infrastructure for Coastal Flood and Erosion Risk Management – A Canadian Design Guide*.
- Nature-based infrastructure for coastal flood and erosion risk management is a form of nature-based solution, consisting of natural or built assets that rely on, or mimic, natural system processes to provide coastal flood and erosion risk management function, while delivering environmental and other societal co-benefits.
- This document provides evidence-based guidance for practitioners on approaches, methods, and techniques for selecting, designing, deploying, preserving, and adaptively managing nature-based infrastructure in Canada's diverse coastal settings.
- This guide consists of four main parts: introductory material; a review of national regional and community contexts; considerations for selecting, designing, and implementing nature-based infrastructure solutions in Canada; and guidance on methods for predicting performance, monitoring performance, and adaptive management.



This is the first edition of *Nature-Based Infrastructure for Coastal Flood and Erosion Risk Management – A Canadian Design Guide*.

The guide is a product of the *Nature-Based Infrastructure for Coastal Resilience and Risk Reduction* project, which was established in 2019 through the Canadian Safety and Security Program (CSSP) managed through Defence Research and Development Canada's Centre for Security Science and led by the National Research Council of Canada. The project brought together engineers, scientists, and practitioners from federal, First Nations, and municipal government and academia to conduct research and share knowledge to address key factors and data gaps limiting the uptake of nature-based infrastructure for coastal flood and erosion risk reduction in Canada.

Nature-based infrastructure for coastal flood and erosion risk management is a form of nature-based solution (IUCN, 2020), defined here as *natural or built assets that rely on, or mimic, natural system processes to provide coastal flood and erosion risk management function, while delivering environmental and other societal co-benefits* (Vouk et al., 2021).

1.2 Background

1.2.1 Escalating Coastal Flood and Erosion Risk

Flooding from coastal and inland sources is the most pervasive and costly natural hazard in Canada (Golnaraghi et al., 2020). Many Canadian coastal communities and shorelines are vulnerable to flooding and erosion caused by the combined effects of high tides, storm surges, and wave action (Lemmen et al., 2016). In many locations, the risks associated with coastal flooding and erosion are projected to increase over the coming decades due to urbanization, development in areas of high hazard, rising sea levels, declining sea ice cover, and shifting weather patterns associated with climate change (Lemmen et al., 2016; Greenan et al., 2019).

1.2.2 The Need for More Sustainable Risk Management Solutions

Coastal flooding and erosion are natural processes, which contribute to natural ecosystem health and function. Risk arises only when flood and erosion hazards intersect with vulnerable communities, infrastructure, or other valued assets (e.g., cultural heritage). Past and present uses and development of coastal lands in Canada have exposed communities, infrastructure, and valued assets to flood and erosion hazard risk. In some cases, legacy land uses and development have locked in long-term "protect" or "hold the line" flood and erosion risk management strategies. Coastal protection solutions in Canada have conventionally consisted of "hard" or "grey" infrastructure including sea dykes (also known as "dikes" or "levees"), seawalls, revetments, and rock armouring, often deployed without adequate consideration to natural processes or system responses. Potential drawbacks associated with widespread hardening of the coast include disruption of natural sedimentation processes (erosion and deposition) with implications for adjacent shorelines, communities, and infrastructure (Sauvé et al., 2020); loss or degradation of productive habitat (e.g., coastal squeeze) (Pontee, 2013); false perceptions of risk in areas protected by hard structures (Barron et al., 2012); and escalating maintenance costs and vulnerabilities in the face of rising sea levels (Eyquem, 2021).

An alternative approach is to develop an in-depth understanding of natural coastal systems and features and their benefits, and to leverage these strengths to achieve the same goals of reducing risk to communities, infrastructure, and valued assets. Nature-based infrastructure spans a continuum of human intervention (Vouk et al., 2021), from "green" or wholly natural systems (i.e., which may be conserved or restored to preserve natural system functions and benefits) to hybrid or "green-grey" systems that combine hard (structural) and natural infrastructure elements (e.g., marsh-dyke systems, or beach nourishment with control structures) (see Section 1.5 for definitions). The natural elements may be engineered and constructed or may be created and sustained through natural coastal processes. A key requirement for being nature-based is that the infrastructure (hard or soft, green or grey) must work in harmony with natural system processes. Nature-based infrastructure is underutilized for coastal flood and erosion risk management in Canada (Vouk et al., 2021; Eyquem, 2021), despite being well accepted internationally (Bridges et al., 2021; IUCN, 2020).

1.3 Objectives and Target Audience

This document aims to provide evidence-based guidance for practitioners on approaches, methods, and techniques for selecting, designing, deploying, preserving, and adaptively managing nature-based infrastructure in Canada's diverse coastal settings, thus supporting wider utilization of nature-based infrastructure for coastal flood and erosion risk management in Canada. Case study examples are provided to illustrate salient points, lessons learned, and to demonstrate that—when properly conceived, designed, and implemented—nature-based infrastructure can play an important role in effectively managing coastal flood and erosion hazard risk in Canada. Although primarily aimed at providing technical guidance to Canadian practitioners and professionals engaged in conceptualization, design, and implementation of nature-based coastal infrastructure, the guide may also prove useful to communities, decision makers, policy makers, or non-technical users.

1.4 Scope

The focus of this guide is on **nature-based infrastructure for coastal flood and erosion risk management,** defined as natural or built assets that rely on, or mimic, natural system processes to provide coastal flood and erosion risk management function, while delivering environmental and other societal co-benefits (Vouk et al., 2021). A common example is the use of or reliance on beach and dune systems (either wholly natural, constructed, or recharged with sediment) to protect seaside communities from storm waves and high water levels, and to act as a buffer against erosion.

The guide comprises four main parts, which are easily navigated using the colour schemes and icons as follows:

Part 1 – Introductory Material (Chapters 1–3)

- Basic concepts and key principles underpinning nature-based coastal infrastructure.
- A framework for design and implementation.
- Existing technical guidance and resources for practitioners.



Part 2 – National, Regional, and Community Contexts (Chapters 4–6)

- Canadian governance contexts, complexities, and considerations.
- Community and partner engagement and perspectives.
- Regional considerations for nature-based infrastructure in Canada.



Part 3 – Nature-Based Infrastructure Solutions (Chapters 7–10)

- Guidance on system characterization, project scoping, project team assembly.
- Methods for selection, design, and implementation of different types of nature-based infrastructure, grouped by three main categories:
  - Sediment-based solutions.
  - Vegetation-based solutions.
  - Hybrid solutions.



Part 4 – Predicting, Monitoring, and Managing Outcomes (Chapters 11–14)

- Modelling and analytical techniques to predict or assess performance.
- Field monitoring to inform modelling, design, and adaptive management.
- Adaptive management of nature-based coastal infrastructure.





Part 3 (Nature-Based Infrastructure Solutions) includes three chapters dealing with different types of nature-based infrastructure (after Eyquem, 2021):

- Sediment-Based Solutions (Chapter 8): referring to infrastructure solutions that are predominantly sediment-based (e.g., beaches, islands, and headlands).
- Vegetation-Based Solutions (Chapter 9): referring to infrastructure solutions that are predominantly vegetation-based (e.g., marsh vegetation, submerged aquatic vegetation, trees, and upland vegetation).
- Hybrid Solutions (Chapter 10): referring to infrastructure solutions that incorporate combinations of natural and structural elements (e.g., living breakwaters, foreshore marsh-dyke systems, anchored woody debris installations).

It is recognized that most nature-based infrastructure projects do not fall cleanly into these categories and may incorporate multiple types of nature-based infrastructure. In addition, sediment budgets and transport processes are evidently important to support vegetation-based approaches (e.g., dunes). Users of the guide will therefore likely need to refer to all three chapters for feature-specific guidance.

The guide is intended to build on, not duplicate, existing international and regional technical guidance for coastal nature-based infrastructure and nature-based solutions. In particular, it aims to provide technical guidance that is specifically relevant and tailored to nature-based infrastructure in Canada's four main coastal regions (Pacific, Arctic, Atlantic, and Great Lakes), which is not necessarily available elsewhere. For the sake of brevity and accessibility of the guide, users are referred to existing guidelines and other resources where these are known to exist.

This document is intended to guide nature-based infrastructure solutions to manage coastal flood and erosion risk where the hazards are predominantly driven by ocean/sea and large-lake processes, including the effects of tides, storm surges, sea-level rise, waves, and in combination with river flows (in estuaries). Nature-based infrastructure to manage risks arising from purely fluvial (riverine), pluvial (intense rainfall), debris, river/lake/sea ice, and groundwater hazards are not explicitly considered, though some of the solutions presented may apply.

1.5 Key Definitions

The terminology surrounding nature-based infrastructure and related concepts is not standardized in Canada and varies across jurisdictions and organizations, which can lead to confusion among lay people and practitioners alike (Vouk et al., 2021). This section aims to establish a clear basis for understanding terms and concepts used elsewhere within this guide.

Nature-based infrastructure (NBI) for coastal flood and erosion risk management is a form of nature-based solution (NBS). **Nature-based solutions** are broadly defined as "actions to protect, sustainably manage, and restore natural and modified ecosystems in ways that address societal challenges effectively and adaptively, to provide both human well-being and biodiversity benefits" (IUCN, 2020). This broad definition encompasses, but is not exclusive to, solutions that are aimed at addressing flood and erosion risk management challenges.

"Nature-based" implies that the infrastructure relied on to provide flood and erosion risk management benefits can either be wholly natural or *based* on nature (meaning that it can consist of **hybrid** features that combine "grey" or "built" infrastructure with "green" or wholly natural elements, or structures that incorporate features or elements that provide some habitat or ecological value). Different types of nature-based infrastructure may therefore correspond to different points on the green-grey spectrum of nature-based solutions, as shown in Figure 1.5-1 below. Solutions at the greener end of the spectrum typically correspond to greater ecological co-benefits but are not always preferred, depending on a variety of contexts, constraints, or considerations. For example, when retrofitting or upgrading shore protection, it may be more appropriate to retain existing structures and combine them with nature-based elements, than to pursue wholly natural solutions.

Terminology (and spelling) associated with particular types of infrastructure varies across Canada and is often associated with historical or cultural regional norms. For example, on the East Coast, earthen dykes used to protect low-lying land from flooding are referred to as "dykes", which are drained by one-way tide gates called "aboiteaux". This reflects the Acadian history of the region originally responsible for the transformation of expansive tidal wetlands in the Bay of Fundy to extensive dykelands, which are still present today. For consistency in this guide, the spelling "dyke" will be used throughout (rather than "dike").

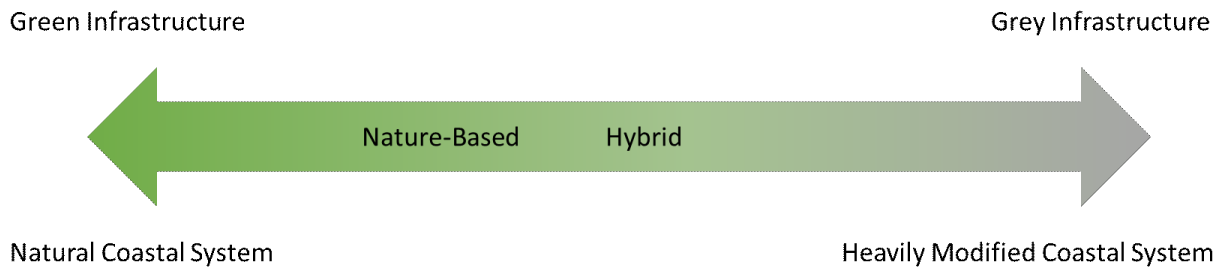


Figure 1.5-1. Green-grey spectrum of nature-based infrastructure (adapted from Bridges et al., 2021).

1.6 Vision for Use of the Guide

This guide aims to provide practitioners (particularly non-specialists) with key foundational information, references, and links to important resources, and information relevant to Canadian applications of nature-based coastal infrastructure that is not necessarily available in other guidance. It is not a "one-stop shop", as a comprehensive manual for design of nature-based infrastructure for coastal flood and erosion risk management could easily extend to thousands of pages, which would likely constrain its accessibility to all but expert practitioners. Our hope is that the guide—which is based on contributions from more than 50 experts from more than 25 organizations, including multiple levels of government, academia, private practice, non-profit groups, and communities—will provide a credible source of evidence and advice encouraging practitioners to consider nature-based infrastructure as an underutilized but potentially effective tool in Canada's portfolio of coastal flood and erosion risk management strategies.

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2 Principles, Key Concepts, Framework

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2.1 Chapter Key Messages

- Nature-based infrastructure (NBI) delivers coastal flood and erosion risk management (FERM) benefits and function in various ways, including:
    - Providing buffer zones between coastal hazards and communities, infrastructure, or valued assets.
    - Attenuating and dissipating storm surges and waves.
    - Providing storage for floodwaters.
    - Attracting and stabilizing sediments.
    - Reducing erosion of sediment.
    - Attracting and stabilizing flora and fauna.
- A key advantage of NBI is that it simultaneously delivers multiple benefits.
- The following principles are recommended for Canadian practitioners as critical to the success of NBI for coastal FERM:
    - Adopt a systems approach.
    - Engage communities, partners, regulators, and multi-disciplinary teams.
    - Embrace Indigenous Knowledge.
    - Deploy strategically.
    - Adaptively manage risk.
    - Choose regionally and locally appropriate solutions.
- A framework for selection and design of coastal NBI in Canada is proposed, based on a typical project lifecycle.

2.2 Introduction

This chapter identifies the relevant concepts and key principles that underpin nature-based infrastructure for coastal flood and erosion risk management and proposes a framework for selection and design of coastal nature-based infrastructure in Canada.

2.3 Relevant Concepts

2.3.1 Coastal Flood and Erosion Risk Management

As explained in Chapter 1, coastal flooding and erosion are natural processes, and vital to healthy ecosystem function. Risk[1] arises only where flood and erosion hazards intersect with vulnerable coastal communities, infrastructure, and valued assets. Flood and erosion risk management (FERM) is the systematic approach and practice of managing uncertainty to minimize potential harm and loss arising from flood and erosion hazards. It involves risk assessment and analysis, and the implementation of strategies and specific actions to control, reduce, and transfer risks (UNEP, 2023). No FERM strategy completely eliminates all risk, partly because the variables that affect risk (i.e., hazard likelihood and severity, exposure, and vulnerability) are prone to change over time (Murphy et al., 2020). These changes may be a result of global-scale issues, such as climate change, which can impact local hazard frequency or severity (e.g., through sea-level rise), or community behaviours (e.g., land use decisions), which may affect exposure and vulnerability (Murphy et al., 2020). Successful FERM strategies therefore tend to have the following characteristics (Sayers et al., 2013):

- Based on long-term, whole-system understanding.
- Rely on knowledge of uncertainty and risk to inform decisions.
- Based on a diverse portfolio of solutions that address multiple objectives.
- Grounded in monitoring, review, and adaptive management.
- Recognize that there is always some residual risk, which may be accepted as a compromise or trade-off for achieving other societal goals.

2.3.2 The Role of Nature-Based Infrastructure in Managing Coastal Flood and Erosion Risk

Nature-based infrastructure, as defined in Chapter 1, delivers coastal FERM benefits and functions in various ways, including (Simm, 2021):

- Providing buffer zones between coastal hazards and communities, infrastructure, or valued assets.
- Attenuating and dissipating storm surges and waves.

[1] Risk is a function of both the likelihood of a particular flood/erosion event occurring, and the consequences (Murphy et al., 2020).

- Providing storage for floodwaters.
- Attracting and stabilizing sediments.
- Reducing erosion of sediment.
- Attracting stabilizing flora and fauna.

2.3.3 Delivering and Accounting for Multiple Benefits

A key advantage of NBI for coastal FERM is that it simultaneously delivers multiple ancillary benefits (known as "co-benefits"). For example, a coastal wetland that provides FERM benefits (e.g., attenuation of storm surges and waves, sediment attraction and stabilization, and flood storage) can simultaneously provide habitat, contribute to biodiversity, enhance water quality, satisfy socio-cultural needs, contribute to carbon storage and sequestration, and provide recreation opportunities (Sherren et al., 2021). The benefits provided by nature-based infrastructure are often referred to as "ecosystem services", also defined as "…direct and indirect contributions of ecosystems to human well-being" (Eggermont et al., 2020). According to the Common International Classification of Ecosystem Services (CICES), ecosystem services may be grouped into three broad categories (Haines-Young & Potschin, 2018):

- The **provisioning** of material and energy needs.
- **Regulation** and **maintenance** of the environment.
- **Cultural** significance.

The Kunming-Montreal Global Biodiversity Framework, signed by Canada, includes Target 11 that calls on parties to "*restore, maintain and enhance nature's contributions to people…*" There is increasing work in Canada to identify, recognize, financially value, and manage the services provided to people by nature-based coastal infrastructure (Eyquem, 2021). This includes work at the local government level to manage natural assets (Eyquem et al., 2022), as well as work at the federal government level on the Census of Environment (Statistics Canada, 2022a) and the Canadian System of Environmental-Economic Accounts - Ecosystem Accounts (Statistics Canada, 2022b). Notably, the extent of protected and conserved ocean and coastal ecosystems is already being tracked (Statistics Canada, 2022c), and ecosystem accounts are being developed and tracked for salt marshes to better value the ecosystem services they provide (Rabinowitz and Andrews, 2022).

2.4 Principles

The following principles—adapted from Bridges et al. (2021) and the International Union for Conservation of Nature (IUCN) Global Standard for Nature-Based Solutions (IUCN, 2020), and reflecting experiences and lessons learned from the Nature-Based Infrastructure for Coastal Resilience and Risk Reduction project (discussed in Chapter 1)—are suggested for Canadian practitioners as critical to the success of NBI for coastal FERM:

- Adopt a Systems Approach (Section 2.4.1)
- Engage Communities, Partners, Regulators, and Multi-Disciplinary Teams (Section 2.4.2)
- Embrace Indigenous Knowledge (Section 2.4.3)

- Deploy Strategically (Section 2.4.4)
- Adaptively Manage Risk (Section 2.4.5)
- Match Solutions to Regional and Local Conditions (Section 2.4.6)

2.4.1 Adopt a Systems Approach

Effective and sustainable FERM requires adopting **systems approaches**. This means working with an understanding of both natural and human systems. Developing a whole-system understanding is crucial to successful implementation of nature-based infrastructure because it provides a broad perspective on the interplay of ecology, geomorphology, hydrology, and hydrodynamics, as well as interfaces with the social system (Vouk et al., 2021; IUCN, 2020; Bridges et al., 2021). Embedded in this principle is the idea that the success of nature-based infrastructure for FERM is dependent on scale (IUCN, 2020; Bridges et al., 2021). The scale of interventions must be commensurate with the scales associated with hazards and risk. However, systems approaches recognize that the cumulative effects of multiple, small interventions can have significant impacts on the system as a whole.

These cumulative impacts can be beneficial in the case of system redundancies provided by multiple-lines-of-defence FERM strategies (e.g., those making use of offshore features, such as islands or reefs, as well as shore-based features, such as beaches and dunes) (Gailani et al., 2021). The potential for negative impacts must also be considered. For example, managed dyke realignment and marsh restoration can deliver FERM benefits (see Chapter 10). However, the potential unintended consequences of altering the tidal prism on flood risk and circulation in adjacent areas must be considered (e.g., Pontee, 2015). As the spatial scales for implementation increase (e.g., multiple managed dyke realignment cells), the potential benefits and risks of unintended consequences both tend to increase.

A key aspect of systems approaches is that they require explicit consideration of a wide range of temporal and spatial scales to arrive at solutions that are sustainable. Consideration of longer timescales is increasingly important for both nature-based and conventional infrastructure, in the context of climate change, and Indigenous Knowledge and oral histories, which may span millennia. For example, the Living Dyke pilot project at Boundary Bay, British Columbia, was designed with consideration for storm conditions lasting a few hours and projected sea-level rise over the 21st century. However, its long-term self-sustainability, needs for replenishment, and potential for scaling up may be determined by geomorphological processes occurring on much longer timeframes (Hill, 2022; Hill, 2024).

An important step in applying a systems approach is establishing system boundaries, which determine the spatial scales that must be considered. At a minimum, coastal FERM strategies and measures should be developed to consider impacts and interactions over an entire coastal sediment cell (a coastal reach that is relatively self-contained, isolated sedimentologically from adjacent reaches, or with clear sediment inputs, outputs and transport pathways), which may transcend municipal boundaries (Figure 2.4-1). Further discussion of coastal sediment cells is provided in Chapter 8. Risk management, analysis, and implementation of adaptation solutions typically benefit from an approach based on these functional coastal units (Lemmen et al., 2016). Systems approaches may be implemented through frameworks, such as Strategic Flood and Erosion Risk Management (issue-specific), or Integrated Coastal Zone Management (ICZM) (holistic) (Vouk et al., 2021) (see Chapter 4).

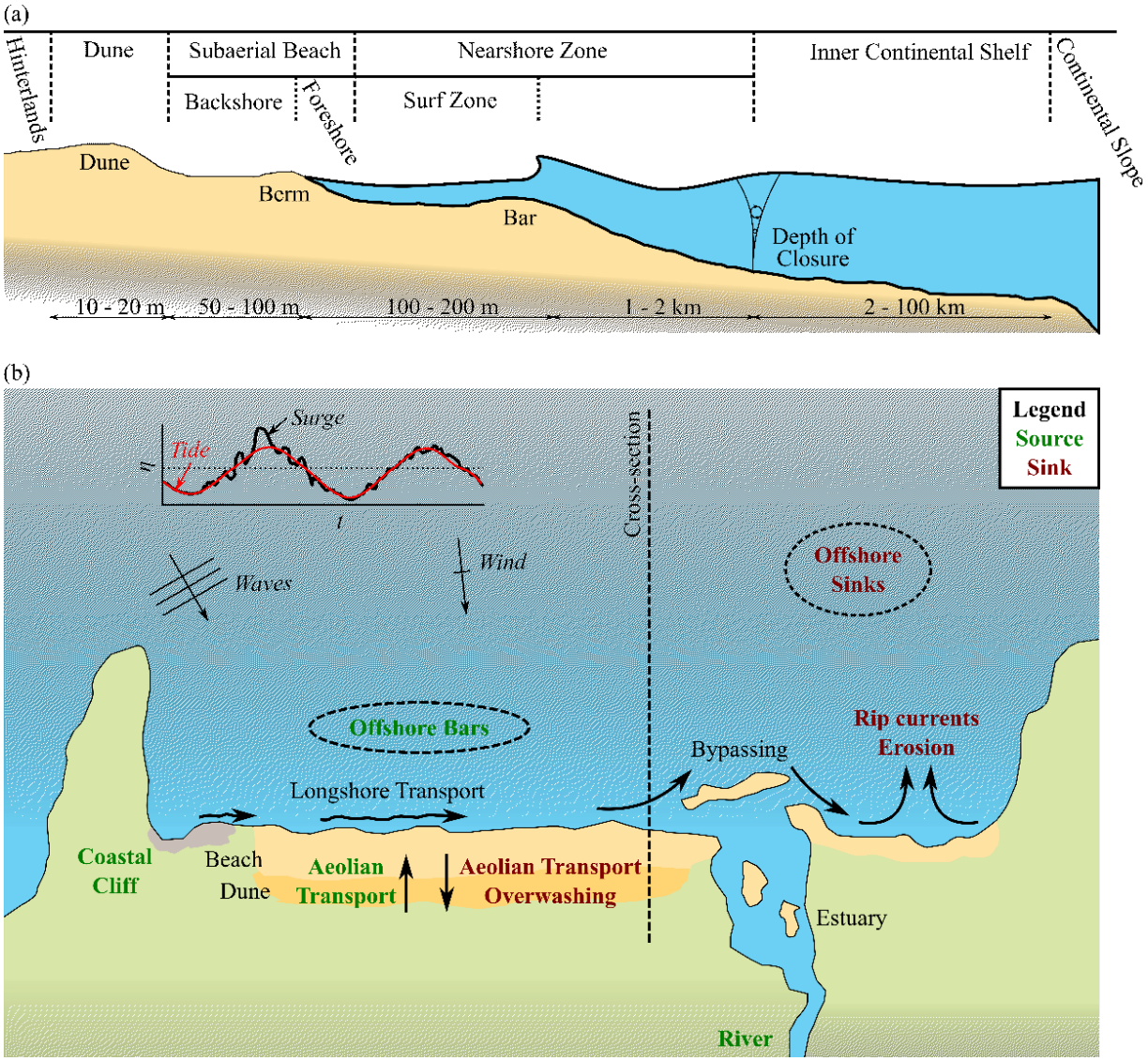


Figure 2.4-1. Conceptual drawing of coastal sediment cell. (a) Cross-shore profile; (b) Planform.

2.4.2 Engage Communities, Partners, Regulators, and Multi-Disciplinary Teams

Meaningful engagement with communities, partners, regulators, and multi-disciplinary teams are important and necessary parts of all planning and decision making for any infrastructure project. For NBI, adopting a systems approach (Section 2.4.1) imposes a requirement for broad engagement and consultation with a variety of rights holders, regulators, stakeholders, and interested or affected parties (Vouk et al., 2021; van Proosdij et al., 2021). Early, comprehensive, and continuing engagement and consensus-building is key to ensuring project success. The multi-objective aspects of NBI mean there are likely to be more beneficiaries to engage than conventional infrastructure projects (Bridges et al., 2021). Engagement should not be viewed as a “box to tick” or a “hurdle to be overcome” but rather as an opportunity to develop and strengthen

synergistic partnerships, build consensus, and steer FERM strategies and projects toward successful outcomes.

NBI design and implementation inevitably requires some degree of innovation, which calls for multi-disciplinary project teams, and diverse perspectives (IUCN, 2020). The planning and design of shore protection projects in Canada has traditionally been led by engineers, due in part to statutory requirements surrounding built infrastructure. Under such circumstances and considering the potential impacts on the environment and public well-being, it is incumbent on engineers or project proponents to build diverse, inclusionary project teams, which may include (but should not be limited to) planners, landscape architects, scientists, and socio-economists. Indeed, Engineers Canada (2016) guidelines require engineers to "…use expertise of others to adequately address environmental and sustainability issues and enhance understanding and improve practices." Similarly, practitioners engaged in planning, restoration, or other activities in coastal zones that have potential to impact flood and erosion risks should ensure appropriate coastal engineering or FERM expertise is engaged.

Considering that the complex and changing regulatory environment is a barrier to NBI uptake in Canada (Vouk et al., 2021), early engagement with regulators is recommended. Comprehensive options appraisal informed by sound technical analyses and multi-disciplinary perspectives, and broad consensus established through collaborative partnerships, can all be helpful in securing regulatory consent.

2.4.3 Embrace Indigenous Knowledge

Prior to European contact, Indigenous Peoples in North America had been co-existing with nature and adapting to changes in natural systems for millennia. Indigenous Knowledge (or Knowledges, since various Indigenous groups may have different knowledge systems and ways of knowing) is therefore crucial to the success of NBI for coastal FERM. Indigenous-led and co-developed solutions to manage coastal flood and erosion risks are vital to uphold the inherent right of Indigenous Peoples to self-determination, which has been recognized by the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP, 2007). A major goal in developing this guide was to showcase Indigenous leadership and co-development of NBI for coastal FERM (Box 2-1).

"Two-Eyed Seeing" provides a possible framework for co-applying Indigenous and "western" science perspectives to NBI solutions for coastal FERM. Mi'kmaw Elder Albert Marshall defines Two-Eyed Seeing as "learning to see from one eye with the strengths of Indigenous Knowledges and ways of knowing, and from the other eye with the strengths of mainstream knowledges and ways of knowing, and to use both these eyes together, for the benefit of all" (Reid et al., 2020). Throughout this design guide, we attempt to provide examples of Two-Eyed Seeing in practice, to demonstrate how this approach can contribute to the success of NBI projects.

Box 2-1. Indigenous Knowledge Contributing to Nature-Based Infrastructure Research

As part of the CSSP Nature-Based Infrastructure for Coastal Resilience and Risk Reduction project, two half-day workshops were organized by the Emergency Planning Secretariat in September 2021. The workshops brought together First Nation communities, local and federal government representatives, engineers, and scientists to discuss the nature-based infrastructure projects that were the focus of the research, and to educate researchers about working effectively with First Nation communities. During Day 1, community members and representatives from the communities (Semiahmoo, Metlakatla, and Mi'kmaw) presented their respective projects to share reflections, highlights, and lessons learned, and to ask questions to each other about their work (Figure 2.4-2). Day 2 focused specifically on important aspects of the process of conducting nature-based infrastructure work with First Nation communities and included presentations and discussions on Indigenous Knowledge or Two-Eyed Seeing as best practices of collaborative project work. Semiahmoo Councillor Joanne Charles provided key take-aways on engagement basics with First Nation communities, including the importance of building trust and relationships, being open and respectful, communicating clearly, and listening with intent.

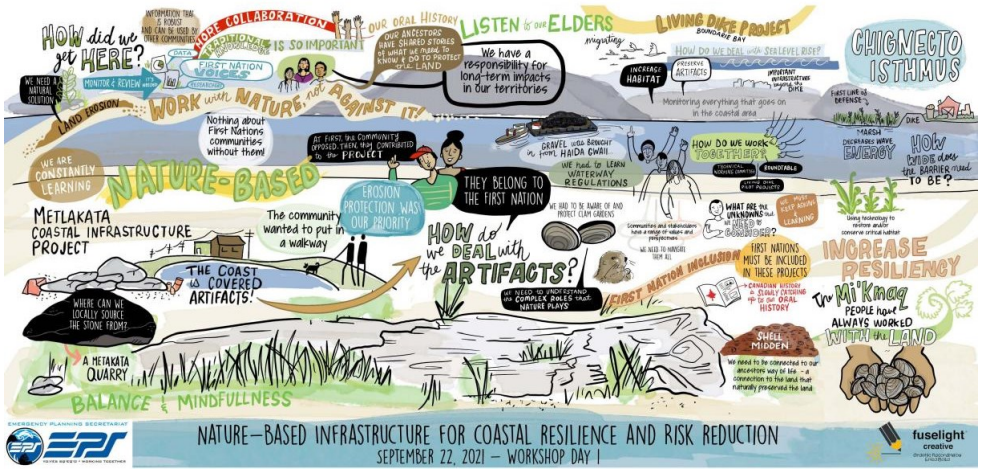


Figure 2.4-2. Graphical recordings of workshop Day 1 discussions (source: Fuselight Creative).

On Day 2, a field visit to the Living Dyke pilot project site in Boundary Bay, British Columbia, was hosted by Semiahmoo First Nation (Figure 2.4-3). Councillor Joanne Charles and Chief Harley Chappell shared teachings about the area's historical, archaeological, ecological, and cultural history, and the stories of the Semiahmoo people, whose Traditional Territory encompasses Boundary Bay.



Figure 2.4-3. Field visit to the Living Dyke pilot site on Semiahmoo Traditional Territory.

2.4.4 Deploy Strategically

Under a systems approach (Section 2.4.1), nature-based infrastructure solutions should be grounded in a comprehensive FERM strategy (or shoreline management strategy) that considers natural and human system boundaries and interactions. Highly localized approaches that do not contribute to, or are not informed by, an overall strategy run the risk of failing to achieve the desired results, causing unintended consequences, being cost-ineffective, or being incompatible with risk management measures implemented in adjacent reaches. For example, hardening or armouring of shorelines by private landowners can exacerbate erosion at downdrift properties (Griggs, 2005; Sutton et al., 2022), resulting in a domino effect that leads to widespread hardening and associated negative impacts on ecosystems and adaptive capacity. This is evident on Canada's Great Lakes shorelines, where extensive hardening has occurred and continues to propagate (Shear et al., 2003). Zuzek (2020) showed that 40 km (or 25%) of the 160-km shoreline of Lake Ontario within the jurisdiction of three conservation authorities had been hardened.

Being strategic about deploying NBI also means recognizing circumstances where nature-based approaches may not be feasible (e.g., because of space restrictions or regulatory constraints), or require hybrid solutions combining hard (structural) and natural infrastructure elements (see Chapter 10).

There is no common framework for strategic coastal FERM or shoreline management planning in Canada. However, there are instances of local governments working together to assess and manage risk arising from coastal hazards that transcend municipal boundaries, which may serve as examples (Zuzek, 2020) (Box 2-2). Proponents may also benefit from comprehensive guidance on developing shoreline management plans from other jurisdictions (e.g., UK Government, 2011) (see Chapter 4).

Box 2-2. Collaboration to Strategically Manage Flood Risk on the Boundary Bay Coast, British Columbia

The City of Surrey, Semiahmoo First Nation, and the City of Delta worked together, and with various other groups, to co-develop a Coastal Flood Adaptation Strategy to reduce coastal flood risk and adapt to sea-level rise (Wong et al., 2022). The collaboration and resulting strategy provided the broad focus needed to access funding through the Infrastructure Canada Disaster Mitigation and Adaptation Fund (DMAF), which had a minimum project size of $20 million, and resulted in the identification of both short-term actions and longer-term strategic directions. Short-term actions included the design and piloting of several innovative NBI concepts, including the Living Dyke pilot (Figure 2.4-4).



Figure 2.4-4. The Living Dyke pilot under construction in Boundary Bay, June 2023.

Once risks are assessed (Murphy et al., 2020) and adequately understood at the system scale, the first steps in developing a coastal FERM or shoreline management strategy are typically to decide on overarching strategic policies for each coastal reach (e.g., Simm, 2021):

- Do nothing.
- Hold the line.
- Advance the line.
- Retreat or managed realignment.

Nature-based infrastructure can play a role in all of these strategic policies. For example, a do-nothing policy may rely on existing flood protection provided by natural coastal features, as well as avoiding development in those areas. Holding or advancing the line may involve beach nourishment (e.g., Box 2-3) or encouraging salt marsh stabilization/expansion to provide flood and erosion risk management benefits, possibly in combination with dyke upgrades (e.g., Box 2-2). Managed dyke realignment may involve breaching of legacy dykes and restoring salt marshes to provide flood risk management benefits further inland. Analogues to these policies exist in the PARA framework for adaptation—Protect, Accommodate, Retreat, Avoid (Doberstein et al., 2019; Eyquem, 2021). Various policies should be explored for each coastal reach, and appraised by considering technical, environmental, social, and economic factors over a variety of timeframes, to arrive at a preferred strategy. Strategic approaches should also reflect Indigenous

and other community values, which may include seeing nature and people working together in harmony, rather than being confrontational, in managing natural hazards (see Chapter 4).

Box 2-3. Nature-Based Infrastructure Contributing to a "Hold the Line" Strategy at Metlakatla First Nation, British Columbia

A sand and gravel beach nourishment was implemented as part of a hybrid shore protection scheme at Metlakatla, a remote First Nation community in northern British Columbia (Figure 2.4-5). The beach was intended to halt progressive erosion that threatened community infrastructure, while mimicking sandy and gravelly shorelines common in that region and many parts of British Columbia.



Figure 2.4-5. Beach nourishment forming part of a "hold the line" shoreline management strategy at Metlakatla, BC. Photo credit: Enda Murphy.

2.4.5 Adaptively Manage Risk

Innovation and faster adoption of emerging best practices are needed to counter escalating coastal flood and erosion risks in Canada. Uncertainty and risk are often barriers to innovation, and a reluctance to embrace nature-based infrastructure solutions is often attributed to perceived greater uncertainty and risk (Vouk et al., 2021). However, conventional FERM measures involving hard infrastructure are not immune to uncertainty and risk, particularly in the context of the changing climate. On the contrary, false perceptions surrounding the "permanence" of hard infrastructure can risk locking in decisions of regret (Cado van der Lely et al., 2021). Interviews with practitioners and experts in Canada have suggested that a shift in mindsets is needed to address a perceived over-reliance on hard (purely structural) risk management solutions (Vouk et al., 2021), and to more openly embrace innovative, adaptable solutions, including nature-based infrastructure.

Phased deployment of solutions and adaptive management are essential for managing risk in an uncertain future, whether for conventional (hard) or nature-based infrastructure, or hybrid systems incorporating elements of both types. In many cases, nature-based infrastructure is more amenable to adaptive management than conventional (hard) infrastructure, which can be an inherent advantage (Cado van der Lely et al., 2021). However, short planning horizons and funding cycles can be a barrier to successful adaptive management.

Future uncertainty (e.g., climate change) can be built into FERM strategies using (for example) the "adaptation pathways" framework, which allows for exploring timing and sequencing of different policies (Haasnoot et al., 2012, 2013; Coulter, 2019) (Figure 2.4-6). Adaptive management can also be applied to manage risk associated with NBI projects, using frameworks such as those presented in Fischenich et al. (2019) (see Chapter 13).



Figure 2.4-6. Five-stage approach to adaptation pathways planning (Coulter, 2019; adapted from Serrao-Neumann, 2015).

2.4.6 Match Solutions to Regional and Local Conditions

To ensure optimal performance, and to maximize co-benefits, nature-based infrastructure solutions should be selected and deployed based on their compatibility with regional conditions (e.g., physical processes, biomes, climates) (van Proosdij & Miller, 2023) and local conditions (e.g., topography and bathymetry, wave exposure, sediment transport gradients, availability of materials, interests of stakeholders and rights holders, local capacity, remoteness and logistics) (van Proosdij et al., 2021). For example, salt marsh creation solutions that may be appropriate on sheltered Atlantic or Pacific coasts may not always be appropriate in Arctic tundra regions (where predominantly sediment-based solutions may be more appropriate) or in the freshwater ecosystems of the Great Lakes. Similarly, submerged reef features may not be suitable for coastal FERM applications in regions with large tidal ranges (like the Bay of Fundy or

northern British Columbia), as they will be too deeply submerged during storms to provide sufficient wave attenuation.

One way to help ensure that solutions are regionally and locally appropriate is to rely on local, natural analogues and local knowledge (including Indigenous Knowledge) to guide identification and selection of nature-based infrastructure options. The presence of local, natural analogues can help to verify that a particular nature-based infrastructure solution is viable and compatible with natural ecosystems, and local environmental forcings (Gailani et al., 2021). However, the presence of natural analogues alone should not be construed as a guarantee of long-term project success, especially in the context of climate change and rising global sea levels. For example, the existence of natural barrier beaches does not guarantee that beach nourishment (or other hold-the-line solutions) will be cost-effective FERM measures, if rates of relative sea-level rise are so high that very large volumes of material are required to sustain performance over time.

2.5 Framework

The international natural and nature-based features (NNBF) guidelines (Bridges et al., 2021) provide a framework for implementing NNBF for coastal flood and erosion risk management that is based on the project lifecycle, assuming a preferred flood and erosion risk management strategy has been identified (e.g., hold the line, or retreat). Here, this framework is adapted (Figure 2.5-1), making it circular to allow for monitoring and adaptive management to inform re-evaluations of scope and design, adding detail to reflect typical project phases in Canada, and incorporating an options analysis/appraisal step (the international guidelines framework assumes nature-based approaches have already been identified as viable or preferred measures to achieve the desired strategy). For the Canadian context, community and partner engagement is further identified as a distinct phase that should be central to, and continuous throughout, the project lifecycle.

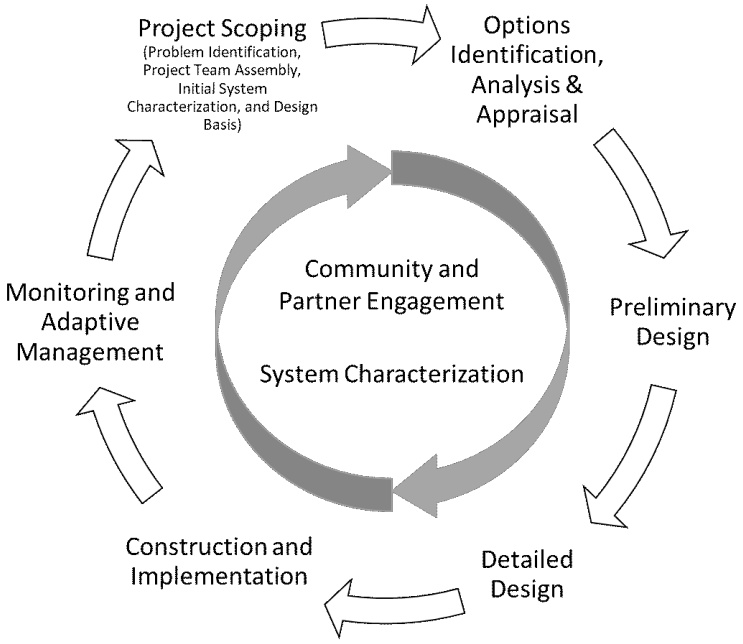


Figure 2.5-1. Framework for development and implementation of NBI projects for coastal FERM in Canada.

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3 Existing Guidance

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3.1 Chapter Key Messages

- In order to effectively plan, design, and implement nature-based infrastructure (NBI), users should draw on existing technical design guidance, as well as guidance relating to strategic coastal planning, policy, funding, options appraisal, and the anticipated impacts of climate change.
- There is extensive international and national guidance on NBI, but existing guidance often lacks the detailed information and specifics required for design and implementation. The maturity of technical design guidance and standards varies depending on the design approach or technique.
- While this chapter identifies key existing guidance for NBI, much of which is applicable in many Canadian contexts, distinct regional and local contexts may determine requirements for alternative approaches or additional considerations not captured in existing guidance.



3.2 Introduction

This chapter signposts two types of guidance and resources for designers of NBI:

- Contextual guidance and resources: relating to international frameworks, understanding of climate change impacts, Canadian policy and funding, and approaches and option appraisal tools to inform strategic coastal management.
- Techniques and method-specific guidance: relating to the design, construction, and/or monitoring of coastal nature-based infrastructure for flood and erosion risk management.

These two sets of guidance provide the fundamental basis for consideration of NBI for coastal flood and erosion risk management (FERM) in Canada. Additional topic-specific references are provided within other chapters of this guide.

3.3 Contextual Guidance and Resources

3.3.1 International Frameworks

There are several key international resources relevant to the design of NBI in Canada. It is recommended that designers of NBI refer to the following publications, at minimum, which provide standards and best practice guidance drawing from experience in countries across the world, including Canada.

Reference	Description
International Guidelines on Natural and Nature-Based Features for Flood Risk Management (Bridges et al, 2021).	Key resource specific to FERM. This publication brings together expertise and lessons learned from the United States, the Netherlands, the United Kingdom, Canada, and several other countries. Chapters 8 to 14 are dedicated to coastal NBI solutions.
International Union for Conservation of Nature (IUCN) Global Standard for Nature-Based Solutions (IUCN, 2020).	A self-assessment standard that aims to support verification, design, and scaling-up of nature-based solutions and provides a framework of 8 criteria to be integrated in their design. Several Canadian government departments are members of the IUCN, including Fisheries and Oceans Canada, Parks Canada, and the Canadian Wildfire Service. This standard, at the time of writing, is the only international standard for nature-based solutions.
Strategic Flood Management: Ten Golden Rules to Guide a Sound Approach (Sayers et al, 2014). (Infographic)	Paper outlining ten “golden rules” to underpin sound strategic flood management decision making, resulting from collaborative research between the World Wildlife Fund for Nature (WWF) and experts in China, the UK, South Africa, Australia, and the U.S.
Words into Action: Nature-Based Solutions for Disaster Risk Reduction (United Nations Office for Disaster Risk Reduction, 2021).	Explores linkage between coastal NBI and the Sendai framework for Disaster Risk Reduction (DRR). There is a specific section on Integrated Coastal Zone Management, and several illustrated coastal NBI case studies from around the world. Canada was signatory to the Sendai Framework for Disaster Risk Reduction 2015–2030 in 2015.

Reference	Description
Nature-Based Solutions for Coastal and Riverine Flood and Erosion Risk Management – Chapter 5 Technical Guidance and Best Practice (Vouk et al., 2021).	A practical introduction to existing international and Canadian technical guidance and manuals, as well as a review of best practices in incorporating NBS for both riverine and coastal infrastructure. Appendix B of the report provides a more detailed description of the summarized documents.

3.3.2 Understanding Climate Change

Designers need to understand the anticipated impacts of climate change on coastal risks, including changes in relative sea level, storm surge conditions, sea ice conditions, coastal erosion, and ecosystem responses. These anticipated changes may be a key driver for implementation of NBI for FERM, and the risk management solutions themselves will need to be designed to address future climate change impacts. A significant amount of climate change–related information is available and scientific understanding is evolving. The table below signposts key international and national resources. Readers should also consult regional climate hubs in Canada for up-to-date information, including Ouranos, the Pacific Climate Impacts Consortium, ClimateWest, and CLIMAtlantic.

Reference	Description
Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT) (Bedford Institute of Oceanography, 2021).	Science-based planning tool for climate change adaptation of coastal infrastructure related to future water-level extremes and changes in wave climate. See further details in Section 6.4.2.3.
Canadian Centre for Climate Services (Government of Canada, 2022a).	Portal and dedicated multi-disciplinary team providing climate-related information and support to organizations.
Climate Impacts (GLISA, 2024).	Provides up-to-date summary of recent research and available data on the impacts of climate change in the Great Lakes region.
Canada's Changing Climate Report – Chapter 7 Changes in Oceans Surrounding Canada (Greenan et al., 2019).	Summarizes current understanding of observed and future changes relating to ocean temperature, salinity and density stratification, marine winds, storms and waves, sea level and ocean chemistry, including levels of confidence.
Climate Change Adaptation (Indigenous Climate Hub, 2022).	Indigenous-led portal developed for Indigenous Peoples regarding the impacts of climate change and efforts to adapt.
Special Report on the Ocean and Cryosphere in a Changing Climate (IPCC, 2022).	Provides a global perspective of the anticipated impacts of climate change on coastal areas and communities.
Relative sea-level projections for Canada (James et al., 2021).	Provides maps and relative sea-level projections for Canada, based on the IPCC Fifth Assessment Report.

Reference	Description
Canada's Marine Coasts in a Changing Climate (Lemmen et al., 2016).	Summarizes key anticipated climate change impacts on Canada's marine coasts together with strategic adaptation approaches. Regional impacts and challenges are presented for east, north, and west marine coasts.

3.3.3 Canadian Policy Context

Designers should be aware of the following resources relating to Canadian policy and funding programs. Appreciation of Canada's national strategy for climate adaptation, including objectives, targets, and indicators, can help users design NBI solutions that contribute to the delivery of the national strategy. Prior awareness of relevant federal government programs and funding application procedures will assist in the design of projects for which proponents wish to seek federal funding.

Reference	Description
Canada's National Adaptation Strategy (NAS) (Government of Canada, 2022b).	Sets out an all-of-society approach for climate adaptation, including specific objectives, targets, and indicators.
Government of Canada Adaptation Action Plan (Government of Canada, 2022c).	Sets out federal government policy and program framework that contributes to achieving proposed targets, goals, and objectives in the NAS. Includes the Climate Resilient Coastal and Northern Communities Program.
Disaster Mitigation and Adaptation Fund (Infrastructure Canada, 2023).	Program providing match funding to Indigenous, provincial, and local governments to prevent, mitigate, or protect against natural hazards. Includes nature-based infrastructure solutions for coastal hazards.
Climate Lens - General Guidance (Infrastructure Canada. 2021).	Mandatory assessment for DMAF and certain other Infrastructure Canada funding streams. Includes Greenhouse Gas Mitigation Assessment and Climate Change Resilience Assessment.

3.3.4 Strategic Coastal Management and Tools to Support Consideration of Alternative Options

There is currently no standardized approach and no strategic planning framework for coastal FERM in Canada. The range and value of benefits that are provided by NBI solutions are also not routinely included in planning and design. The following resources therefore provide important context for the designer, in the form of substantive reviews of strategic coastal adaptation approaches that may be applied, and methods of selecting between different coastal risk management options that more fully take into account the benefits of NBI.

Reference	Description
Good Practices for Integrated Climate Change Adaptation in Canadian Coastal Communities (Government of Canada, 2023).	Guidance for practitioners and decision makers for coastal climate adaptation, highlighting six practices that can assist in developing integrated solutions, notably including system-based approaches, adaptive management supported by monitoring and evaluation, and leveraging nature-based solutions.
Flood and Coastal Erosion Risk Management appraisal guidance manual (Defra, 2021).	Established comprehensive appraisal guidance to support assessment of, and select between, different options for flood and coastal erosion risk management projects, developed and applied in England and Wales since 1999.
Getting Nature on the Balance Sheet: Recognizing the Financial Value of Natural Assets in a Changing Climate (Eyquem et al., 2022).	Review of the state of play of natural asset valuation and management across Canada, framed within the context of international trends, national natural capital accounting approaches, and accounting standards development.
Rising Tides and Shifting Sands: Combining Natural and Grey Infrastructure to Protect Canada's Coastal Communities (Eyquem, 2021).	Reviews international and country-specific approaches to coastal adaptation in the Netherlands, England, the U.S., Australia, and Japan. Provides an overview of nature-based infrastructure coastal protection techniques, and reviews a) options appraisal tools that take into account the benefits of nature-based infrastructure, b) monitoring requirements, and c) opportunities for standardization in Canada.
Nature-Based Solutions for Coastal and Riverine Flood and Erosion Risk Management (Vouk et al., 2021).	Reviews strategic coastal management approaches and the uptake of nature-based infrastructure solutions in Canada. Identifies key challenges and opportunities, together with knowledge gaps and research needs.
Increasing Coastal Resilience with Nature-Based Solutions in the Great Lakes (Zuzek Inc., 2021).	White paper exploring how nature-based solutions can increase coastal resilience in the Great Lakes and help communities and ecosystems bounce back from damaging coastal storms and prolonged periods of high lake levels.

3.4 Techniques and Methods Guidance

Literature on NBI techniques and methods continues to flourish as interest expands in enabling more natural approaches to coastal FERM—when and where feasible or strategically appropriate. This section provides some key overarching guidance available online and easily accessed by practitioners and designers who have an interest in utilizing NBI for coastal FERM. Guidance specific to technical and situational methods is referenced in other chapters of this document.

Reference	Description
International Guidelines on Natural and Nature-Based Features for Flood Risk Management – chapters 8 through 13 (Altman et al., 2021; Gailani et al., 2021; Lodder et al., 2021; Lowe et al., 2021; Piercy et al., 2021; Simm, 2021).	The guidance introduces the context and application of coastal natural and nature-based features for flood and erosion risk management in chapter 8. The following chapters (9 through 13) provide advice on design, implementation, and other necessary considerations to installing each of the following NBI: beaches and dunes, coastal wetlands and tidal flats, islands, reefs, and submerged aquatic vegetation and kelp.
The Coastal Engineering Manual (USACE, 2002).	A comprehensive and detailed manual presenting methods and techniques for analyzing coastal hydrodynamics, coastal sediment transport processes, coastal geology and morphodynamics, coastal project planning and design (including beach nourishment and sediment management), and design of coastal structures.
Coastal Adaptation Toolkit (CLIMAtlantic, 2023).	An online tool kit managed by CLIMAtlantic identifies most suitable flooding and erosion management options for specific locations (i.e., community sites or individual properties) using a questionnaire. Options include land use planning tools, coastal interventions, and engineering tools. The tool is primarily designed for community staff and elected officials, while a more simplified tool is available to property owners. The accompanying guidance explains engineering and land use planning tools suitable to Canada's East Coast shorelines.
Adapting to Climate Change: Solutions to Enhance Great Lakes Coastal Wetland Resilience (ECCC, 2022).	White paper describing the benefits of coastal wetlands in the Great Lakes and solutions to enhance their resilience to climate change. Among a number of adaptation strategies and measures, included are options for integration of coastal wetlands to reduce flood and erosion risk. Though the paper pertains to the Great Lakes, the principles and advice are easily transferable to other coastal Canadian wetlands.
Nature-Based Solutions Guidance (Engineering With Nature, 2023).	Links to key international, Canadian, and U.S. guidance material via the Engineering With Nature® site. The site is regularly updated.
Working with Natural Processes to Reduce Flood Risk (FCERM & Environment Agency, 2021).	UK's Working with Natural Processes evidence base in one place, including reports such as the comprehensive Evidence Directory (with an in-depth focus on NBI in Chapter 5) and case studies.
Marine Shoreline Design Guideline (Johannessen et al., 2014).	Developed for the Puget Sound region in Washington State (U.S.), this design guideline contains potentially useful coastal design checklists and detailed consideration of "soft shore protection" methods—beach nourishment, use of large wood, and re-sloping/revegetation.
Managing Natural Assets to Increase Coastal Resilience, Guidance Document for Municipalities (MNAI, 2021).	Aids coastal municipalities in managing coastal natural assets. A large portion of the guide focuses on the Coastal Toolbox designed to evaluate alternatives, such as NBI, to existing hard infrastructure. Appendix B lists hard and soft coastal solutions or strategies, and a short narrative describing methods in selection of potential strategies.

Reference	Description
The Australian guide to nature-based methods for reducing risk from coastal hazards (Morris et al., 2021).	Developed for the Australian coastline, the guide equips practitioners with a decision-making process for incorporating nature-based methods, followed by engineering and ecologic considerations for developing NBI given the ecosystem or habitat in question.
Nature-Based Solutions for Coastal Management (Natural Resources Wales, 2022).	A site managed by Natural Resources Wales with national guides and policies related to nature-based solutions. Of note are links to enhancing existing hard infrastructure with green features, as well as links to a number of NBI-related case studies throughout the UK.
U.S. Climate Resilience Toolkit (NOAA, n.d.).	A comprehensive website managed by U.S. National Oceanic and Atmospheric Administration (NOAA) providing a framework to identify climate-induced hazards, more than 500 digital tools to aid in the process of decision making, design, and implementation, and case studies serving as examples throughout the U.S. (including coastal NBI) and links to expertise. The site is easy to navigate, with regional and topic-oriented classification, as well as a range of filtering options.
Guide for Applying Working with Nature to Navigation Infrastructure Projects (PIANC, 2018).	A framework aiming to preserve the integrity of ecosystems neighbouring navigation infrastructure while maintaining the resiliency of existing and new infrastructure via the use of natural processes. This guide can be purchased directly from the PIANC website.
Natural and Structural Measures for Shoreline Stabilization (SAGE et al., 2015).	An illustrated, quick guide to generic hard, hybrid, and soft implementation techniques to consider given: shoreline characteristics, energy exposure, construction cost estimates, operation and management costs, advantages and disadvantages.
Strategies for Adapting Great Lakes Coastal Ecosystems to Climate Change – chapter Menu of Strategies and Approaches for Coastal Ecosystems (Schmitt et al., 2022).	Provides a host of strategies to protect the coastlines of the Great Lakes, including: maintenance of existing natural processes; regional characteristics and vegetation; and alteration of ecosystems to accommodate current and predicted changes. Strategy 6 focuses on coastal infrastructure where suggestions for implementation of potential NBI are included.
Building with Nature & Beyond: Principles for Designing Nature-Based Engineering Solutions (Slinger, 2021).	An online course available in an online book format. The first half provides basics in engineering and ecological design principles intertwined to create NBI. A number of existing case studies, including coastal implementations, are provided as examples and exercises. The second half of the book focuses on the importance of the social context of design development.
Green Shores for Homes Credits and Ratings Guide (Stewardship Centre for BC, 2023).	Certification system for “Green Shores” that incorporate NBI and Canada’s “go-to” for homeowners interested in naturalizing their shorelines. The guide applies to new development, as well as renovations and modifications of existing structures, for both freshwater and marine shorelines. Originally developed for the Pacific marine shorelines, the guide was recently updated to include the Atlantic marine shorelines.

Reference	Description
Green Shores Guide to Expedited Permit Process for Nature-Based Shoreline Projects in BC (Stewardship Centre for BC, 2022).	This guide and a complementary checklist were developed in partnership with the Government of British Columbia to expedite the incorporation of a shoreline protection strategy using NBI over hard engineered structures for landowners and managers. Emphasis is placed on working with a qualified coastal professional throughout the project who will define the site's existing coastal processes, flood and/or erosion potential and new protective measures (if required) incorporating nature-based design.
Green Shores for Shoreline Development Credits and Ratings Guide (Stewardship Centre for BC, 2020).	Certification system for "Green Shores" that incorporate NBI. Applicable to residential and commercial marine waterfront development projects, as well as to infrastructure development (such as public walkways) and shore protection works in public spaces (parks and recreational areas).
Shoreline Stabilization Resiliency Design Guide (Texas General Land Office, n.d.).	Provides guidance to planning and design of measures for shoreline stabilization with an emphasis on alternatives to traditional hard infrastructure (i.e., NBI).
Nature-Based Solutions Resource Guide (White House Council on Environmental Quality et al., 2022).	A compendium of tools and resources—many related to coastal NBI—developed by U.S. federal agencies. Table 1 provides links to latest documentation useful to designers and practitioners.
The Efficacy and Design of Coastal Protection Using Large Woody Debris (Wilson, 2020).	Implementation of large woody debris (LWD) as a coastal protection measure is increasing along British Columbia and Washington State coastlines. This thesis is a thorough study of the strengths and failures associated with a number of anchored LWD installation methods. Chapter 6.1.4 provides preliminary guidance imparting advice whether or not to install such a protection measure; and considerations to take into account before installing.
Making Room for Movement: A Framework for Implementing Nature-Based Coastal Adaptation Strategies in Nova Scotia (van Proosdij et al., 2021) (Box 3-1).	White paper providing guiding principles for the implementation of nature-based coastal adaptation strategies for FERM based on comprehensive review of literature on barriers and drivers for NBS, surveys and focus groups of practitioners, coastal residents, and policy makers, and analysis of regional case studies of NBI projects. Particularly applicable for the Maritime provinces but principles are broadly applicable.

Box 3-1. Canadian Tools and Guidance for Coastal Climate Adaptation

In Atlantic Canada, *Making Room for Movement* not only provides foundational principles for coastal nature-based climate adaptation, but also addresses new projects through the "Five R's"—Reimagine, Reserve, Relocate, Restore, Reinforce—which serve to shift paradigms of traditional infrastructure development to new and innovative project decisions, as shown in Figure 3.4-1 (van Proosdij et al., 2021). Other tools from Atlantic Canada include CLIMAtlantic's Coastal Adaptation Toolkit, which supports both community and individual adverse impact assessments and planning for coastal flooding (CLIMAtlantic, 2023). This resource, along with a three-part series of guidance documents serves to highlight opportunities for implementing NBI. In Western Canada, British Columbia provides a wealth of tools for climate change adaptation including assessment reports focused on examining and mitigating risk, as well as their portal to *ReTooling for Climate Change*. This online resource provides adaptation toolkits across both ecosystems and sectors to support new approaches (2023). These examples from Canada's coasts provide a gateway to critical guidance for conducting pioneering approaches to NBI.

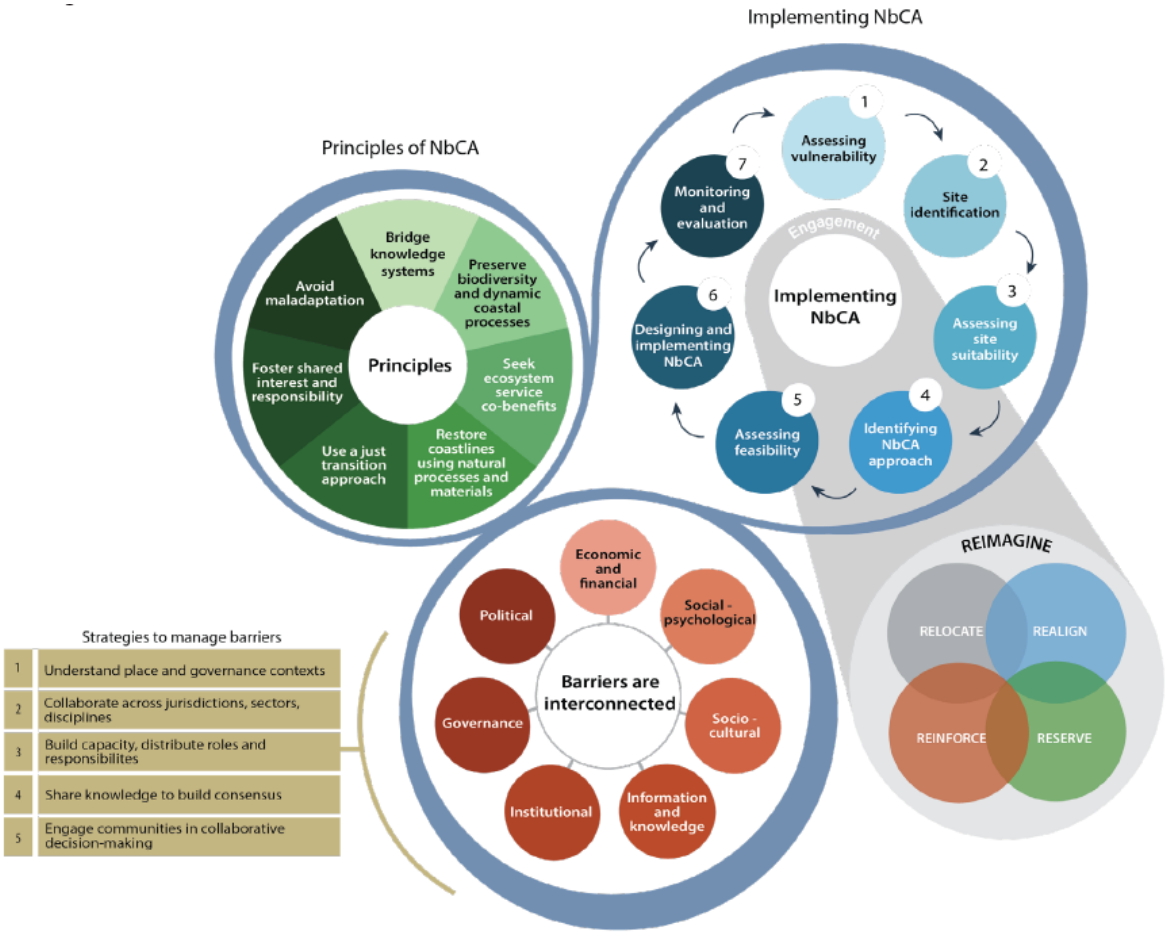


Figure 3.4-1 Atlantic Canada's *Making Room for Movement* framework building upon guiding principles, implementation stages, and breaking down barriers (van Proosdij et al., 2021).

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4 Governance

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Contributors

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4.1 Chapter Key Messages

- Effective governance is essential to adopting a systems approach to coastal flood and erosion risk management (FERM), including the planning, design, and implementation of nature-based infrastructure (NBI).

- Governance needs to reflect the role of different Indigenous and non-Indigenous communities, governments, industry and resource users, non-governmental organizations, practitioners, and researchers in making decisions that impact coastal management. These roles differ across and within Canada's coastal regions.

- There is a current mismatch between the spatial and temporal scales required for effective coastal governance and those typically considered in NBI projects for coastal flood and erosion risk management in Canada. Ideally all projects or risk management measures should be designed as part of long-term integrated coastal zone management (ICZM) or comprehensive FERM strategy.

- In the absence of an established strategic approach, additional work will be required at the project level in order to understand and work effectively with natural coastal processes over the long term and at system-wide spatial scales, to avoid unforeseen or undesirable consequences, and to engage appropriate stakeholder groups in the development of socially acceptable solutions.

4.2 Introduction

Governance is key to adopting a systems approach to managing coastal flood and erosion risk, and therefore fundamental to support the implementation of NBI. As mentioned in Chapter 2, this involves working at spatial scales that reflect natural processes operating within coastal sediment cells, which may cross jurisdictional boundaries. Governance also describes how different Indigenous and non-Indigenous communities, governments, industry and resource users, non-governmental organizations, and researchers come together to make decisions that impact on coastal management. Without effective governance, it is not possible to implement coastal risk management best practices, including NBI solutions.

Box 4-1. The Living Dyke Pilot Stretched Conventional Approaches to Coastal Governance

The Living Dyke pilot project (see Boxes 2-1 and 2-2 in Chapter 2) required extraordinary steps over an approximately 10-year period to develop partnerships and concepts, build political support, secure funding, overcome regulatory challenges, and build capacity and technical knowledge.

"The $20 million qualifying minimum for projects supported through the Disaster Mitigation and Adaptation Fund stretched us to think about bundled approaches and making new partnerships. For example, critical railway upgrades were integrated with flood control upgrades, and in the Foreshore Enhancements Project, we partnered with the City of Delta to evaluate alternative approaches to managing coastal flooding along the shared Boundary Bay. Nature-based solutions were eligible for funding and encouraged us to advance new initiatives."

-Tjasa Demsar and Matt Osler, City of Surrey, British Columbia

Canada does not have a nationally consistent approach to integrated coastal zone management or strategic management of flood and erosion risks in coastal areas (Vouk et al., 2021; Eyquem, 2021). In the absence of a common approach, this section aims to provide readers with understanding, resources, and tools to work toward effective governance for the implementation of coastal NBI.

4.3 Key Concepts and Terminology

Governance is not synonymous with government (Graham et al. 2003). It includes governments, as well as governmental entities and other influencing organizations, institutions, rules, movements, groups, and their decision-making processes. In simple terms, governance involves the answers to three key questions (Institute on Governance, 2024):

- How are decisions made?
- Who has a voice in making these decisions?
- Ultimately, who is accountable?

In terms of what constitutes "good governance", the Institute of Governance has identified five principles based on work of the United Nations Development Program (UNDP) (Graham et al. 2003):

- Legitimacy and Voice
- Direction and Purpose

- Effective Performance
- Accountability and Transparency
- Fairness and Ethical Behaviour

Evidently, coastal governance is only one element of governance, and exists within a framework of formal government. This includes policies, laws, regulations, codes, and standards, as well as other forms of non-mandatory guiding principles. Laws and regulations may require certain actions to be carried out, using incentives, disincentives, permitting procedures, or minimum mandatory standards. At the same time, guidelines or voluntary standards can also support the application of best practices.

Governance, in non-Indigenous systems, has historically employed "top-down" approaches, such as government regulation (Bellanger et al., 2020). In more recent years, there has been greater emphasis on participatory decision making to reflect more fully the values of stakeholders and rights holders (e.g., Bussu et al., 2022). In the context of climate change and biodiversity loss, there is also focus on how adaptive or transformative governance approaches can help support decision making to tackle these key social and environmental challenges (Chaffin et al., 2016). In terms of coastal governance, approaches that have been developed to address a) spatial scales appropriate to the management of natural systems, and b) participatory decision making are:

- **Integrated coastal zone management (ICZM):** A multidisciplinary approach to governance and planning that seeks to balance development and use of resources in coastal areas with environmental and social goals (Post & Lundin, 1996). ICZM addresses a range of issues, one of which is flooding and erosion management, and can involve shoreline management planning.

- **Shoreline management planning or regional coastal planning:** An established approach toward strategic management of coastal flooding and erosion that takes into account natural processes operating within littoral cells over long-term timeframes. This approach includes active stakeholder engagement, and similar approaches have been implemented in countries including the United Kingdom (UK Government, 2011; Environment Agency, 2019a; Environment Agency, 2019b), Australia (Department of Agriculture, Water and the Environment, 2021) and New Zealand (Department of Conservation, n.d.), as well as some areas of Canada (see section 4.6.1).

Further information about the role of ICZM and shoreline management planning in supporting the implementation of NBI is provided in Vouk et al. (2021).

It is also important to recognize that, prior to colonization, Indigenous Peoples were already self-governing within their ancestral lands, and Indigenous laws, reflecting Indigenous legal traditions, applied to these lands and the people living on or moving across them. Many of these legal traditions continue in Canada today (First Nations Financial Management Board and the Institute on Governance, 2018).

4.4 Relevant International Frameworks

Several international frameworks are relevant to coastal governance and implementation of NBI for flood and erosion risk management in Canada. Only a brief overview of three key frameworks is provided here, and readers are recommended to review the frameworks themselves for further details.

- **The Sendai Framework for Disaster Risk Reduction 2015–2030** was adopted at the Third UN World Conference on Disaster Risk Reduction in 2015 (United Nations Office for Disaster Risk Reduction, 2015). The framework outlines seven global targets and four priorities for action to prevent new and reduce existing disaster risks. Priority 2 is "*Strengthening disaster risk governance to manage disaster risk.*" Public Safety Canada is the lead federal department for the implementation of the Sendai Framework in Canada (Public Safety Canada, 2018).

- **The United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP)** was adopted by the UN General Assembly in 2007 and established a universal framework of minimum standards for the survival, dignity, and well-being of Indigenous Peoples and it elaborates on existing human rights standards and fundamental freedoms as they apply to the specific situations of Indigenous Peoples (United Nations, Department of Economic and Social Affairs, n.d.). In 2019, the Government of British Columbia passed the Declaration on the Rights of Indigenous Peoples Act (DRIPA) to establish the UN Declaration as BC's framework for reconciliation (Government of British Columbia, 2019). In 2021, the United Nations Declaration on the Rights of Indigenous Peoples Act became law in Canada (Government of Canada, 2021). As of February 2023, no other provincial governments have implemented legislation enacting UNDRIP.

- **The Kunming-Montreal Global Biodiversity Framework** was adopted in 2022 with a key aim to halt and reverse biodiversity loss. As signatory, Canada has agreed to implement the framework's 23 targets. The role of nature in climate adaptation is underscored by Target 11 of the framework, which calls for parties to use nature-based solutions to "*restore, maintain and enhance nature's contributions to people*", including protection from natural hazards, while Target 14 requires integration of biodiversity and its values within governance arrangements (Convention on Biological Diversity. 2022a).

4.5 Coastal Governance in Canada

This section provides a brief introduction to key elements influencing coastal governance in Canada. This is a complex topic, therefore several resources for further reading are highlighted.

4.5.1 Indigenous Governance

Indigenous Peoples have special rights under Canadian law because their ancestors had distinct legal traditions and rights before Europeans began to colonize the land referred to as Canada (McIvor, 2022). Respect of these rights was written into treaties signed with the Crown in many areas and they were later protected in Section 35 (1) of the Constitution Act 1982 (Government of Canada, 1982).

Upholding and recognizing Indigenous rights across Canada is critical to supporting the Truth and Reconciliation Commission's Calls to Action and relationships between Indigenous and non-Indigenous Peoples. Designers must collaborate with communities on Indigenous-led coastal management values and practices for designing and implementing NBI solutions. The information below should be used to support further learning and understanding of the past, present, and future, together with Indigenous engagement, to act on reconciliation (Wilson-Raybould, 2022)

"First Nations, Inuit and Métis, as the original peoples of this country and as self-determining peoples, have Treaty, constitutional, and human rights that must be recognized and respected" (Truth and Reconciliation Commission of Canada, 2015).

- **First Nations** Peoples were the original inhabitants of the land that is now Canada. There are more than 630 First Nation communities in Canada (CIRNAC, 2024). The Assembly of First Nations (AFN) works to advance the aspirations of First Nations individuals and communities across Canada, which includes more than 900,000 people living in First Nation communities in cities and towns across the country (Assembly of First Nations, 2024).

- **The Inuit** homeland, Inuit Nunangat, stretches across Arctic lands and waters. According to the Inuit Nunangat Policy, the land encompasses 51 communities spanning four Inuit regions: the Inuvialuit Settlement Region, Nunavut, Nunavik, and Nunatsiavut, which have their own governance arrangements as set out in Inuit-Crown treaties. Together, they comprise *"nearly one third of Canada's landmass, more than half of its coastline, and major marine areas, including land fast sea ice, inland waters and offshore areas"* (Government of Canada, 2022).

- **Métis Peoples** are of mixed European and Indigenous ancestry, and live mostly in the Prairie provinces and Ontario, but also in other parts of the country. The Métis Nation of Canada (MNOC) unites and represents Métis People across Turtle Island (Métis Nation of Canada, 2022)

Box 4-2. A First Nation's Perspective on Coastal Governance

"It's important to listen to the First Nations and have them speak their truth of where things are at, how things have been and to be able to hang onto understanding the values of the First Nation. And... being able to listen to them and being able to move forward together in finding a way to do things in understanding how historically the First Nation managed the land, the water, and the resources to help better understand what new ways... of using new technology to do things in an old, traditional way that may help our Mother Earth, our land, our resources."

-Councillor Joanne Charles, Semiahmoo First Nation

4.5.2 Governmental Jurisdictions

All levels of government in Canada—Indigenous, federal, provincial, local—have some jurisdiction in coastal areas with different associated legislation and roles that influence coastal governance. No single body or level of government is responsible or accountable for coastal flood and erosion management, which contributes to a fragmented and inconsistent approach to both coastal governance and implementation of NBI solutions. A review of flood risk management governance in Canada by Golnaraghi et al. (2020) identified the following key roles:

- Federal government: convenes, coordinates, and provides resources.
- Provincial government: has authority over flood risk management, preparedness, mitigation, response, and recovery.

- Local government: implements and enforces flood risk management legislation and manages pluvial flood risk.

The complexity of governmental jurisdictions within the coastal zone may be best illustrated through specific examples, such as have been prepared for British Columbia (West Coast Environmental Law, 2018)[2] and Nova Scotia (East Coast Environmental Law, 2018).

Within the **federal government** alone, several ministries are responsible for certain aspects of coastal management, including, for example (not an exhaustive list):

- Fisheries and Oceans Canada – e.g., fisheries protection under the *Fisheries Act*
- Crown-Indigenous Relations and Northern Affairs Canada – e.g., funding for coastal adaptation for First Nations, Inuit, and Métis Peoples
- Environment and Climate Change Canada – e.g., species-at-risk protection, federal environmental assessment, National Adaptation Strategy
- Infrastructure Canada – e.g., funding for coastal adaptation through the Disaster Mitigation Adaptation Fund or the Natural Infrastructure Fund
- Transport Canada – e.g., the *Navigable Waters Act*, and delivery of Oceans Protection Plan
- Parks Canada – e.g., management of coastal national parks

The policy and legislative context within which NBI approaches are considered in Canada also varies significantly between **province and territory**. The fact that authority over flood risk management is held at the provincial level leads to a fragmented approach, due to different capacities and interests (Golnaraghi et al. 2020).

Along the shoreline of Ontario's Great Lakes, for example, conservation authorities have a legal mandate for flooding and erosion risk management and nature conservation, as well as for permitting development in areas that are "adjacent or close to the shoreline of the Great Lakes-St. Lawrence River System or to an inland lake and that may be affected by flooding, erosion or dynamic beach hazards" (Conservation Authorities Act, R.S.O. 1990, C. C.27, 2023). Other provinces and territories lack legally mandated organizations that operate according to natural system boundaries and have combined responsibilities for regional flood and erosion management and nature conservation. For example, in British Columbia, inconsistent application of international best practice guidance, or national and professional association guidelines was highlighted as a weakness in coastal risk management following the 2021 floods (Murphy & Osler, 2022).

Local governments, including municipalities, districts, and Indigenous governments, also have key roles to play in implementation of NBI for coastal flood and erosion management. Local governments are directly at the receiving end of coastal impacts and are often actively involved in seeking solutions to reduce future risks. However, the level of resources (e.g., data and existing knowledge, staff, funding, equipment) varies significantly between local governments and affects the capacity to plan and design effective NBI solutions.

Bi-national and tri-national organizations, such as the International Joint Commission, and the Commission for Environmental Cooperation, have been established to facilitate co-governance of transboundary waters

[2] https://www.wcel.org/sites/default/files/publications/2018-05-coastaljurisdiction-infographic-updated.pdf

and knowledge-sharing on nature-based solutions for coastal flood risk management with international partners.

Given the jurisdictional complexities, and the regional differences in coastal governance within Canada, it is not possible to provide a “one size fits all” guide to permitting and approvals for NBI projects. However, illustrative examples from British Columbia (Box 4-3) and Nova Scotia (Box 4-4) may provide some insight to typical requirements and jurisdictions in different regions. These examples are provided for information only, and do not constitute legal opinions.

Box 4-3. Example of Jurisdictions and Permitting Requirements for an NBI Project in British Columbia

Federal, Indigenous, provincial, and local (municipal) levels of government all have jurisdiction in shoreline, coastal and marine areas under Canadian Law. In some places there is overlap of jurisdictions, such as intertidal zones, for which province's typically have ownership of the land while federal laws, such as the *Fisheries Act,* apply on provincial and local government lands. Indigenous Peoples also have sovereign powers over their territories and Indigenous laws apply to those territories, as well as Canadian laws (West Coast Environmental Law, 2020).

Within Canadian Law, provincial jurisdiction generally extends seaward to include all land to the "low tide mark" as well as all "inland waters". Of note, "inland waters" includes those areas within bays, harbours, and coves that are between headlands (historically referred to as *inter fauces terrae* as "within the jaws of the land") (West Coast Environmental Law, 2020). In practice, this will include most coastal estuaries.

Notably, the Supreme Court of Canada ruled in 1984 that the waters between Vancouver Island and mainland British Columbia are interpreted to be "inland waters" within the province of British Columbia. As such, the Government of BC has governance of the seabed (on matters within its jurisdiction) of the Strait of Juan de Fuca (Canadian side), the Strait of Georgia, Johnstone Strait, and Queen Charlotte Strait.

According to West Coast Environmental Law, "Ownership of the seabed further north along the BC coast remains unresolved." In practice, the provincial, federal, and First Nations governments are effectively sharing jurisdiction with precedence varying depending on location and situation.

An example list of regulatory authorities with jurisdiction and permits typically required for an NBI project in British Columbia is provided in Table 4.5-1.

In the case of an NBI project at Metlakatla Village near Prince Rupert, enquiries of land title under the British Columbia *Land Act* directed to the Crown Lands office (FrontCounter BC) received a response that the Government of BC recognized no title either on the shoreline or the land. Their determination was the work would be entirely within the jurisdiction of the First Nation reserve lands. There was no attempt by the provincial government to claim jurisdiction on the seabed between Metlakatla Village and Digby Island to the south in this case. However, the BC Archaeology Branch was notified of the work (as recognized Archaeological sites were being altered through burial by sediments). The primary regulator for this project was Fisheries and Oceans Canada (DFO) within the *Fisheries Act*, as it was deemed in review that some compensation was required due to the impact of the project on fish and fish habitat.

Box 4-3 (continued). Example of Jurisdictions and Permitting Requirements for an NBI Project in British Columbia

Table 4.5-1. Example of federal, provincial, and local laws, regulatory authorities, and permits typically applicable to an NBI project in British Columbia.

Federal	
Fisheries Act (Fisheries and Oceans Canada)	Projects near water must apply for authorization from DFO under the Fish and Fish Habitat Protection branch.
Canadian Navigable Waters Act (Transport Canada)	This federal act regulates major works and obstructions on all navigable waters within Canada. Any projects that extend into the mid to low intertidal or subtidal, or otherwise could obstruct vessel navigation, must submit for approval.
Provincial	
FrontCounter BC	BC has created a single point of contact for projects and this office coordinates all of the required provincial permits required for project approval from the provincial government as summarized below.
Land Act	NBI project footprints often extend beyond private lands onto Crown Lands. An application for a tenure on Crown Lands is required in such a case. A legal land survey of the project site is required. Gaining land tenure approval will require consultation with local First Nations.
Heritage Conservation Act	All archaeological sites in British Columbia are protected under the *Heritage Conservation Act*. This applies on both public and private land. A site alteration permit is often required for any projects that are on or near known archaeological sites. It is becoming best practice to bring an archaeologist into the project team early to study the site and manage permits as required.
Wildlife Act	The *Wildlife Act* protects “wildlife” within the Government of British Columbia’s jurisdiction. Of note, amphibians and reptiles are protected and it is illegal to capture, move, or harm them under the *Act*. This is significant as many shoreline rock revetments can be habitat for snakes, and a biologist should assess for reptiles prior to any construction at a project site. Some shoreline areas within BC are designated as Wildlife Management Areas. Projects are possible in such areas but require additional habitat assessment and permitting efforts to gain approvals.
Local	
Different municipalities have different levels of capacity and regulatory oversight within their local bylaws.	

Box 4-4. Example of Jurisdictions and Permitting Requirements for an NBI Project in Nova Scotia

The Green Shores Technical Advisory Committee prepared an "issue sheet" to aid in clarifying First Nations, federal, provincial, and municipal jurisdiction within Nova Scotia's coastal zone. Jurisdictions are defined based on three areas of the coastal zone (as shown in Table 4.5-2): the backshore (landward of the natural boundary), the foreshore (the area between the natural boundary and the low water mark), and the nearshore (the area extending from the low water mark to 200 nautical miles offshore). The natural boundary is defined as "…the visible high water mark of any lake, stream, or other body of water where the presence and action of the water are so common and usual and so long continued in all ordinary years as to mark upon the soil of the bed of the lake, river stream, or other body of water a character distinct from that of the banks, both in vegetation and in the nature of the soil itself." It is generally determined as the lower elevation of terrestrial vegetation or the upper boundary of distinctive aquatic vegetation.

Table 4.5-2. Overview of jurisdictions within Nova Scotia's coastal zone.

<table>
<tr><th></th><th>Municipal</th><th>Provincial</th><th>Federal</th><th>First Nations</th></tr>
<tr><td>Backshore</td><td>Planning and regulation of land use through municipal planning strategies, zoning, development permits, etc.</td><td>Permitting, lease and sale of provincial Crown lands.</td><td>Fish habitat protection, including shoreline/riparian vegetation and timing windows (DFO).</td><td rowspan="3">Planning and regulation in Reserve lands; the Mi'kmaq have full rights to the lands, waters, and resources, as described in the Treaties of Peace and Friendship.</td></tr>
<tr><td>Foreshore</td><td rowspan="2">No jurisdiction.</td><td>Permitting, lease and sale of foreshore land.</td><td rowspan="2">Fish and fish habitat protection (DFO).

Navigable waters (Transport Canada).</td></tr>
<tr><td>Nearshore</td><td>Subject to debate. Nova Scotia claims that some inlets and marine areas seaward of the low water mark are within its territory.</td></tr>
</table>

As an illustrative example, Table 4.5-3 provides a list of the permits that were secured by Coastal Action, an NGO leading a living shoreline project in Mahone Bay, Nova Scotia.

Box 4-4 (continued). Example of jurisdictions and permitting requirements for a NBI project in Nova Scotia

The project was conducted in collaboration with the Town of Mahone Bay, who secured the necessary municipal development approvals. Given the small footprint of the project, after consultation with Nova Scotia Environment and Climate Change it was determined that a provincial environmental assessment was not required, and the project did not trigger an archeological resource assessment through the Nova Scotia *Special Places Act*.

Table 4.5-3. Permits secured for a living shoreline project in Mahone Bay, Nova Scotia.

Level	Authority and Program	Permitting Requirements/ Regulations
Provincial	Nova Scotia Department of Natural Resources and Renewables – Application to Use Crown Land.	Permits for coastal infilling, rock sills and breakwaters, armouring below the high-water mark (*Crown Lands and Beaches Act*).
Federal	Fisheries and Oceans Canada (DFO) – Fish and Fish Habitat Protection Program.	Fish and fish habitat considerations (*Fisheries Act*).
	Transport Canada – Navigation Protection Program.	Approvals for alteration to navigable waterways (*Canadian Navigable Waters Act*).

4.5.3 Non-Governmental Organizations (NGOs)

A multitude of organizations, other than governments, operate to influence decisions taken within the coastal zone, including the consideration (or not) of NBI. This includes financial and business organizations, such as real-estate developers, banks, insurers, and investors, as well as industry organizations, coastal design consultancies, and researchers that provide advice and best practice guidance. Other organizations apply societal influence, such as environmental NGOs, community and faith-based groups, or ideological/political movements. Environmental NGOs working specifically on coastal flood and erosion risk management and the use of NBI in Canada include the Coastal Zone Canada Association and its Nature-Based Coastal Solutions community of practice[3], the TransCoastal Adaptations Centre for Nature-Based Solutions at Saint Mary's University[4], West Coast Environmental Law, East Coast Environmental Law, the

[3] https://coastalzonecanada.org/NBCS/

[4] www.transcoastaladaptations.com

Intact Centre on Climate Adaptation at the University of Waterloo, Ducks Unlimited Canada, and the Natural Assets Initiative.

Each individual, organization, department, profession, and participant has a different set of values, whether explicit or implicit, that influences their approach to coastal flood and erosion risk management and NBI. The stakeholder landscape is also different along each section of coast, and part of the challenge is effectively mapping the roles of different stakeholders in coastal governance and engaging them in developing preferred solutions.

4.5.4 Evolution of Strategic Coastal Management

Although the need for ICZM has long been recognized in Canada, practical implementation on the ground has been slow, as documented by Eger et al. (2021). In 1996, the Government of Canada acknowledged the importance of involving multiple actor groups in decision making for Canadian coasts and oceans through the *Oceans Act* (Government of Canada, 1996). An Oceans Strategy, with an associated policy and operational framework, was subsequently developed by Fisheries and Oceans Canada (Government of Canada, 2002a, Government of Canada, 2002b). In terms of participation, the policy and operational framework included an integrated management collaborative process, involving:

- Indigenous Organizations and Communities
- Federal Authorities
- Provincial/Territorial/Regional Authorities
- Industry and Resource Users
- Non-Governmental Organizations
- Community Groups
- Academic, Science, and Research Community

With regard to management units, the 2002 framework envisaged the establishment of a system of large ocean management areas (LOMAS) within which were nested smaller coastal management areas (CMAs) (Government of Canada, 2002b). Integrated management plans have since been developed for LOMAS—the Beaufort Sea, Pacific North Coast, Gulf of St. Lawrence, and Placentia Bay/Grand Banks—together with a regional oceans plan for the Scotian Shelf, Atlantic Coast, and Bay of Fundy (Fisheries and Oceans Canada, 2019). However, the ocean management plans do not consider coastal flooding and erosion risks, and plans for the smaller CMAs have not been developed as originally anticipated.

The Oceans Protection Plan, launched in 2016 and further expanded in 2022, represents a more recent whole-of-government initiative that includes “better protected coastal ecosystems” as one of its four key objectives (Transport Canada, 2022). The plan covers Canada’s marine coastlines, the Great Lakes, the St. Lawrence Seaway, and some inland waters. While it includes NBI solutions, they are not specifically targeted at coastal flood and erosion risk management objectives, focusing rather on preserving and restoring marine ecosystems.

In the absence of a consistent national approach, planning and implementation of NBI for coastal flood and erosion risk management is currently led by a variety of actors, including Indigenous, federal, provincial, and local governments, and considers a variety of different spatial scales and approaches.

4.6 Examples of Governance Approaches

The following sections provide selected examples to illustrate the variety of governance approaches that are currently applied in Canada.

4.6.1 Shoreline Management and Marine Spatial Planning

Several strategic shoreline management and marine planning initiatives have been undertaken across Canada but with differing degrees of consideration of NBI for coastal flood and erosion risk management.

After extensive property damages in 1985 and 1986, the province of Ontario established a program that required shoreline management plan (SMP) development to be led by Conservation Authorities (Lawrence, 1995). Although this is not a current provincial requirement, SMPs are still being undertaken or updated by Conservation Authorities and local governments, for example, for a 135-km reach of Lake Ontario (Zuzek Inc, 2020), Credit Valley Conservation (Aquafor Beech Ltd., 2011; Credit Valley Conservation, 2018a, b), Quinte Conservation (Zuzek Inc., 2022), and Municipality of Lakeshore (Stantec, 2022). Development of these SMPs included understanding natural processes and risks for functional sections of the shoreline, public engagement, and recommendation of approaches for shoreline management (avoid, accommodate, retreat/realign, and protect), including use of grey and NBI solutions.

In British Columbia, marine plan partnerships have been forged between the provincial government and First Nations to support marine spatial planning and decision making for the protection, conservation, and management of coastal and marine areas and resources. For example, the Haida Gwaii Marine Plan addresses coastal and marine management, economic development, and land use planning. While the plan includes broad, ecosystem-based strategies to address the impacts of climate change on communities and marine ecosystems, the strategies do not address flood or erosion risk management in detail (Haida Nation and Government of British Columbia, 2015). Nevertheless, on relatively undeveloped coastlines, such as those in Haida Gwaii, conservation and effective land use planning are likely the most effective ways to harness the benefits of nature for managing flood and erosion risk.

In Nova Scotia, the recently passed *Coastal Protection Act* aims to support current and future planning for coastal development, taking into account future impacts of climate change, such as sea-level rise and communities vulnerable to increased erosion (Nova Scotia Legislature, 2019). However, the act has not yet come into force as the accompanying regulations are not yet fully developed and approved (Nova Scotia Government, 2023).

4.6.2 Governance Supporting Disaster Mitigation and Adaptation Funded Projects

In terms of implementation of solutions, coastal flood and erosion risk management projects are currently being led by a range of actors, at a range of spatial scales, under different governance arrangements. This is illustrated by analysis of coastal flood and erosion management projects that were funded by the Disaster Mitigation and Adaptation Fund (DMAF) in the first intake in 2019 (Infrastructure Canada, 2023). Of the 12 DMAF-funded coastal adaptation projects:

- 4 were led by provincial governments, 3 were led by Conservation Authorities in Ontario, 1 was led by an Indigenous government, and 4 were led by municipalities.
- 1 project involved interventions across the province of Nova Scotia, 6 projects involved a regional approach benefiting several towns, and 5 projects concerned only one community.
- 4 projects involved use of NBI approaches.

These were projects with over $20 million in total eligible costs. Despite being relatively large-scale projects (in terms of total eligible costs), not all were undertaken at large enough spatial scales (i.e., littoral cells, or regions) that would be needed to enable system-based approaches that are most effective at delivering successful NBI. In addition, NBI was not a mainstream approach to addressing coastal flood and erosion risks in 2019. Nevertheless, the DMAF initiative appears to represent a significant step forward in terms of enabling NBI, by supporting evaluation of co-benefits, innovation, partnerships, and relatively long timeframes for projects to be implemented.

4.6.3 Indigenous-Led and Co-Developed Initiatives

Regional-scale Indigenous-led and co-developed initiatives are rapidly gaining greater traction, including development of innovative conservation financing initiatives (e.g., Project Finance for Permanence). An example is the Great Bear Rainforest and planned network of protected areas in the Great Bear Sea recently endorsed by 15 First Nations and the Governments of Canada and British Columbia (Coastal First Nations & Nanwakolas Council, 2022). Conservation can be an effective mechanism for harnessing the benefits of NBI for FERM (Vouk et al., 2021). In other regions, co-management agreements, such as the Nunavut Land Claims Agreement, empower Indigenous communities to play a central role in decision making and governance related to coastal and marine resources. The Living Dyke Roundtable (Section 5.6.4) is an example of an Indigenous co-developed initiative that has supported collaborative decision making, knowledge sharing, dialogue, and delivery of NBI in Boundary Bay, British Columbia.

Box 4-5. Sea2City Design Initiative

The Sea2City design initiative within the City of Vancouver incorporated Indigenous viewpoints in envisioning future shoreline management along False Creek. This project demonstrated that climate adaptation and reconnection with nature, including through the use of nature-based infrastructure, can also contribute towards reconciliation. Shared values were communicated in a vision that modified typical coastal flood and erosion risk management approaches to reflect mutual benefits and harmony between people and nature (City of Vancouver, 2023):

- *"Restore: a revitalized and rehabilitated shoreline that restores natural functions, features, and ecosystems and includes improved flood protection for upland communities.*
- *"Host: a dynamic place where water, nature, and culture are welcomed and stewarded. Human uses are flexible, adaptable, and leave a light-touch. Infrastructure works with nature to enhance resilience.*
- *"Acknowledge: spaces are retrofitted or relocated over time to improve their resilience and better care for and steward natural systems."*

4.7 Overcoming Governance Challenges

4.7.1 Working at Appropriate Spatial and Temporal Scales

There is a current mismatch or "lack of fit" between:

- Natural coastal system functional units (e.g., sediment cells – Section 2.4.1), coastal governance structures, and local government jurisdictional boundaries.
- Long-term timeframes required for effective coastal flood and erosion risk management planning (often 100 years) and the shorter timeframes considered in funding programs, political cycles, and financial returns.

Ideally all NBI projects should be identified, scoped, planned, and designed as part of a long-term ICZM plan or a comprehensive flood and erosion risk management strategy (see Chapter 2). In the absence of such a strategy, the onus to understand and work effectively with natural coastal processes over the long term, to avoid unforeseen or undesirable consequences, and to engage appropriate stakeholder groups in the development of socially acceptable solutions falls to project proponents (often local governments, communities, and landowners) and the professionals they engage. In the absence of a strategic plan or framework to steer or guide FERM measures (strongly preferred), project proponents and designers should at a minimum consider implications of, and impacts on, natural processes at a system-wide (e.g., sediment cell) scale, not simply at the project scale. Potential changes or disturbances to the system on timescales ranging from hours (e.g., storms) to centuries (e.g., climate change) or even millennia should also be considered.

Post-contact, jurisdictional boundaries and maps have historically served as a tool for asserting colonial power over Indigenous Peoples through the dispossession of land and dismantling Indigenous sovereignty (Lucchesi, 2018). A reassessment of current governance boundaries can serve to engage with historical narratives and support decolonial thinking by refocusing efforts on working with nature for collective benefits.

4.7.2 Inclusion, Equity, and Values

> *"What is considered successful and legitimate adaptation…is determined in part by what people perceive to be worth preserving and achieving, and these in turn hinge on their underlying values and objectives" (Wolf et. al, 2013).*

The fragmented approach to coastal governance in Canada means that effective engagement of an appropriate range of organizations, and people, in development of solutions can be challenging and take significant time. This is particularly true where established working relationships, forums, or common goals are lacking, and where values are not commonly shared among the proponents and community. Those who are underserved, racialized, marginalized, or socially vulnerable can find it more challenging to participate, which may make achieving equitable outcomes more difficult as these viewpoints are under-represented.

When scoping and planning NBI projects, care should be taken to allow sufficient time and resources for stakeholder and community engagement (see Chapter 5) to reach socially acceptable solutions. Where Indigenous or community governance structures already exist, it is often effective to make use of them, since effective engagement also requires building and strengthening trust and meaningful relationships.

4.7.3 Data Management and Sovereignty

A significant amount of data is often required to effectively plan, design, and implement NBI solutions. If there is no comprehensive flood and erosion risk management strategy, time and resources are required to gather and analyze data at the littoral-cell scale, as well as to understand the social and cultural context of the project.

Since there is no consistent approach to coastal management in Canada, data are currently gathered, maintained, and stored in fragmented systems by a wide variety of data providers. The data are also not always readily accessible to all organizations involved in coastal flood and erosion risk management. Responsibilities for collection of the data required for strategic coastal management are also not clearly established. CEC (2024) recommends that the FAIR approach (Wilkinson et al., 2016) to data management be adopted for NBI projects, that is, data should be Findable, Accessible, Interoperable, and Reusable. CEC (2024) also lists some practical considerations for data management from Roche et al. (2015):

- Be mindful of public data archiving
- Make data discoverable
- Provide detailed metadata
- Use descriptive file names
- Archive unprocessed data
- Use standard file formats
- Facilitate data aggregation
- Perform quality control
- Choose a publishing license
- Decide on an embargo

Canada, through its pledge to UNDRIP and policy outlined in the Intellectual Property Strategy, recognizes First Nations, Métis, and Inuit rights to data sovereignty (Innovation, Science, and Economic Development Canada, 2020). Data sovereignty in this context refers to “Indigenous Peoples’ right to maintain, control, protect, and develop their cultural heritage, traditional knowledge and traditional cultural expression, as well as their right to maintain, control, protect, and develop their intellectual property over these” (Tauli-Corpuz, 2016). Project proponents should agree on a data strategy at the outset of a project to ensure “consistency with the laws, practices, and customs of the nation-state in which it is located” (Snipp, 2016), and to cover:

- Step 1: The type of data collected.
- Step 2: The data collection process.
- Step 3: Data storage plan.
- Step 4: Ownership and governance on data accessibility.

Indigenous data governance organizations have been established throughout Canada and can provide further advice. These organizations are based on the principles of Indigenous ownership, control, access,

and possession (OCAP) of data and include the First Nations Information Governance Centre (2019, 2023), as well as regional initiatives, such as the British Columbia First Nations Data Governance Initiative (2017), the Alberta First Nations Information Governance Centre, and the Union of Nova Scotia Mi'kmaq Information Governance and Data Projects Office.

4.8 Future Directions

Coastal governance continues to evolve in Canada although progress towards integrated coastal zone management is slow (Eger et al., 2021). Ongoing trends include greater leadership and involvement of Indigenous Peoples, and increased support from different levels of government for NBI solutions. Two national initiatives that may be important in guiding future governance approaches in coastal zones are:

- **The Climate Resilient Coastal and Northern Communities Program:** Canada's National Adaptation Strategy and the accompanying Government of Canada Adaptation Action Plan introduced a new approach to regional climate resilience through the Climate Resilient Coastal and Northern Communities Program. This program aims to enable "communities to work together to overcome barriers and develop solutions to climate change risks" and could help foster coastal governance and management actions at appropriate spatial and temporal scales (Government of Canada, 2023).

- **National Biodiversity Strategy and Action Plan:** The main instrument for implementing the Kunming-Montreal Global Biodiversity Framework at the national level is via National Biodiversity Strategy and Action Plans (NBSAPs) (Convention on Biological Diversity, 2022b). The Canadian Biodiversity Strategy (Canada's NBSAP) currently dates from 1995 (Minister of Supply and Services Canada, 1995) and will require updating in order to implement the 23 targets for 2030 identified in the new Global Biodiversity Framework. Governance arrangements identified in Canada's updated NBSAP may also be relevant to the implementation of NBI approaches for coastal FERM.

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5 Community and Partner Engagement and Perspectives

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5.1 Chapter Key Messages

- Engaging with communities of stakeholders, Indigenous Title and Rights holders, and other interested and affected parties is essential to the success of nature-based infrastructure (NBI) projects.
- Every community is unique. They are comprised of diverse members with distinct relationships to place and space. NBI project proponents and designers should consider project impacts on all affected groups, including those who are not geographically proximate to a project site.
- Consultation with Indigenous Peoples is not the same as community engagement and is founded on inherent rights, sovereignty, and self-determination in the *Constitution Act*, the *United Nations Declaration on the Rights of Indigenous Peoples Act*, and the Truth and Reconciliation Commission of Canada: Calls to Action, as well as through treaties and other arrangements.
- Engagement should be included early and consistently through all project phases. It should begin with project scoping and be built into each subsequent planning step, through to monitoring and evaluation.
- Successful engagement recognizes that working through challenges often leads to more relevant, inclusive planning, and increases benefits for those involved. Engagement should be supported through a properly resourced engagement framework.
- Engagement approaches should be adapted to fit specific contexts and community needs. There are many engagement approaches to choose from, and what works best for one project may not be best for others.
- Digital engagement strategies provide new opportunities to engage with communities and partners by overcoming conventional barriers, such as costs of attending in-person meetings.

5.2 Introduction

Engaging with communities of stakeholders, Indigenous Title and Rights holders, and other interested and affected parties is essential to the success of nature-based infrastructure (NBI) approaches, and flood and erosion risk management (FERM) in general. The engagement process allows for co-development of values-based principles that are woven into the fabric of risk management and project phases, including scoping, options analysis/appraisal, planning, design, implementation, monitoring, and adaptive management. Community engagement generates a collaborative relationship built on listening with intent, respectful discourse, trusted partnerships, and balancing worldviews, such as Two-Eyed Seeing, which blends Traditional Ecological Knowledge and western science (Bartlett et al., 2012). Designing and implementing an appropriate engagement plan will not only support the project's technical success but also achieve social co-benefits within the community, such as improving local planning efforts, generating new educational experiences, and volunteerism (e.g., in support of conservation). In this way, effective community engagement integrates with all aspects of a project, enhancing inclusivity, equity, diversity, and justice for all participants in the process.

Box 5-1. Consulting with Indigenous Title and Rights Holders is not the same as Engaging with Communities

Community engagement and Indigenous consultation are not the same. Consulting with Indigenous Peoples is an **inherent Right of sovereignty** that has foundations in Section 35 of the *Constitution Act*, the United Nations Declaration on the Rights of Indigenous Peoples, the Truth and Reconciliation Commission of Canada: Calls to Action, areas with treaties and other arrangements, as well as places throughout Canada with unceded ancestral lands.

Human values drive decision making, which makes understanding human behaviour as important as understanding environmental processes to inform the successful delivery of NBI projects. Most projects or FERM strategies require support from governments, industries, Indigenous Title and Rights holders, and the public, making them human-centred. Implementing nature-based solutions shifts away from standard infrastructure management practice in Canada to embrace new approaches and international best practices. As approaches are normalized, cultural change and support may follow. With each NBI context, the point at which normalization occurs will vary based on familiarity and what infrastructure or approaches are currently accepted.

Successful NBI approaches will require collaborative knowledge development and transparent communication between project implementers, partners, and impacted communities. Within this context, respectful and meaningful community engagement and participation are crucial. Good community and partner engagement will build deeper, stronger relationships and contribute to decisions and projects that provide benefits for those involved. These approaches may also serve to normalize NBI—serving as best practices by sharing experiences across practitioners, highlighting future opportunities, and changing expectations, policies, and regulations regarding nature-based projects. This chapter uses applied insights and case studies to provide guidance and develop understanding about community and partner engagement for NBI approaches.

5.3 Key Concepts and Terminology

Communities include diverse groups of people with social and cultural ties who engage in joint action in a geographic setting or location (MacQueen et al., 2001). Place attachments are influenced by connections to the land, air, and water; ancestral, sacred, and spiritual relationships; past and current familial significance; connections to language; existing land ownership and use; governance responsibilities, and more. For many Indigenous communities, place-based bonds have existed since time immemorial. For other communities, changing land and water rights or jurisdictional authorities lead to newer bonds. Some land and water boundaries are fuzzy, like those dependent on social connections. Others, like land deeds, are exactingly clear.

Stakeholders include anyone affected by a potential project. Affected people and groups may include residents, government officials and regulators, academics, and private businesses.

Title and Rights holders are people with inherent, protected legal rights regarding a potential project (Bull et al., 2019). Section 35 of the *Constitution Act* establishes that in Canada, Indigenous Peoples have constitutionally protected rights. The *Constitution Act* recognizes the federal government's **"duty to consult"**, while provincial and territorial protocols are defined by each government and outline consultation requirements with Indigenous Peoples for conduct that might impact their established rights (CIRNAC, 2021). The Canadian federal government's adoption of the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) and the Truth and Reconciliation Commission of Canada: Calls to Action further acknowledges the duty to uphold Indigenous Rights.

Ethical space is a metaphorical space where Indigenous and western worldviews can interact through dialogue and knowledge sharing (ICE, 2018). Ethical spaces allow people with different types of knowledge to work in partnership towards mutually beneficial outcomes.

Values-led management incorporates practices and objectives built on and guided by consistent, transparent values pertaining to environmental interactions that connect people to places and build sustained relationships (Artelle et al., 2018). A values-led approach is based on values specific to a community and its environment. Values are translated into environmental management objectives, which guide policies, and ultimately direct interactions with a place (Artelle et al., 2018).

Engagement is the process organizations use to understand and include communities in decisions that may impact them. Figure 5.3-1 depicts an adapted version of the International Association for Public Participation's (IAP2) (n.d.) participation spectrum. On the left side of the spectrum is informative engagement, which is led by the practitioner and involves a one-way conversation based on information sharing. Informative engagement is a top-down approach, as those with authority provide information without accepting feedback. Advancing along the spectrum, each stage identifies and promotes a methodology that grows in inclusion. Consultation includes opportunities for feedback, but feedback may not be incorporated into decisions. (Note: consultation in the participation spectrum is not the same as consultation with Indigenous Title and Rights holders. See section 5.2 for more information.) During the involve, collaborate, and empower stages, engagement moves beyond the process of simply receiving feedback to building an ethical space that supports community participation and dispersed decision making. Empowering communities provides co-benefits, such as relationship building, innovation, and working toward a shared vision.

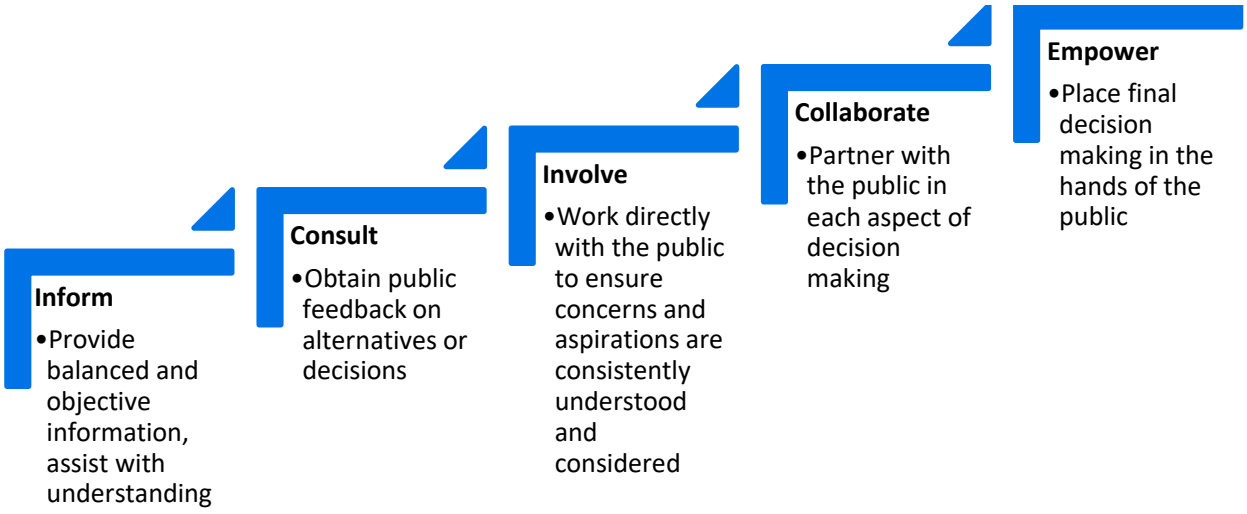


Figure 5.3-1. Public Participation Spectrum (IAP2, n.d.).

5.4 Key Principles for Effective Engagement

Allocate adequate resources for engagement. Effective engagement begins before communities, stakeholders, and Indigenous Title and Rights holders are involved. Adequate resources, including time and funding, will need to be apportioned to engagement efforts.

Engage early. People are impacted by a project as soon as they hear about it, so the earlier they are brought into a planning process, the better (Vanclay, 2018). If communities are included in initial planning stages, proponents can get a more accurate understanding of local conditions, and set a standard for transparent, open communication. Consider bringing ideas to initial meetings, rather than developed concepts or solutions, to create space to include community input.

Engage often. NBI approaches can be complicated, introducing ideas and construction methods that communities and partners may not be accustomed to. Consistent, frequent engagement allows space to clarify ideas and intentions, build trust, and grow relationships.

Meaningfully consider community input. Meaningfully considering community input emphasizes involvement, collaboration, and empowerment. Learning and understanding community perspectives can mitigate future challenges associated with project implementation, operation, and re-capitalization.

Create space for open discussions. Fostering a welcoming environment and open dialogue allows space for listening, considering ideas, and ensuring that those impacted by a proposed NBI approach feel heard. Open discussions can spark new lines of thought and lead to solutions that incorporate different perspectives.

Consider intangible impacts. Discussions about NBI tend to focus on physical interventions to address immediate risks (Neef et al., 2018). Discussions should address both physical risks *and* social and cultural risks (O'Brien et al., 2010). People's perceptions and understandings of the world are tied to local landscapes, and physical changes and interventions to these places will have profound cultural and symbolic impacts (Adger et al., 2008; Chappell et al., 2020). In addition to discussing physical landscape

changes, consider intangible impacts, such impacts on values and culture. It is also important to convey that do-nothing or status-quo FERM strategies represent risks for social settings, particularly in the context of climate change impacts on risk (see Chapter 2).

Recognize potential exclusion and non-participation. Often the loudest, most organized, and most resourced individuals or groups are the ones whose voices end up being heard. Silence is not the same as acceptance or support. Consider impacted people who may not be currently participating and make efforts to include them.

Establish an engagement process. An engagement process based on values-led management will support quality community engagement. Engagement processes should prioritize key principles, while maintaining flexibility to adapt to individual NBI approach contexts and community needs. The process outlined in Figure 5.4-1 is intended as a guide and has been adapted from the IAP2's Standard Process for Community and Stakeholder Engagement (IAP2, n.d).

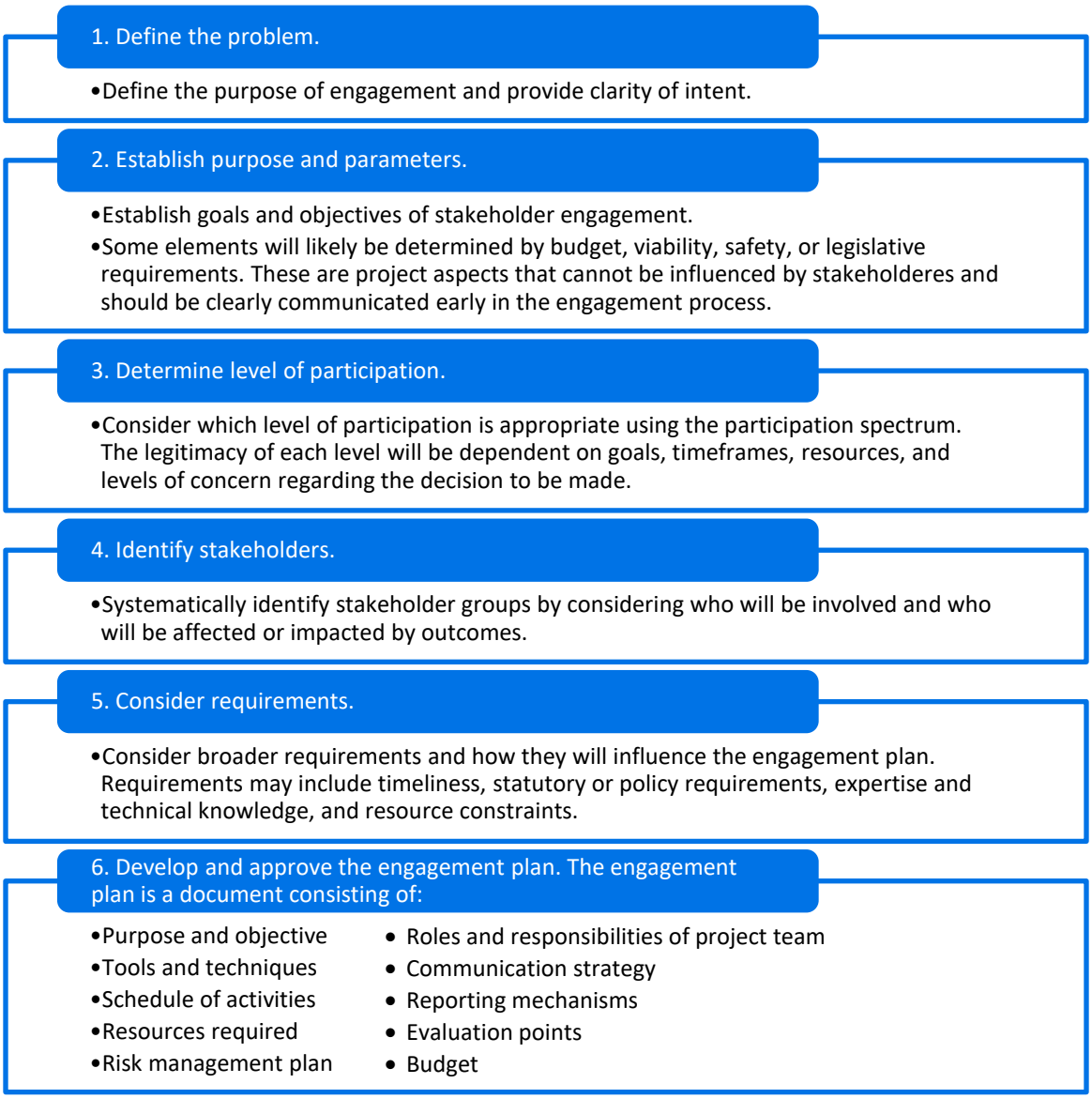


Figure 5.4-1: Process for community and stakeholder engagement (IAP2, n.d.).

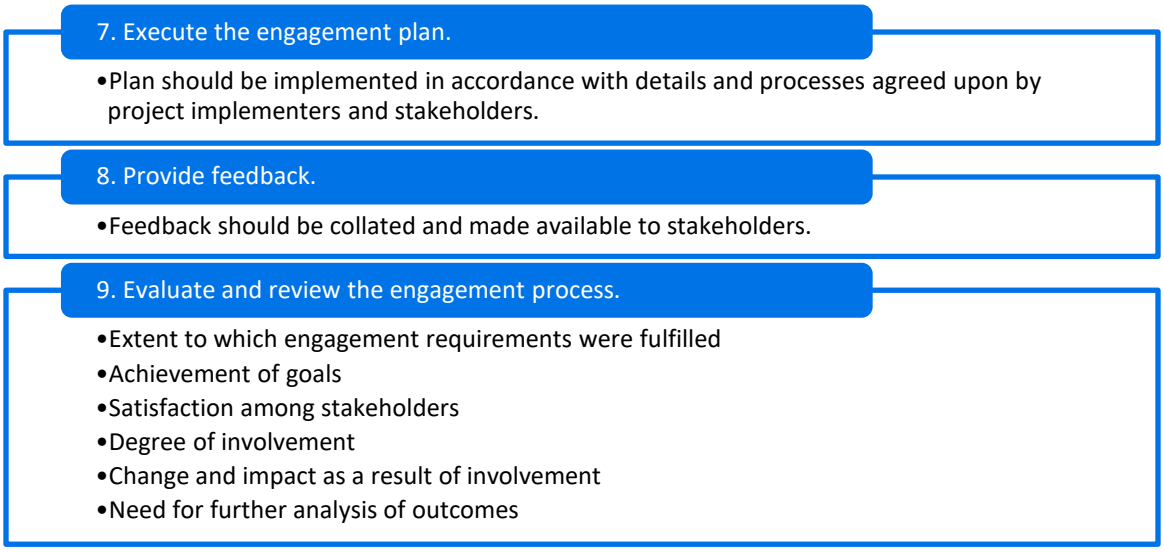


Figure 5.4-1 (continued): Process for community and stakeholder engagement (IAP2, n.d.).

5.5 Collaboration with Indigenous Title and Rights Holders

First Nations, Inuit, and Métis Peoples in Canada have distinct Rights guaranteed under section 35 of the *Constitution Act* (1982). Indigenous communities are Title and Rights holders, not stakeholders, meaning they have sovereignty over their territories, stories, and communities. Therefore, building and maintaining respectful working relationships with Indigenous communities is not the same as community engagement. Indigenous communities should be included in project planning as partners, prior to community engagement efforts. Goals of partnership include co-production of ideas, knowledge sharing, and embracing the varied perspectives of people affected by the project. The intention of each goal is developing better relationships, increasing capacity, and advancing efforts towards reconciliation. The process and protocol for engagement with Indigenous Peoples should be developed by leadership and representatives from Indigenous nations.

Every Indigenous community is different, with unique histories, traditions, culture, spiritual beliefs, and governance. The structure of their governance systems may vary, and it is critical for proponents to be familiarized with this. In Canada, it is important to recognize the difference between a hereditary Chief and elected Chiefs and band councils. Hereditary Chiefs, traditional leaders, or Clan leaders have different power and positions within a community (ICT, 2021; Sorenson & van Dyk, 2022). The position is determined by each community's unique decision-making processes following traditional governance structures. Elected councils and Chiefs are part of a system enacted by the *Indian Act* in 1876 (ICT, 2021). Elected council and Chief positions are colonial in nature, as Canada sought to establish a system of representation and governance in Indigenous nations that reflected westernized governance structures. Elected and hereditary Chief positions may be held by the same person or may be held by different people. Communities assign different weight to the positions, and their social organization will influence whose approval is required (Sorenson & van Dyk, 2022). Therefore, it is important to learn about each Indigenous community's governance structure, procedures, and decision making.

Experiences and protocol established with one group may not be effective or appropriate with another. Leadership or representatives from Indigenous communities should be consulted to initiate dialogue and contribute to joint understanding regarding planning, as well as create an environment of respect. It is important to recognize that Indigenous band offices or administrative offices are often overwhelmed with requests for information or involvement and have limited resources to commit to responding. Basic communication steps should be followed, recognizing that Indigenous governing bodies are responsible for vast areas of land, resources, and people, so the project proposal may not be an immediate priority.

Inclusion of Indigenous communities as formal partners in decision making surrounding flood and erosion risk management must be a priority, given their sovereignty and rights to self-determination. There is also an onus to support and promote Indigenous-led FERM and capacity-building. Ensuring engagement strategies prioritize and uphold national and regional legal commitments is essential when moving forward with projects. Nationally, this includes Section 35 of the *Constitution Act*, articles laid out in the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) (UN General Assembly, 2007), and the *United Nations Declaration on the Rights of Indigenous Peoples Act* (UNDRIPA) (formerly Bill C-15). This also includes the Truth and Reconciliation Commission of Canada (2015) Calls to Action. Provincial considerations may include the Alberta-Métis Settlements Accord, Nunavut Tunngavik Incorporated resolutions towards Inuit Self-Government, and other historic treaties and agreements across Canada. Several cases have been brought to the Supreme Court of Canada, where existing aboriginal and Treaty Rights have been recognized. Cases include Marshal I, Marshall II, and R. v. Sparrow (OECD, 2020). In the past 15 years, legal philosophy has evolved from justifying infringements of Indigenous Rights on Section 35, to recognizing, affirming, and protecting rights (OECD, 2020). Successful NBI planning and implementation must continue recognizing, affirming, and protecting Indigenous Rights through full consent and participation by impacted Indigenous Peoples.

First Nations, Métis, and Inuit have unique protocols regarding ceremony, governance, social relationships, and more. Proponents of NBI must seek to learn the unique engagement circumstances of the Indigenous Peoples they are working with. This may involve providing support through compensation or honoraria for Indigenous staff, Elders, knowledge holders, community members, and other individuals whose participation in engagement activities is not directly related to their daily jobs. It is important to determine and plan for appropriate compensation for different participants. Gifts can be appropriate when engagement activities involve youth and caretakers. Language support and translation capacity should also be considered and factored into planning.

Box 5-2. Canadian Safety and Security Program (CSSP) Nature-Based Infrastructure Research Project, Boundary Bay, BC – Slowing Down and Collaborating

The CSSP Nature-Based Infrastructure Research Project began in June 2020, at the height of the COVID-19 global pandemic. The pandemic necessitated that all the collaborators pause from immediately advancing field activities and focus on relationship building and collaboration with Semiahmoo First Nation, who are Rights holders in the study area. After numerous informal, online meetings, two half-day workshops in September 2021 brought together First Nation communities, local and federal government representatives, engineers, scientists, and academics to discuss the CSSP nature-based infrastructure research projects from the three study sites.

During Day 1, community members or representatives from the communities (Metlakatla, Semiahmoo, and Mi'kmaw) presented their respective projects to share reflections, highlights, and lessons learned and to ask questions to each other about their work. Day 2 focused specifically on important aspects of the process of conducting nature-based infrastructure work with First Nation communities and included presentations and discussions on Indigenous Knowledge or Two-Eyed Seeing as best practices of collaborative project work.

Many communities share similarities (e.g., the connection to water, way of living on the land, concern with Mother Earth, and a dark past) but each is independent and individual with unique stories, traditions, knowledge, governance, protocols, treaty/non-treaty, rural/urban, etc.

First Nation community participation, questions, input, perspectives, knowledge, and history are imperative to the development of the nature-based infrastructure. These are required to work through ideas, challenges, and solutions. First Nations communities provide huge amounts of valuable information based on their experience with the coast, such as archaeology, historical plantings, where river systems were in the basin, how the floodplain reacted historically.

These online workshops were followed by an in-person field visit at the Living Dyke Pilot Sites in Boundary Bay. This visit connected all project partners for a day of collaborating and sharing. Semiahmoo First Nation Councillor Joanne Charles and Chief Harley Chappell made welcoming remarks and spoke of the cultural, archaeological, and geological history of the region. After a group lunch, discussion continued on the history, ecology, and biology of area, the living dyke design concept and the research plans for instrument deployment and data collection.

A second in-person workshop was hosted on the Semiahmoo Reserve in April 2022, where initial research results were shared and discussed. Councillor Charles also shared the history and recent challenges Semiahmoo First has had during a walk around the community.

As the project progressed, there were additional online meetings, as well as in-person opportunities to connect, share, and collaborate.

5.6 Challenges

Successful FERM strategies that incorporate NBI will need to recognize and overcome current social barriers to adoption of innovative solutions, or solutions that may be perceived as innovative or untested. Common challenges have been characterized as processual, socio-cultural, institutional, or technical (Geekiyange et al., 2020; Pathak et al., 2022, Rahman et al., 2023). Each type of challenge is discussed below, along with insights for managing and overcoming them to support successful NBI implementation.

5.6.1 Processual: Turning Challenges into Objectives

Processual challenges occur during planning and implementation of the engagement process. Processual challenges can result from difficulties establishing clear expectations and communicating across spatial and temporal barriers. One of the most effective ways to address processual challenges is establishing an engagement plan that identifies potential challenges and solutions. Part of developing an engagement plan includes creating a list of potential stakeholders or stakeholder mapping to show existing relationships and spatial locations within the impacted landscape. Knowing potential stakeholders helps when designing appropriate engagement techniques. For example, if a proposed dyke realignment project primarily impacts farmers whose fields are flooding, engagement meetings should be scheduled outside of planting and harvesting times, when farmers are especially busy and likely unable to attend a meeting.

Other processual considerations should include adapting communication for disabilities and impairments, adjusting for digital capacity and access to the internet, recognizing various languages may be spoken within a community and having interpretive services, and providing convenient locations for gathering or childcare support. When processual challenges arise during an engagement process, adaptation may be required. It is important to reflect after each engagement session and adjust as necessary.

5.6.2 Socio-Cultural: Cultural Engagement and Creating Meaningful Dialogue

Socio-cultural challenges stem from relational barriers between communities and project proponents. Stakeholder and community attitudes and behavior are critical for successful NBI implementation, maintenance, management, and monitoring (Ferreira et al., 2020; Anderson & Renaud, 2021; Bark et al., 2021). Common challenges include differing perceptions about nature-based approaches (Rahman et al., 2021; Sutton et al., 2022; Rahman et al., 2023), misaligned expectations (Anderson et al., 2021; Verbrugge et al., 2017), and lack of familiarity with novel nature-based approaches (Wolff et al., 2022). Even when there is common subject matter, perceptions of that subject matter vary. Values, beliefs, norms, and standards influence perceptions of nature-based adaptation approaches, and may result in conflicting narratives (Rahman et al., 2021; Rahman et al., 2023). Relational tension may exist from “top-downism”, where past projects were implemented by governing bodies and did not include groups of impacted people. Common barriers that must be overcome include broken trust, disillusionment, lack of engagement or non-participation, and consultation fatigue.

Overcoming socio-cultural challenges takes time and intentional relationship building by everyone involved with a project planning process. Relationship building starts with learning and understanding communities’ concerns and perceptions pertaining to a proposed NBI or initiative. Finding an ethical space for meaningful dialogue is also essential (ICE, 2018). In that ethical space, time can be spent learning and developing

understanding about challenges identified by the community. It is important to focus on concerns associated with the challenge or problem being addressed by NBI, the needs of people impacted by the problem, and desired outcomes from community members. Doing so creates space to design holistic approaches that will meet stakeholders' and rights holders' objectives, while simultaneously delivering multiple co-benefits.

In many cases, bringing in a good facilitator can help bridge gaps between NBI proponents and communities. Facilitators bring unbiased, open communication tools that can help identify implicit and explicit socio-cultural challenges. A good facilitator will also prioritize representativeness, equity, and finding common ground between involved parties. When seeking a facilitator or facilitating team, consider including people that have experience working successfully with communities affected by the proposed project or FERM strategy. Also consider working with a diverse facilitation team to ensure different perspectives are brought to the table.

5.6.3 Institutional: Institutions and Expectations

Institutional challenges pertain to jurisdictional fragmentation and institutional constraints. FERM strategies involving NBI projects require permissions and involvement from varying levels of governance and organizational support. Working across jurisdictional boundaries can be complicated and decisions may be prolonged as they require various levels of approval. Additionally, many institutions currently have a bias towards structural (hard) FERM solutions. Roles, structures, policies, and norms may need to be adapted to better facilitate adoption of nature-based solutions (Rahman et al., 2019).

Box 5-3. New Institutional Arrangements Contributed to Successful Salt Marsh Restoration in Truro, Nova Scotia

A case from Truro, Nova Scotia (Figure 5.6-1), provides an example of how salt marsh restoration for flood adaptation was made possible through new institutional arrangements (Rahman et al., 2019). Institutional challenges were overcome using "communication, trust building, diplomatic networking, making sense of messy social situations, political advocacy and leadership among institutional actors" (Rahman et al., 2019). Overcoming challenges resulted in shifting roles and responsibilities for various responsible parties and contributed to successful salt marsh restoration (Sherren et al., 2019). Additional details can be found at https://www.transcoastaladaptations.com/onslow-north-river.



Figure 5.6-1. Onslow North River Managed Dyke Realignment and Tidal Wetland Restoration site, one year post restoration, depicting evolution of tidal channel and infilling of ditches facilitated by high suspended sediment concentrations on spring tides. Oblique low-altitude aerial image using DJI Phantom 4, pilot Samantha Lewis, CB Wetlands & Environmental Specialists Inc. (Oct. 17, 2022). Credit: TransCoastal Adaptations, 2022.

5.6.4 Technical: Bridging Technical Challenges and Introducing the Unfamiliar

Technical challenges relate to finances and resource availability, as well as the need to bridge unfamiliar technical language and different knowledge systems. Specific challenges include capacity issues, financial concerns, and constraints on time and staff availability. All these challenges can hinder successful community engagement strategies by creating inconsistency in communication, delaying timely information sharing, and causing institutions to fail to engage with communities through the entire length of the project process.

Establishing technical capacity prior to community engagement can help mitigate issues that result from technical challenges. Considerations include determining how funding will be allocated and establishing a fixed communication budget to ensure communication efforts are sustained throughout the process. Additionally, reviewing personnel, time, and financial resource requirements throughout the project will help identify how resources can be used most effectively, and if changes are necessary for more effective resource allocation.

Establishing a plan for sharing technical ideas and knowledge can be included in the engagement strategy, with the goal of building collective understanding about project goals or objectives, performance criteria, and desired or anticipated outcomes of NBI. NBI often involves novel and less widely understood approaches for managing flooding, erosion, and other potential hazards. Technical knowledge should be shared in a respectful and balanced way that demonstrates how nature-based solutions can contribute to community objectives as part of a broader FERM strategy, deliver co-benefits, as well as covering any uncertainties, risks, or potential drawbacks.

Box 5-4. Working Through Technical Considerations in Surrey, BC

In Surrey, BC, within the core territory of the Semiahmoo First Nation, extensive community and partner engagement was led by the City of Surrey Engineering Department to develop a Coastal Flood Adaptation Strategy (CFAS). CFAS identified the need for new solutions and developed engagement and buy-in for implementing nature-based coastal climate adaptation solutions.



Figure 5.6-2: Group photo taken in Crescent Beach, Surrey, BC, on the initial study tour.

With a high level of support developed for implementing CFAS, the City was able to secure federal funding through the Disaster Mitigation and Adaptation Fund to implement an innovative, phased approach that applies adaptive management to pilot a variety of nature-based solutions. This project involved extensive collaboration, supported through an external process called the Living Dyke Roundtable. This is described further in Chapter 12; however, it is important to emphasize that in the case of a large city, such as Surrey, the foundational work of building relationships and knowledge exchange between various organizations, stakeholders, and rights holders helped create a shared understanding of current and projected coastal flood hazards with sea-level rise. These relationships and knowledge were built upon to secure funding to proceed and ultimately successfully implement specific nature-based solutions, such as the Living Dyke shoreline project.

Extensive community and partner engagement developed over three years ultimately supported all orders of government to come together to take action through the Disaster Mitigation and Adaption Funding of the Project: Reducing Coastal Flood Vulnerability in the Coastal Lowlands of City of Surrey, City of Delta, and Semiahmoo First Nation.



Figure 5.6-3: Construction milestone with leadership from Semiahmoo First Nation, Government of Canada, City of Surrey, and City of Delta.

5.7 Tools and Resources

There are many ways communities can be engaged as part of planning, design, and implementation of NBI. Effective use of tools and resources will make space for the communities to drive engagement by creating space for them to share and establish the terms of their engagement. Below is a selection of different engagement methods that could be used during different phases of the project. These methods are not mutually exclusive but provide examples that can be used depending on the scope and needs of the project. Each of the following approaches is designed to create a sense of co-ownership of adaptation solutions and open opportunities for co-creation and co-management of NBI.

***Shoreline Walks*:** Shoreline walks are an excellent way to bring together community members, knowledge holders, and Elders as a form of land-based learning. More than simply a "site visit", the goal of shoreline walks is to open a safe space for learning and healing that may include discussions about the importance of language and the geography of stories, cosmologies and world views, land protections and rights, relationality and accountability, a connection to reconciliation, and much more. Shoreline walks can create opportunities for intergenerational and cross-cultural knowledge transfer and can educate settlers about other value systems and relationships to the land that should be foregrounded in FERM and climate adaptation practice.

Shoreline Stories: A public call for shoreline stories offers opportunities to learn more about how community members and their ancestors connected with the shoreline. This type of engagement is best done as part of a public call, and by offering participants (or winning entries) gift cards or other forms of compensation. It can also be integrated as part of school curricula to have youth engage community members and knowledge holders about the practices and ways of life embedded within shorelines.

Focus Group Discussions: A focus group discussion involves gathering a small group of usually 8 to 12 people (e.g., knowledge holders, youth, volunteer groups, etc.) with specific knowledges or experiences to discuss topics relevant to the project. In contrast to semi-structured interviews, which allow for in-depth conversations with one person, focus groups encourage discussions among other group members, which may be useful to develop shared values as well as the generation of new ideas that can be very useful for decision making. Focus groups are effective for in-person and virtual engagement. Videos and on-screen polls can be used to help facilitate conversation (Sutton et al., 2022). Online focus groups also help overcome barriers from bringing coastal residents together over long distances (Sherren et al., 2022).

Questionnaire Surveys: Mailed and online surveys provide opportunities to better understand experiences, needs, priorities, and feedback on coastal adaptation initiatives. Surveys are among the most popular methods to collect data and can vary in length and format. Surveys can reach a large audience and data can be analyzed in various ways. However, surveys must be carefully designed, may be limited in reach (e.g., lack of internet and time, or remoteness), and are not suitable for follow-up.

Photovoice: Photovoice equips individuals with cameras so they can create photographic evidence and symbolic representations to offer insight, teach others about their experiences and help others see the world through their eyes. Similar to participatory mapping, participants are often given a prompt as a starting point for taking specific photos. This method provides an accessible and inclusive way for participants of all ages to document and convey their understandings of "what matters most" to them about their community and coastal areas through visual media.

Hosting a Community Dinner: Bringing people together around food is a great way to build relationships and social capital and learn more about community dynamics. It also provides opportunities to introduce people to local cuisines that are connected to the coast. The dinner could be organized as a social event only, or it may have an agenda (e.g., knowledge holders are given a platform to share their thoughts).

Physical Models: Model-making involves hands-on activities engaging community members in building physical models of the project site and its larger context. Since challenges related to flooding and sea-level rise (SLR) are connected to topographic differences, physical models (Box 5-5) provide an accessible and effective means to communicating these challenges with communities. Moreover, studies have shown that both the making of the model, and the model itself provide a forum for participants to share Traditional Ecological Knowledge about important land uses, practices, and events. Whereas physical models allow for visualizing and developing an in-depth understanding of coastal processes and hazards, they also enable the community to see, comprehend, interact with, and connect to the landscape. In this way, the model is more than just a map, it can become a means to gather spatial knowledge, and a tool to foster community discussions and interpretations around key issues (Leon et al., 2015). Physical models provide community members and other stakeholders with opportunities to view planned NBI in three dimensions, including interactions with various wave and water level conditions and the resulting coastal processes (nearshore currents, sediment movements and wave runup levels), and provide feedback and input to designers. Rapidly developing Virtual Reality (VR) and Augmented Reality (AR) technologies (e.g., Zhou, 2022) offer promise for new digital tools to complement or provide alternatives to the immersive, interactive experience delivered by physical models.

Box 5-5. Physical Model for Metlakatla Shore Projection Project



Figure 5.7-1. Metlakatla staff and community members visit physical models at NRC labs.

Metlakatla First Nation has implemented a hybrid shore protection scheme along their reserve shoreline in northern British Columbia. Metlakatla staff and community members visited physical models at the NRC labs. Photo credits: Enda Murphy.

Pop-Up Installations: Pop-up installations may include kiosks with project information or a "do-it-yourself" approach to temporarily transform spaces to raise awareness and increase opportunities for social interaction. Pop-up installations can be short term (a day or multiple days) or longer term (several months) and provide an opportunity to directly engage with users of a site. One example is the Mud Gallery in

Olympia, Washington, which engaged the public imagination and got people excited about the mud of the restored Deschutes Estuary (ASLA, 2021).

***Community Planting/Monitoring/Stewardship*:** There are a range of different ways individuals, groups and communities can be engaged in the enhancing, monitoring, and stewarding of the coastal zone. Community members can be invited to participate in "planting days" (planting of vegetation), "clean-up days" (removal of debris), and "monitoring days" (e.g., through habitat mapping, inventory of different species, etc.). Many of these activities can be linked to school curricula to expand traditional curricula with opportunities for outdoor and land-based learning. These stewardship activities are essential in bringing individuals, groups, and communities together and creating a shared responsibility for our lands and waters.

Box 5-6. Community Planting in Shelburne, Nova Scotia

In the town of Shelburne, Nova Scotia, more than 40 community volunteers, municipal staff, and project partners spent a weekend installing a living shoreline in 2020. The Shelburne living shoreline uses logs, haybales, and native vegetation to stabilize and naturalize the bank (Manuel et al., 2020). More information can be found in the case study summary or at TransCoastal Adaptation's website.



Figure 5.7-2. Living shoreline in Shelburne, Nova Scotia. Photo credit: CB Wetlands & Environmental Specialists Inc.

***(Design) Workshops*:** Workshops are hands-on, activity-based sessions to address challenges and questions that emerge during specific stages of the design process. Most often workshops are conducted in person, but platforms such as Zoom in combination with Jam Board and Miro enable effective online variants as well. Virtual workshops may be a good fit when participants are geographically spread out, as hosting a virtual workshop eliminates travel and accommodation costs. Workshops provide an opportunity to bring together a diverse group of people—they are about collaboration and creative problem solving. Workshops can help foster teamwork and innovation, support breaking down silos, and encourage participants to challenge their assumptions. It is important to select a location that is easily accessible to the community and create enough time and space during the workshop for people to respond.

***Participatory Mapping*:** Participatory mapping makes use of an existing map of the project area that participants can provide ideas and feedback on. Participants are asked to mark places of interest to them that are relevant to the project or target project outcome(s), using specific prompts. Prompts can be related to understanding how areas are used or valued for certain activities. Prompts can also refer to direct observations, such as effects of shoreline erosion. These prompts can be used to spark discussion with the participant group after the mapping exercise about landscape and lived values, existing challenges and areas of importance, and potential opportunity sites (Nicholas Institute for Energy, Environment, & Sustainability, n.d.). *Note: Since certain information gathered as part of participatory mapping processes may be confidential, it is important to have protocols in place related to how information is communicated with broader audiences. When practices include Indigenous partners, OCAP principles of ownership, control, access, and procession should be adhered to (First Nations Information Governance Centre, 2019)* (see Section 4.7.3).

5.8 Future Directions

Engagement approaches for NBI are continually evolving and adapting. Recent decades have shifted towards participatory approaches that involve local communities and impacted peoples. Good practice entails community engagement at the outset of a potential project, from scoping through to evaluating outcomes. Communities are increasingly involved in project design and implementation, creating new opportunities to incorporate their knowledge and capacity to develop sustainable solutions. Given communities' key role in NBI approaches, it is important to acknowledge challenges and shifts that will impact engagement going forward. This section addresses two major considerations for the future of community engagement: 1) increasingly uncertain and unpredictable situations like COVID-19, and 2) increasing digitalization and data availability.

Coastal communities are some of the most vulnerable to negative impacts from climate change and human-caused stressors. Combined with other threats, like a worldwide pandemic, coastal communities face multiple challenges and will require ongoing effort to maintain meaningful and effective engagement. COVID-19 fundamentally changed the landscape of community engagement. Methods developed or advanced during the public health crisis emphasize virtual meeting spaces and platforms to connect with communities. Specific technologies include virtual meetings with breakout rooms and digital whiteboards alongside chat panels. Going forward, digital platforms provide opportunities to improve participation by offering flexible, broadly available spaces.

Data are also increasingly digitized. Climate change data are becoming more accessible as they are housed with agencies and organizations, like the Canadian Centre for Climate Services and CLIMAtlantic, which serve as platforms for knowledge mobilization and dissemination. For organizations that can access and process considerable amounts of data, large, digitized datasets are an asset. For others without those capabilities, it can be overwhelming. Counterintuitively, the democratization of data can exacerbate issues, such as marginalization and disenfranchisement, by excluding community members who are unable to engage in online project information due to lack of technical skills or the ability to translate technical data into meaningful information. There is also a substantial discourse over appropriate data management, including usage, ownership, and dissemination planning. For example, ensuring Indigenous Knowledge is protected and kept private, and shielding archaeological sites from looting (see Chapter 4 regarding the direction of OCAP and specific regional initiatives).

Supporting communities must include focusing on capacity building to empower them to synthesize data into usable information. Capacity building includes providing learning opportunities and trainings to facilitate adoption of new skills. There are opportunities for new technologies to utilize available data and improve community engagement. For example, augmented reality can be used to help project participants visualize outcomes of a changed space and place before groundwork is completed (Tomkins & Lange, 2019). Looking to the future there will not be a one-size-fits-all approach for adapting community engagement in the digital age. Rather, careful planning focused on inclusivity and innovation will facilitate further exploration of how community engagement can continue to contribute to effective nature-based coastal adaptation.

Box 5-7. Incorporating Digital Platforms into Engagement Efforts

Before:

- Determine which digital meeting platform best serves participants.
- Identify opportunities that combine whichever tools and resources will be used and how an electronic space will support knowledge sharing (e.g., breakout rooms, chat panel, live surveys, or polls).
- Decide whether the meeting will be recorded based on participant approval.
- Support participant training on use of the digital platform prior to the meeting, if needed.

During:

- Ensure meeting privacy is maintained (use of codes or participants must be permitted entry to the meeting).
- Determine the need for multiple moderators and note takers to ensure chat panel discussions are captured and heard.
- Support inclusivity and equity in the voices of those attending the meeting.

After:

- Assign access to the meeting link if the meeting was recorded.
- Follow up for information that was not covered and unanswered questions.
- Assess the effectiveness of engagement and adapt for future engagement.

The practices discussed in this chapter provide examples and guidance for community and partner engagement for NBI. Successful community and partner engagement involves continuous learning, communication, and collaboration. Prior to embarking on NBI projects, Indigenous Title and Rights holders must be consulted to ensure appropriate strategies are developed within relevant legal frameworks. When possible, consider moving beyond historical top-down approaches to collaborate with and empower impacted communities. Doing so offers opportunities to recognize co-benefits and support societal challenges by implementing NBI that considers the needs and perspectives of groups of impacted people. Effective engagement may require those involved to step outside of their comfort zones and implement new tools and methods, including those outlined in Section 1.5. Nature-based solutions can have a positive role facilitating and enabling effective engagement by providing connections to nature and a space to explore how NBI can be successful. Meaningfully considering communities can also help build relationships that will last beyond the conceptualization, development, and implementation of specific NBI approaches.

Engagement will look different for every context, but in every context, good, effective engagement practices can contribute to successful NBI approaches and flood and risk management.

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6 Regional Considerations for Nature-Based Coastal Infrastructure

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6.1 Chapter Key Messages

- Four coastal regions of Canada are defined and summarily characterized: the East Coast, North Coast, Pacific Coast, and Great Lakes regions.
- There is tremendous diversity across and within Canada's four major coastal regions. Developing a thorough understanding of the regional and local system setting, including climate, meteorology, oceanography/limnology, physiography, ecology, socio-economics, culture, and governance are essential steps in the systems approach needed to successfully implement nature-based infrastructure (NBI).
- NBI solutions must be well suited to their setting and local environment. This implies that NBI must be designed to function and thrive in concert with local system processes (natural, socio-cultural), and with existing coastal infrastructure.
- Regional and local system characteristics may determine the types of NBI that are viable. For example, submerged aquatic vegetation or reefs are expected to be effective at attenuating waves only where tidal ranges are small, or as part of multiple-lines-of-defence systems.
- Different types of NBI are often favoured in different types of coastal settings:
    - Sediment-based solutions (see Chapter 8) are often most suitable on sediment-rich coasts and should be considered on all coasts. Solutions comprised of coarser sediments are often most appropriate for coasts where the native shoreline sediments are coarse, or coasts with higher wave exposure and/or sites where the available cross-shore width is limited. Solutions comprised of finer sediments are often appropriate on coasts where the native sediment is predominantly fine and greater cross-shore width is available.
    - Vegetation-based solutions (see Chapter 9) should be considered on coasts with relatively modest wave exposure, or as part of a multiple-lines-of-defence strategy, and where climate, hydrodynamic, and soil conditions are suitable to support vegetation growth. The chosen species must of course be appropriate for the region.
    - Hybrid infrastructure (see Chapter 10) solutions are often favoured along partially developed or urban coasts where some form of anthropogenic (human-constructed) coastal infrastructure may already exist, or in high wave exposure environments.

  Effective NBI solutions can involve combining all three types of NBI (vegetation-based, sediment-based, and hybrid) to create a range of coastal environments and habitats, hence supporting greater biological diversity, greater resilience to disturbances, and a wider range of co-benefits.



6.2 Introduction

Canada's coastline, stretching approximately 243,000 km, is longer than that of any other nation. Following Lemmen et al. (2016), Canada's coastline can be divided into four large regions: East Coast, North Coast, West Coast, and Great Lakes (Figure 6.2-1). A common thread across these regions is the tremendous diversity both among and within these regions. For example, coastal permafrost is a key feature across much of the North Coast but is unimportant elsewhere. Some subregions, notably the Bay of Fundy in the East Coast region and Ungava Bay in the North Coast region, feature extremely large tidal ranges whereas other regions, such as the Great Lakes, experience much smaller water level fluctuations. Some portions of Canada's coastline, notably exposed portions of the west coast of Vancouver Island and Haida Gwaii and the east coast of Newfoundland and Cape Breton are frequently exposed to high wave energies, whereas other coasts are far more sheltered. Climatic conditions and the characteristics of the natural environment (flora and fauna) are other important aspects influencing NBI design and performance that vary greatly across Canada. The population density along Canada's coast and the capacity to implement, monitor and maintain NBI also varies greatly across the country and within each region.



Figure 6.2-1. Map showing the extent of the West, North, and East Coast, and Great Lakes regions.

Another common thread is the reality that coastlines are dynamic regions that are continuously changing in response to ever-fluctuating conditions. Rocky coasts tend to change very slowly (depending on material geology) whereas sandy coasts can change dramatically during a single storm event. Lemmen et al. (2016) and Greenan et al. (2019) document how climate change is impacting Canada's marine coastal regions

and accelerating the rate and nature of change along Canada's dynamic coasts, with widespread impacts on natural and human systems. Lam and Dokoska (2022) present a practical overview of climate trends and impacts in the Great Lakes region based on climate and water-level projections. When changes occur slowly or disturbances occur infrequently, many natural coastal systems have an ability to adapt to the changes or even restore previous conditions. However, when the pace of change accelerates, the ability of natural systems to adapt or heal can fail, often leading to loss of productive coastal habitat, or exposure of coastal communities and valued assets to flooding and erosion hazards. The CanCoast study highlighted in Box 6-1 attempts to map the diverse vulnerability of Canada's marine coasts to erosion and flooding.

As discussed in Chapter 2, and in Vouk et al. (2021), nature-based infrastructure (NBI) should be implemented following a systems approach (de Vries et al., 2021) in which a broad range of physical, biological, and social processes and their interactions are considered across a range of temporal and spatial scales. This chapter provides a high-level overview of key regional factors and differences that should be considered when characterizing coastal systems with a view to NBI design and implementation in Canada. Existing reports describing aspects of Canada's coastal regions in more detail (e.g., Lemmen et al., 2016; Greenan et al., 2019), and sources of regional data (e.g., Murphy et al., 2020), are signposted as key resources for further guidance.

6.2.1 Objectives

The main purpose of this chapter is to provide guidance on how regional differences may affect the scoping, design and implementation of NBI. It will set the context for how preferred NBI solutions differ by regions in Canada, and establish a foundation for characterizing site-specific coastal processes within broader system contexts (see Chapter 7).

6.3 Canada's Coastal Regions

The following sections provide a broad description and overview of key distinguishing characteristics of the four coastal regions of Canada (East Coast, West Coast, North Coast, and Great Lakes). More in-depth information is provided in Lemmen et al. (2016), and Greenan et al. (2019) for the marine coastal regions, and in Lam and Duskoka (2022), and ECCC & USEPA (2022) for the Great Lakes region.

Box 6-1. CanCoast – Sensitivity of Canada's Marine Coasts

To understand the sensitivity of Canada's marine coasts, 6 descriptive coastal characteristics have been compiled and mapped on a common shoreline from CanVec (NRCan, 2011). In the 2023 version of CanCoast, these characteristics are:

- Sea-level change, early and late 21st century (James et al., 2021)
- Modelled monthly mean wave heights, early and late 21st century (WCRP, 2011)
- Tidal range data from reference and primary tide stations (CHS, 2022)
- Backshore relief from Canadian Digital Elevation Model (NRCan, 2023)
- Bedrock geology from Wheeler et al. (1996) and surficial materials from Fulton (1995)
- Ground ice in permafrost from Heginbottom et al. (1995)

Box 6-1. CanCoast – Sensitivity of Canada's Marine Coasts (continued)

Each of the 6 coastal characteristics was classified from 1 to 5 in order of increasing sensitivity (susceptibility to erosion and flooding). The 5 classes can be combined to define a coastal type. Canada's coast comprises 1,227 coastal types in the early century and 1,670 types in the late century, with the increase being due to changing sea level and wave height distributions. Coastal types can be used to extract information about Canada's coasts and derive a sensitivity index.

Over the 21st century, sea level fell on approximately 50% of the shoreline, rose on 40%, and 10% had no significant change. Approximately 55% of the shoreline has very low mean wave heights in the early century, but this decreases to 40% in the late century as sea ice decreases and storminess changes. Fifty percent of Canada's coast has extreme tides (i.e., is microtidal or hypertidal), and the other 50% has more moderate ranges (i.e., mesotidal or macrotidal). Nearly 50% of the coast is low relief, nearly 50% of the coast is bedrock, and approximately 10% of the coast has moderate to high amounts of ground ice in permafrost.

A Coastal Sensitivity Index (CSI) was developed by ranking types and then normalizing rankings (Hatcher & Manson, 2022) (Figure 6.3-1). In the early 21st century, parts of the western Arctic and Atlantic Canada are most sensitive, and the least sensitive areas are in the central Arctic Archipelago and the fjords of Southwest BC. A Coastal Sensitivity Change Index (CSCI) was developed using the changes in sea level and wave heights over the entire 21st century (Figure 6.3-2). Sensitivity is expected to greatly increase along the Beaufort Coast, and moderate increases are expected in James Bay, and the Bay of Fundy and Southern Gulf of St. Lawrence regions in Atlantic Canada. Sensitivity in the Arctic Archipelago is expected to greatly decrease. The change in sensitivity on the Pacific coast is complex with large decreases in the fjords, more moderate decreases or no change along much of the outer coast, and, notably, increasing sensitivity in the Lower Mainland and northern Haida Gwaii.

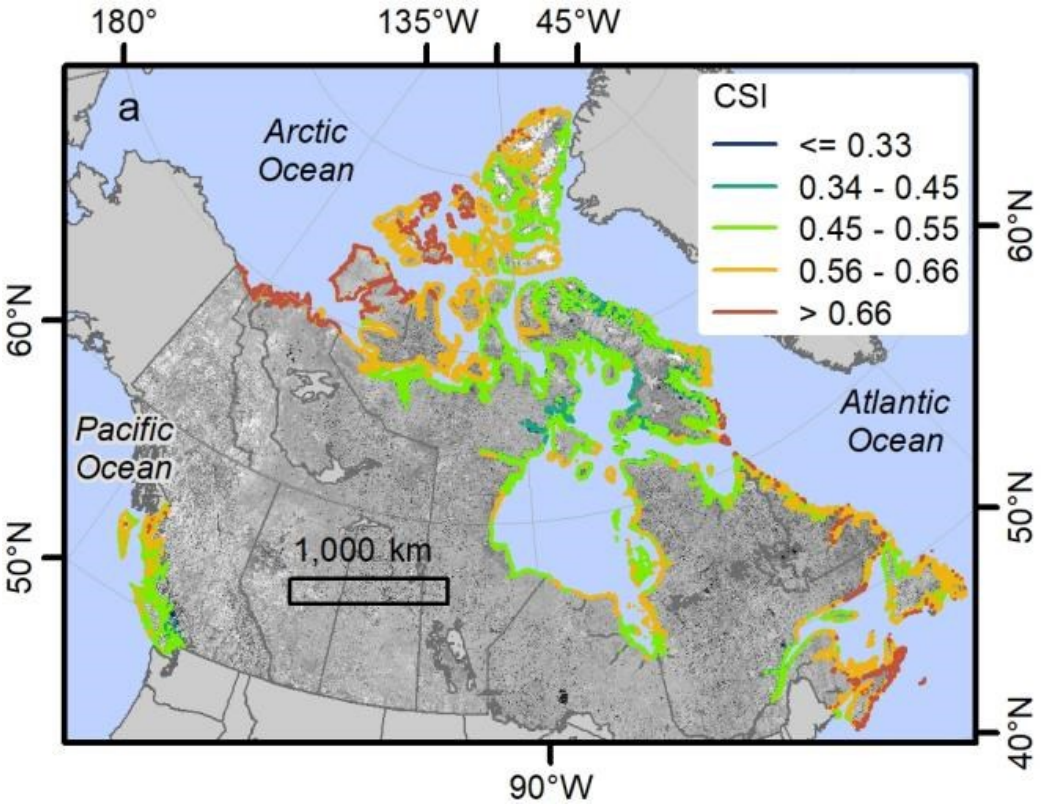


Figure 6.3-1. Map of Canada's marine coasts showing the early 21st century physical sensitivity.

Box 6-1. CanCoast – Sensitivity of Canada's Marine Coasts (continued)

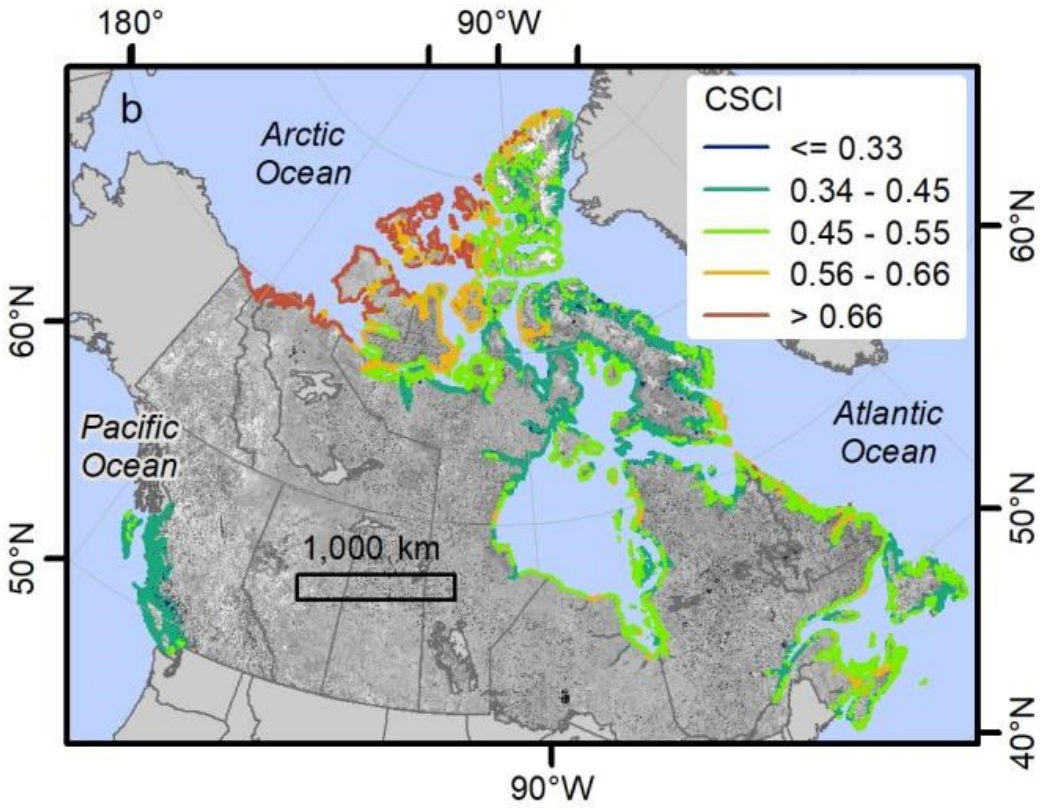


Figure 6.3-2. Map of Canada's marine coasts showing the change in the physical sensitivity over the 21st century.

6.3.1 East Coast

Following Lemmen et al. (2016), the East Coast region includes the marine coasts of the four Atlantic Provinces (except for the northern portion of the Labrador coast) as well as the marine coasts along the estuary and Gulf of St-Lawrence up to Quebec City, see Figure 6.2-1. The coastline in the East Coast region is approximately 43,000 km long, supports a coastal population of about 3 million, and features a great variety of landscapes featuring rich and diverse ecosystems (Savard et al., 2016). The wave exposure varies from negligible in sheltered settings to very high along the exposed coasts of Nova Scotia, Newfoundland, and Labrador. The region features tidal ranges varying from micro-tidal to the highest tides in the world, in the upper Bay of Fundy. New Brunswick and Prince Edward Island are well known for their lengthy sandy beaches while Newfoundland is famous for its rugged rocky coasts. Extensive intertidal mud flats and coastal marshes are common in the upper Bay of Fundy and elsewhere. These areas often front expansive, low-lying dykeland systems created by the historical reclamation of tidal wetlands. Much of region experiences seasonal sea ice (Savard et al., 2016). Coastal reworking of glacial sediments from eroding cohesive bluffs and glacial till landforms, such as drumlins, is widespread along much of the East Coast region, and the nature of the sediments influence the prevailing landscape. Gravel and mixed sand-gravel beaches and barriers are common throughout much of the East Coast region, except in the southern Gulf of St. Lawrence, where sand-rich glacial deposits support the localized development of extensive

sandy beaches, dunes, nearshore bars, spits, and barrier islands associated with specific sources or sinks of sand. In regions with more erosion-resistant bedrock, the glacial deposits tend to be coarser, leading to the formation of gravel-dominated beaches and shorelines.

East Coast region coastal flood and erosion hazards arise from a variety of sources and meteorological drivers, notably including post-tropical storms originating from tropical hurricanes (McLaughlin et al., 2022) that weaken as they encounter the mainland United States to the south. Examples of recent, named post-tropical storms that have caused extensive flooding and erosion-related damage in the East Coast region include Dorian in September 2019 (George et al., 2021), and Fiona in September 2022 (Mulligan et al., 2023). Nor'easters, which are intense extra-tropical storms that form in the North Atlantic Ocean when cold, Arctic air meets the warmer Gulf Stream, also generate storm surges and high waves that can drive coastal erosion (e.g., Forbes et al., 2004).

6.3.2 West Coast

Canada's coastline in the West Coast region measures approximately 27,000 km in length, all within the province of British Columbia, supports a coastal population of roughly 4 million, and again features a wide range of landscapes (Vadeboncoeur, 2016). The south-central west coast of Vancouver Island is well known for its lengthy sand beaches and pounding surf while metropolitan Vancouver is largely built on the low-lying Fraser River delta and is thus potentially vulnerable to the combined threats of coastal and riverine flooding. Much of the coastline, particularly where the Coast Mountains abut the coast, feature deeply indented fjords where steep and narrow shorelines predominate. Eroding bluffs feeding sandy or mixed-sediment beach systems are common features on Salish Sea and Vancouver Island coasts. Before the construction of dykes and training structures in the 1900s, floods regularly deposited silt and clay on the flat Fraser delta plain with sand that reaches the river mouth, slumping occasionally into deep submarine canyons. At present there are many competing pressures for the use of the delta land: it is an important agricultural area; it is experiencing dramatic urban and industrial growth centred in Richmond, Ladner, and Delta; and the tidal flats and marshes are vital habitats for salmon fry and migratory waterfowl (Turner et al., 1998). Away from the Fraser River delta, southern Vancouver Island, and the Sunshine Coast, the coastline, while sparsely populated, is home to many smaller communities and remote settlements, many within the Traditional Territories of numerous First Nations. Winters in the West Coast region are milder than in the rest of Canada, and therefore, the coastal waters remain ice-free year-round. Many of the species prevalent along the west coast are distinct from those found in the other three regions.

West Coast region coastal flood and erosion hazards are dominated by storm surges, waves and intense precipitation driven by extra-tropical storms that propagate northward from the Pacific in fall and winter, often coinciding with perigean spring tides (Murphy & Osler, 2022). Regional sea levels and storm frequency and intensities are influenced by climate variability patterns, such as the El Niño-La Niña Southern Oscillation (ENSO) and the Pacific Decadal Oscillation. El Niño years tend to correlate with elevated regional water levels, higher winter storm surges and waves, and high rates of coastal erosion in the region.

6.3.3 North Coast

Canada's vast northern coastline extends over 176,000 km from the Yukon to Labrador, including Hudson Bay and the many islands of the Arctic Archipelago. Roughly 75,000 people reside in 58 remote

communities scattered across the North, all but two located on the northern coast (Ford et al., 2016). Most of the human population is Inuit, First Nations, or Métis, who share a strong connection with the coastal environment. Canada's North Coast region is characterized by long, cold winters interrupted by short, cool summers. The presence of sea ice for much of the year is a defining characteristic of Canada's northern coasts and effectively isolates the northern coastline from coastal processes for much of the year. However, in many regions, climate warming is extending and expanding the open-water season, increasing the exposure of northern coasts to energetic wave conditions, and accelerating coastal erosion. Roughly 62% of the northern coastline consists of unlithified materials that would normally be highly erodible. However, permafrost is widespread across the northern coast, and serves to stabilize coasts that would otherwise be prone to reshaping and erosion. However, climate warming is causing the coastal permafrost to thaw during the summer season in many regions, thereby weakening the resistance of the coast and accelerating coastal erosion. Gravel beaches are common across much of the northern coastline. Much of the coastline in the eastern Arctic features fjords bordered by steep cliffs, while boulder-strewn tidal flats are common in some macrotidal areas on southern Baffin Island and around Ungava Bay. The Beaufort Sea coast generally is composed of unlithified materials that are often rich in ground ice. In this region the coast consists of low bluffs fronted by low barrier beaches, barrier islands, and spits. The western shores of Hudson Bay are bordered by a region known as the Hudson Bay lowlands, an area drained by many rivers and dominated by a characteristic landscape known as muskeg. In contrast, the eastern shores form the western edge of the Canadian Shield in Québec and are rocky and hilly. The dominant landscape on the eastern shore is boreal forest in the south transitioning to tundra further north.

The North Coast region is exposed to storms tracking from the east, from the Labrador Sea into Baffin Bay, and from the west, across the Beaufort Sea and into the Amundsen Gulf (Atkinson et al., 2016). There has been an increasing trend in storm frequency and intensity observed in long-term datasets for this region, and extreme water level events are expected to become larger and more frequent due to declining sea ice (Greenan et al., 2019). Northern regions of Canada have experienced some of the most rapid climate change anywhere on the globe, and projected future climate change impacts in the North Coast region are significant. Impacts on the physical environment include declining sea-ice concentration, earlier ice break-up and later freeze-up, a lengthening of the ice-free open-water season, permafrost warming and thaw, coastal erosion, sea-level rise (in the western Arctic), and changing weather patterns, including wind and waves (Atkinson et al., 2016; Greenan et al., 2019). Many northern coastal communities are vulnerable to these climate change effects, which can exacerbate existing socio-economic challenges, such as poverty, food insecurity, and lack of access to housing (Canadian Council of Academies, 2019).

6.3.4 Great Lakes

The Great Lakes are the largest group of freshwater lakes on Earth by total area, and the second largest by total volume. The total surface area is approximately 244,000 km^2 and the total length of coastline is roughly 16,900 km, almost equally divided between Canada and the United States (ECCC & USEPA, 1995). The Great Lakes contain nearly 20% of the fresh surface water on Earth and provide drinking water to roughly 40 million people (Lam & Dokoska, 2022). Over 4,000 species of plants, fish, and wildlife call this area their home. The region is of vital importance to the economies of both Canada and the United States, supporting shipping (via the Great Lakes St. Lawrence Seaway), manufacturing, transportation, farming, tourism, recreation, and energy production.

The Great Lakes' shoreline features a diverse range of landscapes and coastal habitats, including marshes, dunes, beaches (sand, gravel, and mixed), rocky shores, and bluffs comprised of both cohesive and non-cohesive sediments. These landscapes support a diversity of species and ecosystems, some of them globally unique. However, these ecosystems face significant pressures, and the 2022 State of the Great Lakes report characterized the overall water quality and ecosystem health (based on 40 indicators) as "Fair" with an "Unchanging" trend (ECCC & USEPA, 2022). Extensive hardening of the shoreline has occurred in many parts of the Great Lakes (e.g., ECCC, 2022a). Various types of coastal infrastructure, including ports, marinas, revetments, breakwaters, seawalls, and groyne systems have been constructed in many locations. Much of the shoreline near urban centres and wherever the shoreline is privately owned feature some form of built infrastructure, although it is not always well constructed or maintained.

The Great Lakes have a humid continental climate, and are influenced by air masses from other regions, including cold, dry Arctic systems, mild Pacific air masses from the west, and wet tropical systems from the south. Freshwater ice forms in all five lakes during winter and ice movements may affect the stability of coastal sediments and vegetation. In the post-glacial period lake levels have been relatively constant, as a result of the balance between evaporation and drainage. While daily and weekly water level fluctuations tend to be small, annual lake level changes can range up to 1.5 m, peaking from May to July and then falling gradually over the autumn and remaining stable over the winter. The most intense storms tend to occur in late fall and winter, such that the joint occurrence of high lake levels and meteorological effects (storm surges and waves) is an important factor controlling coastal flooding and erosion hazards.

6.4 Climate, Meteorology and Oceanography

Canada's coastal regions experience unique climate and weather patterns, and oceanographic conditions including storm surges and sea-level rise. Understanding regional and local meteorological and oceanographic (metocean) conditions is essential for assessing potential threats and designing NBI that can withstand exposure to hazards. Coastal flooding and erosion hazards arise from a variety of sources and drivers that vary within and across Canada's regions, such as tsunamis, tides, storm surges, and waves. The influence of climate change on these drivers and their impacts also varies within and across coastal regions.

6.4.1 Winds, Storms, and Waves

Winds, storms, and waves are major drivers of coastal flood and erosion hazard risk in all of Canada's coastal regions. Descriptions of historical and projected future changes in winds, storms, and wave climates in Canada's marine coast regions are provided in Lemmen et al. (2016) and Greenan et al. (2019). The North and East Coast regions are expected to experience increased wave activity as sea ice declines (Greenan et al., 2019). There remains a number of challenges and uncertainties associated with translating (i.e., downscaling) future projections of global winds, storms, and waves to scales and resolutions useful for NBI project-level applications (e.g., Cousineau & Murphy, 2022; Zuzek, Inc., 2019).

Wave exposure, which is a function of both regional wave climate and nearshore wave transformation processes, plays an important role in determining the types of NBI that may be appropriate for a given site. For example, salt marshes are most typically found in environments that are relatively sheltered from large waves (compared to beaches, for example), unless the marshes are sufficiently large and resilient to absorb and recover from storm wave exposure. Sources of wave data for Canada's coastal regions, and methods

of wave analysis and modelling are described in Chapter 11 and by Murphy et al. (2020). Values of various wind-related design parameters in the National Building Code of Canada based on historical observations and regional climate model projections are provided in the online Design Value Explorer developed by the Pacific Climate Impacts Consortium (2022).

6.4.2 Water Levels

Guidance and sources of data for evaluating water-level contributions to coastal flood hazards in Canada's coastal regions is provided by Murphy et al. (2020). There is significant variability in different components of water level within and across Canada's coastal regions.

6.4.2.1 Tides

Astronomical tides are the most predictable components of coastal water levels but are highly variable from place to place (ranging from more than 16 m in parts of the Bay of Fundy to almost negligible in the Great Lakes, and from semi-diurnal to mostly diurnal), and are a dominant driver of coastal flooding in parts of the West and East Coast regions. Tides are also broadly important in the context of NBI, since they determine the normal frequency and duration of inundation, which affects conditions for survival of different vegetation species (see Chapter 9). The tidal range may also determine which types of NBI are appropriate for flood and erosion risk management. For example, submerged reefs or deeply submerged aquatic vegetation (such as eelgrass) are unlikely to be effective at dissipating storm waves in areas with large tidal ranges, since those features will be too deeply submerged during storm events that coincide with high tides.

Sources of tidal data for Canada's coastal regions are described by Murphy et al. (2020) and include a permanent network of tide gauges maintained by the Canadian Hydrographic Service (CHS).[5] Characteristic tidal planes, Lower Low Water Large Tide (LLWLT) and Higher High Water Large Tide (HHWLT), are provided with reference to several commonly used vertical datums in the Canadian Extreme Water Level Adaptation Tool (CAN-EWLAT) (Zhai et al., 2023) for CHS's network of tide gauges and small craft harbours along Canada's marine coasts.

6.4.2.2 Storm Surges

The frequency and magnitude of storm surges vary substantially within and across Canada's coastal regions in response to the driving meteorological and climate patterns, the effects of ice, local bathymetry, and shoreline geometries. Sources of storm surge data, and methods of analysis and modelling are described in Chapter 11 and in Murphy et al. (2020).

6.4.2.3 Relative Sea-Level Change

Global sea-level rise is a key consequence of climate change and its impact on Canada's coastline varies widely from one region to another and within regions. Rates of relative sea-level change are important considerations for NBI, as they may determine the viability of a project over medium (decadal) to long (century or millennia) time horizons, and they control the frequency of exposure to waves and extreme water levels. James et al. (2021) provides projections of relative sea-level change (sea-level rise minus vertical land motion) across Canada (Figure 6.4-1), which are available at the ClimateData.ca web portal.

[5] https://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/twl-mne/index-eng.htm

Sea level is projected to rise relative to land along the West and East Coasts, in the Beaufort Sea and along the south-east coast of Baffin Island; and fall throughout the central Arctic, Hudson Bay, and Hudson Strait. The size of the projected change depends on the time horizon and future climate scenarios, which are largely determined by trends in global emissions of greenhouse gases.

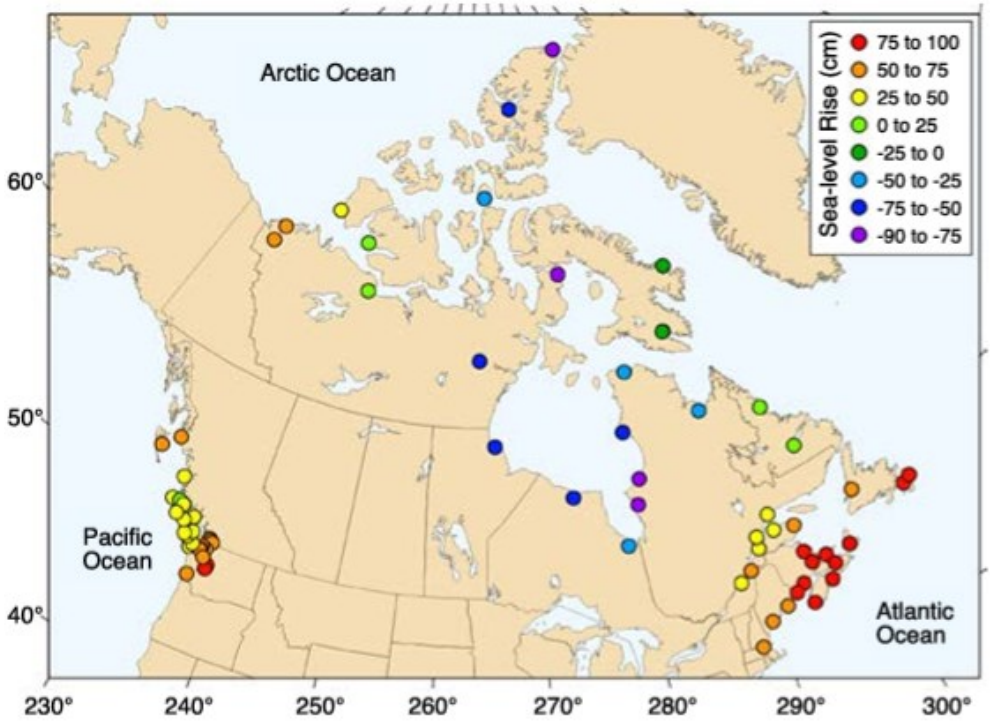


Figure 6.4-1. Projected relative sea-level change at 2100 for the median of the high-emissions scenario (RCP8.5) at 69 coastal locations in Canada and the northern United States. From Lemmon et al., 2016.

CAN-EWLAT[6] (Zhai et al., 2023) is an adaptation planning tool that provides sea-level rise projections for Canada's coastlines over the coming century, and advice on vertical allowances for coastal infrastructure to accommodate the projected rise. The vertical allowances are based on projected relative sea-level rise, coupled with historical tides, storm surges, and wave climate.

6.4.2.4 Climate Variability Effects

Sea-level anomalies resulting from oceanic-scale climate variability phenomena, such as El Niño–Southern Oscillation (ENSO), Pacific Decadal Oscillation, Arctic Oscillation, and North Atlantic Oscillation, can significantly influence the potential for coastal flooding in some regions. For example, regionally elevated water levels on the order of tens of centimetres in the West Coast region resulting from a strong El Niño event can contribute to an increased likelihood of flooding during high tide and/or storm surge events (Greenan et al., 2019; Murphy & Osler, 2022). ENSO conditions also influence the characteristics of atmospheric river events in the northeast Pacific (Kim et al., 2019), which can lead to intense, prolonged precipitation, and compound flood hazards in the West Coast region. Projecting changes in climate

[6] https://www.dfo-mpo.gc.ca/science/oceanography-oceanographie/accasp-psaccma/can-ewlat-ocanee/index-eng.html

variability in Canada's coastal regions into the future is challenging, and an area of active research (Greenan et al., 2019).

6.4.2.5 Seiches

Seiches are long wave amplifications that typically occur when meteorological or hydrodynamic forcing (e.g., long waves propagating from the open ocean into a coastal harbour or bay, or meteorological events passing through the Great Lakes) results in oscillations at the natural (resonant) periods of a lake, bay, or harbour. Methods for evaluating the potential for seiching are described in Murphy et al. (2020).

6.4.2.6 Freshwater Supply

Water levels in the Great Lakes are controlled by the net basin supply, which is the balance between precipitation and evaporation over the lakes, runoff from the watershed, and regulated outflows through the St. Lawrence River. There is uncertainty surrounding the direction of changes in annual mean lake levels in the Great Lakes region under a warming climate but consensus that the range and variability of water levels may be expected to expand, with more extreme highs and lows possible in the future (ECCC, 2022b).

6.4.3 Air Temperature

Air temperature is an important factor affecting NBI, particularly in so far as it influences:

- Water quality, growing season duration, and the types of plant species that can survive (see Chapter 9).
- Ice and permafrost characteristics in affected regions.
- Storm genesis and intensity.

Annual and seasonal mean temperature is projected to increase in all of Canada's coastal regions in the 21st century, with much larger changes in the North Coast region in winter (Zhang et al., 2019). These trends will be accompanied by longer growing seasons, and declining ice and permafrost. The historical trend towards more extreme temperatures (high and low) is projected to continue in the future (Zhang et al., 2019). The implications of changing mean temperatures and extremes over a NBI project lifecycle should therefore be considered in all of Canada's coastal regions. Further information on sources of temperature data and regional climates is provided in Zhang et al. (2019). Historical and projected future temperature data is available for a range of variables and Shared Socio-economic Pathways (SSPs) at ClimateData.ca. Values of various temperature-related design parameters in the National Building Code of Canada (historical and projected) are provided in the Design Value Explorer (Pacific Climate Impacts Consortium, 2022).

6.4.4 Precipitation

Precipitation is a consideration for NBI in terms of its potential to contribute to compound flood and erosion hazards (through snowmelt, surface runoff, fluvial discharges, or ground saturation), its influence on plant suitability for vegetation-based solutions (see Chapter 9), and in determining needs for upland flood storage, drainage, or infiltration.

Precipitation varies widely across and within Canada's coastal regions (Figure 6.4-2), with parts of the West Coast region receiving annual averages of 3,000 mm of precipitation or more (Zhang et al., 2019). By contrast, parts of the North Coast region receive less than 200 mm per year on average, owing to the fact that cooler air can hold less moisture (Zhang et al., 2019). Annual and winter precipitation is projected to increase everywhere in Canada over the 21st century, with a shift towards less snowfall and more rainfall (Zhang et al., 2019; Bush et al., 2022). Further information on sources of temperature data, and regional climates is provided in Zhang et al. (2019). Historical and projected future precipitation data is available for a range of variables and Shared Socio-economic Pathways (SSPs) at ClimateData.ca. Intensity-Duration-Frequency (IDF) curves describing the likelihood of a range of extreme (short-duration) rainfall events are provided based on historical observations and adjustments for future climate scenarios at stations throughout Canada's coastal regions on ClimateData.ca.

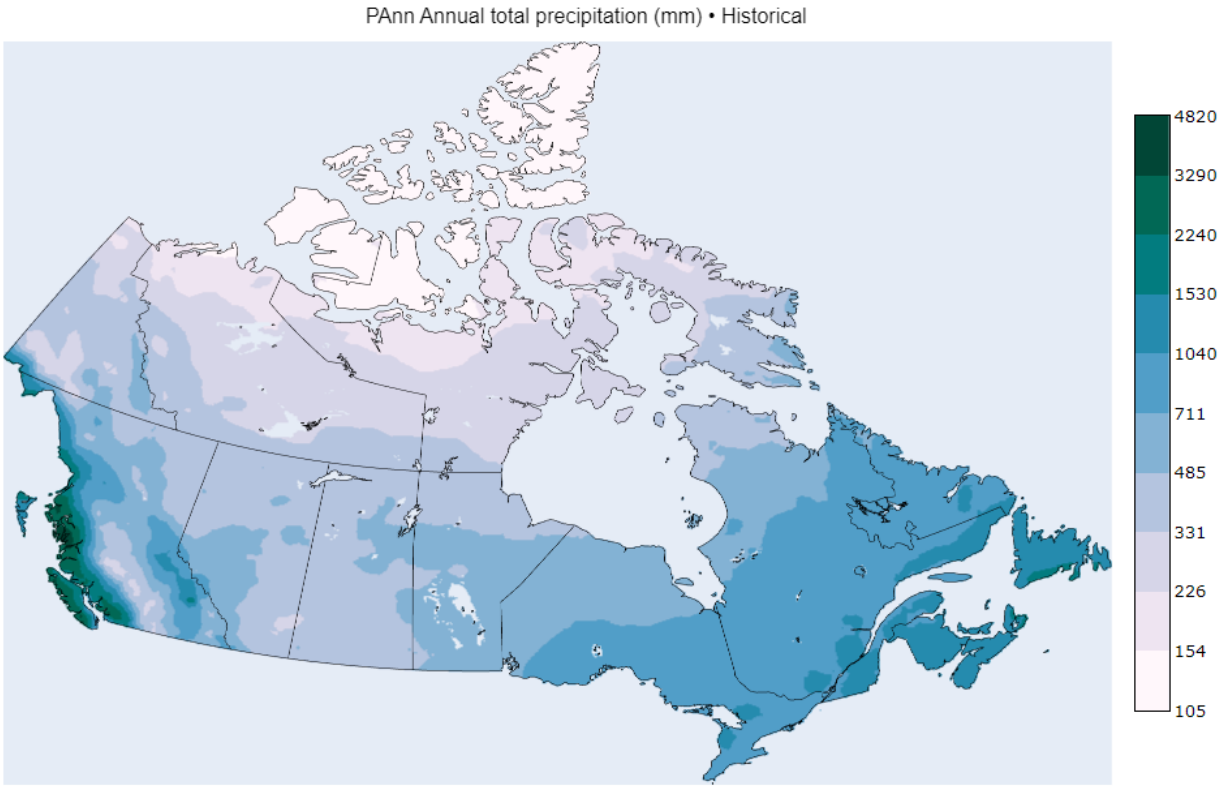


Figure 6.4-2. Annual total precipitation for 1986–2016 from the Design Value Explorer (Pacific Climate Impacts Consortium, 2022).

6.4.5 Ice, Frost, and Permafrost

Ice cover and dynamics are significant considerations for NBI in the Great Lakes, East Coast, and North Coast regions. Ice cover and shorefast ice formation impede wind wave formation and wave exposure on shorelines. Ice cover can also influence the propagation and magnitude of storm surges, with the effects strongly dependent on ice concentrations (Kim et al., 2021). Ice has been thinning and decreasing in extent in the North Coast, East Coast, and Great Lakes regions for decades (Atkinson et al., 2016), and climate change is expected to result in continued reduction in ice area in the North Coast region in summer, the

East Coast region in winter (Derkson et al., 2019), and the Great Lakes region in winter (Zuzek Inc., 2020). Most North Coast region areas are expected to be ice-free during summer by mid-century (Derkson et al., 2019). Lake Ontario and Lake Erie may be ice-free by the end of the century under a high-emissions scenario (Zuzek Inc., 2020).

A consequence of climate change is that, in Canada's East Coast, North Coast, and Great Lakes regions, declining ice is expected to result in increased wave heights, more frequent and higher extreme water level events, and longer open-water seasons (Greenan et al., 2018; Zuzek Inc., 2020). Ice affects sedimentary processes (see Chapter 8) and biological activity in the coastal zone, including coastal marshes and other nearshore vegetation.

Shorefast ice describes the formation of ice attached to shorelines in cold climates (Dionne, 1973). In tidal environments the ice foot forms at high water and grows vertically and laterally within the intertidal zone. The ice foot is separated from dynamic sea ice by a hinge zone of fractures resulting from tidal action (Nielsen, 1979). In both lakes and ocean environments, wind and wave action may maintain an area of open water and the ice foot thickness develops around the open water margin by the accumulation of ice from the freezing of wave spray, splash and accumulation of ice floes or slush, as well as precipitation as snow. As the size and thickness increase, the ice may become grounded over a significant width of nearshore (Atkinson et al., 2016).

Since ice cover impedes wave formation and transmission, the shortening of the ice season increases the total energy of storm waves developing in an ice-free water body, such as the Gulf of St. Lawrence (Neumeier et al., 2013). This, in turn, will modify the coastal sediment balance, activating shore erosion in some areas while reducing erosion in others as material is redistributed (Jones et al., 2009; Overeem et al., 2011).

Box 6-2. Ice in the East Coast Region

In the Gulf of St. Lawrence, the period of wave inhibition by sea ice decreased by 30% for the period 1995–2007 (average ice-covered period of 55 days/year) relative to the period 1960–1995 (average ice-covered period of 80 days/year; Savard et al., 2008). In comparing future conditions (2041–2070) to the recent past (1982–2011), model simulations suggest that the period of sea ice cover will decrease by 36 days and the number of days that the ice foot completely protects the coast will decrease by an average of 33.4 days (Senneville et al., 2014). Ice-foot development currently occurs during some winters along coastlines in the southern Gulf of St. Lawrence and around the Avalon Peninsula, NL, and more frequently along the Québec North Shore, in northeastern Newfoundland, and in Labrador.

Vegetation is sensitive to frost, which can damage susceptible plant species through desiccation and rupturing of plant cell walls and membranes. Regions with large numbers of frost days tend to have short growing seasons. The frost characteristics of a region may therefore determine suitable plant species for incorporating in NBI or determine periods of the year when vegetation species can effectively deliver flood and erosion risk management benefits. Historical and projected future frost days per year are available for a range of Shared Socio-economic Pathways (SSPs) at ClimateData.ca.

In permafrost regions, coastal erosion results from the combined effects of mechanical and thermal processes (Aré, 1988; Wolfe et al., 1998; Nielsen et al., 2022). Thermal erosion occurs at or above the

normal waterline where surface air temperatures and higher water levels associated with storm surge and waves thaw the permafrost. It also occurs at or below the waterline when thawed material at the water-sediment interface is removed mechanically by waves, currents, or sea-ice scour, and the underlying frozen sediment is then exposed. Permafrost is warming and thawing across Canada's North Coast region, and this trend is expected to continue into the future (Derkson et al., 2019). These topics are addressed in some detail by CSA W205:19 (Erosion and sedimentation management for northern community infrastructure).

6.4.6 Water Quality

Water quality, including water temperature, salinity, and chemistry, is an important consideration for NBI, particularly vegetation-based solutions, since plant species may be sensitive to water quality conditions. Under some circumstances, NBI can also contribute to improving water quality, for example, through nutrient uptake by vegetation in constructed wetlands for wastewater treatment (USEPA, 2000), or by trapping and sequestering particulates (e.g., microplastics) or contaminants adsorbed to sediments (e.g., heavy metals).

The upper oceans have been warming in most of Canada's coastal regions over the last century, and they are projected to continue to warm over the coming century in response to climate change (Greenan et al., 2019). Increases in summer ocean temperatures will be greatest in ice-free parts of the North Coast region and to the south of the East Coast region. Winter temperature increases will be highest in the East Coast region, followed by the West Coast region, and then the North Coast region (Greenan et al., 2019).

Freshening of the ocean surface has occurred and is projected to continue through the 21st century in most of Canada's coastal regions (Greenan et al., 2019). However, increased salinity below the surface is expected to result in stronger density stratification, which will negatively impact dissolved oxygen levels and marine ecosystems (Greenan et al., 2019).

Poorly managed urbanization, industrialization and agricultural intensification has introduced large quantities of contaminants to parts of Canada's coastal regions (e.g., Hall & Schreier, 1996). This is a particular concern in urban estuaries and lake systems, where contaminant loads and residence times tend to be higher than on the open coast. Prevailing and potential future water quality conditions should be considered when developing NBI designs, as they may influence the type of NBI that is feasible, details of the design (e.g., plant species selection), and long-term sustainability.

6.4.7 Tsunamis

Tsunamis are waves generated by a sudden displacement of water, which may be triggered by earthquakes (Leonard et al., 2012, 2014), landslides (Mulligan & Take, 2017), rockslides (e.g., 1964 event in Alaska), explosions (Halifax Harbour event in 1917), asteroids, and meteorological phenomena (meteotsunamis) (Thomson et al., 2009). All Canada's coastal regions are potentially exposed to tsunamis, but the overall hazard likelihood and severity is difficult to assess, due to uncertainties surrounding potential sources. The preliminary tsunami hazard assessment for Canada's marine coasts by Leonard et al. (2012, 2014), which was limited to near- and far-field earthquake and landslide sources, indicated that the cumulative hazard associated with potentially damaging tsunami wave runup events in the outer West Coast region is orders of magnitude higher than for the East Coast and North Coast regions. This reflects the importance of the Cascadia subduction zone off Vancouver Island as a known tsunamigenic source.

6.5 Coastal Physiographic Features and Environments

The Canadian coastline spans over 240,000 kilometres, includes a tremendous array of coastal environments, physiographic features, and biological diversity, and is a defining feature of the nation. Its profound significance transcends its sheer length, impacting Canada's ecological, economic, and cultural landscapes. The following brief overview explores the rich diversity of these coastal landscapes, including their geological, geomorphological, and ecological characteristics and highlights the significance of understanding these coastal environments for conservation, resource management, scientific research, coastal zone management, and implementation of NBI to mitigate erosion and flood risk. The central objective of this section is to emphasize how comprehensive research and understanding of coastal ecosystems, environments, and processes are essential to support the development of resilient NBI to counteract the escalating threats of flooding and erosion. A secondary objective is to highlight some unique features and considerations germane to each region.

6.5.1 Geological Foundation

The geological history of the Canadian coast is shaped by billions of years of Earth's evolution (Hill et al., 2014). It began during the Precambrian eon, when the Canadian Shield, one of Earth's most ancient geological formations, emerged as a stable craton. Over time, this shield served as the foundation upon which subsequent geological events played out. The assembly and breakup of supercontinents, such as Rodinia and Pangea, significantly influenced the geological formations along the coast.

Sedimentary basins are vital geological features along the Canadian coast. The sedimentary rocks found in these basins preserve a record of past environments, climate changes, and life forms. Notable examples include the Western Canada Sedimentary Basin, which hosts extensive hydrocarbon reserves, and the Grand Banks off Newfoundland, known historically for its rich fisheries. Research by the Geological Survey of Canada has provided insights into the stratigraphy and resource potential of these basins (Pronk et al., 2007).

Tectonically, the Canadian coast is influenced by the interactions of several major plates, including the Pacific Plate, North American Plate, and the Atlantic Plate. These interactions have led to the formation of various geological features, including mountain ranges, coastal uplift, and volcanic activity. The Cordilleran Orogeny, for instance, resulted in the formation of the Rocky Mountains along the western coast. These are classified by Inman and Nordstrom (1971) as collision coasts (subduction or leading edge) with continental margins characterized by cliffed shorelines, narrow coastal plains, and deep ocean trenches with high mountains just inland. Conversely, the East Coast is classified as a trailing edge (passive) coast that has a wide continental shelf allowing for formation of extensive sandy coastal features, such as spits, beaches, and barrier islands, and associated intertidal flats and tidal wetlands.

The Canadian coast is dissected by numerous fault lines, often associated with tectonic plate boundaries. The Queen Charlotte Fault, for instance, extends along the western margin of British Columbia and is an active strike-slip fault capable of generating significant earthquakes. Geological studies, such as those conducted by Hyndman and Wang (2006), have characterized the seismic hazards associated with these

fault systems. Earthquakes along these coastal faults can trigger tsunamis, which can cause extensive flooding and damage along exposed coasts (Leonard et al., 2014). On the East Coast, the St. Lawrence rift system also has a well-defined pattern of seismic activity (Kumarapeli & Saull, 1966).

6.5.2 Effects of Glaciation

The effects of glaciation, primarily driven by the advance and retreat of massive ice sheets, are responsible for shaping many of the coastal landscapes seen today, and are evident in all four Canadian coastal regions.

Glacial erosion created deep, narrow fjords and U-shaped valleys along many parts of Canada's coastline, particularly along the coasts of British Columbia and Newfoundland and Labrador. These features are the result of glaciers carving through pre-existing river valleys, leaving behind deep, steep-walled inlets and valleys that are often submerged by seawater. Glacial deposits, such as moraines (ridges of unsorted sediment deposited by glaciers) and drumlins (elongated hills made of glacial till), can be found along many parts of Canada's coastline and contribute to the diverse topography of the coastal regions. Many of Canada's coastal islands bear the imprint of glaciation. Features like striated bedrock, drumlins, moraines, glacial till, and glacially scoured depressions provide evidence of past ice coverage. Glacial erosion and transport also left behind large boulders known as glacial erratics. These erratics can be found scattered across coastal areas, sometimes perched high on cliffs or hillsides, indicating the former presence of glaciers. As glaciers retreated, they deposited vast quantities of sediment, including clay, silt, and sand, into coastal areas and the adjacent sea floor. These sediments contribute to the composition of coastal beaches, estuaries, and offshore continental shelves.

The tremendous weight of glaciers can lead to temporary subsidence of landmasses. When the glaciers retreated and landmasses rebounded (a process known as isostatic adjustment), ancient shorelines became elevated and set back from the new shoreline. Raised beaches and coastal terraces located above and inland from the new coastline are visible along parts of Canada's eastern coastline and can provide insight into past sea levels and geological history. Isostatic adjustment continues to influence the spatial distribution of relative sea-level change along Canada's coasts as discussed previously in the introduction to this chapter.

Glaciation often led to the formation of large glacial lakes as meltwater was trapped by ice dams. When these dams eventually broke, catastrophic outflows occurred, carving deep channels and gorges in the landscape. During the last ice age, the 1.6-km thick Laurentide ice sheet covered most of Canada and the northern contiguous United States. The massive weight and movement of this glacier gouged out the earth to form the Great Lakes' basins. When the vast ice sheet retreated roughly 20,000 years ago, water from the ice sheet filled the basins forming the Great Lakes. The Great Lakes only reached their present shapes and sizes approximately 3,000 years ago.

The geological history, sedimentary basins, fault lines, plate tectonics and glaciation-related processes discussed in this section merely scratch the surface of the rich geological tapestry that characterizes this diverse coastal region. In summary, glaciation has left an indelible mark on Canada's coastal landscape. The geological legacy of ice sheets and their interactions with the land, combined with ongoing processes

like glacial isostatic adjustment, continue to shape the coastlines seen today. Understanding these glacial influences is crucial for both appreciating the natural beauty of Canada's coastal regions and deciphering its historical formation and ongoing evolution.

6.5.3 Geomorphological Features

The Canadian coastline, spanning many thousands of kilometers across diverse climatic zones, is a mosaic of striking geomorphological features. From the rugged fjords of the Pacific Coast to the expansive sand and gravel beaches of the Atlantic Coast, each region presents unique coastal landforms shaped by a combination of geological, oceanographic, and climatic factors. What follows is a brief introduction to ten important geomorphological landscapes found on Canada's coasts.

Sandy Shores

The coastal sandy system is an integrated system encompassing feeder bluffs, beaches, dunes, and back barrier environments (Davidson-Arnott et al., 2019). Some coastal sandy systems also have lagoons. Some beaches may be fully or partially separated from the main coast and are referred to as barrier islands (Gailani et al., 2021) or spits. Coastal sandy systems are highly dynamic and vary in how they respond to wave and water-level conditions. The dynamics and long-term resilience of sandy coast systems are strongly dependent on sediment budgets (including supply by feeder bluffs or updrift beaches), rates of relative sea-level rise, and storm exposure (including clustering of storms, which affects recovery). Sandy shores are characterized by wide, gently sloping beaches and are prominent along Canada's Atlantic coastline, notably in Prince Edward Island, portions of the east coast of New Brunswick and along the Gulf of St. Lawrence. Sandy shores can also be found in the Great Lakes and along portions of the western and northern coasts. These shores are generally found in or near regions where sandy sediments or rocks lie near the surface and are primarily formed through the deposition of sediments carried to the coast by rivers and redistributed by coastal currents (Hayes et al., 2016). Erosion of updrift coasts can also be an important source of sediment feeding sandy shores. Sandy coasts are notable for their dynamic nature; they tend to reshape rapidly during high-energy wave events when sediment transport rates are high and then reshape more slowly during "normal" conditions when transport diminishes (Walker et al., 2017).

Dunes develop as windblown sand accumulates behind the beach, providing habitat for unique flora and fauna (Lodder et al., 2021). Moreover, dunes serve as important reservoirs and as natural barriers against inland flooding. Swamps, wetlands, and even large coastal lakes can form behind the dunes where the wet sand gives these systems more stability than the surrounding dunes and extensive plant and wildlife communities can become established. The front face of the foredune is usually the most dynamic part of any dune system, and it is here where most sand is initially trapped, by dune vegetation, such as grasses and other plants that are particularly hardy, as they need to survive the forces of wind, waves, and salt spray. Mature dune systems may eventually become stabilized and covered with woody shrub and hardy tree species, forming coastal forest.

Sandy beach and dune systems are inherently very dynamic with large morphological changes occurring seasonally (e.g., winter versus summer beach profile) and after significant storms (Mathew et al., 2010; Davidson-Arnott et al., 2019). Sand is stored in nearshore bars during the fall and winter months, often revealing an underlying layer of gravel or cobbles. The sand stored in the nearshore bars is gradually

transported back to the beach during calmer wave conditions over the spring and summer months. These two conditions are referred to as a summer beach profile and a winter beach profile. These beaches result from a dynamic equilibrium or balance of sediment erosion, transport, and deposition. Sand may also move along the shore (alongshore), through the process of “longshore drift”, also called “littoral drift”. The natural movement of sand on and offshore as well as alongshore (up and down the coast or longshore drift) is essential to maintaining a sustainable coastal ecosystem (Davidson-Arnott et al., 2019). Sand bars can grow to form sand spits (a thin ribbon of sandy land connected to the mainland), barrier islands (Gailani et al., 2021), and eventually chains or complexes of barrier islands (formed when sand spits grow, become detached from the mainland through storm erosion, and subdivide). Sandy coasts also provide specific services, such as coastal protection, recreational use, or habitat for species at risk (Lodder et al., 2021).

Gravel Beaches

Gravel beaches, characterized by coarse sediments (gravels and cobbles) and steeper cross-shore slopes (than sandy beaches), are common in all four coastal regions of Canada. The transport of coarse materials by ice and waves is a key factor in their formation and evolution. The western shores of Hudson Bay exemplify the prevalence of gravel beaches (Forbes et al., 2018). Gravel beaches are also dynamic, reshaping during high wave-energy events when water levels and wave energies are sufficient to mobilize the coarse sediments, then becoming relatively stable during normal climatic wave and water level conditions. While gravel beaches are generally more resistant to wave-driven erosion than many other shoreline types, they are potentially less amenable to natural post-storm recovery and progradation than sandy beaches (Blenkinsopp et al., 2019). Bayle et al. (2020) and Austin and Masselink (2006) showed that, under certain conditions, it is possible for cobble and gravel beaches or berms to recover and reform naturally during and after storm events. However, most of the movement during storms tends to be in a landward direction (Sirianni et al., 2022), sometimes resulting in overwash events that transport coarse sediments into lagoons and barachois ponds that are often behind them, with limited opportunity for seaward progradation after the storm (van Proosdij & Miller, 2023), unless driven by upland flows (Figure 6.5-1). The tendency for landward transport of coarse sediments by storm waves, and the uncertainty surrounding mechanisms of recovery or progradation, suggest that gravel beaches may be susceptible to coastal squeeze (Pontee, 2013), if not given space to migrate landward. Research is needed to better understand complex gravel and mixed-sediment beach dynamics (Buscombe & Masselink, 2006; Wilson, 2020; Young et al., 2023), particularly recovery processes.



Figure 6.5-1. Warren Brook, flowing northeastward to Broad Cove beach on Cape Breton, Nova Scotia. A cobble and gravel berm repeatedly formed across the mouth of the Creek in response to swell wave action at high tide (observed over several days in July 2023), causing ponding of freshwater and subsequent breaching of the berm at low tide, which transported coarse sediments back down the beach face. The remnants of the berm are visible on either side of the breach in the background. Photo credit: Enda Murphy.

Estuaries, Intertidal Flats, and Tidal Wetlands

Estuaries are dynamic coastal ecosystems where freshwater rivers meet the sea. These regions are characterized by fluctuating salinity levels and serve as vital nurseries for marine life. Estuaries result from the interaction of fluvial and marine processes, with sediment deposition occurring where freshwater and seawater mix (Blades et al., 2004). Intertidal flats are often formed on the margins of estuaries or deltas through the deposition of fine sediments transported by rivers to the coast but can also be found in other coastal areas. Tidal wetlands form when intertidal flats are colonized by specialized flora that thrive under repeated immersion. They are diverse ecosystems shaped by sediment deposition and vegetation. They include salt marshes and tidal flats across a continuum of fresh to brackish and fully saline conditions that are colonized by vegetation that is adapted to these conditions. These wetlands provide essential habitat for wildlife and serve as a buffer against storm surge and sea-level rise (Davidson-Arnott et al., 2016). Significant areas of tidal wetlands were historically converted to agricultural land or urbanized through construction of dykes and hydraulic control structures particularly in the Bay of Fundy, St. Lawrence Estuary, and Fraser Estuary.

Tidal Inlets

Tidal inlets are critical coastal features where the interaction between ocean tides and coastal morphology creates unique hydrodynamic and geomorphic environments. These inlets serve as connectors between open ocean and more sheltered coastal estuaries, bays, or lagoons.

Tidal inlets are characterized by the complex interplay of tidal currents, waves, sediment transport, and bathymetry. Key hydrodynamic aspects include:

- Tidal Prism: Tidal inlets have a tidal prism, which represents the volume of water exchanged during each tidal cycle. This exchange of water profoundly influences the adjacent coastal ecosystems and sediment transport.
- Tidal Currents: Strong tidal currents are a hallmark of inlets. Flood and ebb tidal currents can reach significant velocities, impacting sediment transport, navigation, and coastal erosion.
- Sediment Dynamics: Inlets act as sediment sinks and sources. They can trap sediment, leading to shoal formation within the inlet, and can also contribute sediment to adjacent coastal areas.

The morphology of tidal inlets is highly dynamic and subject to continuous change due to fluctuating hydrodynamic forces. Key geomorphic characteristics include:

- Ebb and Flood Channels: Inlets often feature well-defined channels for ebb and flood tides. These channels can migrate over time due to shifting sediment dynamics.
- Barrier Islands and Spits: Inlets are frequently associated with the formation of barrier islands or spits, which protect the adjacent coastal areas from wave action and provide habitat for coastal flora and fauna.
- Shoals and Bars: Accumulated sediment in the inlet can lead to the formation of shoals and bars, which can affect navigation and sediment transport.

Tidal inlets hold significant ecological, economic, and navigational importance. Tidal inlets serve as critical nurseries and habitats for various marine species, where the mixing of saline and freshwater in these dynamic environments supports diverse ecosystems. They also often provide access to sheltered coastal areas, ports, and harbours. Under such circumstances, proper inlet management (through regular dredging and/or sediment by-passing and/or construction of inlet control structures) is crucial for maintaining safe navigation and may create opportunities for beneficial use of dredgeate in NBI. Furthermore, well-functioning tidal inlets can help dissipate storm surges by allowing excess water to flow into estuarine or lagoon systems, reducing the impact on adjacent coastal communities. Finally, barrier islands and spits formed by tidal inlets act as natural buffers against wave energy and coastal erosion, providing protection to inland areas.

Deltas

Deltas form when rivers deposit sediments as they flow into an ocean or lake. This process is influenced by sediment supply, river discharge, and wave action. The Mackenzie River Delta, situated along the Arctic Coast, exemplifies a deltaic landform. In the Arctic, permafrost dynamics also play a role in delta formation (Kokelj et al., 2017). Deltas are very sensitive to sediment supply (Davidson-Arnott et al., 2019). On the West Coast, the Fraser River delta historically received a significant amount of sediment, however today sediment is dredged to maintain the shipping channels below New Westminster, the river is channelized by dykes and training structures, and there is reduced sediment supply to the front of the delta. These human-induced changes, along with deltaic subsidence and loss of marsh vegetation, have contributed to recession of the delta front over time (see Box 8-3 in Chapter 8).

Fjords

Fjords, like those on the Pacific Coast in British Columbia and the Atlantic Coast of Newfoundland and Labrador, are deep, glacially carved coastal inlets with steep, U-shaped profiles. During the last ice age, roughly 20,000 years ago, glaciers carved these dramatic landforms, which later filled with seawater as sea levels rose (Carrara et al., 2013).

Rocky Shores

Rocky shores are prevalent along all four Canadian coasts. These landforms result from erosion of bedrock and sedimentary rocks by wave action exacerbated by weathering effects (e.g., frost action). The rate of erosion depends on rock hardness, wave energy, weathering effects, and sea-level fluctuations. The rugged shores of Newfoundland and Labrador exemplify this geomorphological feature (Greenwood et al., 2019). Rocky coastal cliffs and bluffs can erode when the combined effects of wave action, freeze-thaw cycles, and landslides attack softer layers near the waterline. On coasts dominated by sedimentary rocks, such as sand and siltstone, for example, on Prince Edward Island and the Bay of Fundy, rates of rocky cliff erosion can range from 0.28 $m \cdot a^{-1}$ to 0.8 $m \cdot a^{-1}$ (Savard et al., 2016).

Soft Cliffs and Bluffs

All of Canada's coastal regions contain soft cliffs or bluffs comprising a variety of sediment types and stratigraphies. These bluffs may consist of non-cohesive sediments, such as sands, gravels, and cobble; cohesive sediments, including clays and silts; or mixed sediments. The coasts of the lower St. Lawrence Estuary and portions of the Atlantic and Great Lakes' shoreline are examples where cohesive sediments influence coastal landforms. These shores are shaped by the interactions between sediment supply, tidal currents, and sediment consolidation (Baar et al., 2013). Coastal cliffs and bluffs composed of cohesive sediment (silt and clay) can erode rapidly when undermining at the bluff toe by wave action exacerbated by aggregate abrasion at high water produces over-steepening of the bluff slope and triggers recession of the slope through shallow slides, mud flows, erosion by rain splash and surface runoff, and occasionally by deep-seated failures (Davidson-Arnott, 2016). Erosion of till bluffs on the East Coast in exposed areas is significant (0.26 $m \cdot a^{-1}$ in Northumberland Strait to 1.38 $m \cdot a^{-1}$ in Nova Scotia) (Savard et al., 2016). Over-steepened, exposed cliff faces comprising unlithified sediments can be prone to instability associated with creek washouts and downcutting, mass wasting of the exposed cliff face by wind and rain, slope creep, and piping erosion by groundwater seepage. In the North Coast region, permafrost often plays a role in stabilizing cliffs comprised of unlithified sediments, and permafrost thaw can trigger mass wasting events referred to as retrogressive thaw slumps (CSA W205:19). Cliffs destabilized by thermal erosion are then susceptible to mechanical erosion by wave action. Material eroded from soft cliffs often plays an important role in supplying sediment to the rest of the coastal system within the littoral cell (see Chapter 8), giving rise to the term "feeder bluffs".

Developed or Managed Coasts

Developed or managed coasts, like those around major urban centres, such as the lower mainland of British Columbia, the Greater Toronto Area, Victoria, and Halifax, represent areas where human activities have significantly altered the natural geomorphology and coastal processes. They are characterized by the

presence of coastal infrastructure, typified by revetments, seawalls, and groyne fields. Such infrastructure may be constructed and managed by government authorities or private landowners and is not always well designed, constructed, or maintained. Older infrastructure may not have been designed for future conditions that include the effects of sea-level rise and climate change. Coastal engineering and urbanization play substantial roles in shaping these regions (Forbes et al., 2013).

In conclusion, the geomorphological characteristics and features of the Canadian coast are tremendously diverse and testament to the dynamic interplay of geological, oceanographic, and climatic processes. From the fjords of British Columbia to the sandy beaches of the Atlantic Coast, each region offers a range of unique landscapes shaped by distinct geological histories and environmental conditions. Understanding these coastal landforms and the processes that shape them is not only essential for conservation but also for informed coastal management and climate change adaptation, including design and construction of NBI.

6.6 Coastal Ecology

Canada's coastal regions are hubs of biodiversity, hosting a wide array of ecosystems. Coastal ecosystems are biodiversity hotspots where various species of plants, animals, and microorganisms thrive due to the availability of abundant resources and favourable environmental conditions. These ecosystems provide essential services like shoreline stabilization, water filtration, and critical habitats and nurseries for marine and terrestrial life, contributing to both local and global biodiversity. Understanding regional and local ecosystems, and ecological diversity, is fundamental to the design of NBI to minimize disruption and enhance ecosystem health. Six of the many important coastal ecosystem types found in Canada are highlighted below.

6.6.1 Kelp Forests

Kelp forests along the Pacific coastline of Canada are a prime example of a unique coastal ecosystem. Dominated by giant kelp (*Macrocystis spp.*) and bull kelp (*Nereocystis spp.*), these underwater forests provide shelter and food for a myriad of species, including sea otters, sea urchins, and numerous fish species. Kelp forests have complex ecological dynamics and play an important role in maintaining marine biodiversity (Tegner et al., 2013). Kelp forests have the potential to attenuate waves due to flow-vegetation interactions. Kelp and seaweed are types of marine multicellular macroalgae, and therefore do not have plant structures, such as roots, stems, leaves, or reproductive mechanisms (flowers). They differ from seagrass meadows, which are flowering plants that colonize protected, shallow coastal areas, such as estuaries, embayments, and coastal lagoons (Koch et al., 2006). Many can colonize soft substrates, such as sand and mud (Barbier et al., 2011). Additional details are provided in Chapter 9.

6.6.2 Intertidal Zones

Intertidal zones, where the land meets the sea, are dynamic and biologically rich environments found across the Canadian coastline. They experience regular fluctuations in water levels due to tides, exposing a wide range of habitats to both marine and terrestrial organisms. Substrates range from fine-grained mudflats to coarser sand flats and bedrock platforms. Studies have demonstrated intricate ecological interactions within intertidal zones, emphasizing their role as nurseries for various fish species and important feeding grounds

for shorebirds (Hamilton et al., 2003, Hamilton et al., 2006, Paine et al., 2019). These ecological interactions have also been shown to influence sediment erodibility and transport.

6.6.3 Coastal Wetlands

Coastal wetlands, including salt and brackish marshes, are critical coastal ecosystems that provide vital ecosystem services (Keddy et al., 2015). Found in all of Canada's coastal regions, coastal wetlands act as buffers against storm surges, filter pollutants, store and sequester carbon, and serve as important habitats for migratory birds (Sherren et al., 2021). Known Canadian salt marsh ecosystems may sequester as much as 785 kilotonnes of carbon per year (Rabinowitz & Andrews, 2022). With adequate sediment supply and proper hydrology (e.g., tidal flushing), coastal wetlands can be resilient in the face of sea-level rise, as they can increase their elevation within the tidal frame over time through sediment accretion and below-ground root production. Historically extensive amounts of coastal wetlands have been lost due to diking, infilling, and construction of tidal barriers. Over the last decade, funding and research has been geared towards removing tidal restrictions and barriers thereby restoring coastal wetlands and enhancing biodiversity in these areas (e.g., Mortsch et al., 2006; van Proosdij et al., 2010; Bowron et al., 2012; Virgin et al., 2020). Additional details are provided in Chapter 9.

6.6.4 Beaches and Dunes

Sandy beach and dune systems, such as those found along the east shore of New Brunswick, the north shore of Prince Edward Island, and the south shore of the Gulf of St. Lawrence are critical habitats used for nesting by certain avian species, including the endangered Piping Plover (*Charadrius melodus melodus*). Protection and restoration of these critical habitats is crucial for the survival of such species. Beaches and dunes are home to numerous marine and terrestrial species that play significant roles in nutrient and energy transfer within these ecosystems and between the barrier spit and adjacent land and sea (Conway-Cranos et al., 2015; McLachlan & Defeo, 2018). In addition, they have protective benefits and biodiversity value (Nordstrom et al., 2011; Spencer & Harvey, 2012). Beach and dune ecosystems are particularly sensitive to grain size therefore nature-based solutions involving sediment addition need to carefully consider source material. Additional details are provided in Chapter 8.

6.6.5 Seagrass Meadows

Seagrass meadows are among the world's most productive marine habitats, providing structure, refuge from predation, and nurseries for fish and invertebrates (Nahirnick et al., 2020). In Canada, the main species of seagrass in all three marine coastal regions is eelgrass (*Zostera marina*). These habitats provide support to commercially and culturally important fish species, including Pacific salmon, herring, and Dungeness crab (Nahirnick et al., 2020). Eelgrass is also known to provide flood and erosion risk management benefits by attenuating waves, particularly when it occupies the full depth of the water column (Fonseca & Cahalan, 1992; Reidenbach & Thomas, 2018). Unfortunately, the condition and extent of eelgrass meadows has been in decline, driven largely by human activity in the coastal zone. Additional details are provided in Chapter 9.

6.6.6 Rocky Shores

Rocky shores and submerged rock outcrops (rocky reefs) are found in all of Canada's coastal regions, particularly in areas exposed to high waves. These habitats and their varying relief provide refuges for juvenile fish, and hard substrate for colonization by algae and invertebrates.

6.6.7 Conservation and Management

Recognizing the ecological, economic, and socio-cultural value of these coastal ecosystems, conservation and management strategies have been implemented in many parts of Canada. Protected marine areas, such as the Gwaii Haanas National Marine Conservation Area Reserve in British Columbia, aim to safeguard kelp forests and other coastal habitats. Additionally, collaborative efforts between government agencies, Indigenous communities, and scientists have been instrumental in the preservation of these ecosystems. As global pressures on coastal environments increase, continued research and conservation initiatives are imperative to ensure the resilience and sustainability of these invaluable coastal ecosystems. Well-conceived NBI that preserves and restores natural habitats and functions in concert with natural coastal processes can create and sustain vital coastal habitats and thus support coastal ecosystems and biodiversity.

6.6.8 Indigenous Traditional Ecological Knowledge

The coastal environments of Canada hold profound cultural, ecological, and economic significance for Indigenous communities. Over millennia, Indigenous Peoples living on the coasts have developed a deep understanding of these ecosystems through their Traditional Ecological Knowledge (TEK). In recent years, collaborative approaches between Indigenous communities and Canadian government agencies have gained prominence in coastal management, recognizing the importance of weaving TEK with western science. Indigenous Knowledge, rooted in generations of observation and experience, offers valuable insights into coastal ecosystems. Key aspects of TEK often include:

- Ecosystem Interconnectedness: Indigenous Knowledge almost always emphasizes the interconnectedness of land, sea, and people. Coastal environments are viewed holistically, recognizing the intricate relationships between species, habitats, and human communities.
- Resource Management: Many Indigenous communities have developed sustainable resource management practices, including selective harvesting of marine life and preservation techniques that maintain the health of coastal ecosystems.
- Seasonal Cycles: Traditional calendars and practices are often intricately tied to the seasonal cycles of coastal regions. Many Indigenous communities have developed a deep understanding of optimal times for fishing, hunting, and gathering based on ecological indicators.
- Adaptive Strategies: Many Indigenous communities possess adaptive strategies for responding to environmental changes, such as sea-level rise or shifts in marine species distribution. These strategies can draw on TEK to ensure resilience.
- Cultural Significance: Coastal environments hold profound cultural significance for many Indigenous communities, serving as sites for ceremonies, storytelling, and the passing down of cultural traditions. They are often central to the identity and spirituality of coastal Indigenous communities.

TEK is increasingly recognized as a critical component of coastal stewardship. It enhances our understanding of ecosystems, contributes to effective management strategies, and fosters cultural preservation. The inclusion of TEK in coastal management, including implementation of NBI, promotes sustainable practices that benefit both the environment and Indigenous communities.

6.7 Socio-Economics and Culture

Implementing NBI requires consideration of place. Place is the physical environment or landscape—natural or developed—that changes through human use and settlement. The landscape also shapes human use and settlement patterns, and many people attach particular meaning to place or landscape. Coastal place is where the land meets the sea. Given the dynamic nature of the coastal zone, this landscape both challenges and sustains human use. Following a systems approach, implementing NBI requires understanding other attributes of coastal place, such as landscape histories, culture, socio-economic conditions, and modern coastal settlement (van Proosdij et al., 2021).

Just as Canada's coastal regions exhibit diverse climates, geographies, and ecologies, they are extremely socio-culturally diverse. As explained in Chapter 5, every community is unique, comprised of diverse members with distinct relationships to place and space. Many of Canada's coastal landscapes have provided resources and transportation corridors, and fostered culture and traditional uses for Indigenous Peoples since time immemorial. The colonial settlers that followed established along tidal rivers, estuaries, coastal bays, and inlets to establish trade and resource-based industries, such as fisheries, aquaculture and forestry, and shipbuilding. The concentration of population near the coast reflects the historical and modern importance of the ocean for natural resources, trade, and travel (Gardner et al., 2005). For some Indigenous communities, the connection to the coast is as (or more) deeply rooted in culture and spirituality than in these practical considerations. For instance, salmon has deep cultural significance to Coast Salish First Nations in the West Coast region, which goes beyond its significance as a food source (Murphy & Osler, 2022). Each of the coastal regions, and the communities within those regions, have a unique history and culture, which influences decision making.

Community vulnerability to coastal flooding and erosion is also influenced by an array of socio-economic, demographic, ethnic, and cultural characteristics (Chakraborty et al., 2021). Indigenous communities are often disproportionately vulnerable, in part due to persistent marginalization and disadvantage by colonial policies and actions. Community vulnerability and capacity should be considered when developing NBI solutions.

6.8 Governance

Implementing NBI requires an understanding of the regional and local coastal governance context and the use of governance tools and strategies. Governance refers to the way in which decisions are made, who has a voice in making these decisions, and who is accountable. As explained in Chapter 4, the policy and legislative context within which NBI approaches are considered in Canada varies significantly within and across Canada's coastal regions. All levels of government in Canada—Indigenous, federal, provincial, local—have some jurisdiction in coastal areas with different associated legislation and roles that influence coastal governance in different regions and localities. Local contexts may vary between communities and municipalities according to local governance systems (e.g., hereditary or elected leaders), economy, community conventions and values, local culture (including political culture), bylaws and regulations, and

land use and development patterns (van Proosdij et al., 2021). The fragmented jurisdictions and inconsistent coastal governance approaches across Canada may present barriers to implementation of NBI, if not properly considered and addressed. An in-depth knowledge of the roles and responsibilities of different actors, and regional and local governance contexts and cultures helps to ensure successful NBI. A more detailed and comprehensive discussion of governance is provided in Chapter 4.

6.9 NBI Projects

There is currently no known comprehensive or consistent national database of coastal NBI projects or case studies that includes performance monitoring data, which could be used to benchmark the success of different NBI concepts within different regions or under different local contexts, and to inform future deployment. However, some regional and non-profit groups have developed project mapping tools,[7,8] which can provide useful reference examples of NBI projects that have been implemented. The U.S. Army Corps of Engineers' Engineering With Nature® program has also developed a Project Mapper (ProMap) tool,[9] which allows project proponents to submit case studies from anywhere in the world. Examples of NBI projects in Canada's coastal regions are provided throughout this guide, including:

- The Living Dyke pilot project, Boundary Bay, British Columbia (Box 2-2 in Chapter 2, Box 10-4 in Chapter 10, and Boxes 13-1 and 13-2 in Chapter 13)
- Metlakatla hybrid shore protection scheme, British Columbia (Box 2-3 in Chapter 2, Box 11-1 in Chapter 11, and Box 12-1 in Chapter 12)
- Several managed dyke realignment and marsh restoration projects in Nova Scotia (Box 9-3 in Chapter 9, Box 10-1 in Chapter 10, Box 11-3 in Chapter 11, and Box 12-2 in Chapter 12)
- Dune restoration in Prince Edward Island (Box 8-1 in Chapter 8)
- Chiasson Office Spit Piping Plover Restoration – sand engine and constructed marsh sill, New Brunswick (Box 8-2 in Chapter 8)
- Cates Park beach restoration, British Columbia (Box 8-5 in Chapter 8)
- Le Goulet dune restoration, New Brunswick (Box 8-8 in Chapter 8)
- Mahone Bay living shoreline, Nova Scotia (Box 9-4, Chapter 9)
- Jim Tovey Lakeview Conservation Area, Ontario (Box 10-5, Chapter 10)

6.10 Importance of Regional and Local Knowledge

To apply a systems approach (see Chapters 2 and 7), a thorough understanding of regional and local coastal environments, physiographic features, oceanographic processes, ecosystem dynamics, and socio-cultural and governance contexts is essential to support the design and implementation of well-functioning NBI.

[7] https://www.naturalinfrastructurenb.ca/case-studies/

[8] https://naturecanada.ca/defend-nature/how-you-help-us-take-action/nature-based-climate-solutions/national-project-map/

[9] https://ewn.erdc.dren.mil/tools/engineering-with-nature-project-mapper-promap/

Coastal areas often experience unique climate, weather, and metocean conditions, including fluctuating water levels, wave action, wave-induced currents, rain, frost, snow, and ice. Understanding both regional and local climate, metocean conditions, and coastal hydrodynamics is essential for designing infrastructure that can function well under the wide range of conditions unique to a site. Moreover, coastal hazards, such as tsunamis, hurricanes, and storm surges, are prevalent in many regions. An in-depth understanding of the local risk profile, which can vary dramatically over short distances, is critical for designing infrastructure capable of withstanding extreme events.

6.11 Summary and Future Direction

There is tremendous diversity of coastal environments, climates, and socio-cultural and governance contexts across and within Canada's four major coastal regions. Under a system-based approach, regional and local conditions, and changes in those conditions over time, must be considered to support successful NBI implementation. Given the scale and diversity of Canada's coastal landscapes, there is a need for ongoing, long-term monitoring networks that can support system-based approaches and monitoring of NBS performance. Since the majority of NBI pilot projects in Canada and internationally have been implemented in warm or temperate regions, there is a need for ongoing research and testing of solutions for cold regions where ice and/or permafrost are important factors. Regional communities of practice, such as the Atlantic, Arctic, Great Lakes, and Pacific chapters of Coastal Zone Canada's Nature-Based Coastal Solutions Community of Practice,[10] can facilitate capacity-building and knowledge-sharing within and across regions.

6.12 Chapter References

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[10] https://coastalzonecanada.org/nbcs/

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7 System Analysis and Design

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7.1 Chapter Key Messages

- The design process for nature-based infrastructure (NBI) is similar to other coastal projects but importantly, requires input from diverse, multi-disciplinary project teams with broad perspectives. The design philosophy for NBI projects may differ significantly from the approach to conventional (grey) infrastructure, reflecting the more dynamic nature of NBI, and incorporating allowances for adaptive management in uncertain futures.
- A design basis is needed to establish clear objectives, design philosophy, design approaches, assumptions, and performance expectations for NBI. In some instances, establishing the basis of design for NBI may be a more involved process than for grey infrastructure because NBI is dynamic.
- Project objectives should be SMART (specific, measurable, achievable, relevant, and time-bound), and linked to performance metrics that can be measured and used to objectively assess performance and guide adaptive management.
- Prior to the design of NBI, a thorough system and site characterization should be completed to understand the natural and socio-cultural system settings and characteristics. Site characterization includes review and analysis of historical data, as well as consideration of existing and future conditions through data collection, modelling, and analysis. The type of NBI that is appropriate for any given site depends on the system context. The system and site characterization may need to be revisited and refined as the design progresses.
- Natural features within and adjacent to the system can provide inspiration for the generation of NBI options and alternatives. NBI concepts that are based on local, stable natural analogues are more likely to mimic natural system behaviours, and be relatively self-sustaining and resilient to disturbances.
- Evaluation or appraisal of project options or alternatives should extend beyond technical or flood and erosion risk management (FERM) performance, considering the potential for NBI projects to score highly in delivering socio-cultural, environmental, and economic benefits.
- Like any coastal project, the number of design phases and levels of analysis can vary, depending on a variety of factors. NBI project proponents should weigh project risks and uncertainty against their risk tolerances when considering trade-offs between investment in design versus adaptive management. While NBI almost always involves some level of adaptive management, upfront investment in modelling, analysis, and design can reap rewards in terms of reducing risk, uncertainty, and overall project costs.

7.2 Introduction

This section outlines the key considerations and best practices with respect to system analysis and design of NBI following the principles and framework identified in Chapter 2. The overarching steps are applicable to all three NBI types described in Chapters 8 to 10, and include:

- Project Scoping
  - Problem identification
  - Project team assembly
  - Initial system characterization
  - Design basis
- System Characterization
- Options Identification, Analysis, and Appraisal
- Preliminary and Detailed Design

7.3 Project Scoping

A clear understanding and definition of risk, goals, objectives, and constraints is crucial to enable effective NBI design (Vouk et al., 2021). The following sections outline considerations in scoping an NBI project, which typically precede options identification, appraisal, and design.

7.3.1 Problem Identification

7.3.1.1 Early Engagement and Consultation

Early engagement with communities of stakeholders, Indigenous Title and Rights holders, and other interested and affected parties is essential to identify risks, priorities, and community values (see Chapter 5), and to frame the problem to be addressed. It can also serve to identify constraints and opportunities for use of NBI.

7.3.1.2 Understanding Risk

To deliver benefits and be cost-effective, NBI must be grounded in a comprehensive understanding of the flooding and erosion risks it is designed to manage. Risk assessments can be used to identify the full range of risks associated with flood and erosion hazards in a system (including social and cultural risks), establish risk tolerances and priorities, and generate alternative risk reduction strategies including NBI (Vouk et al., 2021). The first priority of the Sendai Framework for Disaster Risk Reduction 2015–2030, to which Canada is a signatory, provides that “disaster risk management needs to be based on an understanding of disaster risk in all its dimensions of vulnerability, capacity, exposure of persons and assets, hazard characteristics and the environment.” This priority is recognized in Canada’s Emergency Management Strategy (Public Safety Canada, 2019), and reflected in the National Adaptation Strategy (Government of Canada, 2023), which establishes a guiding principle that “decision making should be informed by an understanding of climate risks and vulnerabilities to minimize impacts and costs before they occur and support emergency preparedness.”

Methods for assessing coastal flood and erosion hazard risk in Canadian settings are described by Murphy et al. (2020) and references therein, and in the Federal Hydrologic and Hydraulic Procedures for Flood

Hazard Delineation (NRCan, 2023). Hazard and risk assessment methods with varying levels of sophistication and complexity may be employed, and tailored to suit strategic priorities, project phases, and project needs.

7.3.1.3 Consider Alignments with Strategic Priorities

Ideally, all nature-based infrastructure (NBI) projects should be guided by an overarching Integrated Coastal Zone Management plan, shoreline management strategy, or flood and erosion risk management strategy (see Chapters 2 and 4). Such plans and strategies, particularly when developed through a "whole of society" lens, can be valuable in identifying needs, priorities, and system boundaries and interdependencies, and in balancing competing interests in the coastal zone (e.g., balancing development and the use of resources in coastal areas with environmental and societal goals) over a range of timeframes. However, there are no consistent approaches to coastal zone management or strategic coastal hazard risk management in Canada, so the onus often falls to project proponents and designers to work with rights holders, stakeholders, regulators, and subject matter specialists to identify system boundaries and interdependencies, constraints, and priorities.

7.3.1.4 Identification of Constraints and Opportunities

Early identification of constraints and opportunities, especially through engagement with interested or affected parties, will help to frame possibilities and maximize the chances of a successful project. NBI projects are typically constrained by considerations such as:

- Regulatory requirements that restrict or are designed to avoid placement of sediment where it could cause harm to fish habitat.
- Rates of natural sediment supply compared to relative sea-level rise (which may make maintenance or adaptive management cost-prohibitive).
- Availability of materials (e.g., imported sediment with appropriate gradation, vegetation seeds or plugs).
- Site access.
- Land ownership and jurisdiction, which may prevent system-wide implementation of NBI.
- Funding for maintenance and adaptive management.

Opportunities may include possibilities to leverage partnerships to identify funding strategies, to access expertise or materials (e.g., beneficial use of dredged sediment), or to broaden the scope or scale of the project to maximize impacts.

7.3.2 Project Team Assembly

Effective delivery of NBI requires multi-disciplinary teams and broad perspectives (Vouk et al., 2021). Input from engineers, biologists, geomorphologists, geophysicists, ecologists, archaeologists, planners, environmental/ecological economists, social scientists, Indigenous Knowledge-holders, local community members, and others will enable a deeper system understanding and more robust solutions. Indigenous Traditional Knowledge can enable a greater collective understanding of system processes and contexts. Early assembly of a core project team, and clear definition of roles and expectations, ensures the necessary expertise and knowledge can be applied to develop appropriate NBI.

7.3.3 Initial System Characterization

Prior to options identification, appraisal or design, a system and site characterization should be completed to understand the natural system setting and characteristics. A preliminary characterization may be sufficient to generate viable options or concepts. However, a thorough system and site characterization (Section 7.4) is generally required before settling on a preferred concept. The natural system characterization should include the relevant geological history and setting, presence of flora and fauna, the present-day morphodynamical character of the shoreline, the regional and local metocean conditions (water levels, winds, offshore and nearshore wave conditions, including extremes), coastal processes (nearshore currents and sediment dynamics), and where appropriate, nearshore ice conditions and permafrost. The socio-cultural system characterization should consider governance and regulatory contexts, community values and sense of place, community vulnerability and capacity, historical uses of the site and surrounding areas, socio-economics, culture, heritage, and history. System characterization and analysis may be iterative throughout project scoping, options appraisal, and design phases, and may even extend throughout the project lifecycle to inform adaptive management.

An important step in applying a systems approach is establishing system boundaries, which determine the spatial scales that must be considered. At a minimum, coastal FERM strategies and measures should be developed to consider impacts and interactions over an entire coastal sediment cell (a coastal reach that is relatively self-contained, isolated sedimentologically from adjacent reaches, or with clear sediment inputs, outputs, and transport pathways), which may transcend municipal boundaries (see Figure 2.4-1 in Chapter 2).

7.3.4 Design Basis

The design process for NBI is generally similar to other coastal projects. A basis of design is particularly important to establish clear objectives, design philosophy, design approaches, assumptions, and performance expectations for NBI. Setting performance expectations is particularly important for NBI, given that it is often dynamic, responding to system changes and disturbances over a variety of timeframes. For example, imported sediment for NBI is rarely placed or profiled precisely to conform to natural or existing cross-shore profiles and planform geometries, for practical reasons. Consequently, substantial reshaping is often expected in the period immediately following construction until the sediment planform and cross-shore profile approach a dynamic equilibrium condition (see Chapter 8). Over longer timeframes, NBI may evolve differently than predicted during the design, particularly when the actual meteorological and oceanographic (metocean) conditions and coastal processes differ from those assumed in the design process, resulting in morphodynamic responses, flood and erosion risk management (FERM) benefits, and co-benefits that also differ from those anticipated at the outset. Predicting the long-term evolution of NBI is often challenging, and long-term predictions should be associated with appropriate levels of uncertainty. Adaptive management should also be firmly embedded in the design basis and philosophy, as a means to deal with uncertainty.

A basis of design is used to establish:

- Project objectives and goals
- Design philosophy
- Design methodology and tools

- Project life and lifecycle cost expectations
    - Performance criteria and metrics
- Design parameters and criteria
    - Environmental constraints (e.g., sensitive areas)
    - Geotechnical information (e.g., sediments, compressibility/stability of existing materials)
    - Coastal metocean design parameters including extremes (e.g., water levels, waves, currents, ice)
- Potential challenges or deficiencies, corrective actions
- Approach to monitoring and adaptive management

7.3.4.1 Objectives and Performance Metrics

Typically, the high-level objectives of NBI for coastal FERM are to (Section 2.3.2):

- Provide buffer zones between coastal hazards and communities, infrastructure, or valued assets.
- Attenuate and dissipate storm surges and waves.
- Provide storage for floodwaters.
- Attract and stabilize sediments.
- Reduce or mitigate erosion.
- Attract stabilizing flora and fauna.

Objectives may also be linked to a range of desired co-benefits, such as: recreational opportunities, preserved or enhanced habitat for fish, amphibians, birds, and benthic species; improved water quality; carbon storage and sequestration; and socio-cultural opportunities (CEC, 2024b). In the case of sediment-based solutions, such as dynamic revetments or cobble beaches (see Chapter 8), the primary objective may be to create a shore that is more resistant to severe erosion and wave overtopping, yet still dynamic and natural in function and appearance. NBI must also meet environmental regulations and satisfy community, regulatory, rights holder, and stakeholder expectations for a successful project.

Development of the design basis typically requires refining and adding specifics to project objectives, which should be clear and ideally measurable, that is, SMART—specific, measurable, achievable, relevant, and time-bound (Bridges et al., 2021). Identified performance objectives should be linked to pre-defined performance metrics (see Chapter 5 of the International Guidelines on Natural and Nature-Based Features for Flood Risk Management – Piercy et al., 2021) (CEC, 2024a), which can be used to objectively measure project success and to trigger adaptive management if performance is not meeting desired metrics.

7.3.4.2 Design Philosophy

The design philosophy for NBI projects may differ significantly from that typically applied to conventional (grey) infrastructure. The goal when designing grey shore protection infrastructure is often to achieve a statically stable solution based on a single set of design conditions or design event; whereas for dynamic NBI solutions, a single design event may not be the determinant of damage or loss of function. For NBI, performance should typically be assessed for multiple conditions or events ranging from frequently occurring to extreme, with consideration for seasonal fluctuations, progressive damage or loss of function, and post-storm recovery. Iteration of design variables (such as sediment characteristics and NBI

configurations) may be required to develop acceptable solutions. All stakeholders and rights holders should be made aware that substantial post-construction changes in geometry are normal and anticipated for some NBI solutions, and that long-term predictions of morphological evolution and project performance are uncertain, pointing to the need to plan for adaptive management.

Examples of typical considerations that may affect the overall design philosophy include:

- Risk tolerances and values of project proponents and communities.
- The types of NBI that are appropriate within the system and site context. Guidance on regional considerations is provided in Chapter 6, and considerations for different types of NBI are provided in Chapters 8 to 10.
- The mobile and dynamic nature of NBI means that a storm event or disturbance can cause widescale and rapid changes (e.g., in morphology, vegetation health and coverage). Some time may be required to recover and re-establish equilibrium, depending on factors such as the extent of damage, NBI scale (which influences capacity to absorb and self-repair), sediment supply, seasonal conditions for vegetation growth, and vegetation maturity. Adaptive management may also be required to support recovery and self-healing.
- Net losses of sediment may be inevitable over the long term, so ongoing monitoring is required to assess maintenance and adaptive management needs.
- The design process must consider performance for a range of conditions and events, including extreme events and future climate scenarios, to establish a range of potential future outcomes and assess potential maintenance and adaptive management needs.
- Interfaces with and potential effects of existing built structures, natural or NBI, human activities, and ecosystem components need to be taken into consideration (e.g., interruption of sediment supply by coastal structures, grazing of vegetation by migratory birds, recreational use of beaches and dunes) and their effects managed or mitigated.

7.4 System Characterization

A thorough understanding of natural system processes and interactions at the site of interest and the surrounding region is essential for the successful design and implementation of NBI. Building on the initial system and site characterization (Section 7.3.3), additional field monitoring and modelling should be used to update and improve the system understanding when progressing through phases in the design process.

Key natural system processes and factors to be considered include bathymetry and topography, meteorology, climate, hydrodynamics (including water levels, waves, currents, and circulation), geology, sediment transport (by waves, currents, and wind), geomorphology, ice and permafrost (in cold regions), and ecology. The following sections focus on physical and ecological system characterization but human activities, uses, and interactions with the natural system should also be considered, based on the guidance in Chapters 4, 5, and 6.

7.4.1 Bathymetry and Topography

Accurate knowledge of topography and bathymetry is a crucial first step in system and site characterization. Ground/seabed elevation and geometry exert controls on inundation, drainage, nearshore wave processes, wave runup and overtopping, and currents and circulation. Given that most coastal NBI projects encompass

the shoreline, developing a seamless digital elevation model (DEM) will typically involve stitching together datasets from both land- and sea/lake-based survey sources, which often utilize different vertical datums. Establishing consistent vertical datums for topography, bathymetry, and water levels, is a crucial prerequisite for accurately assessing coastal system processes and a common pitfall. Guidance on establishing vertical datums for coastal analysis in Canada is provided in Murphy et al. (2020). Resolution and accuracy of topographic and bathymetric data are key considerations. The lack of time series bathymetry and topography data for establishing erosion or accretion patterns and trends, and for validating sediment transport and morphodynamics models, is a common shortcoming and limitation. Guidance on sources of bathymetry and topography data in Canada, and quality control of datasets, is also provided in Murphy et al. (2020).

7.4.2 Meteorology

An understanding of marine and coastal meteorology is needed to successfully plan and design NBI (USACE, 2002). Important meteorological considerations relate to the role of wind in wave generation, water level forcing (e.g., wind set-up and seiches), driving coastal currents, and aeolian sediment transport; and to the role of atmospheric pressure changes in driving water level changes (e.g., barometric set-up).

Wind is usually considered in terms of its role in driving extreme wave and water level events that may be encountered over the NBI project lifecycle. Wind regime is also fundamentally important to the characterization of aeolian transport required for design of dune nourishments and dune restoration. NBI design and planning should also consider the time history and variability of winds (or sequence of events), as well as the magnitude and frequency of extreme events.

Estimates of winds and atmospheric pressure in coastal areas for design purposes may be derived from site-specific direct measurements, from atmospheric models (or coupled earth system models), or from reanalyses (combining models and measurements). Atmospheric data is discussed in Chapter 11 and sources of meteorological data for Canadian practitioners are identified in Murphy et al. (2020).

Guidance on procedures for the analysis of wind records from measurements or hindcast time series for input to aeolian transport calculations and wave and current prediction may be found in USACE (2002), Rogers et al. (2010), and CIRIA et al. (2007).

7.4.3 Climate

Climate change is often the primary impetus for consideration and adoption of NBI. As discussed in Chapter 6, climate is both a major driver of the extreme weather events that dominate coastal flood and erosion risk, and an important factor controlling the viability of different types of NBI. The potential effects of climate change must be considered in the design of NBI. Considering potential changes over multi-decadal time horizons and accounting for them through design and planning for adaptive management is essential to ensure adequate performance and avoid undesirable consequences.

The ClimateData.ca portal and Canada's Changing Climate Reports (Bush & Lemmen et al., 2019; Bush et al., 2022) are useful places to start for identifying future climate scenarios, projected changes and effects, and datasets. Other sources of climate data are discussed in Chapter 6.

Publicly accessible climate projections, based on global earth system models, and downscaling using regional climate models, are useful in understanding potential future changes in mean atmospheric variables, such as temperature and precipitation. However, they typically do not (at present) provide sufficient spatial and temporal resolution to support a fulsome characterization of future natural system processes and extremes at scales needed to support NBI project design, since hazards and NBI responses are often driven by variability at high frequencies and small spatial scales. Dedicated downscaling studies may be performed (e.g., Zuzek Inc., 2019; Cousineau & Murphy, 2022), but these are resource-intensive exercises and substantial uncertainties often remain. There are also outstanding uncertainties and deficiencies in the capabilities of existing models to reliably forecast coastal winds over long timeframes (e.g., Cousineau & Murphy, 2022). Improving projections of future atmospheric climate variables, particularly extremes, is a topic of ongoing research. In the interim, NBI designers should make use of the best available data, conduct sensitivity testing of designs for different potential future climate scenarios, and plan for adaptive management by identifying adaptation pathways (Murphy et al., 2020; Government of Canada, 2023).

7.4.4 Hydrodynamics

Coastal hydrodynamic processes are primary factors controlling the performance of NBI, and are influenced by multiple driving forces including astronomic, geologic, seasonal, interannual, and long-term meteorological and climatological processes, as well as water quality (e.g., salinity and temperature). Many texts and references are available for guidance on characterizing hydrodynamic processes at system-wide and local-site scales. Parts I and II of the Coastal Engineering Manual (USACE, 2002) provide guidance on many of the essential hydrodynamic processes of relevance to NBI design, including:

- Analysis of water levels including astronomical tides and storm surges and the hydrodynamics of coastal inlets and harbours.
- Fundamental principles of wave theories and wave analysis (including spectral analysis), ocean wave generation, wave propagation, wave transformation, and interactions with bathymetry and coastline.

The impacts of climate change on hydrodynamics, such as changing sea levels (Section 6.4.2.3), changing frequency and intensity of extreme events, and changing baroclinic circulation patterns, should also be considered.

7.4.4.1 Water Levels

Water level is a key design parameter due to its control on exposure to and modulation of waves and currents that directly influence sediment transport, vegetation health, wave runup and overtopping. In tidal areas, the water level regime controls the frequency and duration of inundation by saltwater, which determines survival of plant species with differing degrees of salt tolerance (see Chapter 9). Anticipated water level fluctuations at an NBI site over the project lifecycle may determine target elevations for certain elements of NBI, such as the elevations of beach berms or dynamic revetments (see Chapter 8). Water levels are also an important input as a boundary condition to numerical hydrodynamic models for prediction of site-specific water levels, currents, wave conditions, and circulation (see Chapter 11).

NBI design needs to consider the mechanisms and processes that influence the fluctuations in water level in both space and time in a coastal setting, which include mean sea level and relative sea-level change over the life of the project, tidal fluctuations, storm surges, seiches, and long waves (e.g., tsunamis), short waves, and wave runup. On the Great Lakes, water levels are controlled by seasonal and interannual changes in the hydraulic cycle, storm surges, seiches, and on Lake Ontario, controls on outflow to the St. Lawrence River. Data sources and guidance on methods of water level analysis, including tidal harmonic analysis and extreme value analysis, are provided in Murphy et al. (2020).

Knowledge of the rate of relative sea-level (RSL) change, integrating global sea-level rise and vertical movements of the land from factors including land subsidence or uplift due to local and regional factors (James et al., 2021) is essential for understanding past and predicting future hazards and coastal evolution. The rate of RSL change is an important control on the natural stability and form of a shoreline, with rapid RSL rise favouring shoreward translation and erosion of beaches (Leatherman et al., 2000) and salt marshes (Miller et al., 2021). When rates of RSL rise exceed rates of shoreline accretion/adjustment, drowning can occur (particularly of barrier beaches/islands as seen, for example, on Prince Edward Island and other parts of Atlantic Canada).

Determining design elevations for NBI may require extreme value analysis of water levels in combination with other variables (e.g., Caires, 2011; Serafin & Ruggiero, 2014; Murphy et al., 2020), analysis of historical records from a reference gauge station, local (site-specific) measurements, accounting for relative sea-level change projections (Section 6.4.2.3), and numerical modelling of storm surges and tidal circulation (see Chapter 11). In the short term, storm surges and/or high tides may be more important to consider than sea-level rise (Lemmen et al., 2016). However, an important consequence of sea-level rise is the associated increase in the frequency and magnitude of extreme water level events, which compounds over time. As discussed in Section 7.4.1, establishing consistent vertical datums for water levels, topography, and bathymetry is of vital importance.

Transient high-water levels caused by tsunamis (e.g., triggered by seismic events or landslides) may also occur (Section 6.4.7). Although damaging tsunamis are relatively infrequent; when they do occur, the impact on the coast and coastal infrastructure, including NBI, can be considerable, and thus should be considered as a source of risk for NBI projects.

7.4.4.2 Waves

Waves are an important source of coastal flood and erosion hazard, and a driver of sediment transport in coastal waters. Waves transfer momentum from offshore to inshore and are a relevant consideration for all types of coastal infrastructure design, including NBI. Detailed information on wave conditions and the wave climate at the site of interest, including extreme conditions, is essential to support successful NBI design.

NBI project teams should include individuals with in-depth familiarity with the following aspects of waves and wave climate analysis, and be able to apply this knowledge to support design:

- Types and limitations of wave theories.
- Wave generation, growth, propagation, transformation, and decay processes, including surf zone processes, short wave and long wave processes, and their role in sediment transport and coastal circulation.
- Wave climate analysis and characterization.

- Empirical wave prediction and hindcasting for simple situations.
- Types and limitations of numerical wave growth and transformation models (see Chapter 11).
- Wave measurement and analysis for model validation and site-specific characterization.
- Sources and availability of measured and synthetic wave data.

A review of the above aspects is well beyond the scope of this guidance. However, seminal guidance is provided by USACE (2002), Goda (2000), Leenknecht et al. (1992), Rogers et al. (2010), CIRIA et al. (2007), and references therein.

Designers must have the ability to determine expected wave conditions and wave climate over the region of interest, including extremes, and select and design NBI elements that are compatible with the local wave and current conditions. For example, in locations where energetic waves are expected, NBI comprised largely of coarser sediments may offer greater stability, resistance to reshaping and longevity than NBI comprised largely of fine sediments, depending on compatibility with natural system processes (e.g., sediment supply and budgets) and features (see discussion of natural analogues in Section 2.4.6). The effects of fluctuating water levels, reshaping bathymetry, nearshore currents, and vegetation on nearshore wave conditions must not be overlooked in design. In addition to existing (pre-construction) conditions, post-construction conditions must be studied to ensure that the NBI will respond as expected to the local environment forcing, and that there will not be unintended consequences, which could be detrimental to healthy system function and recovery. Where substantial morphological changes are expected (e.g., in response to major storms), the effects of these changes on wave conditions and NBI performance should be assessed. Ideally, the expected evolution of the proposed NBI and surrounding system to wave, current, and wind forcing over several years and including several significant high-water and high-energy wave events should be modelled (see Chapter 11) and assessed. Prevailing wave conditions may influence the construction methods and practices that may be used to construct NBI safely, hence the expected nearshore wave conditions during the construction window should be studied and considered. The methods and equipment used for construction must be compatible with the expected wave conditions, water levels, and meteorological conditions.

Sources of wave data for Canada's coastal regions, and methods of analysis and modelling, are provided in Murphy et al. (2020) and in Chapter 11.

7.4.4.3 Currents and Circulation

Currents and circulation are important drivers of transport of fluids, sediments, nutrients, pollutants, and floating debris (including logs and driftwood) that have the potential to impact NBI performance. Currents may cause or contribute to erosion (scour), and transport sediments (often mobilized by waves) to areas of deposition. From a construction standpoint, currents may also influence operational conditions that control navigability of access channels; operation of equipment, such as barges, dredges, and excavators; and berthing and downtime for vessel operations.

Currents and circulation may be driven by tides, wind, shoaling and breaking waves, temperature and salinity gradients, river discharges, and regional ocean current systems. Water depth (influenced by water levels and bathymetry) and morphological feedback also play a significant role in controlling current magnitudes.

Currents may be characterized by site-specific measurements (see Chapter 12) and numerical or physical modelling (see Chapter 11). A combination of both measurement and modelling typically yields the best results. Measurements provide data for model development, calibration, and validation, while modelling allows for expanded spatial and temporal characterization, and the investigation of extreme conditions and potential future conditions not captured by short-term monitoring.

7.4.5 Geology

Components of a geological characterization include identifying: rock outcrops, including cliffs and subtidal platforms/reefs, which provide "hard" boundary conditions; sources and characteristics of unlithified sediments, including erodible soft "feeder" bluffs, rivers, and nearshore deposits; and stratigraphy, which can exert control on which sediments are exposed to wave action under different water level scenarios.

7.4.6 Sediment Transport and Geomorphology

Sediment transport plays a crucial role in determining the viability of almost all types of NBI. A detailed description of considerations for sediment transport is provided in Chapter 8.

The characterization of present-day morphodynamics should be based on a detailed geomorphological description of the site within the context of the regional geomorphological setting (see Chapter 6) combined with a detailed description of the coastal processes that drive the morphodynamics. The coastal system may comprise several interrelated geomorphological elements, such as salt marshes, tidal flats, beaches, dunes, and coastal barriers, each with distinct processes, roles, and contributions to the overall system behaviour. Each of these elements have a range of potential configurations, which can be determined from video remote sensing, air photo/satellite image analysis, and/or detailed mapping with LiDAR and multibeam sonar. For example, beaches range from broad ultra-dissipative to narrow reflective beach types, which depend on four variables: breaker height, wave period, sediment fall velocity, and tide range (Masselink & Short, 1993). Such classifications can therefore be useful as a semi-quantitative basis for future measurement programs or design concepts.

Data may be obtained from a variety of sources to assist with sediment transport and geomorphic characterization. Information on bathymetry and topography (particularly changes over time), meteorology and climate, hydrodynamics (waves, water levels, and currents), geology, and sediment characteristics is needed to support sediment transport and geomorphology assessments.

More detailed measurements can be made to understand and constrain the natural rates of change (see Chapter 11). Similarly, models (numerical and physical) of nearshore wave transformation, nearshore circulation, and sediment dynamics can be developed and applied (see Chapter 11). Models can be used to forecast the range of possible morphodynamic futures for the project, informing planning for adaptive management. The geomorphic site characterization should also consider the potential impacts of climate change on sediment budgets and morphodynamics through changes in relative sea level, extreme wind and wave conditions, and permafrost and/or ice cover in cold regions.

Information on historical shoreline translation and erosion can be gleaned from Indigenous Traditional Knowledge, archaeology, historical maps (reaching potentially hundreds of years into the past), and air photo and satellite analysis (reaching back to the early 20th century). More recent rates of coastal change

can be derived from repeat surveys by remotely piloted aircraft systems (RPAS – drones) or conventional surveying methods (e.g., repeat surveys of cross-shore transects). Similar methods and data sources can be used to reconstruct the history of human-caused modification of the shoreline, such as emplacement of shoreline protection structures, dredging/beach mining, sediment replenishment, and peat cutting.

7.4.7 Ice and Permafrost

In addition to the regional influence of sea and lake ice on wave and storm surge generation and propagation (Section 6.4.5), local ice conditions and their potential influence on NBI should be considered. This may include identifying based on historical data or observations whether there is potential for ice pile-up, ride-up, or plucking of sediments or rocks to occur (Murphy et al., 2020), and determining whether such events might be damaging to NBI (e.g., by gouging or reshaping protective features), or contribute to natural system function (e.g., ice is known to be an agent of dispersal of sediments and seeds within cold region marsh systems). If shorefast ice thickness records are available at or near an NBI site, a variety of methods may be employed to develop site-specific estimates of projected future ice conditions (Johnston, 2023).

In the North Coast region, the potential for rapid changes in ground conditions (e.g., subsidence or thermal erosion) at a coastal site due to permafrost thaw should be considered. Characterization of permafrost conditions may include measuring or identifying active layer thickness, ground temperature, ice content, massive ice (wedges or lenses), soil porewater salinity (Canadian Standards Association, 2019). Consideration should be given as to how NBI might affect drainage, and particularly whether it could result in conveyance of water towards areas of ice-rich permafrost, which could contribute to thawing. Thermosyphons, thermoprobes, insulation, and other strategies may be considered to locally mitigate or reduce permafrost thaw (Canadian Standards Association, 2019).

Indigenous Knowledge can contribute greatly to an understanding and characterization of ice and permafrost conditions at a site. SmartICE[11] is an example of co-application of Inuit knowledge and western science and technology to develop an improved understanding of ice conditions in the North Coast region, which may be considered an example of “Two-Eyed Seeing” in practice.

7.4.8 Ecology

An in-depth characterization of existing ecosystem components and health should be conducted to provide a baseline for setting environmental objectives, and for monitoring NBI performance and environmental co-benefits. This should include measuring and mapping the inundation regime, water quality (temperature, salinity, suspended sediment concentrations, and nutrient load in some instances), native habitat types, and the abundance, diversity, and condition (health) of flora and fauna (both native and invasive species, as well as species-at-risk, if present). If working in degraded ecosystems (e.g., where development has adversely impacted ecosystem health over time), obtaining information on historical ecosystem states can provide inspiration for strategies, NBI types, or ecosystem restoration measures to support coastal flood and erosion risk management. Local natural analogues can serve as “reference” ecosystems and play an important role in design and post-implementation monitoring. Detail regarding the use of reference sites and “Before-After Control-Impact” are provided in CEC (2024a). In this respect, Traditional Ecological

[11] https://smartice.org

Knowledge has enormous potential to contribute to improved NBI solutions, since it draws upon the collective knowledge of many generations of Indigenous Peoples with close connections to land and water.

Ecological models, such as water quality and biogeomorphological models (e.g., Willemsen et al., 2022) that are typically coupled with hydrodynamic models (see Chapter 11), are increasingly being employed to assess potential future changes in ecosystems, and habitat suitability, with and without NBI interventions. However, such models are data- and resource-intensive and prone to uncertainty. At the very least, an understanding of potential future changes in physical conditions (e.g., water levels, wave exposure, circulation, sediment transport, sediment budgets) and water quality conditions at an NBI site should be used to estimate likely impacts on habitat suitability for target native species of interest. Ecological risk factors for particular types of NBI should also be considered (e.g., the potential for grazing of immature vegetation by migratory birds) and mitigated.

7.5 Options Identification, Analysis, and Appraisal

Once the design basis has been established, and at least a preliminary characterization of the system and site has been completed, work can begin on identifying potential options or design alternatives. General guidance on formulating and evaluating options is provided in Chapter 2 of the International Guidelines on Natural and Nature-Based Features for Flood Risk Management (King et al., 2021). It is generally preferable to develop several options initially, to raise awareness among the project team and rights holders or stakeholders of the range of possibilities, to avoid prematurely narrowing the focus or locking in decisions of regret, to hedge against unforeseen constraints or opportunities, and to allow for hybridization as options are refined. Although the “do nothing” scenario is often not considered a viable option for communities facing imminent risks, it is often helpful to retain this as an illustrative alternative during the appraisal process, to provide a baseline for comparison and to enable quantification of the benefits of intervention.

7.5.1 Natural Analogues

The study of natural analogues at similar coastal sites is an effective way to generate NBI options for analysis and appraisal (Section 2.4.6). Natural analogues can be used to select or choose process conditions, materials, placement geometry, habitat types, and more. Learning and applying what works for nature in a similar setting (see Chapters 2, 6, and 7), will likely prove more successful than forcing a design to fit to a site for which it is poorly suited. The key to this way of thinking is to develop options that work with natural processes as much as possible. Considerations may include:

- Alignment with underlying geometry, structure, and resisting elements (e.g., headlands, structures, bluffs), sediment supply, sediment budget, sediment characteristics, as well as landform shape and stability now and in future climatological conditions.
- Orientation and exposure to winds, waves, currents.
- Tidal regime, elevation, slope, and frequency of inundation (for vegetation).
- Accommodation space to facilitate natural dynamics and recovery from disturbances.
- Water quality (including temperature, salinity, turbidity).
- Habitat types and suitability.
- Drainage and hydraulic storage.
- Shade and sunlight exposure.

- Exposure to ice or debris.

For example, a project that takes advantage of longshore drift will function better, last longer, and cost less than a project that interrupts longshore drift. Application of this principle requires a combination of geomorphological and ecological interpretation to first identify the relevant matching patterns in landforms and habitat, and then visualize the implementation of the concept at a potential project site. Key considerations for coastal settings and NBI include the orientation of the shoreline relative to wave exposure, the composition and distribution of material sizes, nearshore and foreshore slope, and the elevations inhabited by resident plants and other living organisms.

In collaboration with rights holders and stakeholders, design alternatives should be developed with consideration to maintaining or enhancing compatible human activities at the site where possible; for example, walking, recreational fishing, or the launching and landing of small craft.

7.5.2 Evaluation of Options

Once potentially viable options or design alternatives have been formulated by the project team (engaging with rights holders and stakeholders), work can begin to evaluate those options in terms of their viability and expected performance, with the goal of identifying a preferred option or set of alternatives to move forward to design. Options evaluation is typically an iterative process involving engagement (see Chapter 5), analysis, and modelling (see Chapter 11). Conceptual options should be compared and evaluated in terms of their likelihood of meeting project performance objectives, as well as being referenced to a baseline "do nothing" scenario. As explained by King et al. (2021), the amount of evidence (data and analysis) needed to support the evaluation of preferred options, will depend on the context and requirements for decision making. Evaluations and comparisons should consider estimated lifecycle costs and benefits over various timeframes to be identified in the Design Basis (Section 7.3.4). The evaluation should not be limited to technical or flood and erosion risk management benefits, especially considering the potential for NBI concepts to score highly in delivering socio-cultural, environmental, and economic benefits. Examples of multi-criteria analysis methods are provided in Chapter 2 of the International Guidelines on Natural and Nature-based Features for Flood Risk Management (King et al., 2021). Selection of the preferred alternative (or alternatives) to progress to the design phase should be through an inclusive and equitable process, reflecting the values and priorities of rights holders, stakeholders, and affected parties (see Chapter 5). This will help to ensure the selected alternative(s) are socially acceptable.

7.6 Preliminary and Detailed Design

Once a preferred option or set of alternatives or options are identified, design typically proceeds in a phased or iterative process similar to any coastal infrastructure project, leading to the development of detailed drawings, construction specifications, and cost analysis. Two phases are typical (i.e., preliminary and detailed design) but the number of design phases, level of analysis at each phase, and deliverables may depend on factors such as: the design philosophy and procurement strategy; the initial level of system understanding or uncertainty; the consequences of underperformance; risk tolerances; the complexity or novelty of the preferred alternative(s); the scale or criticality of the project; and trade-offs between detailed analyses at the design phase versus field experimentation and adaptive management. At a minimum, modelling, analysis, and design deliverables (drawings, specifications, cost analyses) should be sufficiently detailed and robust to adequately reduce residual project risks to within acceptable tolerances. In other

words, a project proponent should consider the various uncertainties associated with an inadequate system understanding, whether these uncertainties are amenable to adaptive management, and the consequences if these uncertainties are not addressed during the design phases. Upfront investment in modelling, analysis and design often reaps rewards in terms of reducing risk, uncertainty, and overall project costs. Further guidance on appropriate levels of modelling and analysis is provided in Chapter 11. As explained by Gailani et al. (2021), "…the level of detail and extent to which construction-related issues and methods are considered or prescribed at the detailed design phase will depend largely on the procurement and contracting approach adopted (e.g., standard, design-build, or turnkey), and the local availability of experienced contractors."

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8 Sediment-Based Solutions

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8.1 Chapter Key Messages

- Sediment is often the foundation for nature-based infrastructure in coastal environments, especially estuarine, deltaic, wetland, and even open coast contexts—sediment provides a dynamic "structure" for flood and erosion resilience on which coastal processes can operate (and actively contribute to reshaping) but also provides the backbone for the establishment and hosting of plants and biota.
- Sediment-based solutions require maintenance over project lifetimes. Monitoring, adaptive management, and maintenance should be proactively planned for.
- A thorough site characterization is needed to understand the natural setting and sedimentary characteristics of the coastal system. The type of sediment-based solution that may be appropriate depends on site-specific contexts.
- Establishing the basis of design for sediment-based solutions requires an understanding that sediment-based infrastructure is dynamic, and subject to change over a variety of timeframes.
- Replicating natural analogues from similar coastal settings has a greater chance of success than forcing a design to fit.
- Various methods may be used for construction of sediment-based infrastructure, often depending on the source of sediment to be used. Common methods include placement by dredger, trucks, and conveyor belts. Two methods of sediment management that may be served by a variety of placement methods include sediment bypassing and sediment recycling.
- Successful implementation of sediment-based solutions often depends on successfully managing and dealing with a broad range of technical, environmental, economic, and socio-political challenges.

8.2 Introduction

Sediment is often the foundation for nature-based infrastructure (NBI) in coastal environments, especially estuarine, deltaic, wetland, and even open coast contexts—sediment provides a dynamic "structure" for flood and erosion resilience on which coastal processes can operate (and actively contribute to reshaping) but also provides the backbone for the establishment and hosting of plants and biota. Sediment often works very well when used in combination with both vegetation and engineered (e.g., rock) structures (see Chapters 9 and 10). The focus in this chapter is on non-cohesive sediment-based coastal systems (sand and gravel-sized material, up to cobbles), such as sand dunes and vegetated dunes, sand, gravel, cobble, and mixed beaches, although sediment-based solutions can also be implemented in cohesive sediment environments (containing muds, clays, and silts). Sediment-based solutions often prioritize nourishment and sediment management approaches that preserve and protect natural processes and enhance habitats. Sediment-based solutions rely on natural coastal processes to reshape placed sediment to form a dynamic beach, dune, berm, or shoal that can dissipate wave and storm energy and provide both flood and erosion protection. The dynamic nature of sediment-based solutions requires different considerations to more static, grey infrastructure (Table 8.2-1).

Table 8.2-1. Comparison of requirements for sediment-based NBI and grey infrastructure.

Requirement	**Sediment-Based Solutions**	**Grey Infrastructure**
Accommodation space	Requires larger accommodation space to allow for dynamic behaviour and natural function of erosion and recovery.	Typically smaller footprint as grey infrastructure tends to have steeper slopes and is often designed to be statically stable.
Lifecycle costs	May be uncertain as sediment-based solutions require monitoring and locally available supply of natural sediment over the lifetime of the project for initial construction and maintenance, which in turn requires substantial historical data and detailed monitoring over the project lifetime. May require consideration of a broader range of design conditions to anticipate maintenance requirements.	Generally assumed to be statically stable (maintenance free) and therefore lifecycle costs can be more readily estimated during project design.

Requirement	Sediment-Based Solutions	Grey Infrastructure
Natural processes function for enhancement of habitat value	Sediment-based solutions depend on a dynamic design allowing for habitat renewal through natural processes. The more flexible and self-regulating the design—by accommodating nature-based design principles—the more valuable and durable the resulting habitat.	Less dynamic and adaptable than sediment-based solutions but can be designed with features to provide habitat for target species and communities.
Associated uncertainty with morphological processes	In addition to the above, estimating and forecasting the response of sediment-based solutions is challenging due to the dynamic, complex, and ever-changing nature of morphological processes across coastal environments.	Grey infrastructure is often fixed, includes scour protection, and uses design guidelines and recommendations that are more mature and developed than guidance currently available for NBI and sediment-based solutions.

As with natural sediment-based coastal systems, sediment-based solutions may take many forms, and may be exposed to widely varying environmental conditions. Sediment-based solutions may be vulnerable to damage including permanent loss of material if ill-suited to a particular site, which could result in loss of FERM function (see Chapters 6 and 7). Hence the need to carry out both a robust site characterization and basis of design for sediment-based solutions (see Chapter 7) and to ensure follow-up monitoring after implementation to assess adaptive management requirements.

Sediment-based solutions may include vegetation, either through natural recruitment or planting. Vegetation often serves to encourage additional natural sedimentation, reduces sediment re-suspension and entrainment, and provides additional habitat value. The use of sediment specifically to support the establishment of vegetation (e.g., by providing substrate for salt marsh or eel grass beds) is addressed primarily in Chapters 9 and 10. In those cases, sediments provide the foundation for vegetation establishment. Sediment-based solutions in which vegetation is not central to the design but can enhance it (e.g., beach/dune systems) will be primarily discussed within this chapter.

Gravel and cobble berms are sediment-based solutions that are particularly well-suited to application in high-energy wave environments and especially locations with limited accommodation space. Their design objective in such contexts is often to mimic natural cobble-boulder beach dynamics, protect against erosion and flooding, and contribute ecological benefits. Design considerations and examples are included in Section 8.4.1.2.

8.2.1 Objectives

The purpose of this chapter is to provide guidance on design and implementation of NBI types that are predominantly sediment-based.

The objectives of this chapter are to address the following topics:

- Key considerations and best practices with respect to design methodologies for sediment-based solutions, with reference to case studies, and regional considerations for implementation of sediment-based solutions in Canada.
- Challenges that apply with respect to design and implementation of sediment-based solutions in the Canadian context will be illustrated through several case studies.
- Practical aspects for implementation of sediment-based solutions, and specific considerations for construction, monitoring, and adaptive management.
- The more important tools and resources available to Canadian practitioners.
- A concise list of knowledge gaps or challenges remaining to be overcome to better enable or improve on guidance and outcomes for sediment-based solutions.

8.3 Key Concepts and Terminology

Sediment-based coastal systems may take on a broad variety of forms depending on their situation within bays, inlets, estuaries, deltas, marshes, dunes, beach, nearshore, and shoreface, which are represented by a tremendously broad range of environmental conditions. This diversity of geographic situation, form, and environment necessitates a fundamental need for understanding the coastal processes that control the dynamics of sedimentary features (morphodynamics) in the design of sediment-based solutions.

Sediment-based coastlines are a complex system of interlinked environments with a range of morphologies and associated dynamics that may be present in profile and planform. These systems are often described based on the concept of a coastal sediment cell, a semi-enclosed system with clear inputs, outputs, and transport pathways (Figure 2.4-1, see Chapter 2). Within this sediment cell, there is a flow of sediment between sources and sinks. For example, overwash events can erode dunes pushing the sediments into the hinterlands where they are unlikely to be mobilized to replenish the beach. This flow of sediment is often described using a sediment budget, a conceptual and quantitative model of sediment transport magnitudes and pathways (Figure 2.4-1 and Section 8.4.1).

Sediment transport is predominantly driven by waves, however, as depth of water increases there is less interaction between waves and the seabed. The active coastal zone is where waves interact with the seabed causing sediment transport. The depth of closure (Figure 2.4-1) is often an important concept to consider with sediment-based systems as this represents the seaward extent of active wave-driven sand transport.

8.4 Key Considerations and Best Practices

Key considerations and best practices with respect to the design, selection, and implementation of sediment-based solutions are similar to those of any other NBI project, as described in Chapter 7. Sediment-based solutions must be formulated and developed based on a thorough understanding of coastal processes on regional, system-wide, and site-specific bases, as explained in Chapters 6 and 7. In

the following sections, additional guidance is provided on detailed considerations for sediment transport. Though presented in the context of sediment-based solutions, the following guidance on sediment transport is also broadly applicable to vegetation-based solutions (see Chapter 9) and hybrid solutions (see Chapter 10) since sediment dynamics typically play important roles in all types of NBI.

8.4.1 Sediment Transport

Sediment transport plays a key role in the design and viability of NBI wholly or partially comprised of sediment or located on coasts where sediments occur, as it controls morphological changes in response to environmental forcing (wind, hydrodynamics). The movement and supply of sediment influences the construction and economic viability of sediment-based solutions (e.g., dredging costs and delivery costs by truck are often critical to project viability), and the integrity of dunes, beaches, and offshore sediment shoals or banks is a crucial factor in dissipating wave energy and ensuring the effectiveness of sediment-based solutions as NBI for coastal FERM (Soulsby, 1997).

Coastal sediment may be moved directly by wind (aeolian transport) or by moving water (hydraulic transport). The latter includes tidal, wind, density, or wave-driven currents, or by waves, or by both waves and currents acting together. Sediment is transported by the basic processes of entrainment, transportation, and deposition, which may occur simultaneously and with interactions. The complexities of sediment transport have been described as “staggering” (Roelvink & Reniers, 2012) and a vast amount of work has been carried out on the principles to develop practical approaches.

Sediment transport rate is defined as the amount of sediment per unit time passing through a vertical plane of unit width perpendicular to the flow direction. The amount of sediment is usually expressed as a mass or volume per unit time and is a vector quantity (Soulsby, 1997).

The rate of net accretion or erosion of an area (e.g., beach, coast, shoal, NBI project) depends on the difference in the rates at which sediment is entering or leaving the area of interest. A surplus of sand entering an area leads to accretion while a deficit leads to erosion.

The operations required to predict the patterns of erosion and accretion in a coastal study area are accomplished iteratively, as illustrated in Figure 8.4-1 and as follows (Soulsby, 1997; Roelvink & Reniers, 2012):

- Calculate the hydrodynamic distribution of waves and currents and dependent quantities of bed shear stress for a given depth, cross-shore profile, coastline, or 2D bathymetry over a period of time.
- Calculate the distribution of sediment transport rates (sediment transport potential) based on the combined flow properties, bathymetry, and sediment characteristics.
- Calculate the distribution of erosion and accretion rates.
- Update the depth, profile, coastline, or bathymetry, and return to the top bullet.

Sediment transport calculations may be performed on small scales using spreadsheet calculations, but most often using a numerical modelling system that integrates hydrodynamic processes with sediment transport calculations and bed morphology change as illustrated in Figure 8.4-1. Numerical and physical models for sediment transport are discussed in more detail in Chapter 11.

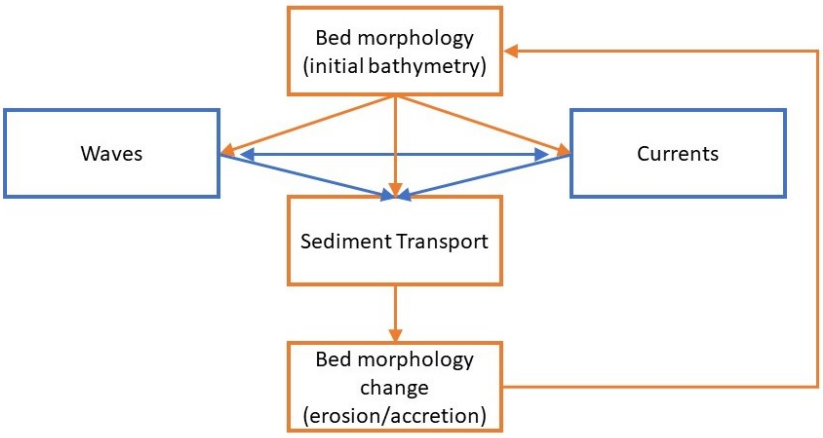


Figure 8.4-1. A morphodynamic model loop illustrating the modules typically included in an integrated process-based coastal morphology model, such as Delft3D or XBeach (adapted from Roelvink & Reniers, 2012).

Guidance on aeolian transport for input to coastal dune restoration and management is generally less developed than for hydraulic transport. Bauer and Davidson-Arnott (2022) provide a useful framework for consideration of aeolian transport and there is a growing body of research on the efficacy of vegetation and other structural measures in trapping sediment.

More recently, the exchange of sediment and evolution of the foredune has been simulated in a number of process-based models including:

- The Coastal Dune Model (Durán & Moore, 2013)
- XBeach (Roelvink & Costas, 2019)
- AEOLIS (Hoonhout & Vries, 2016)

Sediment budgets (Section 8.4.1.4) are a useful framework for understanding sediment erosion and accretion over time in complex coastal systems, whether natural or engineered, and should be considered as a methodology for design and evaluation of sediment-based solutions.

8.4.1.1 Beach Planform and Alongshore Processes

The 3D shape of beaches is dynamic; governed by a range of processes including wave energy flux, nearshore currents, sediment availability, water levels, and the presence of control points (non-erodible shoreline features, such as headlands, jetties, and groynes). The 3D form is often described by an equilibrium planform and cross-shore profile, which assume that beach shape fluctuates around a mean profile. The beach profile is dependent on tidal range, wave energy, and sediment characteristics and availability. Although sediment transport and coastal morphology changes are three-dimensional, it is often acceptable practice to consider the cross-shore profile and planform morphological evolution separately (e.g., Figure 2.4-1, see Chapter 2). Dean (2002) suggests this separation may be partially justified by the different timescales involved: cross-shore profile evolution often occurs on shorter timescales than planform evolution. Understanding the nature of the planform setting and evolution is key to design of successful sediment-based solutions.

Beach equilibrium planform and the orientation of beaches and coastal sedimentary features exposed to coastal processes are governed by the nearshore mean wave energy flux, the direction of the mean wave energy flux, dominant nearshore currents, and availability of sediment relative to control points (González & Medina, 2001; Silvester & Hsu, 1993). Key design considerations for planform in sediment-based solutions include wave exposure and dominant wave directions. Wave obliquity to the shoreline and breaking are the primary drivers of longshore sediment transport in wave-dominated coastal systems and on exposed beaches. Beach orientation and long-term stability are key indicators of net sediment movement and littoral transport along a coast. For conceptual design, stable beach planforms and orientations are often best developed to mimic observed, naturally developed, and stable shorelines. This can be achieved by observing local, natural analogues, and/or by designing beach planforms to be consistent with dominant wave directions. Engineered beaches are generally constructed on an alignment perpendicular to the dominant nearshore wave direction, and if not constructed to this alignment, natural coastal processes will tend to rotate them to that alignment.

A beach nourishment project constructed on a long, open-coast beach represents a perturbation, which under wave action will spread out alongshore with a loss of sediment from within the initial placement area balanced by a similar gain in sediment volumes along the adjacent downdrift beach. Total sediment volumes on the beach may decrease over time due to losses to offshore bars or aeolian transport to nearby dunes. The rate of spreading determines the volumetric performance of the project within the placement area (Dean, 2002). To represent the spreading out process it is necessary to relate the longshore and cross-shore transport to the planform (and profile) perturbation of the sediment placement. Several shoreline modelling tools, such as UNIBEST-CL+ (Deltares, 2011), LITPACK within the MIKE Zero software package (DHI, 2009), and GenCade (Frey et al., 2012) can be used to guide the design of planform geometry for sediment-based solutions including beach nourishments both with and without structural barriers. These techniques and tools are discussed in more detail in Chapter 11.

8.4.1.2 Profile and Cross-Shore Processes

Seaward of the back beach and dune, the cross-shore profile shape and its dynamic range are key design considerations for any sediment-based solution that is expected to respond to changing wind, waves, water levels, nearshore currents, and sediment transport. There is a positive correlation between median sediment size and average beach slope, with coarser material naturally forming steeper slopes (Rogers et al., 2010; Bujan et al., 2019) and a natural tendency towards an equilibrium morphology. Typical beach slopes and corresponding sediment sizes in the upper foreshore and shallow nearshore are shown in Table 8.4-1 and provide high-level target ranges for sediment-based solutions design. For a given grain size, beaches will tend to adopt flatter slopes in areas exposed to more energetic wave climates (Rogers et al., 2010). In general, there is a strong dependence of beach slope on grain size for fine-medium sediment and a weaker dependence for coarse sediment. The latter is most plausibly related to variation and reduction in infiltration during uprush and backwash on coarser beaches (Bujan et al., 2019). Steeper storm waves cause a beach of a given sediment type to flatten and become more dissipative, whereas small amplitude waves (with relatively long period) tend to build steeper and more reflective beaches. Wider beach material gradations typically result in flatter slopes than narrowly graded (i.e., more uniform) material but may also develop composite slopes when material sorting by waves occurs. On many sand and gravel coasts, cross-shore profiles tend to change seasonally as the beach adapts to seasonal changes in incident wave conditions, becoming flatter or more dissipative in winter (with a wider surf zone and spilling breakers) and steeper or more reflective in summer (with a narrow surf zone and plunging or surging breakers). The

relationship between sediment grain size, wave climate, beach slope, and breaking wave characteristics can be assessed using the surf similarity parameter (or Iribarren Number) (e.g., Rogers et al., 2010) and the Dean parameter (e.g., Wright et al., 1985). On high-energy coasts, mobile sediment may migrate offshore to form both inter-tidal and submerged bars during the higher-energy winter months, and then slowly return to the beach face during the milder summer season. As the inter-tidal beach is exposed to wind, aeolian transport may result in the formation of a dune system in the back beach (see Section 8.4.1.3). Beach planform may also rotate seasonally in response to seasonal changes in dominant nearshore wave direction.

Wave climate and water level exposure are key process factors that influence cross-shore behaviour. A range of methods of varying levels of sophistication from empirically based predictions to 2D hydrodynamic and morphodynamic models may be applied to predict the morphodynamic response of sediment-based solutions to typical and extreme events and to characterize flood and erosion risk management benefits. Choice of methods and models depend on the complexity of the project, stage of design, and risk associated with the project.

Table 8.4-1. Typical beach slopes for various median sediment sizes (Rogers et al., 2010).

Sediment Type	Median Sediment Size D50 (mm)	Mean Beach Slope (V:H) Minimum	Mean Beach Slope (V:H) Maximum
Sand	0.2	1:50	1:100
	0.3	1:25	1:50
	0.5	1:20	1:40
Gravel	5.0	1:8	1:15
	10.0	1:7	1:12
	35.0	1:4	1:8

Beaches can be classified according to morphodynamic types—reflective, intermediate, and dissipative (e.g., Wright & Short 1984; Wright et al., 1985)—based on relatively simple parameters that consider the relative contribution of wave and tidal processes to sediment transport, and the characteristics of available sediment. Such morphodynamic classifications often provide useful context for initial development of sediment-based solution concepts as a precursor to more advanced methods in later stages of design. Morphodynamic considerations integrate key process factors with characteristic morphodynamic response and can thus serve to understand how sediment-based infrastructure options may stand up to varying hydrodynamic conditions (Jackson et al., 2022). Beach profile response to hydrodynamic conditions can be estimated using a variety of analytical or modelling techniques (e.g., Chapter 7 of Rogers et al., 2010), including the application of numerical models, such as XBeach (Roelvink et al., 2015) or XBeachG (McCall, 2015)—see Chapter 11. It should be noted that predicting the long-term profile response of a nourishment or structural intervention by modelling is very difficult due to the challenge of realistically predicting natural behaviour of sandbar morphology (Roelvink & Reniers, 2012).

In general, coarser sediment (e.g., cobble, boulders, gravel, riprap) is less mobile than sand and performs better during storms (less cross-shore erosion). Mixtures of coarse sediments may be used to build dynamic revetments (e.g., cobble berms, berm breakwaters, or reshaping breakwaters) that provide highly effective resistance to erosion as well as dissipation of wave runup to reduce overtopping and flooding (van der Meer, 1988; Ahrens, 1990). Stone size for dynamic revetments is smaller than for traditional static revetments and therefore may be less expensive and much easier to construct, as placement does not require special care (Ahrens, 1990). However, the uniformity of grain size distributions may affect performance (Van Gent, 2010). Dynamic revetment designs often mimic natural cobble-boulder beach profiles in geometry and function, providing acceptable coastal protection combined with ecological and dynamic response benefits. In December 2018, a dynamic revetment was constructed using adaptive management approaches at North Cove, Washington, U.S., along a historically eroding 2-km shoreline reach of coastal barrier at the northern entrance to Willapa Bay (Kaminsky, et al., 2020; Bayle et al., 2021). Experience with similar cobble revetments in the Pacific west coast environment is growing (see Komar & Allan, 2010; Allan et al., 2005). The North Cove revetment is composed of poorly sorted angular quarry rock ranging in size from pea gravel to small boulders, as well as large wood debris and structures, a dune ridge, and native vegetation integrated with the revetment. The design, aim, and maintenance of the dynamic revetment is to simulate the functions of naturally forming cobble berms along composite beaches in the U.S. Pacific Northwest (Kaminsky et al., 2020).

8.4.1.3 Back Beach and Dune

The zone landward of the beach needs to be considered when designing NBI in sandy coastal systems (e.g., Figure 2.4-1, see Chapter 2). The geomorphology of sandy systems, such as barrier islands, spits, and barrier beaches, often extends landward to include dune, heath, tidal wetland, and lagoon habitats.

The stabilizing influence of vegetation is a critical control on overall performance for most sediment-based infrastructure (e.g., mud, sand, gravel, or mixed-sediment systems). Dunes, for example, are an integral part of sandy coastal systems. Dunes are accumulations of windblown sand starting on the backshore, usually in the form of small hills or ridges, stabilized by vegetation or control structures (Rogers et al., 2010). They occur where sand from the beach dries out at low tide and is transported inland by wind and deposited in the hinterland, where specialized vegetation may subsequently colonize the sandy deposits. Dunes form a necessary temporary store of sediment that can be reclaimed by the sea during extreme events, helping to buffer against the erosion of the beach naturally. The size and shape of dunes are a function of climate, geology, and geomorphology, wind and wave regime, and tidal range (Reed et al., 2009).

Dune restoration typically involves placing some form of resistance element to reduce wind velocities and induce settling in the lee of the barrier. This can include natural, biodegradable elements, such as recycled Christmas trees (Box 8-1), brush fences, and drift logs, or elements that are constructed from materials that may degrade over time, such as lobster traps. It should be noted that the latter elements may become eroded and mobilized during storms, posing additional hazards to communities and valued assets. Site-specific consideration is needed for appropriate selection of resistance elements. Projects may or may not include the planting of marram grasses and other dune species that will further trap sediment. Although vegetation plays a key role in foredune evolution, the rate, magnitude, and morphology of the foredune system is a function of supply-limiting (available dry sand, beach width) and transport-limiting (wind speed, direction) conditions (Hesp, 2002). Wide sandy beaches with oblique winds provide ideal conditions for

foredune formation and persistence (Davidson-Arnott et al., 2019). Thus, pairing dune restoration with beach nourishment can help enhance the overall resilience of the sandy coastal system as a whole.

Consideration of the geomorphic feedback between beach and dune systems is important, in particular when projects are also designed to provide compensation for habitat that may be impacted by development elsewhere or for consideration of the overall resilience and recovery of the beach-dune system after a significant storm. For example, the endangered piping plover (*Charadrius melodus melodus*) uses the backshore, foreshore, foredunes, and beach ridges of sandy Atlantic coasts for reproduction, growth, rest, and nutrition (ECCC, 2022). Washover, blowouts, and other storm-related features provide a mixture of sand, gravel and/or cobble, woody debris, and wrack that can provide camouflage and foraging opportunities for eggs, young, and adults alike. Incorporating and allowing for natural disturbance at restoration sites is important. Therefore, using an approach such as a “sand engine” where a large volume of dredged sediments is placed at the updrift end of a project and allowed to naturally redistribute through longshore sediment transport downdrift to the nearshore and beach system can be effective nature-based solutions (Box 8-2) (Ellis et al., 2021). The beach and dune system are allowed to naturally adjust their morphology through wave action and aeolian transport processes, creating more natural ecosystems. Research on the Zandmotor (sand engine) in the Netherlands has shown that placing a large volume of sediment in a single installation avoids (or reduces) the need for frequent renourishment and disturbance (Taal et al., 2016), compared to more conventional (i.e., smaller) beach nourishments. This also allows more time for ecosystem recovery and naturalization between nourishments/disturbances (Lodder et al., 2021).

Consultation with appropriate vegetation ecologists is essential to help maximize the efficacy of the sediment-based infrastructure for both flood and erosion risk and habitat management. The involvement of ecologists is also necessary to avoid unintended negative consequences associated with, for example, the introduction of inappropriate non-native, invasive species to an area or the interruption of nutrient dispersion. Another consideration is whether to plant vegetation or let vegetation develop through natural regeneration or establishment. Both options require an investigation of habitat suitability (Bridges et al., 2021).

Box 8-1. Dune Restoration and Climate Change Adaptation, PEI National Park



Figure 8.4-2: Dune restoration using evergreens at PEI National Park. (Source: Parks Canada, 2016. YouTube: https://www.youtube.com/watch?v=_e0Sq_1v474)

PEI National Park is situated on the northeast shore of Prince Edward Island and is a sandy mainland and barrier spit beach-dune complex with a transgressive dune field inland and an established foredune ridge at the seaward edge. The beach and foredunes are exposed to strong winds and large waves from the Gulf of St. Laurence. The beach and foredunes are scarped during large storm events, such as Hurricane Fiona most recently (CBC, 2022), with blowouts and overwash occurring in low-lying or disturbed areas (e.g., unauthorized trails). However, the system has been rebuilding since a major surge in October 1923 produced catastrophic overwash along the majority of the system (Mathew et al., 2010). Although scarping and significant erosion has occurred in some areas, the foredune ridge system has generally withstood more contemporary storms and has not been breached. This speaks to the resilient nature of a dune system with sufficient supply of sediment (Ollerhead et al., 2012). Over the last decade, Parks Canada has increasingly been adopting nature-based approaches to beach and dune management and climate change adaptation. One example is mitigation of an eroding blowout that had breached the foredune at Cavendish Beach using staked evergreen trees to trap windblown sand (CBC, 2014; Parks Canada, 2016; CBC, 2021). Christmas trees donated by the public as well as Scotch pine removed from other areas of the park since it is an invasive species were staked and tied down within a modified wattle fence. Two hundred trees were planted in three rows across the blowout, parallel to the former foredune ridge (Parks Canada, 2016). Marram (dune) grass from the provincial nursery was also planted. The trees provide structure (sand trapping and habitat) and nutrients for ongoing restoration efforts. This work was paired with the establishment of designated beach/dune crossings. Over a metre of sand accumulated within one year in some areas as a combined effort of physically trapping sand, establishing a dune management plan, and community education (Parks Canada, 2016). Additional longer-term climate change adaptation plans include relocation of some park infrastructure.

Box 8-2. Chiasson Office Spit Piping Plover Compensation Offsetting Project, Shippagan, NB

The Chiasson Office project site was historically a dynamic barrier island/spit system extending from the southwestern corner of Lamèque Island to the Acadian Peninsula, NB. The spit is designated as critical habitat for the endangered piping plover (*Charadrius melodus melodus*), which uses such barrier spit beach environments as nesting and foraging habitat (ECCC, 2022). The Shippagan Gully that runs between Chiasson Office Spit (Lamèque Island) and LeGoulet Small Craft Harbour (mainland NB) is an important route for fish harvesting vessels to travel between ports safely and efficiently in Shippagan Bay and fishing grounds in the Gulf of St. Lawrence. As a result, the site has experienced significant alteration and habitat degradation over time due to fish harvesting and processing, navigation and transportation activities, and channel maintenance. Historical and modern seawalls, a lighthouse and associated infrastructure (access road and power), and dredge spoil from 1983 are all currently impacting the site, as is recreational off-road vehicle use. Due to hazardous channel conditions and the deteriorating breakwater, emergency dredging was conducted in 2017, while plans were developed to redesign the channel and breakwater. Disposal of material from emergency dredging and construction of the redesigned channel and breakwater were anticipated to and did alter the barrier spit and therefore impact piping plover critical habitat. The environmental impact assessment process required the offsetting of 48,000 m^2 of piping plover critical habitat, along with 3,600 m^2 of wetland habitat and 37,000 m^2 of fish habitat at a minimum 2:1 ratio. CB Wetlands & Environmental Specialists determined that the offsets could be created through the removal of human-made structures (e.g., wooden seawalls and access road) and the implementation of nature-based techniques involving the beneficial reuse of dredge material: a sand engine and a marsh sill with living shoreline (Ellis et al., 2021).

In late fall 2020, ~165,000 m^3 of sand and gravel to a height of 3.5 m above chart datum was added updraft of the proximal end of the Chiasson Office spit. Aerial imagery collected in September 2020, April 2021, and August 2021 document landscape level changes, with breakwater construction and the sand engine dredge deposit completed by April 2021, and beach accretion increasing from September to April to August. Beach elevation increased during the same time interval, and the beach's volumetric change between 2018 and 2021 was 104,849 ± 6,845 m^3, an amount largely attributed to the sand engine dredge deposit along the shore. Bathymetric surveys found that elevation increased between the spring and summer and decreased between the summer and fall, reflecting seasonal differences in nearshore sediment deposition. Preliminary analysis indicates that the rate of sediment accretion has exceeded model predictions. The wider beach however was able to mitigate the effects of post-tropical storm Fiona in September 2022 with some dune scarping, but much less than storms pre-nourishment. In addition, in 2022, two nesting pairs of piping plovers were identified at the site, the first time in over a decade.

Box 8-2 (continued). Chiasson Office Spit Piping Plover Compensation Offsetting Project, Shippagan, NB



Figure 8.4-3: Chiasson Office Spit pre-nourishment in Sept. 2020 looking west towards gully (arrow) (downdrift from DS1 where dredge material to be placed late autumn 2020) and on Sept. 28, 2022, after post-tropical storm Fiona looking east illustrating accreted beach sediments and new breakwater.

8.4.1.4 Sediment Budget Analysis

A sediment budget is an account of sediment sources and sinks. Sediment budgets provide a conceptual and quantitative model of sediment transport magnitudes and pathways within an environment over a given time period. Often sediment budgets are evaluated for a baseline (pre-project) condition as the basis for evaluating the sediment system response to a proposed NBI project (Rosati & Kraus, 1999; McGill et al., 2022). Sediment budget analyses can provide useful insight to sediment transport magnitudes and pathways for past (historical), existing, and future conditions, and are therefore a useful diagnostic approach, particularly when applied in conjunction with monitoring, and/or sediment transport modelling (see Chapter 11).

Sediment budget analysis tools (e.g., Sediment Budget Analysis System or SBAS; Rosati & Kraus, 1999; McGill et al., 2022) typically involve calculating the sediment balance for a series of cells (see Figure 8.4-4 and Figure 8.4-5) in the area of interest (or influence) based on a conservation of sediment volume (or sediment volume flux) approach, as follows:

$$\sum Q_{source} - \sum Q_{sink} - \Delta V + P - R = \text{Residual}$$

Where:

Q_{source} = input of sediment into cell (e.g., riverine inputs, longshore drift, bluff erosion, longshore transport)
Q_{sink} = loss of sediment from cell (e.g., net offshore transport, net onshore transport by aeolian transport)
ΔV = Volume change within cell (e.g., net erosion and accretion)
P = Placement into cell (e.g., beach fill or dredged material placement)
R = Removal from cell (e.g., dredging or mining)
Residual (= 0 for a balanced cell)

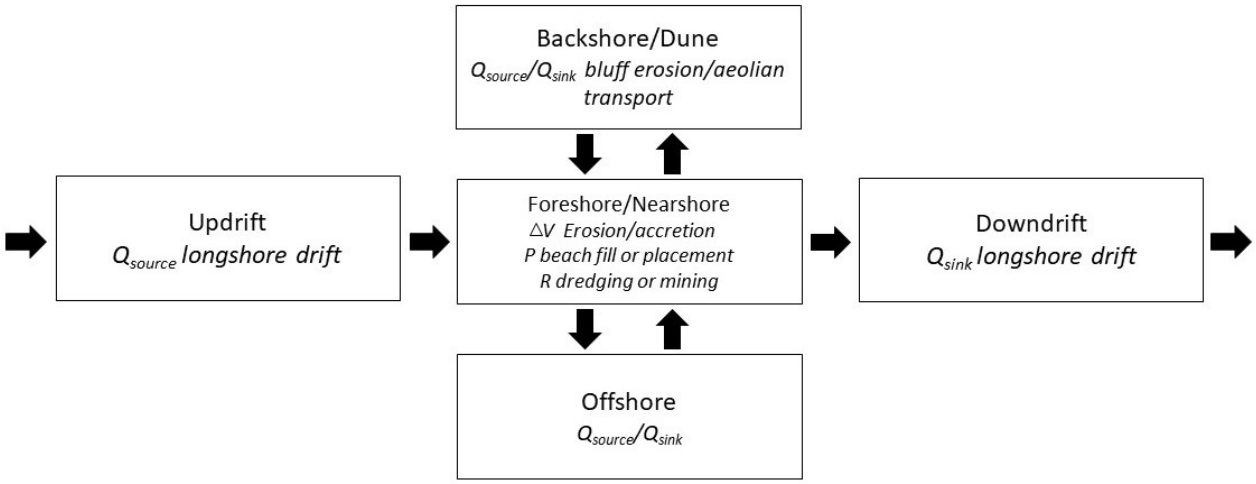


Figure 8.4-4. Conceptual sediment budget cell and pathways for a simple beach and nearshore system based on equation 7-1 (adapted from Rosati & Kraus, 1999).

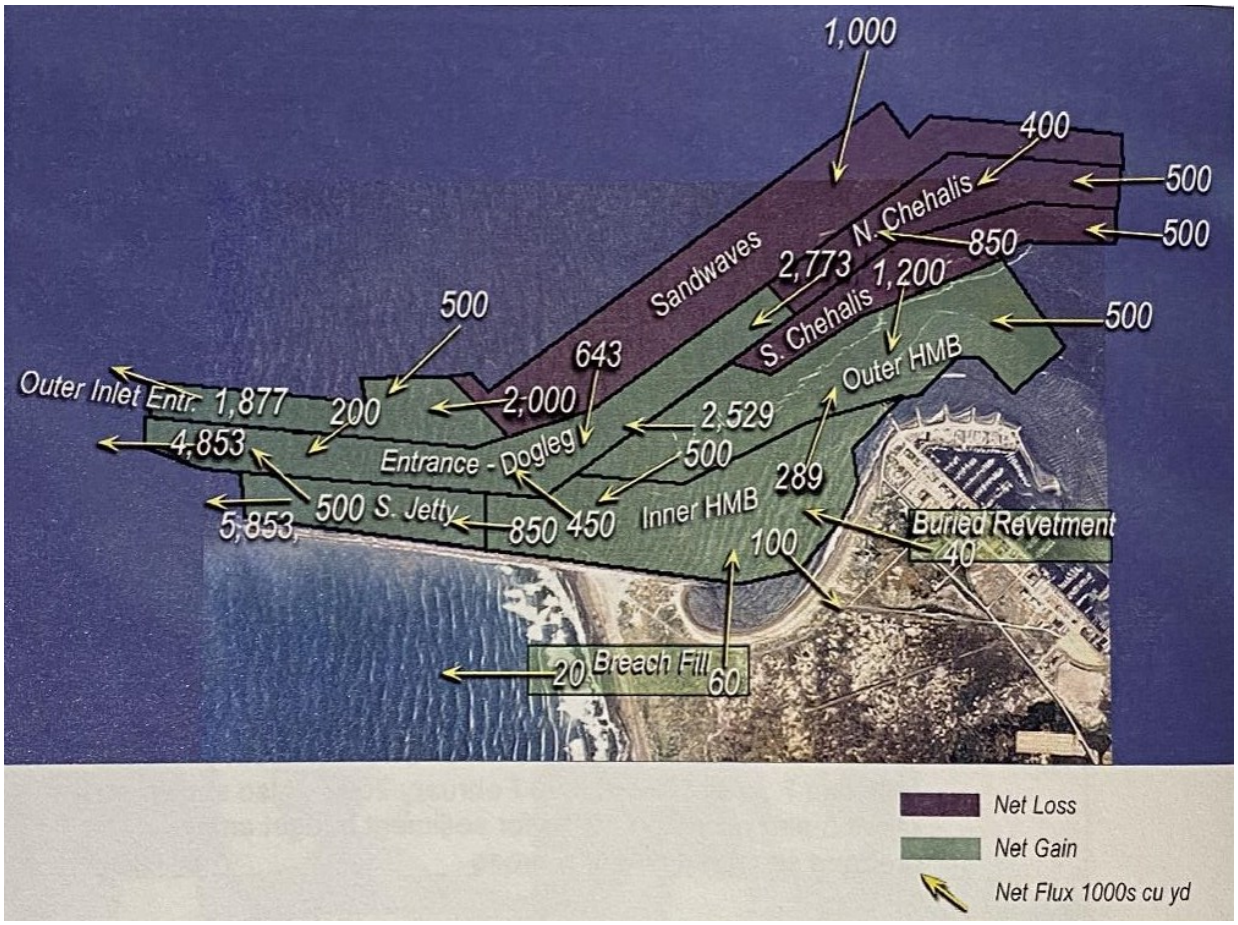


Figure 8.4-5. Illustration of a sediment budget analysis based on bathymetry change and coastal processes modelling (Source: Osborne et al., 2003).

The sum of sources ($\sum Q_{source} + P$) minus sinks ($\sum Q_{sink} + R$) should be equalized by the volume change (ΔV) in the cell. Sediment budget analysis most often involves estimating sediment volume changes by a combination of differencing between repeat topographic and bathymetric surveys for a given area over a period with sediment transport potential modelling (see Chapter 11). The sediment pathways define the cell-to-cell exchanges within the sediment budget and are often derived from sediment transport modelling or qualitatively based on a geomorphological interpretation of sediment transport indicators (Figure 8.4-4). Guidance on sediment budget analysis may be found in Rosati & Kraus (1999), McGill et al. (2022), and the Coastal Engineering Manual (Part III, Ch. 2) (USACE, 2002).

8.4.1.5 Sediment Characteristics

A key design and performance criterion of any sediment-based solution is the compatibility of the imported sediment materials with native (in-situ) materials. Several properties of sediment are important for the design of sediment-based solutions including particle size distribution, mineral composition (as it impacts grain density, hardness, and resistance to abrasion), particle shape (e.g., sphericity, angularity), and the bulk characteristics of the sediment mass.

Natural particle sizes vary widely from clay and silt (~10^{-6} to ~10^{-5} m diameter); to sand (~10^{-4} to ~10^{-3} m diameter); through pebbles, gravel, and cobbles (10^{-2} to 10^{-1} m diameter); and boulders (>10^{-1} m diameter). Density of sediment particles is on average 2.5 to 3 times the density of water; however, heavier minerals with a much higher density may also be present (Dronkers, 2005). Without turbulence or upward water motion, sediment particles will move downward (settle). Several useful formulae exist for the estimation of settling velocities of clastic particles in the sand through pebble range (e.g., Ferguson & Church, 2004) and for clays (Winterwerp, 2002).

Baseline characterization of the in-situ (native) sediment properties and structure is often an important step in sediment-based solutions project design and planning. Sediment composition, grain size distribution, and sedimentary structure information reflect the original sources of sediment and their relative importance and can thus be a useful indicator of process dynamics, including illuminating sediment transport pathways, and energetics (e.g., entrainment shear stress), and may allow reconstruction of depositional history. Most coastal sediments in temperate and cold regions are composed principally of quartz and feldspar derived from weathering of granites and metamorphic gneisses, schists, and continental rocks (Komar, 1998). Both lighter minerals (e.g., carbonates) and heavier minerals (e.g., hornblende, garnet, and magnetite) exhibit significantly different hydraulic behaviour from quartz and feldspar resulting from their varying densities and grain diameters. As a result, beach sediments exposed to wave and swash action exhibit distinctive size and mineral sorting (Komar, 1998; Osborne, 2018). Clay particles are very small and platey and as a result exhibit distinct rheological and hydraulic behaviour (Lambe & Whitman, 1969). The platey surface area of a clay mineral is chemically active, and especially when wet, the aggregate of clay surfaces produces cohesive, plastic, and slippery characteristics of its bulk form (USACE, 2002). Sediment transport, in both theory and practice, is typically separated into clastic (non-cohesive) and cohesive considerations owing to the significant differences in rheology and hydraulics. A basic starting point for characterization and classification is the use of ternary diagrams to graphically show the relative proportions among the grades of sediment (e.g., gravel, sand, silt, clay) within a sample (e.g., Shepard, 1954; Folk, 1954, 1974).

Typically, it is not practical for imported material to exactly match the native particle size distribution. Ideally for beach nourishment, the imported beach fill should be similar in grain size (or slightly coarser),

composition, angularity, and colour. The grain size distribution of beach fill material will affect the evolution of the cross-shore profile of constructed beaches, the mobility of the material, the long-term transport rates and losses, and how the beach will respond to storms and high-water levels.

Specification of sediment for sediment-based solutions should be based on:

- Existing local conditions (sediments, sediment supply, processes, control points underlying form).
- Range of sediment sizes associated with stable forms (morphodynamic principles).
- Experience with or findings from previous similar NBI projects.
- Available materials sourced from local sites or dredge borrow areas and matching the sediment characteristics of the natural regional analogue used as the reference condition.
- Modelling and analysis using tools as discussed in Chapter 11.

Material specifications should also provide constraints on:

- Quality of materials (free of contaminants)
- Quantity (realistic tolerances)
- Expectations regarding system response and monitoring requirements

Guidance on aspects of sediment specification is provided in the Beach Management Manual (Rogers et al., 2010), the Coastal Engineering Manual (USACE, 2002), and the following references:

- Sediment size classification – Modified Wentworth Classification (https://pubs.usgs.gov/of/2006/1195/htmldocs/images/chart.gif)
- Grain size sorting – Komar, 1998; Osborne, 2018
- Sediment sampling, grain size analysis and processing – Larson et al., 1997; Poppe et al., 2000
- Grain size statistics packages – Blott and Pye, 2001 (GRADISTAT- Microsoft Excel), Dietze and Dietze, 2019 (EMMAgeo – R)

8.4.1.6 Ice and Permafrost

As discussed in Chapters 6 and 7, ice and permafrost impact sedimentary processes in northern latitudes.

Ice is known to be an agent of transport for sediment in the Arctic (Eicken et al., 2005). Ice grounding and freezing to the bed leads to sediment becoming incorporated into the bed of the ice, which may then be transported during breakup. Aeolian sediment may be blown onto the ice surface and transported by mobile ice floes. Ice crust and frozen sediments can impede aeolian sediment transport processes on beaches and dunes during winter conditions (Delgado-Fernandez & Davidson-Arnott, 2011). In the absence of shorefast ice, strong onshore winds combined with high tide and storm surge can force ice onto the beach face or into intertidal marshes. Distinction is usually made between ice ride-up, where intact sheets of ice move landward over low-relief beaches and coastal features, and ice pile-up, which involves buckling and failure of ice upon contact with the shore (Reimnitz et al., 1990). Such events can deliver large quantities of sediment transported by the ice onto the shore, but can also gouge and scour beach faces and significantly damage coastal marshes and infrastructure. Consideration for the potential effects of ice on sediment-based solutions should be given in regions prone to seasonal or multi-year ice.

In permafrost regions, both thermal and mechanical processes contribute to coastal erosion (see Chapter 6). Details on considerations for the North Coast region are given in the National Standard of Canada, "CSA W205:19 Erosion and sedimentation management for northern community infrastructure" (Canadian Standards Association, 2019). However, the development of predictive models coupling thermal and mechanical erosion processes is a topic of ongoing research (Ravens et al., 2012; Islam & Lubad, 2022)

8.5 Types of Sediment-Based Solutions

Coastal sediment-based solutions include a variety of types and approaches, including the creation and re-creation of natural habitats, or enhancements of existing habitats or coastal protection features. Sediment-based solutions for coastal FERM tend to be concentrated near the shoreline, often defined in relation to mean high water level. Examples of sediment-based solutions include:

- **Sand and gravel beach nourishment:** Nourishment is the artificial placement of sediment to advance the shoreline seaward, often for the purpose of compensating for natural erosion (Box 8-2; Box 8-5) or to provide enhanced storm surge protection (Box 8-7). Nourishment may be achieved by land-based or marine-based construction.
- **Dune nourishment and stabilization:** Dune stabilization is the addition of vegetation, or some form of resistance structure (e.g., fences or large wood) to enhance entrapment of wind-blown sand. Dune nourishment involves artificial placement of sand within a dune field or in a location where it may beneficially feed the growth of dunes by aeolian transport (Box 8-1; Box 8-2).
- **Accretional spits and beach recycling (Box 8-7):** Spits are accretionary features formed and maintained by littoral drift due to prevailing oblique wave incidence and consist of a long narrow accumulation of sand or gravel, lying generally along the coast, with one end (proximal) attached and the other end (distal) projecting into the open sea or across the mouth of an estuary or lagoon (Davis, 1985). Spit recycling involves removal of sediment from the distal end of a spit and replacement at the proximal end of the spit to address erosion or enhancement of storm surge protection.
- **Inlet sediment bypassing:** Inlet sediment bypassing is the process by which sediment moves past tidal inlets through littoral drift. In natural inlets, sediment is transferred to the downdrift shoreline most often on stable inlets by offshore to onshore feeding from the ebb shoal due to wave refraction on the shoal, but may also occur by ebb-tidal delta breaching, spit breaching, and inlet migration (Fitzgerald & Miner, 2022). In modified inlets, jetties and dredging are used to maintain a navigable entrance and may result in channel deepening, seaward displacement of the ebb shoal, inlet stabilization, and subsequent disruption of bypassing processes. Beneficial use placements of dredged sediment may be used to artificially restore sediment to the littoral sediment budget on the downdrift side of the inlet (Box 8-6).
- **Dynamic reefs and revetments:** Dynamic reefs are a form of submerged breakwater designed to reduce incident wave energy, thus providing enhanced coastal protection (Ahrens & Cox, 1990). They can also act to modify and trap nearshore sediment transport for beach restoration. Dynamic reefs may be designed to roll over under wave action and eventually result in accretion of a berm on the shoreline. Dynamic revetments (also known as cobble berms) use boulder-, cobble-, and gravel-sized sediment to mimic a natural cobble beach. They are most often used to reduce wave energy and wave runup to mitigate erosion and flooding (e.g., Ahrens, 1990; Allan et al., 2005) and

are especially suited to high energy wave environments and situations with limited accommodation space.

- **Wetlands and salt marshes:** Salt marshes are coastal wetlands flooded and drained with salt water due to tidal processes. Wetlands are freshwater equivalents and maintained by seasonal and storm-induced water level changes in lakes. Wetlands and marshes provide protection from erosion and flooding by reducing wave energy and trapping sediments as well as dissipating precipitation runoff. Wetlands and marshes provide many additional benefits and are further described in Chapter 9.
- **Islands and shoals (Box 8-4):** Islands are bodies of land surrounded by water while shoals are submerged ridges, banks, or bars that may be partially exposed by tidal or water level variation. Islands and shoals provide significant benefits in terms of enhancing coastal resilience to both flooding and erosion and may be effective where other, land-based natural and nature-based features (NNBF) are not feasible (e.g., urban areas) (Gailani et al., 2021). Islands and shoals may be created or restored for FERM purposes, through marine reclamation and/or beneficial use of dredged sediment.
- **Land reclamation:** In coastal and marine contexts, land reclamation is the process of creating new land by reclaiming portions of the seabed or lakebed by placing fill. It may be used to restore land that has been previously lost by erosion or become permanently inundated by sea-level rise or a change in lake level, for example. The creation of artificial islands may also be considered a form of reclamation. Land reclamation may be achieved by drainage of inundated land, placement of fill derived from terrestrial excavation, marine dredging, and by allowing natural sedimentation to occur. Reclamations often require some form of shoreline protection to retain fill and prevent future erosion. Not all land reclamation may be considered NBI, since it is often implemented purely for commercial or “nation-building” purposes, without due concern for the negative environmental impacts of reclaiming large areas of intertidal or subtidal habitat.

Many of the above types are often combined with enhanced structural measures (see Chapter 10) and vegetation (see Chapter 9) for environmental, social, and engineering benefits (see Simm, 2021; Bridges et al., 2021).

8.6 Implementation

This subsection describes practical aspects of applying the guidance discussed in previous subsections, and specific considerations for construction, monitoring, and adaptive management of sediment-based solutions.

Practical considerations for the implementation of sediment-based solutions include:

- Accessibility of the site for construction equipment and the quantity of excavation and fill material that may need to be imported to the site to achieve the substrate and protective framework.
- Permitting requirements and timing of activities relative to fish windows, and seabird or shorebird nesting season.
- Ice cover (season).
- Wave and tide exposure during construction.

8.6.1 Methods of Construction

Several methods may be used for construction of sediment-based solutions including sediment placement by dredge, trucks, and conveyor belts. The preferred method will often depend on the source of sediment to be used in construction, whether it is sourced from the sea or lake, or on land. Two methods of sediment management, namely sediment bypassing and sediment recycling, may be served by a variety of placement methods.

8.6.1.1 Placement by Dredge

Many sediment-based solutions are constructed in tandem with dredging projects. The advantage of dredging methods is that large quantities of suitable sediment often can be located within a few hundred metres to a few kilometres from the sediment placement site and can be moved efficiently (and cost effectively), and often while fulfilling a need for navigation improvement. The opportunity for increasing the beneficial use of dredged sediment for shore protection schemes in Canada is substantial, considering that more than 3 million tonnes of sediment are estimated to be delivered to offshore disposal sites on an annual basis (Khunger, 2022). Placement of dredgeate usually involves one or more of three primary types of dredging equipment:

- Hopper placement (typically from split hopper barges, trailing suction hopper dredger, or cutter suction dredger)
- Hydraulic pipeline placement (Box 8-3)
- Rainbow spraying ("rainbowing") from a trailing suction hopper dredger or cutter suction dredger

The rainbowing technique is often use in thin-layer placement[12] (TLP), which is the "…purposeful placement of thin layers of sediment (e.g., dredged material) in an environmentally acceptable manner to achieve a target elevation or thickness" (Piercy et al., 2021; de Looff et al., 2021; Piercy et al., 2023). TLP often involves beneficial use of dredged sediment to raise coastal wetland elevations (see also Chapter 9). However, consideration must be given to the ability of existing marsh vegetation and ecosystems that are disturbed by TLP to recover. Rules of thumb are that plant shoots can penetrate layers of sediment that are 8–23 cm thick, and that 15–30 cm is the maximum placed sediment layer thickness that will allow marsh recovery over a 2- to 5-year timeframe (Piercy et al., 2023). Larger areas of marsh disturbed by TLP will generally take longer for vegetation to recolonize than smaller affected areas, since many wetland plant species colonize via rhizomes from the edges of an area where TLP has been applied (Piercy et al., 2023).

There are many useful references describing different types of dredging equipment and their application in sediment placement (e.g., USACE, 1987; van't Hoff & van der Kolff, 2012; and USACE Dredging Operations Technical Support Guidance for Beneficial Uses of Dredged Sediment[13]). Examples of beneficial reuse of dredged sediment include the Cat Island Chain Restoration (Box 8-4), and the Benson Beach Littoral Drift Restoration by pump-ashore (Box 8-6). The process of relocating large volumes of sediment by dredging can be accompanied by the release of suspended sediments into the water column contributing to turbidity. Mitigating the impacts of turbidity is usually managed by limiting the amount suspended sediment released by dredging and placement activities using silt curtains, containment bunds,

[12] https://tlp.el.erdc.dren.mil/

[13] https://budm.el.erdc.dren.mil/guidance.html

or selective use of dredging equipment. Sediment-based solutions designers and owners are expected to comply with provincial and federal regulations regarding maintenance of water quality standards associated with dredging projects.

Box 8-3. Sturgeon Bank Sediment Enhancement Pilot Project, Richmond, British Columbia, Canada

The Fraser River Delta is a Ramsar Wetland of International Importance, within which the Sturgeon Bank tidal marsh at the west coast of Richmond, British Columbia, comprised an estimated total area of 543 ha at its greatest extent this century. At least 160 ha of tidal marsh at the Lulu Island foreshore have died off since the 1980s, which has transformed much of the area into unvegetated mudflats.

Since the marsh recession was first realized in 2011, various studies have attempted to understand the causes of tidal marsh recession and identify restoration opportunities. River training structures constructed almost a century ago divert freshwater and sediment away from Sturgeon Bank into the Salish Sea, meanwhile maintenance dredging throughout the Fraser River Estuary results in the disposal at sea of over 1.8 million cubic metres of sediment. These sediments are the foundational materials that allow the marsh platform to grow vertically to keep ahead of rising sea levels.

As the culmination of over 12 years of research, discussions, and planning, the Sturgeon Bank Sediment Enhancement Pilot seeks to address one of the key factors for marsh resilience by placing fine sediment on the tidal flats to enhance natural processes that have been modified by human interventions over the last 100+ years. Led by Ducks Unlimited Canada in partnership with several organizations, the objective is to mimic natural riverine sediment delivery processes by using a temporary floating pipeline to pump sediment dredged from the Fraser River directly onto the Sturgeon Bank foreshore. Sediment is pumped into three mounds and fine sediments are dispersed by currents, tides, and storms throughout the foreshore. Short-term success for this pilot is to demonstrate proof of concept how to add sediment to Sturgeon Bank to support tidal marsh restoration, while long-term success will be to scale up the project to the rest of Sturgeon Bank and apply this concept more broadly across the Fraser River Delta.

Box 8-3 (continued). Sturgeon Bank Sediment Enhancement Pilot Project, Richmond, British Columbia, Canada

The first round of sediment addition occurred in February 2023, when approximately 11,000 cubic metres of sediment was added. The project intends to continue annual, incremental sediment addition for 5–10 years in order to evaluate the biophysical response of the foreshore to sediment addition. The works are currently supported primarily by federal and provincial salmon habitat restoration funding, thus providing a unique opportunity to test, refine, and evaluate how strategic, incremental annual sediment addition can help restore tidal marsh, support ecological resilience with sea-level rise, and provide coastal flood protection for the adjacent City of Richmond.



Figure 8.6-1. The Fraser River delta front has lost about 250 ha of low-elevation bulrush marsh between 1989 and 2011, including >160 ha at the west coast of Lulu Island at Sturgeon Bank (red polygon, Balke & Boyd, 2020). Sediment addition began in February 2023 with 11,000 m^3 added along the Sturgeon Bank foreshore. Photo credit: Nathan Vadeboncoeur.

Box 8-4. Cat Island Chain Restoration, Green Bay, Wisconsin, United States

Green Bay once contained one of the largest and most diverse wetland habitat complexes in the Great Lakes. This area was protected from waves and storms by the Cat Island Chain of barrier islands, but during high water levels in the mid-1970s, a series of severe storms caused catastrophic erosion and ice damage to the islands. While parts of the islands and wetland habitat remained, most of this habitat was lost or degraded due to erosion negatively affecting both habitat and water quality.

Planning and design for the restoration of the barrier islands began in 1988. The design included the beneficial reuse of dredged material from the Port of Green Bay, which requires annual dredging of approximately 100,000 to 250,000 cubic yards (approximately 75,000 to 200,000 m^3) of sediment. When completed, the barrier islands will total about 272 acres (~110 hectares) of restored area, and the project is estimated to provide disposal capacity for approximately 30–50 years for clean dredged material from the outer harbour in Green Bay. The project will protect 1,225 acres (~500 ha) of critical wildlife habitat. The reconstruction began in 2012 with the construction of a 2.5-mile (~4-km) long stone wave barrier and side dykes, and the nourishment of the islands is ongoing. The construction method includes a combination of hydraulic and mechanical dredging where the sediment is dredged from the harbour, placed on barges, and then hydraulically pumped from the barges to the cells of Cat Island.



Figure 8.6-2. Aerial photos of the Cat Island Chain of barrier islands in 1938 (pre-reconstruction) and 2020 (post-construction of stone wave barrier and side dykes). The lower image shows a small island formed by placement of dredged sediment within the nearest wave barrier.

8.6.1.2 Placement by Truck or Conveyor from Upland Sources

Upland sources, such as pits and quarries that mine fluvioglacial, glacio-lacustrine, and historic riverine deposits, are often a source of sediment for smaller projects when a borrow site is available within proximity to a project site. Upland sources may be the only viable source for coarse material, such as gravel, cobble, or boulders. Placement is typically by direct dumping from truck and arrangement by bulldozer or by placement and spreading by conveyor. The latter can be effective in the case where heavy vehicle access to the placement site is constrained or restricted, as in the case study highlighted in Box 8-5, or where marine access is restricted by shallow waters or wave climate.

Box 8-5. Transport by Truck from Upland Source and Placement by Conveyor at Cates Park, North Vancouver, BC

Cates Park is a point beach in Burrard Inlet, North Vancouver. Beach erosion was impacting park facilities and resulting in loss of significant cultural assets in the back beach area, as well as the recreational asset of the inter-tidal foreshore. A solution was designed to nourish the beach on the point to restore the littoral transport to the west and northeast to provide protection to the eroding back beach bluff. The solution needed to be implemented without putting equipment on the beach to avoid disturbance of cultural assets. Naturally rounded gravel and natural sand were trucked to site from a local borrow site and placed on the beach using a conveyor. The restored beach has performed well and re-established longshore transport, as well as allowing natural recolonization of native dune grass to occur in the upper foreshore.

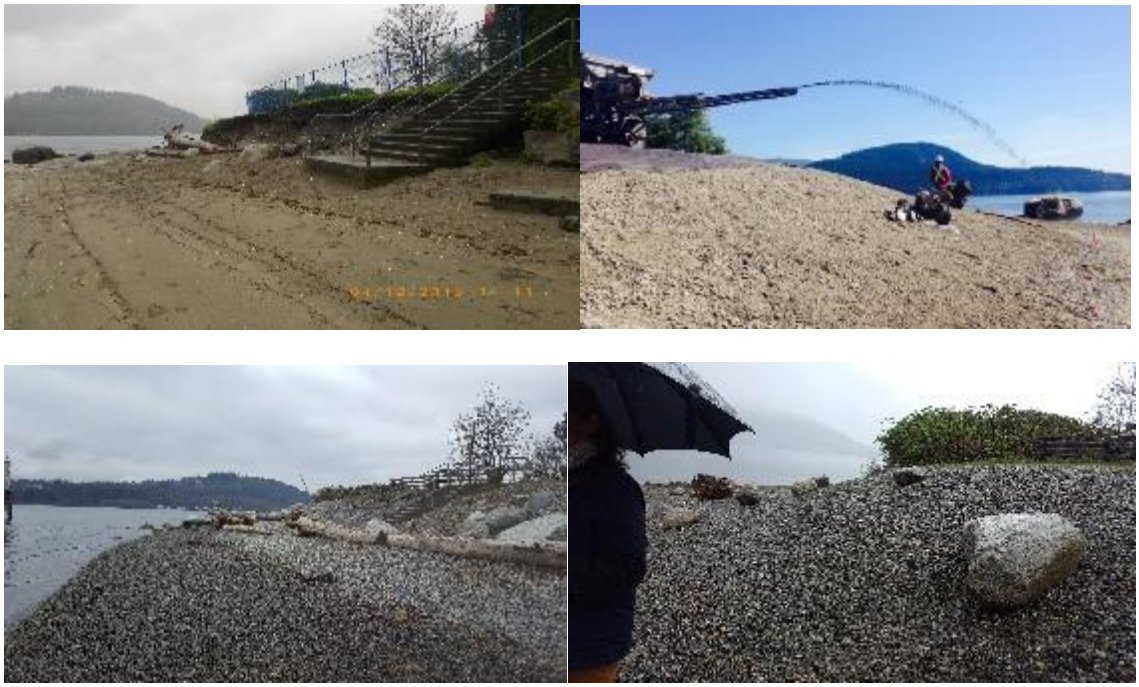


Figure 8.6-3. Cates Park beach pre-construction in 2013 (upper left), under construction in 2014 (upper right), 2018 (lower left), and in 2019 (lower right). Permission for use provided by Phil Osborne.

8.6.1.3 Sediment Bypassing

The use of sediment-based solutions to help stabilize inlets on sandy coasts has received a lot of attention due to the importance of inlets for reasons of navigation, their role as entrances to ports and harbours, and the associated need for sediment management. The hydraulic geometry of tidal inlets reflects a system of dynamic adjustment involving reversing (flood and ebb) tides, incident wave climate, and sediment budget. Introduction of structures, such as entrance jetties, and interventions, such as long-term dredging intended to control sediment deposition within the channel, can interrupt the natural flow of sediment at coastal inlets, which can have long-term consequences for sediment balance. Many of these processes have been extensively documented in scientific and engineering literature but nonetheless continue to be an active area of research (see, for example, Coastal Inlets Research Program[14]).

Sediment bypassing is a method used to offset an imbalance in sediment budget that may result from natural interruptions of sediment supply (e.g., headlands) or more often anthropogenic (human) interventions used to control inlet sediment dynamics (e.g., placement of entrance jetties or inlet dredging). Sediment bypassing, the mechanical transport of sediment from the updrift to the downdrift side of an inlet, may be used to restore a sediment supply to a downdrift shoreline that has been cut off. The method is often effectively combined with dredging as a beneficial use project, as in the case study highlighted in Box 8-6.

[14] https://cirp.usace.army.mil/

Box 8-6. Pump-Ashore, Hopper Placement, and Inlet Sediment Bypassing at Benson Beach, WA, U.S.

The Benson Beach Demonstration Project began in 2001 to mitigate a deficit in northward littoral drift at the mouth of the Columbia River resulting from long-term reduced sediment supply that arose from a combination of factors, including hydroelectric power development in the catchment, placement of entrance jetties and maintenance dredging of the inlet to control navigation channel shoaling and provide safe and reliable commercial navigation. For many years prior to the project, the USACE conducted regular maintenance dredging operations and placed the majority of the sediment in water depths extending 40–300 ft (~12–90 m). Extensive coastal processes studies led to two pump-ashore demonstration projects in which sand dredged from the entrance channel was pumped directly onto Benson Beach to the north of the north jetty. In July 2002, a trial placement of 43,000 cubic yards (~33,000 cubic metres) was placed and in September 2010, 300,000 cubic yards (~230000 cubic metres) were placed. Ongoing operations involve hopper placement in nearshore shoals, which is intended to feed the littoral system by wave refraction processes.



Figure 8.6-4. Benson Beach pump-ashore methods. Permission for use provided by Phil Osborne.

8.6.1.4 Accretional Beaches (Spits) – Beach Recycling

A sandspit (spit) is a depositional coastal landform that forms where downdrift deposition of alongshore transport ends in deep water (e.g., at the point of shoreline re-entrance). Spit stability is achieved through continued supply of sediment, by the establishment of size grading, or the development of a counteractive cell (e.g., natural recycling) (Carter, 1986). Spits often extend alongshore at the same time as moving onshore. Spits may become unstable when the original sediment supply is interrupted or cut off, or spit elongation leads to net withdrawal of material from the proximal end leading to thinning and sometimes breaching (e.g., Nicholls & Webber, 1987). The process of elongation, thinning, and onshore migration accelerates under rising sea levels.

The natural spit processes described above may pose a significant challenge for the long-term protection of infrastructure that may be located on sandspits. Sandspits have often been inhabited by Indigenous communities due to proximity to subsistence food sources, and an abundance of flat land makes them attractive for the construction of airports, and municipal and residential infrastructure. The process of beach recycling involves borrowing sediment from the distal end of the spit where a sediment surplus exists, transporting and placing the sediment towards the proximal end to make up for the deficit (see Box 8-7).

Box 8-7. Spit Recycling at Shaktoolik, AK, U.S.

Shaktoolik, Alaska, a remote village of 260 people located 125 miles (~200 km) east of Nome, on a narrow spit of land between the Tagoomenik River and the Bering Sea, faces threats from coastal flooding and erosion. The village has been relocated twice in the past; however, a recent assessment concluded that the current location now also faces increasing flooding risk from both sides of the spit, and erosion from waves and storm surges, with potential to damage infrastructure. In the short to medium term, the community has made the decision to stay and defend in place for as long as they can hold out. Out of necessity, they have adopted a nature-based approach, constructing a 5-km long berm using approximately 80,000 m^3 of sand excavated from a borrow pit at the distal end of the spit. Although the berm provides protection from erosion and flooding, the structure is frequently reshaped by waves requiring seasonal reconstruction. In September 2022, the berm was impacted by a storm in which offshore wave heights exceeded the 1-in-15-year return period (~7% annual exceedance probability), and storm surge levels were greater than 1-in-20-years return period (5% annual exceedance probability), causing significant reshaping of the berm early in the storm season and shortly after it had been reconstructed following a storm in July 2022. The community now questions the sustainability of the approach, given available sand resources and ongoing maintenance requirements.



Figure 8.6-5. The Shaktoolik berm view north (left) and view south (right); alongshore sediment transport is from south to north. Permission for use provided by Phil Osborne.

8.6.2 Maintenance, Management, Monitoring

Sediment-based solutions require maintenance over their lifetime due to their dynamic nature and the possibility of changes in hazard exposure or sediment supply; project geometry, such as crest elevation, alignment, slopes, and volumes; and structural condition (including changes in particle size distribution from winnowing and sorting, and health of stabilizing vegetation). Monitoring, adaptive management, and operation and maintenance need to be built in from the start to support project risk management (Bridges et al., 2021). This aspect may require a shift in mindset for project owners and stakeholders due to the need to fund ongoing operational costs beyond initial capital investment.

When evaluating the performance of sediment-based solutions, metrics and indicators need to be selected that inform how well the sediment-based feature is addressing the broad project objective, which may be flood or erosion risk reduction, or habitat enhancement. In the case of flood and erosion risk management, core objectives may be to reduce wave overtopping and storm-surge flooding, to stabilize the shoreline, or achieve a net sediment balance. Habitat enhancements would seek to provide sediment-based features with some measure of dynamic stability that are capable of supporting biota. Core metrics specific to sediment-based solutions may include (CEC, 2024):

- Reduced maximum still water flood levels for target areas
- Shorter flood duration for target areas
- Reduced wave effects
- Maintain stability of structural components (permit compliance)
- Resilience or contingencies for failure
- Erosion protection
- Wave attenuation
- Improved sediment supply or maintenance of sediment balance

Performance indicators that need to be measured and monitored to determine if core metrics are being achieved include (CEC, 2024):

- Water level
- Flood extent
- Location (geography) of features, especially the position of the shoreline over time
- Geometry and dimensions of features, including berm crest elevation, slopes, and volumes of material (sediment budget)
- Sediment characteristics, including particle size distribution

As with all NBI projects, monitoring should be integrated into all aspects of the project lifecycle (CEC, 2024). This will include data collection of core indicators using standardized methodologies. Additional details are provided in Chapter 12 and in *Monitoring the Efficacy of Nature-Based Solutions: Proposed Methodology and Indicators* (CEC, 2024). This guidance document focuses on assessing metrics core to flood and

erosion risk management, however environmental, social, and economic performance indicators are also important, and specific methods can be found in CEC (2024) and Dumitru and Wendling (2021).

Sediment-based solutions are inherently spatially and temporally dynamic. Sandy beach and dune systems are often very dynamic with large morphological changes occurring seasonally (e.g., winter versus summer beach profile) or after significant storms. Often these projects require flexibility in design and maintenance, and it is important to consider downdrift impacts both from an ecological/environmental perspective and an economic perspective, as both erosion and accretion can have impacts on navigation infrastructure (e.g., bathymetry may change, significantly impacting boat passage) (CEC, 2024) or result in damage to structures. Therefore, monitoring programs will need to consider both updrift and downdrift effects. Also, the addition of sediment through nourishment will need to consider the ecological effects and resultant changes due to habitat transition.

Seasonal and annual assessments of sedimentation and erosion can also be performed along transects using a combination of RTK GPS or LiDAR surveys with single beam echo-sounding data. Care must be taken to convert bathymetric depths (commonly relative to chart datum) to a terrestrial vertical datum. Annual surveys should be taken at the same time of year. Profiles can then be compared to a reference coastline (Elias et al., 2012). The increased availability of high-resolution digital elevation and surface models derived from LiDAR or repeat low-altitude aerial surveys with control points surveyed with high precision allow for accurate volumetric measurements of sand volume and sediment budgets to be calculated at low tide (see Box 8-8 and Chapter 12). Changes in the sediment budget will reveal a continuum of changes in foredune characteristics, beach width, and the ability to recover from disturbance events, such as hurricanes (Ciarletta et al., 2020). Post-storm monitoring will be important to understand and document post-storm recovery. Analysis of beach and dune morphodynamics and morphologies can also be used to assess if the sediment-based solution is exhibiting the desired level of dynamic stability and resilience to storm conditions (see 8.4.1.4). See Chapters 12 and 13 for further information on these topics.

Box 8-8. Dune Restoration Monitoring at Le Goulet, NB

In Atlantic Canada, erosion and coastal flooding are frequent issues that communities need to manage, and climate change will only increase this tendency. Different adaptation strategies were thus developed and tested to protect coastal municipalities. At Le Goulet (New Brunswick, Canada), techniques such as sand retention structures made of old lobster traps and conifers, as well as beach nourishment were used between 2013 and 2018 to rebuild the eroding natural dunes. The effectiveness of these techniques has been measured over five years (2014 to 2018) by doing monthly beach profiles (from May to November, when possible) of transects along the Le Goulet coast and by calculating seasonal and annual sand volume variations. To facilitate comparison, the coast was divided into four accretion/erosion sectors (Figure 8.6-6).

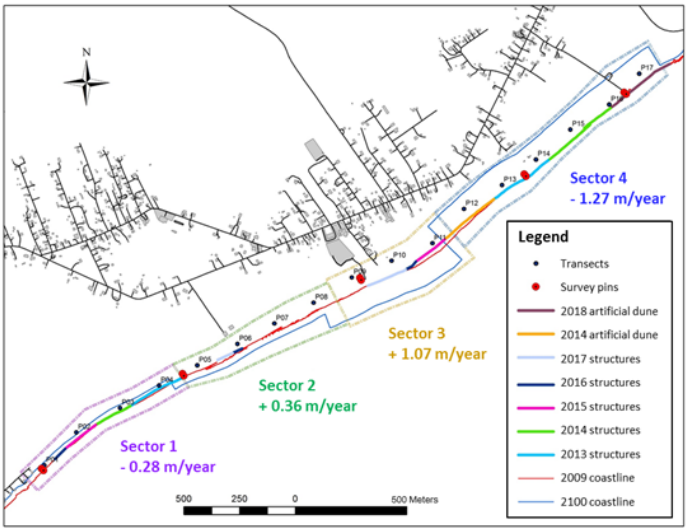


Figure 8.6-6. Map of the study site at Le Goulet with location of the observation transects, sand retention structures, and artificial dunes built between 2013 and 2018. Permission for use provided by Marion Tétégan Simon, PhD.

Le Goulet is a small coastal village of about 793 inhabitants and 321 dwellings in the Acadian Peninsula, bordered by a 5-km sandy beach on the Gulf of St. Lawrence. The height of the dunes is approximately 0.5 m above sea level, with the width of the beach being around 12 m. The village struggles with flooding issues that are only getting worse with the rising sea level and the gradual erosion of the dunes and the beach. Overall, over the five years of the study (2013–2018), the sediment volume of the Le Goulet beach had an increase of 71.9 m^3/m. Seasonally, sediment accumulation was generally observed from spring to fall (between 1.4 m^3/m in 2015 and 4.1 m^3/m in 2016), while sediment loss, probably caused by winter storms and ice movements, occurred from fall to spring.

Sand retention structures and artificial dunes can easily be damaged by storms the year following their construction. Then, progressively, sediment accumulates, and vegetation grows near the structures and artificial dunes, stabilizing them and integrating them into the surrounding natural dunes. The only sector that underwent a volume decrease during the study is the one without sand retention structures. Sediment tends to accumulate near the structures and at the foot of artificial dunes. Sediment loss in the lower part of the beach is observed up to two years after the installation of sand retention structures. A short-term loss of shore width could occur, followed by a long-term recovery. The reconstruction of the dunes using sand retention structures and beach nourishment is a process that will take many years. The benefits noticed over the 5 years of observation are a net accumulation of sediment, a reduced risk of flooding, and protection against waves and large floating debris.

8.7 Challenges

Table 8.7-1 identifies some of the challenges that may apply to successful design/implementation of the best practices for sediment-based solutions identified in Section 8.4.

Table 8.7-1. Potential challenges with successful design/implementation of sediment-based solutions.

CATEGORY	CHALLENGE	MITIGATION
Technical	Net losses of sediment due to longshore and cross-shore coastal processes.	• Sediment processes study to evaluate options and quantify sediment budget over life of project. • Sediment control structures, such as headlands and groynes; monitoring; and periodic renourishment.
	Lack of adequate space for sediment-based infrastructure.	• Where appropriate, make use of coarser materials that are generally less mobile and require less space to enhance FERM benefits. • Combine sediment placement with control structures to reduce overall footprint (see Chapter 10).
	Uncertainty predicting behaviour/performance in extreme conditions and over longer timeframes.	• For coarser sediments, physical modelling can be used to assess and validate infrastructure performance in extreme conditions. • Given the substantial uncertainty surrounding climate change impacts over longer timeframes, more dynamic/adaptable solutions may offer an advantage.

CATEGORY	CHALLENGE	MITIGATION
Regulatory	Permitting complexity and timescales for solutions involving sediment placement on foreshore.	• Early engagement with regulators to seek buy-in for potential solutions. • Identify potential habitat diversity benefits provided by more gently sloping cross-shore profiles compared to vertical or steep-sloping grey infrastructure (e.g., Gailani et al., 2021).
Economic	• Dredged sediment is often viewed as waste material (beneficial reuse may not be least cost). • Monitoring and renourishment ongoing cost requirements over the life of the project may not be acceptable to project owners.	• Consider costs and benefits over full project lifecycle, including habitat enhancement benefits. • Lifecycle costs—sediment-based solutions may be lower cost than shoreline armouring. • Opportunities for reuse of dredged material. For example, dredged sediment from the Fraser River is now being used for construction of habitat restoration and coastal protection projects (including Sturgeon Bank and Boundary Bay).
Social/Public Perception	• Due to the dynamic nature of sediment-based solutions, they may not be viewed as robust for FERM. • Potential release of turbidity or contaminants in sediment.	• Education regarding sediment-based solutions and NBI. • Sediment quality assurance study.

8.8 Tools and Resources

Several resources are available to Canadian practitioners to assist with the design and implementation of sediment-based solutions. Resources applicable to all types of NBI are listed in Chapter 3 (Existing Guidance). The following list of additional resources is more specific to sediment-based solutions:

- CEDA (2019). Sustainable Management of the Beneficial Use of Sediments. Information Paper. [Online] Available at: http://www.dredging.org/media/ceda/org/documents/resources/cedaonline/2019-05-BUS-ip.pdf

- CSA. (2019). Erosion and Sedimentation Management for Northern Community Infrastructure, CSA W205:19, Canadian Standards Association, Toronto, ON, CAN.
- Dean, R.G. (2002). Beach nourishment: theory and practice. World Scientific. Advanced Series on Ocean Engineering. Vol- 18.
- Rogers, J., Hamer, B., Brampton, A., Challinor, S., Glennerster, M., Brenton, P., Bradbury, A. (2010). Beach Management Manual, 2nd ed. London, UK: CIRIA, 2010.
- Suedel, B., Magar, V., & Sittoni, L. (2022). Development of New PIANC Guidance for the Beneficial Use of Dredged Material. In *Ports 2022* (pp. 108-118).
- Van Rijn, L.C. (2005). Principles of sedimentation and erosion engineering in rivers, estuaries and coastal seas. Aqua Publications, The Netherlands.
- Van Rijn, L.C. (2014). Beach nourishment. https://www.leovanrijn-sediment.com/papers/Beachnourishment2014.pdf
- van 't Hoff, J, & van der Kolff, A.N. (2012). Hydraulic fill manual for dredging and reclamation works. CRC Press/Balkema Taylor & Francis Group. The Netherlands.

8.9 Gaps and Future Directions

A concise list of knowledge gaps or challenges remaining to be overcome to better enable or improve on guidance and outcomes that this chapter has attempted to provide include:

- Illustrated long-term performance of sediment-based solutions and associated risk reduction benefits.
- Multi-disciplinary research and collaboration.
    - Improved prediction of coastal erosion of permafrost soils including thermal, mechanical, and liquefaction effects for improved design of sediment-based solutions in cold regions.
    - Integrated guidance based on long-term performance on benefits and risks of incorporating vegetation (aquatic and riparian) with sediment-based solutions.
    - Enhanced understanding, uptake, and upscaling, and improved implementation of sediment-based solutions in coastal resilience projects (Bridges et al., 2021).
    - Developing and implementing long-term strategies for sustainable coastlines in relation to long-term processes, such as climate change and socio-economic developments (Bridges et al., 2021).
    - Enhanced tools for prediction of sediment-based solutions reshaping and evolution over medium and long timescales.

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9 Vegetation-Based Solutions

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9.1 Chapter Key Messages

- Vegetation-based solutions can be resilient, self-sustaining nature-based infrastructure (NBI) options for coastal flood and erosion risk management (FERM) if appropriate biophysical (e.g., elevation, tidal range, salinity, sediment supply, sediment characteristics, wave exposure) and ecological (e.g., native species, diversity, competition) conditions are met. These conditions should be considered both for their present position and that in the future with changing climate conditions.

- Coastal vegetation includes a wide range of plants (grasses to trees) with different structural forms, root depths, lifecycles, substrate, salinity, and hydrological, biogeochemical, and nutrient requirements. Therefore, the ability to attenuate waves, stabilize soil, and reduce flooding will vary between species. Diversity of vegetation in the design of nature-based infrastructure (NBI) can increase resilience.

- The ability of wetlands and submerged aquatic vegetation to reduce wave heights is well established through modelling, laboratory, and empirical field studies. A relatively narrow band of vegetation can achieve significant wave height reduction. However, the degree of wave height reduction depends on topography, vegetation characteristics, and metocean conditions (e.g., wave height, water level, wave period, wind speed and direction) with the greatest attenuation occurring under circumstances where plants occupy the majority of the water column. The ability of vegetation to dissipate wave energy is limited to wave heights below thresholds for damage and/or uprooting of vegetation. Some vegetation types change their form significantly between seasons, and their wave attenuation capacity thus changes throughout the year.

- Designing to allow for ice and winter conditions is essential in most regions of Canada. While ice can induce local scour and erosion, ice blocks (floes) also provide an important mechanism for transport of sediments, rhizomes, seeds, and nutrients into the vegetated system, helping it to self-engineer. Incorporating plant structural elements that remain (e.g., brush, branches) during winter conditions or topographic elements can help reduce erosion when other vegetation has died back.

- Vegetation-based infrastructure can also incorporate inert organic material (e.g., sphagnum moss, dead trees, root wads, or oyster shells) that biodegrades over time and provides a temporary substrate, dissipates water velocities, reduces erosion, and/or stimulates sedimentation.

- Submerged aquatic vegetation, kelp, and intertidal vegetation can complement other NBI techniques and provide additional co-benefits.

- Project management cycles should include and anticipate adaptive management within the first few years after construction of vegetation-based solutions to allow time for vegetation to become established, including the use of temporary protective structures (e.g., wattle or brush fences) to protect young seedlings after planting.

9.2 Introduction

Vegetation-based solutions leverage the natural capacity of plants to stabilize soils, attenuate waves, reduce overland flow velocities, and improve water quality (e.g., Temmerman et al., 2013; Piercy et al., 2021). They include plants that range from fully submerged, such as submerged aquatic vegetation (SAV) and kelp, to tidal wetland species within the intertidal zone and riparian vegetation, including grasses, shrubs, and trees at the upland edge. Other biota, such as algae and biofilms, also play a role in bioengineering (e.g., Chen et al., 2017). Combined, they play an important role in coastal flood and erosion risk management (FERM). In addition, vegetation-based solutions provide co-benefits, such as carbon sequestration, habitat creation, traditional foraging, and cultural significance for Indigenous communities (e.g., Davis et al., 2015; Gittman et al., 2016; Sherren et al., 2021).

Vegetation-based solutions can be used in combination with other NBI (e.g., hybrid solutions) or complement other approaches (e.g., beach/dune restoration). The complementary use of vegetation-based solutions is discussed in more detail in Chapters 8 and 10. This chapter will focus on NBI where plants play the dominant role in providing the FERM benefits. This includes tidal wetlands, SAV and kelp beds, riparian forests, and bioengineering approaches. Due to their ability to self-engineer (e.g., propagate, photosynthesize), vegetation-based solutions can be very resilient and adapt to changing conditions, such as sea-level rise (Kirwan et al., 2010). However, this also means that they must be designed carefully with those specific environmental conditions in mind to facilitate optimal growth.

Vegetation-based solutions rely on dynamic natural coastal processes and biophysical feedback mechanisms to survive. This requires consideration of the following:

- Physical environmental conditions that match species requirements for salinity, inundation frequency (bed elevation, tidal regime), light availability (turbidity and photoperiod), sediment composition (grain size, organic matter, bulk density), exposure (wave and wind energy, ice), sediment supply, and competition (Mudd et al., 2009; Silinksi et al., 2016; van Proosdij et al., 2021).
- Differences in these conditions exist across coastal zones in Canada (see Chapter 6 for more detailed discussion). The choice of appropriate vegetation-based infrastructure needs to be regionally specific and locally sourced.
- Additional time for plants to grow and lag time to provide protective and ecosystem functions (Poppema et al., 2019).
- Plant form (e.g., herbaceous or woody) and lifecycles, including seasonal changes that will impact the flood and erosion protective functions (Silinksi et al., 2015; Schulze et al., 2019).
- Future space requirements to accommodate changing sea levels and provide ability for vegetation to migrate inland (Kirwan et al., 2016).
- Design of monitoring programs to address differences in vegetation lifecycles, and expectation that adaptive management will be required and thus incorporated into the full project lifecycle and budgeting (CEC, 2024).

9.2.1 Purpose and Objectives

The purpose of this chapter is to provide guidance on design and implementation of nature-based infrastructure (NBI) types that are predominately vegetation-based. The objectives of this chapter are to address the following topics:

- Key considerations and best practices with respect to design methodologies for vegetation-based solutions, with reference to case studies, and regional considerations for implementation of this type of infrastructure in Canada.
- Challenges that exist with respect to design and implementation of vegetation-based solutions in the Canadian context, illustrated through several case studies.
- Practical aspects for implementation of vegetation-based solutions, and specific considerations for construction, monitoring, and adaptive management.
- Introduction and explanation of the important tools and resources available to Canadian practitioners for the implementation of vegetation-based solutions.
- Identification of knowledge gaps or challenges remaining to be overcome to better enable or improve on guidance and outcomes for vegetation-based solutions as NBI for coastal FERM.

9.3 Key Concepts and Terminology

9.3.1 Overview

Vegetation-based solutions can utilize a suite of plants adapted to coastal conditions and occupying the full range of the coastal zone from the nearshore up to the landward limit of wave action (and exposure to salt spray on marine coasts) within distinct elevation zones (Figure 9.3-1). On marine and estuarine coasts, vegetation is exposed to saltwater. Salt-tolerant vegetation includes a wide range of plants (grasses to trees) with different structural forms, root depths, lifecycles, substrate, salinity, and hydrological, biogeochemical, and nutrient requirements. Therefore, the ability to attenuate waves, stabilize soil and reduce flooding will vary between species. Combining different species within a project site has the potential to optimize ecosystem health, diversity, and performance, and potentially take advantage of unique coastal protection benefits associated with diverse species (Schoutens et al., 2020; Markov et al., 2023). However, vegetation species within the coastal zone are generally adapted to specific environmental niches, therefore careful consideration of species requirements, as well as interspecific competition, should be made when designing vegetation-based solutions comprised of heterogeneous vegetation (Finotello et al., 2022). Considering plant diversity is also valuable for long-term adaptation to sea-level rise (SLR) on marine coasts, as the vulnerability of SLR differs among species and relative position within the tidal frame (Zanousek et al., 2019). In order to adapt to SLR, vegetation-based solutions, such as tidal wetlands, require space to migrate inland unconstrained by topographic or constructed (e.g., road, causeway, dyke) barriers (Schuerch et al., 2018, Ouyang et al., 2022). This horizonal zone for sediment accumulation is referred to as **accommodation space** (Schuerch et al., 2018).

Seagrasses are flowering plants that generally colonize protected, shallow coastal waters, such as estuaries, embayments, and coastal lagoons (Barbier et al., 2011; Koch et al., 2006). Many seagrass species colonize on soft substrates, such as mud and sand (Barbier et al., 2011). The soft-substrate colonizers generally require wave-sheltered conditions (Koch et al., 2006). A few seagrass species are capable of colonizing hard substrate, such as cobbles or rock (Koch et al., 2006). These species are alternatively exposed to relatively high wave energies. In wave-dominated environments, seagrasses are generally found in areas where waves are classified as intermediate type (i.e., water depth to wavelength ratio between 1:20 and 1:2) (Manca et al., 2012). Seagrasses provide a wide range of ecosystem services, including provisioning (food and medicinal uses), coastal protection, erosion control, water purification, fishery enhancement, carbon sequestration, and recreation (Barbier et al., 2011). The wave attenuation capacity of seagrasses has received attention for its application to coastal protection (Fonseca & Cahalan, 1992; Mendez & Losada, 2004; Sanchez-Gonzalez et al., 2011; Manca et al., 2012; Maza et al., 2013;

Henry et al., 2015; Chen & Zou, 2019; Suzuki et al., 2019). The coastal protection capacity of seagrasses is maximized when the plants occupy most of the water column, often referred to as a seagrass canopy (Altman et al., 2021; Barbier et al., 2011; Koch et al., 2006). When most of the seagrass biomass is found near the bottom, wave attenuation capacity is reduced (Fonseca & Cahalan, 1992; Barbier et al., 2011).

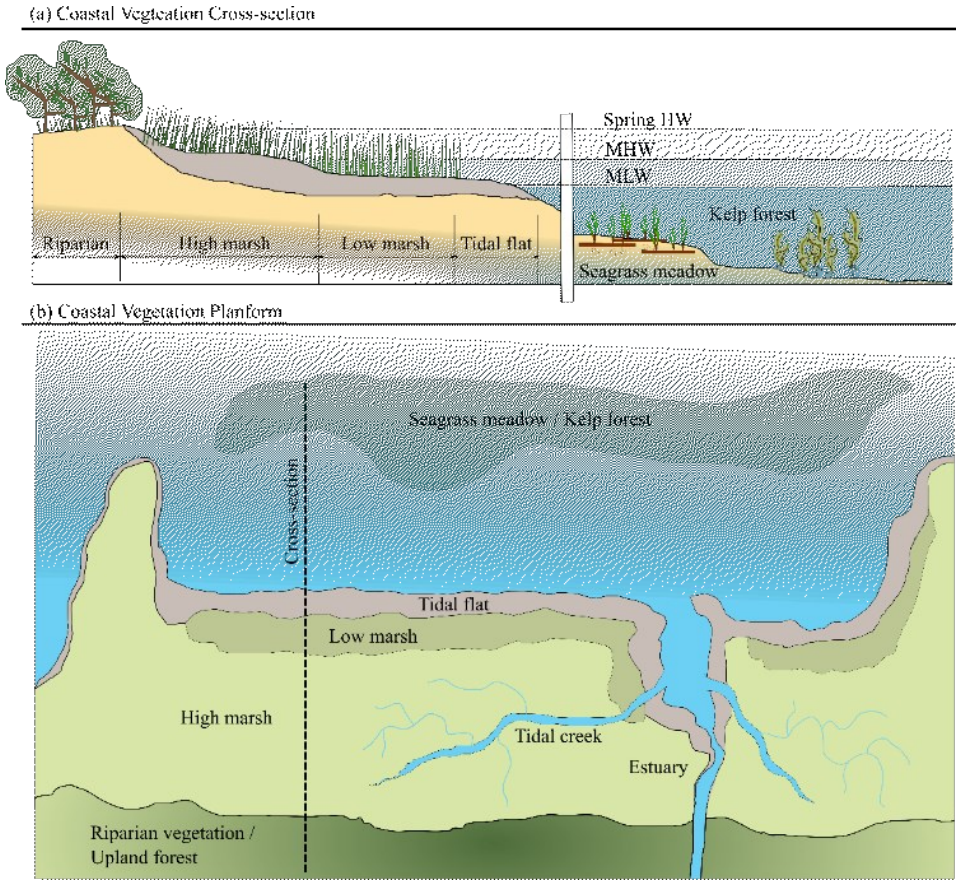


Figure 9.3-1. Zonation of coastal vegetation across tidal gradient.

Kelp and **seaweed** are types of marine multicellular macroalgae that have little to no vascular tissues. They do not contain the same structures (roots, stems, and leaves) and reproductive mechanisms (flowers) as aquatic plants, such as seagrass, but are instead comprised of stipes, blades, floats, and holdfasts; the latter being responsible for anchoring the organism to hard surfaces, such as rocks or shells (Schroeder et al., 2019). Floats, also referred to as pneumatocysts, are air-filled bulbs that allow the plants to stand upright in the water column and form a canopy of blades (Schroeder et al., 2019). Kelp may form dense communities, known as kelp forests, which, similar to other vegetated coastal ecosystems, have the potential to provide wave attenuation due to flow-vegetation interactions. However, the high flexibility and thus passive motion of these plants under waves or currents may reduce this potential. In the literature, the reported coastal protection capacity of kelp forests ranges from negligible (Morris et al., 2020) to as high as 85% wave height reduction (Mork, 1996); likely highly dependent on the relative proportion of the water column occupied by the kelp, the species, and the hydrodynamic conditions (Altman et al., 2021).

Tidal wetland (also known as **"tidal marsh"**) systems, and therefore estuaries, are inherently complex, particularly dynamic, and exist on a gradient that ranges from wetlands directly adjacent to the ocean (salt marshes), to tidal rivers dominated by freshwater (tidal fresh wetland) yet drain into estuaries and maintain

marine influences (Odum et al., 1984). Tidal wetlands are intertidal grasslands, often found along protected shorelines or at the edge of estuaries (Barbier et al., 2011; Wu et al., 2011). Marshes form upon fine sediment that has been transported by water and stabilized as vegetation establishes (Wu et al., 2011). The extent of tidal wetlands can range from vast complexes enclosing tidal creeks to narrow fringe marshes along the shoreline (Bilkovic & Mitchell, 2017). The extent of marsh development is primarily controlled by shoreline slopes, tidal range, sediment process, and the hydrodynamic climate (Bilkovic & Mitchell, 2017). Depending on salinity, the marshes can be classified as freshwater or saltwater marshes.

Saltwater marshes (salt marshes) are dominated by **halophytes** (salt-tolerant species). These species may be facultative (does not require salt) or obligatory (requires salt) halophytes. **Freshwater wetlands** can be found around estuaries, rivers, and lakes in continuously or frequently flooded areas. Unlike saltwater marshes, these systems tend to have high species diversity with plants that are adapted to saturated soils. Saltwater intrusion in freshwater marshes (through sea-level rise, storm surge, or human-caused influences) can cause mass die-offs of freshwater species and invasion of halophytes in the disrupted system.

Frequent tidal inundation and nutrient uptake through enhanced sediment deposition make these environments some of the most productive in the world (Barbier et al., 2011; Temmerman et al., 2013; Davis et al., 2015). Salt marshes provide numerous ecosystem services, similar to those mentioned for seagrass environments (Barbier et al., 2011). Salt marshes provide nursery habitat for many species of fish and shellfish, thus supporting fisheries and biodiversity (Wu et al., 2011). The ability of salt marshes to slow flow and enhance deposition of suspended sediments also makes them effective for water purification, often benefitting nearby ecosystems, such as seagrasses, which can be sensitive to nutrient pollution (Barbier et al., 2011). High productivity and slow remineralization processes also make salt marshes highly effective carbon sinks (Davis et al., 2015).

Coastal dunes are vegetated accumulations of sand located primarily at the backshore of sandy beach systems. The size and morphology of coastal dunes is dependent on the complex interaction between sediment supply, controlling winds, and the geomorphology of the beach and nearshore environment (Sloss et al., 2012; Davidson-Arnott et al., 2019). At the most basic level, dunes can be divided into primary and secondary dunes. Primary dunes form from the direct supply of sediment from the beach face while secondary dunes form from the subsequent modification of primary dunes (Sloss et al., 2012; Hesp, 2002). Foredunes develop at the rear of the backshore environments, landward of the active beach, and have varying morphologies. They can be classified into three main types: incipient foredunes (also known as yellow and white dunes; Lodder et al., 2021), established foredunes (or gray dunes), and relict foredunes (Short & Hesp, 1982; Hesp 2002). Creating healthy habitat conditions and supporting processes for the establishment of incipient foredunes is a central goal of NBI for FERM in sandy systems. If these conditions exist, colonization by appropriate flora and fauna is likely (Lodder et al., 2021). Since their primary role as an NBI for FERM is to trap sediments in association with beach systems, they are discussed in more detail in Chapter 8. This chapter (Chapter 9) will focus on the ecological and environmental conditions required for optimal vegetation growth, while physical beach/dune processes and interactions are discussed in Chapter 8.

Vegetation-based solutions may also benefit from the use of grasses, shrubs, and trees in a **riparian buffer zone** at the upland boundary. Vegetation within riparian buffer zones may need to tolerate periodic inundation and/or salt spray. Species such as *Salix* (willow) have been proposed for these applications; they are native to most regions of Canada, and proven effective in coastal protection applications. For example, willow trees are used as wave screens for high energy storm events at the upland boundary of

hybrid dyke designs in the Netherlands (EcoShape, 2023) or woven into living structural mats anchored into eroding bluffs and interplanted with native species for erosion reduction (Ellis et al., 2022).

Various natural elements can be incorporated in vegetation-based solutions to provide structure, stabilizing function, heterogeneity, substrate, and nutrients. Some vegetation-based solutions are used primarily for their physical form as roughness elements and for the ability to biodegrade in situ. For example, inverted root wads[15] can be used for bank stabilization in estuaries and sheltered coasts (Figure 9.3-2), recycled Christmas trees act as a fence to trap sand and form a biodegradable core for dune restoration[16] (Figure 9.3-3), or innovative sphagnum fibre rolls are used for erosion mitigation (Box 9-1). Biodegradation provides valuable inputs of nutrients for many NBI projects.



Figure 9.3-2. Installation of inverted root wads sourced onsite during *Making Room for Wetlands* managed dyke realignment at Belcher Street marsh in June 2018 and, two years later, successful sedimentation and establishment of tidal wetland vegetation through natural recruitment. Surface fully vegetated and persists with no erosion in 2022 (Graham et al., 2022). Initial design and implementation were funded through the National Wetland Conservation fund from Environment and Climate Change Canada, with monitoring and adaptive management funded by the Coastal Restoration Fund from Fisheries and Oceans Canada. Additional details can be found at: https://www.transcoastaladaptations.com/belcher-street-marsh.

[15] https://www.transcoastaladaptations.com/making-room-for-wetlands-
[16] https://visionh2o.com/projets/restauration-des-dunes



Figure 9.3-3. Use of recycled Christmas trees anchored in place using wooden stakes at Aboiteau Beach (Plage Aboiteau) in Cap-Pelé, NB, to trap sand transported by wind from the beach. This is the first step in dune restoration and provides a substrate for planting or natural colonization of dune vegetation, such as *Ammophila breviligulata*. Community-based dune restoration initiative led by NGO Vision H20 and funded by the Government of New Brunswick. Trees were sourced from local community members in le Village de Cap-Pelé and Beaubassin-est. Similar approaches have also been applied successfully by Parks Canada in PEI National Park and other areas within the Maritimes (see Chapter 8).

Box 9-1. Sphagnum Fibre as a Tool to Mitigate Coastal Erosion: Case Study at Petit-Lamèque, NB

In an effort to develop new eco-friendly and accessible infrastructure to help mitigate coastal erosion, a new tool composed of a renewable resource has been developed by VALORÉS: the sphagnum roll. Because of their advantages as a growth medium and their ability to regenerate, sphagnum mosses, which are common bog plants, are a uniquely interesting genus of bryophyte in the family *Sphagnaceaegenus*.

A sphagnum roll prototype installed in 2020 in the northeast of New Brunswick at Petit-Lamèque was monitored monthly to assess the evolution of erosion and the potential impact on the landscape. The site is characterized by a soft micro-talus coastline with a restricted beach top. Located on one of the points southwest of Lamèque Island, the selected site faces a lagoon connected to Lamèque Bay. The site is devoid of any human-made protective structures. Herbaceous vegetation is present on the site, but traces of water and wind erosion are observable.

After 26 months, the prototype halved the erosion and increased the accretion on the beach by 5 times compared to the control site (Figure 9.3-4). Overall, this study provides preliminary insight on the use of sphagnum, a natural and renewable resource, as a new nature-based and eco-friendly tool to mitigate coastal erosion.

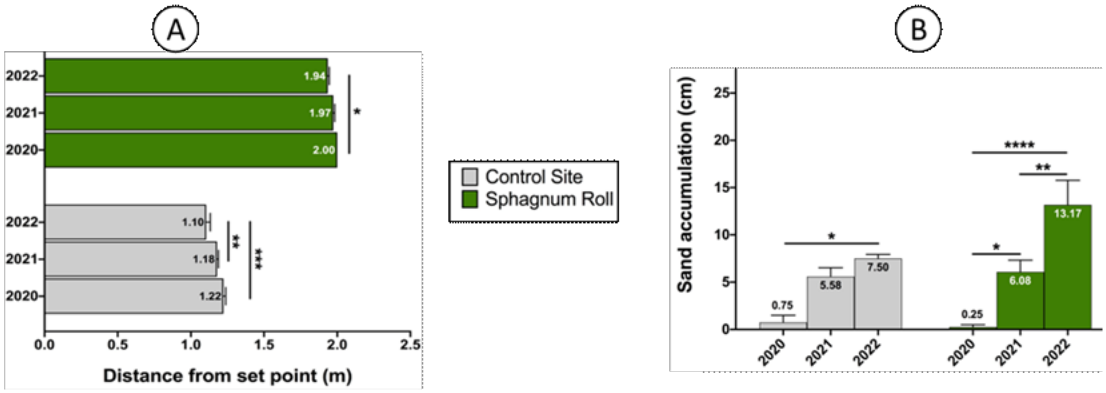


Figure 9.3-4. (A) Erosion of the bank at the experimental site: monthly measures of the distance of the bank from a standard set point in metres at both the sphagnum roll site and the control site. (B) Sand accumulation at the experimental site: monthly measures of the height of the bank from beach level at both the sphagnum roll and the control site. Values are expressed as the mean: n = 4 (2020), n = 6 (2021), and n = 6 (2022). Two-way ANOVA followed by Tukey's multiple comparison test where *p < 0.05, **p < 0.01, ***p < 0.001 & ****p < 0.0001. Permission for use provided by Marion Tétégan Simon, PhD.

9.3.2 Wave Attenuation

Hydrodynamic conditions have a significant influence on the efficacy of vegetation-based solutions. Vegetation attenuates wave energy through the work done by the plants on the water column. The work done is proportional to the drag force acting on the vegetation, which is roughly proportional to the orbital velocity squared (neglecting plant motion). Therefore, energy dissipation is roughly proportional to the wave height cubed. The spatial dissipation of waves across a flat, rigid vegetation field can be approximately estimated as (Dalrymple et al., 1984):

$$\frac{H}{H_0} = \frac{1}{1+\beta x}$$

$$\beta = \frac{4}{9\pi} C_D b_V N H_0 k \frac{\sinh^3(k\alpha h) + 3\sinh(k\alpha h)}{(\sinh(2kh) + 2kh)\sinh(kh)}$$

where H is the wave height [m], H_0 is the incident wave height [m], x is the horizontal coordinate [m], β is the energy dissipation coefficient, C_D is the drag coefficient [-], b_V is the plant area per unit height [m^2], N is the number of plants per unit area [-], α is the submergence ratio ($\alpha = h_v/h$) [-], h is the water depth [m], h_v is the plant height [m], k is the wave number ($k = 2\pi/L$) [m^{-1}], and L is the wavelength [m]. As can be seen from the equations, plant characteristics play an important role in dictating dissipation. A summary of dissipation values for select species can be found in Table 9.3-1.

Table 9.3-1. Water depths and wave heights for field studies, with similar vegetation species to those found in Canadian salt marshes, that quantify wave energy dissipation (modified from Table 1 in Vuik et al., 2016, and Table 1 in Tempest et al., 2015).

Publication	**Vegetation Characteristics**	**Maximum water depth over marsh platform, *h* (m)**	**Maximum significant wave height, H_s (m)**	**Transect Length (m)**	**Average wave height reduction (%)**	**Exponential wave decay constant, β (m^{-1})**
Jadhav et al. (2013)	*Sporobolus alterniflorus*	0.80	0.39			
Knutson et al. (1982)	*Sporobolus alterniflorus*	0.95	0.32*	10 20 30	65 87 94	0.105 0.102 0.094
Möller (2006)	*Sporobolus anglicus, Salicornia sp.*	0.70	0.32	10 10	15–20 11–17	0.016–0.022 0.012–0.019
Yang et al. (2012)	*Scirpus, Sporobolus alterniflorus*	1.61	0.73	51	79	0.031
Ysebaert et al. (2011)	*Sporobolus alterniflorus, Scirpus mariqueter*	1.86	0.64	>50	80	0.032
Vuik et al. (2016)	*Sporobolus anglicus,*	1.90	0.69	50	60 (h = 0.4) 20 (h > 0.8)	
Vuik et al. (2016)	*Scirpus maritimus*	1.27	0.59	50	80 (h = 0.4) 50 (h = 0.8)	

Publication	Vegetation Characteristics	Maximum water depth over marsh platform, h (m)	Maximum significant wave height, H_s (m)	Transect Length (m)	Average wave height reduction (%)	Exponential wave decay constant, β (m^{-1})
Möller et al. (1999)	*Limonium vulgare, Aster tripolium, Atriplex portulacoides, Salicornia sp., Spartina ap., Sueda maritima, Plantago maritima, Puccinellia maritima*	1.39	0.58	180	61	0.005
Wayne (1976)	*Sporobolus alterniflorus*			20	71	0.063

*Based on estimation in Vuik et al. (2016)

Theoretically, wave energy dissipation should be greater for higher waves (Dalrymple et al., 1984; Koch et al., 2006). Several studies have identified that the effectiveness increases with increasing wave height until a limiting value where plants undergo significant damage and failure for the wave heights above this value (Garzon et al., 2019; Möller et al., 2014). Wave attenuation by vegetation is thought to be frequency-dependent, where plants act as a low-pass filter by attenuating principally the higher frequency (shorter period) waves (Bradley & Houser, 2009; Lowe et al., 2007). However, those results have not been consistently observed across multiple studies (Möller, 2006; Phan et al., 2019), and the influence of wave period on wave attenuation is generally weak by comparison to wave height (Maza et al., 2019; Baker et al., 2022).

Several studies investigated the influence of water depth over vegetation on wave attenuation using two non-dimensional quantities: relative incident wave height h_r (wave height to water depth ratio) and submergence ratio h_s (water depth to plant height ratio). Higher wave damping coefficients have been observed with larger relative incident wave height ratios (Garzon et al., 2019; Möller, 2006). However, the use of h_r does not separate out the effects of depth-induced wave breaking and topographic effects, therefore the use of h_s is encouraged. Wave damping is observed to be higher for emergent vegetation ($h_s < 1$), where plant stems obstruct the highest orbital velocities observed at the top of the water column (Augustin et al., 2009), than for submerged ($h_s > 1$) vegetation (Anderson & Smith, 2014; Augustin et al., 2009; Garzon et al., 2019; Luhar et al., 2017) (Box 9-2). Few field studies separate the effects of depth-induced wave breaking (that would occur with or without vegetation) and vegetation-induced wave height attenuation. Isolating the effects of vegetation on wave transformation from other processes can be more easily achieved in controlled laboratory settings (e.g., Wu & Cox, 2015).

The arrangement (spacing/stem density) and physical properties of vegetation can also significantly influence wave attenuation. In most studies, a positive correlation between wave decay and stem density

has been demonstrated (Anderson & Smith, 2014; Maza et al., 2015; Lei & Nepf, 2019; Baker et al., 2022). Plant flexibility can play a significant role in wave attenuation, especially in hydrodynamic settings that can induce plant bending and motion. In literature, the highest wave attenuation was observed for plants with higher stiffness (Lei & Nepf, 2019; Paul et al., 2012). Flexible plants resulted in reduced attenuation by reducing the drag force acting on them as they bend in phase with fluid-forcing (van Veelen et al., 2020).

Higher above-ground biomass has also been observed to increase wave dissipation (Maza et al., 2015; Ondiviela et al., 2014). In fact, it has been found that both rigid and flexible vegetation can result in the same wave dissipation when regarded on a biomass basis; implying that flexible vegetation can achieve the same wave dissipation levels as rigid vegetation with increased biomass and inferring that standing biomass has a higher influence on wave attenuation than plant stiffness (Bouma et al., 2010; Maza et al., 2022).

Similar processes apply for submerged aquatic vegetation (SAV). The magnitude of wave attenuation is dependent on the rigidity and height of the canopy relative to the total water-column height. The latter varies with changing tide and water level conditions. For SAV, this protective value is maximized when canopy height and water-column height are equal (Altman et al, 2021). As such, SAV is expected to be most effective at attenuating waves in regions with relatively small tidal ranges or water level fluctuations, and/or when the area covered by SAV meadows is large. Consequently, SAV and kelp are rarely used in isolation for coastal FERM. However, numerous coastal resiliency projects have included SAV and kelp as part of multiple-lines-of-defence systems to help ensure the integrity of created features, such as beaches and dunes (Hanley et al., 2014) or to enhance ecological co-benefits (Altman et al., 2021). The Seattle seawall project (in the State of Washington, U.S.) used kelp to provide a sheltered migratory corridor for salmonid species alongside the newly designed seawall enhanced with a “bench” that encourages growth of algae and invertebrates (Dunagan, 2020).

Salt-tolerant trees, such as willow, can be planted in the upper extents of flood zones or in front of engineered structures, such as dykes, to serve as a wave screen during extreme storm events. Studies in Europe have shown that a strip of willows 100 metres wide can reduce the height of 1-m high waves by 80% (De Vries & Dekker, 2009, in EcoShape, 2023). In the Noordwaard Polder in the Netherlands, the dyke was raised one metre less than originally planned, and did not require rock armouring (Bal et al., 2001, in EcoShape, 2023). Willows can withstand a maximum of 10–60 days per year of flooding (EcoShape, 2023). Willows cannot survive in salt water, but they can tolerate short periods of brackish conditions. As well as attenuating waves, willow woodland can provide added co-benefits of leisure and biodiversity, while providing cultural and heritage value.

Box 9-2. Effectiveness of Vegetated Foreshore Marshes and Managed Dyke Realignment for Risk Reduction in the Chignecto Isthmus

Foreshore marshes (salt marshes in front of dykes) have been increasingly recognized for their ability to protect dyke infrastructure in Europe by reducing wave energy at the toe of the structure. However, until recently, no studies were available to quantify this natural protection function within a Canadian climate. Saint Mary's University and the Geological Survey of Canada (Atlantic) co-led a field study (2020–2023) to quantify the seasonal attenuation capacity of different foreshore marsh morphologies, including those created through managed dyke realignment in the Chignecto Isthmus, a low-lying dyked landscape between Nova Scotia and New Brunswick. This research was one site within the Nature-Based Infrastructure for Coastal Resilience and Risk Reduction project led by the NRC. Additional objectives included providing recommendations for the integration of natural or constructed marshes in dyke design; providing empirical field data to inform numerical and physical modelling efforts at NRC and Queen's University. Five RBR Ltd. wave loggers were deployed along a 50-m transect extending from unvegetated mudflat to vegetated salt marsh during ice-free conditions from 2020 to 2022. Two transects were installed simultaneously to quantify and compare wave attenuation at a new ramped foreshore created through managed dyke realignment (MDR) in 2010 with natural marshes of varying morphologies, platform elevations (e.g., ramped, cliffed) and marsh species. Vegetation surveys were completed every 4 weeks throughout the growing season and included quadrat measurements and biomass sampling.

The study results show that vegetation height and water depth play an important role in dissipating wave energy and attenuating significant wave heights. Furthermore, the results show that where the water depth is less than 1 m, there is a greater reduction in significant wave height within the first 10 m of the transect compared to where the water depth is greater than 1 m. For water depths less than 1 m, over 60% of wave energy is dissipated within the first 10 m of the marsh, whereas for water depths greater than 1 m, between 50% and 72% of the wave energy is dissipated at a much further distance of 50 m. Marsh morphology also plays a large role in the resultant wave height pattern with cliffed, high marsh platforms attenuating wave energy even early in the growing season with minimal vegetation.

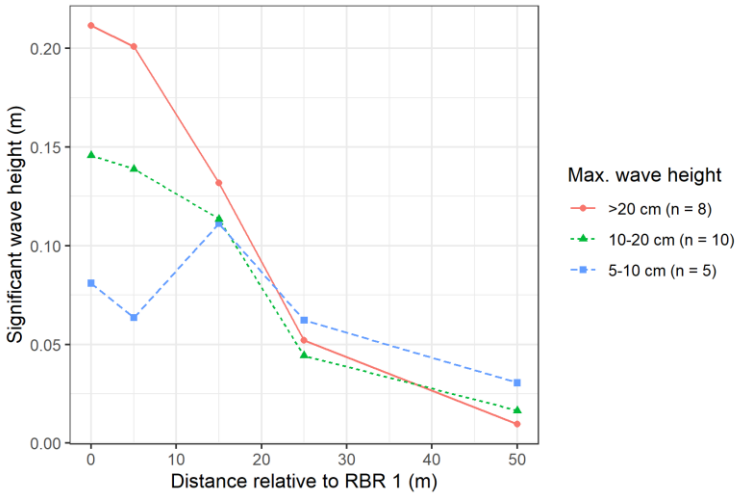




Figure 9.3-5. MDR transect July 15–29, 2021, mean significant wave heights per burst across the different RBRs, and maximum significant wave height at RBR1 divided into three classes of 5–10 cm, 10–20 cm, and >20 cm. RBR1 5 m from edge of marsh.

This study provides a step towards closing the knowledge gap in studies on coastal protection and how to build climate-resilient communities and ecosystems through nature-based adaptation and implementation of natural infrastructure solutions, specifically within the Bay of Fundy.

9.3.3 Dynamic Adaptation

Under the right conditions (e.g., wave exposure and sediment supply; see Chapters 6 to 8), vegetated coastal ecosystems, such tidal wetlands, have a self-adapting capacity in a changing climate, particularly considering their ability to adjust with sea-level rise (Kirwan & Temmerman, 2009; Mudd et al., 2009). Feedback between vegetation characteristics and coastal geomorphology have been identified in which certain species can modify marsh elevation to keep pace with sea-level rise (Allen, 2000; Mitchell & Bilkovic, 2019). Above-ground biomass can attenuate waves, dissipate the wave energy, and reduce shear stress at the sediment-water interface (Christianen et al., 2013; Feagin et al., 2019), which in turn reduces erosion. In addition, above-ground biomass contributes to suspended sediment deposition directly by particle/biological trapping (Barcelona et al., 2021; Hendriks et al., 2008; Stumpf, 1983). Below-ground biomass (roots and rhizomes) also reduce bed-load erosion and stabilize the sediment by increasing the critical bed shear stress that is needed for bed erosion through soil reinforcement (Bryant et al., 2019; Marin-Diaz et al., 2020). Therefore, in the long term, salt marshes can accumulate sediment and adjust bed elevation with sea level, which can increase biomass production and fix sediments with their root systems (Cahoon et al., 2006; Kirwan & Temmerman, 2009). However, this requires a low-energy wave environment and sufficient sediment supply. In areas with low sediment supply, sea-level rise will likely outpace sediment accretion and result in marsh drowning (e.g., Best et al., 2018).

One of the important characteristics of vegetation-based infrastructure is its capacity to self-engineer and expand its range. With sea-level rise, the original extent of the marsh changes and migrates landward creating new habitat (Mitchell & Bilkovic, 2019; Morris, 2007; Kirwan et al., 2016). However, adaptation to sea-level rise highly depends on the factors like rate of sea-level rise, sediment availability, accommodation space, and hydroperiod—the percentage of time that water is above the marsh surface (Schuerch et al., 2018; Shepard et al., 2011). Particularly on developed coastlines, hard structures backing marshes will result in a “coastal squeeze” restricting landward marsh migration and the overall loss of habitat. Designers of vegetation-based infrastructure must therefore consider current and future conditions and include sea-level rise when considering design options. For example, for the Medmerry managed realignment scheme in southern England, land was acquired adjacent to the current extreme flood boundary and included within the design for future conditions with SLR (Harvey, 2017). Re-introducing tidal flow and restoring tidal wetlands to low-lying areas currently isolated by tidal barriers, such as causeways, dykes, or tide gates can increase accommodation space.

Coastal dunes also require sufficient development space to respond to changing sediment supply and sea levels (Lodder et al., 2021). This provides space for natural processes of erosion and deposition by wind and water to create and maintain healthy beach/dune habitats. This habitat extends from the embryo dunes at the backshore landward through dune swales influenced by groundwater levels. Part of this process involves allowing for the natural reactivation of sand in blowouts and space for natural dune recovery post storm events (Delgado-Fernandez et al., 2019; Lodder et al., 2021). This can involve restricting human activities at the backshore to promote development of sand ramps and embryo dunes as part of early successional stages (Lodder et al., 2021). The rate of colonization by plants and development of a continuous vegetation cover depends on the relationship between the rate of sediment supply and the ability of colonizing plants to withstand burial (Hesp, 2002). The rate of colonization will be dictated by the rate at which sediment is transferred inland (Ruggiero et al., 2018). Matrices of large wood, whether placed or naturally occurring on foredunes, can act as barriers to windblown sediment transport, trapping aeolian sediments and modulate or inhibit sand transport to the backshore (Grilliot et al., 2019). Dune stabilization, restoration or enhancement projects are often coupled with beach nourishment (see Chapter 8). “Stabilizing” or “sealing” a dune through intentional planting across the front of or within active dunes has

been identified as contributing to a decrease in ecological diversity and species richness (Delgado-Fernandez et al., 2019; Martinez et al., 2013; Jones et al., 2010).

Overall, there are several components that may contribute to the evolution and dynamic adaptation of vegetation-based solutions. As described above, vegetation biomass directly influences accretional processes as plant stems can trap sediment transported by water (wetlands, SAV) or wind (dunes), slows floodwaters to encourage sediment deposition, and produces organic matter in the marsh subsurface (Zhang et al., 2020). However, these processes are highly complex as vegetation biomass is also connected to the elevation relative to the water level regime, as well as external environmental factors, such as floodwater salinity, sediment supply, tides, waves, currents, and extreme water levels (Lodder et al., 2021; Altman et al., 2021). Consequently, there are numerous feedback loops that must be considered when evaluating the sedimentation processes within these systems, and when designing monitoring programs for vegetation-based solutions (Box 9-3) (CEC, 2024).

9.3.4 Carbon Sequestration

Vegetated coastal areas are highly efficient carbon sinks, and carbon sequestration potential has been highlighted as a co-benefit associated with vegetation-based infrastructure (Mcleod et al., 2011; Davis et al., 2015). “Blue carbon” (or “blue C”) is the term used to describe the carbon (C) storage ecosystem service of coastal wetlands, such as tidal marshes, mangroves, and seagrass meadows (Nellemann et al., 2009). These ecosystems exhibit high rates of primary productivity and can efficiently trap suspended particles from the water column, together contributing to elevated rates of organic matter accumulation. Low soil oxygen levels slow the decomposition of this organic matter, preventing the remineralization of organic carbon to atmospheric carbon dioxide (CO_2). Below-ground plant structures (e.g., roots and rhizomes), also work with the above-ground plant canopy to stabilize soils and prevent carbon mobilization via erosion. Accumulation of carbon in coastal wetlands is a term that is often used interchangeably with carbon sequestration; however, sequestration is the amount of carbon dioxide directly taken up by vegetation, removed from the atmosphere, and stored in biomass and soil (i.e., autochthonous organic carbon—OC) and accumulation is the rate that new OC enters the ecosystem from both autochthonous and allochthonous (i.e., external, derived from marine or terrestrial ecosystems) sources (Van de Broek et al., 2018).

The carbon sequestration potential associated with vegetation-based infrastructure will vary with project size, type, age, and the relative contribution of autochthonous (internal sources, originating from the marsh primary productivity), and allochthonous (external) sources (Mcleod et al., 2011). For example, large-scale restoration projects (typically associated with managed realignment) may yield better carbon accumulation co-benefits than a living shoreline with narrow vegetation strips. Carbon stocks will also vary if marshes are minerogenic (sediment based) or organogenic (organic-peat based). Restored minerogenic marshes in tidal estuaries are often credited with accumulating significant amounts of OC in the short term (Mossman et al., 2022; Wollenberg et al., 2018) (Box 9-3; Figure 9.3-7).

Research suggests that allochthonous OC makes up most of the preserved C stock and autochthonous OC decomposes quickly (i.e., over decades) (Komada et al., 2022; Van de Broek et al., 2018). Distinguishing between the sources of OC (allochthonous versus autochthonous) becomes important for consideration of vegetation-based solutions in carbon markets. The Verified Carbon Standard – Methodology for Tidal Wetland and Seagrass Restoration (VM0033), provides guidance for estimating carbon stocks and net greenhouse gas emissions reductions associated with such projects, including considerations for differences in OC sources (Verra, 2023). Restored marshes are often credited with

accumulating significant amounts of OC in the short term (Mossman et al., 2022; Wollenberg et al., 2018); however, the majority of the OC that accumulates in restored marshes is likely of allochthonous nature (Drexler et al., 2020; Mueller et al., 2019).

Under global voluntary C market methodologies (e.g., the Verified Carbon Standard's VM0033: Tidal Wetland and Seagrass Restoration), coastal wetland restoration projects can only receive credit for accumulation of allochthonous OC if it would have been respired to the atmosphere in the absence of the project (Needelman et al., 2018), mainly due to concerns around "double-counting" of allochthonous OC that may already be attributed to neighbouring ecosystems (Gailis et al., 2021; Macreadie et al., 2019). Given the high rates of allochthonous sedimentation in areas such as the Bay of Fundy (Wollenberg et al., 2018; van Proosdij et al., 2023), and an argument that in cases of managed realignment, this material is rarely remobilized, current efforts are underway to include these OC contributions in carbon accounting. At present in Canada there is no formal mechanism for accounting for carbon credits within coastal ecosystems. Projects wishing to do so are encouraged to follow international sampling standards (e.g., Howard et al., 2014; Emmer et al., 2021) to quantify carbon stocks.

Box 9-3. Field Measurements of Vegetation Establishment and Carbon Accumulation After Managed Dyke Realignment

The Belcher Street Marsh (NS091; BEL) is located on the north side of the Jijuktu'kwejk (Cornwallis River), downstream (east) from the town of Kentville, NS. The site was a mix of active (forage and crop) and fallow (impounded freshwater wetland) agricultural lands prior to restoration. Being part of the Bay of Fundy's Minas Basin, Jijuktu'kwejk is a significant tidal river with the head of tide extending a short distance upstream from the project site. Suspended sediment concentrations range from a maximum of 15,644 $mg \cdot L^{-1}$ to a minimum of 80 $mg \cdot L^{-1}$ with salinities varying from 14.9 to 30.7 ppt (van Proosdij et al., 2023). A section of dyke was realigned and tidal flow restored to 6.5 ha of low-lying land in June 2018 as part of *Making Room for Wetlands*, a Coastal Restoration Fund project funded by Fisheries and Oceans Canada (Graham et al., 2022). The project is a collaboration between academic (Saint Mary's University), private (CB Wetlands & Environmental Specialists Inc.), and public (NS Department of Agriculture) partners.

The site experienced massive deposition of sediments in Year 1, burying pre-existing vegetation and soils with rapid recolonization of vegetation in Year 2 (Figure 9.3-6). Measured increases in elevation ranged about 818 cm at the rod sediment elevation table (RSET) locations in the first year following hydrological restoration, many times that at the reference foreshore marsh. Net elevation changes reflect both above-ground processes of erosion and accretion, as well as below-ground processes of biomass growth and consolidation/dewatering. The large amount of sediment deposited in the first few years drove marsh elevation increases, despite evidence of some losses due to consolidation and dewatering of sediments in Year 2. Initial values of carbon inputs (~1,500–3,700 $gC/m^2/yr$) are comparable to values found at other sites in the Bay of Fundy and these show similar declines after the first year (van Proosdij et al., 2023).

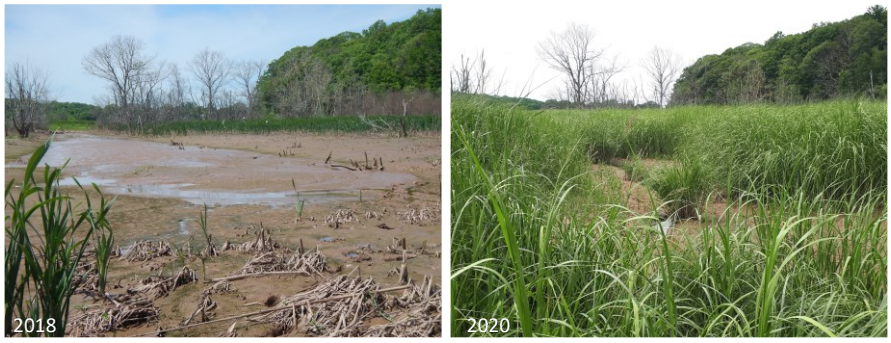


Figure 9.3-6. a) Former fallow agricultural surface approximately 2 months post restoration and b) complete vegetation establishment within two years.

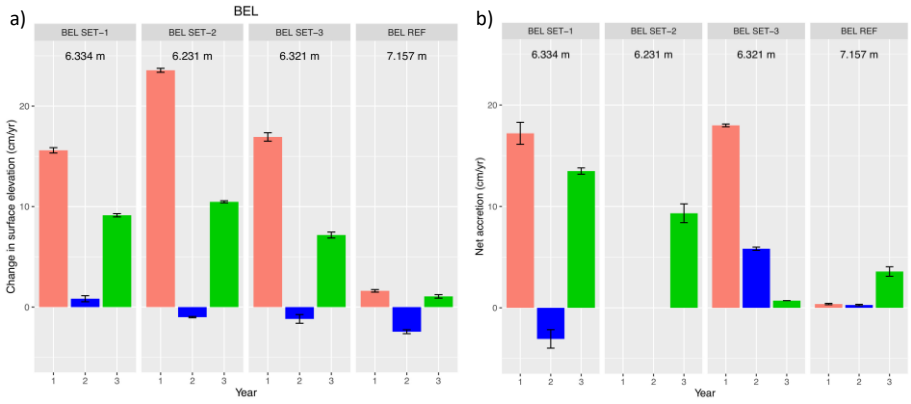


Figure 9.3-7. a) Changes in surface elevation measured using rod sediment elevation tables Years 1–3 post restoration; b) Sediment accretion measured using feldspar marker horizons. REF = natural.

9.4 Key Considerations and Best Practices for Implementation

9.4.1 Physical Environment

Coastal vegetation used for NBI projects naturally occupy the full range of the coastal zone within distinct elevation zones (Figure 9.3-1). It is therefore important to consider the physical environment as this directly influences establishment, growth, survival, and resilience (recovery from disturbance events).

On marine coasts, dunes occupy the zone above the spring high-tide elevation on the backshore, which can be considered one of the most physically stressful places affecting seed, seedling, plant growth, and survival (Hesp, 1991). Stresses include aeolian sand burial, sand abrasion, swash erosion, swash inundation and ponding, salt spray, high temperatures, high light intensity, heat stress, and moisture and nutrient deficiencies (Hesp, 2002; Lodder et al., 2021). Therefore, facilitating natural regeneration or planting dune vegetation for vegetation-based solutions requires understanding the physical environment, natural processes, and habitat characteristics that are location-specific, and requires input from a multidisciplinary team including dune ecologists (Lodder et al., 2021; Delgado-Fernandez et al., 2019; Martinez et al., 2013). Site-specific assessment should include analysis of beach conditions (e.g., slope, width, sediment grain sizes, hydrodynamics, wind speed and direction, hydrodynamics, and geomorphology) since the beach/dune systems are inherently coupled (see Chapter 8). Figure 9.21 in Lodder et al. (2021) provides a flow chart for assessment of habitat conditions and processes for establishment of incipient foredunes in the Netherlands, which can likely be applied to Canadian coasts.

Marshes are generally located in shallow sloping regions along the coast. This natural topography also contributes to the attenuation of wave energy along the marsh platform. Wave shoaling and breaking on the platform results in energy loss and the type of marsh (e.g., sloping or cliffed) will influence the overall attenuation, independent of the presence of vegetation (Möller & Spencer, 2002). Recommended slopes for constructed wetlands or living shorelines are 8–10:1 (Horizontal:Vertical) for low marsh and 3–8:1 for high marsh zones (VIMS, 2023a). Tidal creeks also influence energy attenuation by providing preferential pathways for water (reducing attenuation), while also increasing the roughness of the overall platform (increasing attenuation).

Vegetation-based infrastructure needs to take into consideration the characteristics of the local site, and/or similar sites (see Chapter 7). Historical analysis of metocean conditions, sediment characteristics and supply, water chemistry, and local ecology is necessary to establish the baseline design principles (van Proosdij et al., 2021) (see Chapter 7). Wherever possible, the design should encourage the natural exchange of water, sediment, and nutrients to ensure ecosystem health. Consideration is needed because the rate of sediment and nutrient transport (both high and low) can influence the establishment and health of the marsh or encourage invasive species to establish (Cao et al., 2021). Tidal creeks are important geomorphological features for controlling natural exchange and can be incorporated into engineering design, though consideration is needed for their effect on attenuation capacity of the marsh (Leonardi et al., 2018; Montgomery et al., 2022) and impact on tidal prism and associated hydrodynamics within a site (Elliot, 2022). Design can also consider providing substrates for natural evolution of tidal creek networks.

Substrate or sediment type also need to be considered when designing vegetation-based solutions using SAV or kelp. While most SAV species have been reported to grow in a wide range of substrates, ranging from coarse sands to clays, the optimal sediment composition varies by species (Altman et al., 2021). Table

13.1 in Altman et al. (2021) provides a comprehensive breakdown of published values for the percentage of fines in sediment colonized by a subset of healthy SAV in a range of settings. Areas with higher percentage of fines will also have higher suspended sediment concentrations that limit light penetration and photosynthesis, and hence suitability for SAV. Table 13.2 in Altman et al. (2021) provides a summary of critical physical requirements for SAV (temperature, water movement, wave tolerance, sediment, porewater sulfide).

Some seagrasses and kelp can attach to rocks and withstand a moderate amount of wave energy (Wyllie-Echeverria & Ackerman, 2003). Estimation of a site's relative exposure index has been proposed by Fonseca et al. (2002) to quantify wave exposure. This index calculates the frequency and intensity with which winds blow from each of the eight cardinal directions. A site's relative exposure to wind waves is estimated by comparing the site orientation to the calculated relative exposure index (Altman et al., 2021). Relative exposure index (REI) (Fonseca et al., 2002) is calculated as:

$$\sum_{i=1}^{\infty}(V_i \times P_i \times (idwF_i)$$

Where *i* represents the compass heading in the *ith* direction (1 through 8 [e.g., north, northeast, east], in 45° increments) and is based on data from the previous 3 years; *v* represents the top 5% of hourly wind observations ($m \cdot s^{-1}$) over the preceding 3 years; *P* is the percent frequency that wind occurred from the *ith* direction; *F* is the effective fetch (m); and *idw* applies an inverse distance weighting function on the variable water depth, where weighting is controlled by *F* (Fonseca et al., 2002). Fonseca et al. (2002) recommend that SAV be planted in shallow areas with water depths less than 2 m and where the REI values are less than 4,000. Constructed bars and shoals are used in conjunction with SAV to provide protected areas for their establishment and survival. Refer to Figure 13.10 in Altman et al. (2021) for a flow chart of general design principles for SAV and kelp vegetation-based solutions.

9.4.2 Plant Selection and Sourcing

The selection of plant species should consider ecological requirements, as well as coastal FERM objectives (see Chapter 7). With respect to the former, selection must take into consideration the local context, including native species, surface elevation, tidal range, salinity, and sediment characteristics. Plants can also be selected in consideration of the desired flood and erosion risk management benefits, capitalizing on species-specific coastal protection traits (e.g., resilience versus resistance to wave forcing; Rupprecht et al., 2017; Schoutens et al., 2020). Plant vertical location within the system is strongly dependent on competition between different species, so species must be selected that occupy different elevation sections of the marsh platform (Box 9-4). Careful consideration of when planting occurs is necessary to align with the natural growth cycle of the species and to avoid damaging wave conditions. This may require allowing for multiple mobilizations/demobilizations in successive years, to avoid planting immediately prior to or during harsh seasonal conditions, and to allow vegetation time to establish and mature before exposure to extreme conditions. In cases where high wave conditions cannot be avoided, designs can include temporary structures (wooden fences, rock sills, etc.) to provide shelter and protection to young plants. The Window of Opportunity (WoO) framework can be a useful tool for guiding design of such protection structures, within which critical disturbance frequency (e.g., flood frequency) and critical disturbance magnitude (e.g., bed shear stress) dictate vegetation establishment (e.g., Hu et al., 2015; Poppema et al., 2019).

Working with scientific experts or practitioners familiar with the specific species used on the project is key, as lifecycles vary between species and geographically (e.g., longer dormancy of *Sporobolus alterniflorus*—formerly *Spartina alterniflora*—in the north St. Lawrence). Field trials of different techniques for introducing vegetation (e.g., plugs, field transplants, seed, wrack, tilling, no planting) in the Bay of Fundy with eight different native marsh species over two years indicate that planting plugs produced the highest abundance of perennial halophytes over both years with high survival rates (76.4%±0.02 SE) (Rabinowitz et al., 2022a). However, local site conditions (e.g., elevation, inundation, soil salinity, and nutrients) may explain some of the differences in performance. Plugs and field transplants may both be useful for restoration in the future, and mixing methods to capitalize on respective strengths may produce best results when planting (Rabinowitz et al., 2022a) (Box 8-4). A diversity of plant morphologies, lifecycles, and root depths provides a more resilient vegetation-based solution (Box 9-5). A comprehensive list of marine and freshwater species suitable for vegetation-based shoreline projects on both the west and east coasts of Canada is provided within Appendix D of the updated Green Shores™ for Homes Credits and Rating Guide 2023.[17]

Species that have historically been present in the project area or that occur in nearby settings with similar physical characteristics are likely to be well suited to the site conditions (Altman et al., 2021; Moksnes et al., 2016). Examination of historical aerial imagery can determine if the site was previously vegetated. If it was not, or there are no natural analogues nearby, it is likely that the conditions are not favourable for survival unless the site is altered to provide those conditions (Altman et al., 2021; Lodder et al., 2021).

Site-specific revegetation requirements (e.g., plugs, seeds, containers with field transplants) should be assessed at the project scoping and design phases of an NBI project (see Chapter 7) to allow for proper timing and budget considerations (Lodder et al., 2021). Plant materials should be reserved through deposit to ensure availability and reasonable pricing. Local commercial sources of native plants (including marsh, dune, and riparian species) are limited in Canada; however, the increased demand is fueling some innovation and entrepreneurship to fill this gap (Box 9-4). Plants can be grown from seed within a greenhouse; however, these need to be collected from local coastal ecosystems in the late summer or early fall and stored under conditions specific to each species to allow for proper germination. This requires additional time and planning including transport and storage of seedlings. Some plants have also been sourced from tidal wetland field sites that are slated to be destroyed through construction activities on both the west and east coast of Canada. For kelp and SAV, the source of the transplanted kelp matters; kelp from a wave-sheltered site can have high mortality when transferred to a wave-exposed site, even if that species has been shown to survive in that environment (Altman et al., 2021). In addition, when choosing transplants, it is important to carefully consider the potential impacts to an existing kelp forest, and to instead use plants from areas where they are unlikely to survive to maturity (i.e., the mid- to low-intertidal zone) (Carney et al., 2005).

[17] https://stewardshipcentrebc.ca/green-shores-home/gs-resources/

Box 9-4. Sourcing and Planting Native Vegetation – Living Shoreline Mahone Bay

The Town of Mahone Bay, Nova Scotia, is extremely vulnerable to storm surge and the effects of climate change, including sea-level rise and increased precipitation. These hazards result in flooding, coastal erosion, and an increase in contaminated stormwater runoff entering the harbour.

To help protect Mahone Bay from flooding and mitigate coastal erosion, a local NGO, Coastal Action, proposed the "Flood Protection and Shoreline Stabilization Project", better known as the Living Shoreline. This project builds on the conceptual designs produced by CBCL Ltd. in 2016 in the Flood Prevention and Shoreline Enhancement Plan. Funding was received from the Intact Foundation for a demonstration site to pilot the construction of a tidal wetland with rock sill along the iconic waterfront. This project represents a collaboration between NGO (Coastal Action), public (Town of Mahone Bay), private (CBCL, CB Wetlands & Environmental Specialists Inc., Rising Tide Nursery), and academic (TransCoastal Adaptations at Saint Mary's University) partners.

After the appropriate permits were received, a rock sill and sediment fill were constructed, and a range of vegetation species were planted by community members. A total of 1,250 locally sourced vegetation plugs were transplanted into the site and additional shrubs and grasses were planted on the bank and upland boundary. Plants were chosen to reflect an elevation gradient from upland transition high marsh and low marsh zones and spaced according to established guidelines. Plants were grown at the Rising Tide Nursery from seeds collected locally or from plants and rhizomes rescued from a salt marsh that was being destroyed due to highway twinning. Sweetgrass (*Hierochloe odoratum*) was also planted due to its cultural significance for Mi'kmaq communities.



Figure 9.4-1. Diversity of plant species planted at Mahone Bay, NS, living shoreline demonstration site along elevation gradient post Hurricane Fiona, approximately 3 months post planting. Vegetation sourced locally from Rising Tide Nursery (https://www.cbwes.com/rising-tide-nursery).

Box 9-5. Physical Modelling of Vegetation-Based Infrastructure – Influence of Vegetation Characteristics on Scaling Practices

Physical modelling of vegetation-based systems can be an important tool in evaluating efficacy and optimizing a design before implementation. However, the physical modelling of these systems needs to be done carefully to avoid spurious results related to the modelling and scaling. Few facilities are capable of performing real-scale testing of designs due to limitations in facility size or maintaining plant health.

Figure 9.4-2 shows a set of experiments performed at the large wave flume at the Institut national de la recherche scientifique (INRS) in Québec City, Canada. The experiments were performed in parallel with medium-scale experiments at the National Research Council of Canada to inform scaling practices. The results showed that scaling practices recommended in the literature result in significantly different performance of the design and the type of scaling depends on the type of vegetation and dominant physical processes (e.g., flexible vs. rigid, inertia vs. drag) being tested.



Figure 9.4-2. Physical modelling of wave-vegetation interaction in the large wave canal at INRS (Québec City, Canada).

9.4.3 Planting, Maintenance, and Adaptive Management

Once plants have been selected for the NBI project that are most suitable for the site-specific conditions, they should be planted according to a detailed plan that indicates timing, spacing, planting depth, aftercare, and maintenance. At the site level, the plan may include planting using multiple lifeforms (e.g., seeds, nursery plugs, and field transplants) and planting strategies. The selection of planting method depends on plant availability, budget, time of year, and site conditions, including proximity to a local source of seeds or rhizomes for natural recruitment.

Detailed guidelines for planting vegetation for NBI or restoration are limited. Some species-specific planting guides exist, such as from the United States Department of Agriculture for *Spartina* (now *Sporobolus*) species.[18] Knutson (1977) remains the most comprehensive guide for plantings for marsh development and bank stabilization. Alternatively, design guides have been developed by academic or NGO groups through research and trial and error for marsh plants (e.g., VIMS, 2023a), dune grasses (e.g., Vision H20, 2021), SAV (e.g., Altman et al., 2021), and kelp (e.g., Carney et al., 2005). Private sector practitioners develop in-house methods and internal best practices with limited material in the public domain.

Planting strategies focus on creating conditions to meet the basic needs and tolerance range for each plant species to allow for germination and seedling survival. For example, seedlings grown within a greenhouse setting for marine coastal applications need to be acclimatized to increasing levels of salinity prior to planting, whereas a field transplant is already acclimatized to the local environment and can be more quickly used. Table 9.4-1 provides some guidance on plant spacing and key references for additional details. One needs to consider balancing environmental stress (e.g., wave exposure) with planting density as there can be trade-offs (Duggan-Edwards, 2019). Duggan-Edwards (2019) undertook a study in the UK, where *Spartina* (*Sporobolus*) species were planted on a sandflat to test the effects of plant density on seedling survival. In challenging high-exposure settings, survival was maximized by dense plantings (712–1,000 shoots/m^2) of patches (or tussocks), which facilitated sediment deposition and dissipation of wave energy. In sheltered conditions, expansion was the greatest at medium density (375–500 shoots/m^2), while dense patches had high mortality and erosion (Duggan-Edwards et al., 2019). Some of effects of wave stress on young seedlings is mediated by plant species morphology (Schoutens et al., 2021). However, Cao et al. (2020) found consistently lower resistance to wave stress in a mesocosm experiment using *Spartina anglica*, *Scirpus maritimus,* and *Phragmites australis,* therefore some form of temporary protection may be needed, or in more exposed locations a hybrid option (e.g., marsh sill) may be considered (see Chapter 10).

[18] https://www.nrcs.usda.gov/plantmaterials/njpmcpg13933.pdf

Table 9.4-1. Planting guidelines for wetland, dune, SAV, kelp, and willow species suitable for vegetation-based solutions. All spacing dimensions measured from centre of each plant regardless of species. LM = low marsh, HM= high marsh.

Class of Vegetation	Spacing or Density	Additional Considerations	Reference
Tidal wetland	46 cm (18") average conditions 30.5 cm (12") for rapid cover 61 cm (24") for large areas	Plant above and below predicted planting zones; mix LM and HM species for 2–3 rows where the zones meet	VIMS, 2023a; Broome, 2015
	Low marsh spartina sp. – 91.5 cm (36") (if used for bank stabilization = 46 cm (18"); High marsh S. species – 46 cm (18")	Includes *S. Alt, S. foliosa* Sp. patens	Knutson, 1977
Dune species	46–61 cm spacing within 20–25 cm (8–10") deep trench; trench 15–20 cm (6–8") deep, cover runners with sand, leave 1/3 shoot above ground	*Ammophila breviligulata* – cool season grass *Panicum amarum*	Broome, 2015
SAV	0.25–0.50 m apart (equivalent to a planting density of 4 to 16 shoots/m^2)	Hand planted or use of weights or mats to hold in plants place; broadcast seed from boat not recommended; minimum size of planted area 1000 m^2	Altman et al., 2021; Rohal et al., 2021; Moksnes et al., 2016
Kelp	Optimal densities vary by species and local environmental conditions; mimic densities of naturally occurring populations in the area; patches with less edge-to-area ratios may be less susceptible to grazing and disturbance	Natural or constructed rocky or concrete substrate required; green gravel technique	Altman et al., 2021; Carney et al., 2005; Fredriksen et al., 2020; Eger et al., 2022a, 2022b
Willow	4 trunks per m^2	*Salix alba, S. viminalis, and S. triandra*	EcoShape, 2023

In all cases, plugs and transplants should be securely packed and planted to an appropriate depth, which varies between species. Some, such as *Spartina alterniflora* or marram grass, can be partially buried while others, such as high marsh or upland species, should be planted only to the top of the root crown. Seeds are typically mixed with sand to allow for easier dispersal and spread by hand or mechanically for large areas. In those cases, the seed application rate is calculated by multiplying the base application rate (Ra) by the seed quality index (Qs). Ra is a base application rate of 19 litres per hectare (2 gallons per acre) of seeds for California cordgrass (*Spartina foliosa*) or 9.5 litres per hectare (1 gallon per acre) of seeds for smooth cordgrass (*Spartina alterniflora*) (Knutson, 1977). Seeds should be watered and kept moist until germination.

The timing of planting will also influence the rate of vegetation establishment. Typically, the optimal conditions depend on the lifecycle of the plant, the presence of grazers and moisture availability for germination and survival. Seeds can be sown in late fall or early spring for germination when conditions are more favourable for germination. Plugs and transplants are best planted in the spring and early summer to allow plants to establish before being subject to higher temperatures and lower moisture availability during the summer months (Fonseca et al., 1998; Broome, 2015; Rabinowitz et al., 2022a). In comparing vegetation establishment between two managed realignment sites in the Bay of Fundy completed in the same year (2018) but different months (Belcher – July; Converse – December), the Belcher site saw rapid vegetation establishment in part due to the influx of annuals that established quickly, facilitating additional

sedimentation and creating favourable conditions for the establishment of perennial species (van Proosdij et al., 2023) (Box 9-3). Vegetation establishment was much slower at the Converse site.

Newly planted seedlings are vulnerable to waves and currents. Therefore, temporary growing materials may be needed in the early stages to increase potential success and survival of planted vegetation or seeds. These materials may include manufactured products and geotextiles that provide temporary stabilization at upland and wetland planting areas. Based on site conditions, different grades, lengths, and diameters can be chosen. These protected materials are most effective above the mid-tide or mean water levels, away from regular wave action. They should have full contact with the ground, be staked on all sides using hardwood stakes, and be inspected frequently. Preferably these materials are biodegradable and non-plastic, so they decay within 3–5 years in tidal settings (VIMS, 2023a). Hay bales or scattered hay/straw can be used above the high-water line to protect against surface runoff and erosion. They also provide a natural source of seeds.

Planting SAV, such as eelgrass, can be more logistically challenging than planting marsh or dune vegetation, since their natural environment is underwater. Rohal et al. (2021) reviews seven different planting methods outlining advantages and disadvantages and recommends using a combination of techniques in order to increase the chances of successful plant establishment. Although these were tested in Florida, these techniques should be applicable to Canadian environments during non-winter conditions. Techniques range from hand planting by divers to the use of weights attached to bare-root plants that are then tossed overboard from a boat. Since they are weighted down, the plants sink to the bottom. Weights range from eco-friendly fishing weights to decomposable blocks made of plaster of Paris encasing the roots. Coir mats, pots, or burlap wraps and blocks can be used to reduce transplant stress and keep plants moist, which is essential during transport (Reynolds et al., 2020; Rohal et al., 2021). Seeds can also be broadcast by boat, however Moksnes et al. (2016) does not recommend this approach due to high costs and very high and variable losses of seeds. When compared to the single-shoot method, seed methods have higher risks of failure, are estimated to cost two to three times more, and take two additional years to obtain a functional eelgrass meadow.

The size of the transplants plays a role in the success of vegetation establishment in all systems. A fine balance exists between above-ground biomass to root mass ratio and transplant stress. Plugs with minimal root mass may not survive if conditions are stressful, however larger transplants may also experience transplant shock. For kelp, Carney et al. (2005) found that smaller stipes, approximately 6 to 12 cm, have greater or equal survival rates when compared to larger (e.g., greater than 1 m) transplanted kelp in other studies. These smaller stipes are also easier to transport, and more can be transplanted.

Kelp requires rock material for their holdfast to adhere to. While natural rock materials are preferred, concrete and other non-natural materials can also be used (Altman et al., 2021). The transplanted or laboratory grown plants are secured in the marine environment by divers. Additional details, including methods for attachment of kelp stripe transplants, are provided in Altman et al. (2021). Fredriksen et al. (2020) proposed a novel technique to establish and transplant kelp into the field. The green gravel technique involves seeding kelp spores onto gravel in a laboratory setting and transplanting them to the field once they are 2–3 cm in size (Alsuwaiyan et al., 2022). The kelp may also be moved while still attached to boulders, from one productive site (donor bed) to the injured location (recipient bed) (Altman et al., 2021). Aquarium tank tests show that that the gametophytes (sexual phase of plant) were found to survive, detach from the gravel, settle successfully, fertilize, and develop into healthy kelp on the surrounding bed material (Alsuwaiyan et al., 2022). Rougher and larger gravel show higher densities of detachment. The constructed kelp feature should be close enough to existing kelp beds to ensure connectivity and propagule exchange,

which allows for kelp systems to sustain themselves (Fredriksen et al., 2020). A comprehensive comparison on planting techniques is provided in Eger et al. (2022a) including examples from Haida Gwaii, BC. Lee et al. (2022) documents the restoration efforts and monitoring at Haida Gwaii (Gwaii Haanas) including the integration of core guiding principles based on ethics and values from Haida law into the project.

As with all NBI, maintenance, monitoring and adaptive management should be integrated within the project lifecycle (see Chapters 12 and 13). This is particularly important with vegetation-based systems, which are created with living elements that will require maintenance for at least the initial years, such as pruning, replacement of dead plant materials, pest and grazer management, post-storm management (e.g., removal of debris that may bury tender shoots, erosion mitigation) including human-made woody debris removal and modification of site conditions (e.g., preventing scour, improving drainage). The length of time for these activities is variable and very dependent on site-specific conditions and time to establish mature vegetation. Maintenance activities, including watering, are typically most intensive within the initial two years of the completed project. The potential for reduced FERM benefits during this period should also be factored into NBI design and may require temporary measures to maintain FERM standards (e.g., use of dynamic gravel berms or brushwood dams to provide temporary stability and/or wave attenuation).

9.4.4 Regional Considerations

9.4.4.1 Seasonal Effects

The development and long-term performance of vegetation-based solutions depends on seasonal processes, including biomass fluctuations and winter ice conditions. The relative influence of these effects varies respectively with dominant species and the region within Canada (see Chapter 6). Many perennial salt marsh species (e.g., *Spartina* spp.) experience a dormant season during which above-ground biomass is reduced due to autumnal die-off. As a result, coastal protection services associated with above-ground plant matter (primarily wave attenuation) can be expected to fluctuate seasonally. Below-ground biomass is generally better preserved in dormant states for perennial species, and thus the erosion protection services associated with vegetation-based infrastructure may be less affected by season (Schoutens et al., 2019).

The presence of ice can also alter the establishment and long-term evolution of vegetation-based solutions. Deposition of entrained sediment from ice rafting processes can provide significant sediment inputs to the systems, providing support for accretion of the vegetated platform (van Proosdij et al., 2006; van Proosdij et al., 2023). Ice rafting may also act as a source mechanism for seed/rhizome distribution (Rabinowitz et al., 2022b). Conversely, ice scour of the marsh edge, or ice rafts dislodged from within pools on the marsh platform, can result in vegetation loss from the system (Argow et al., 2011). Declining seasonal ice cover and the increasing duration of open water seasons as a result of climate change may result in increased wave and extreme water level exposure (see Chapter 6, and the discussion of relative exposure index in Section 9.4.1). Consideration of these physical processes is essential for design and monitoring of vegetation-based solutions, and potential adaptive management actions.

Moknes et al. (2016) provides recommendations for planting SAV in Scandinavian countries and specifically provides comprehensive guidance to reduce winter mortality from ice-scour and insufficient light. They recommend that shoots be planted in early June, between 1.5 and 2.5 m depth. It is also recommended that shoots are planted 0.25 to 0.50 m apart (equivalent to a planting density of 4 to 16 shoots per square metre) and that the size of the planted area is at least 1000 m^2. During optimal conditions, shoot density can increase 10x before winter.

9.4.4.2 Invasive Species or Bioturbation

Implementation of vegetation-based solutions needs to also consider the unintentional introduction and potential impact of invasive species. For example, *Sporobolus alterniflorus* (formerly *Spartina alterniflora)* is a native and foundational species on the east coast of Canada, but it is considered invasive on the west coast. Some species, such as *Phragmites*, have both native and invasive forms, which can be challenging to distinguish. Protocols and methods for preventing or controlling the spread of invasive species, particularly when importing materials to a site (such as sediment) should be established. This is particularly important for remote sites or sites of environmental significance, where introduction of invasive species through imported materials can be particularly damaging to ecosystems. Monitoring for invasive species is important and plants should be removed when they are identified before they spread or become established.

Herbivory by grazing geese and other waterfowl can be a challenge for newly established seedlings, and in areas such as the west coast and St. Lawrence estuary. Various measures have been developed and implemented to try and mitigate the impacts (e.g., provision of raptor perches) with varying degrees of success. Grazing gastropods and sea urchin are also a significant consideration when transplanting kelp and SAV (Eger et al., 2022b; Altman et al., 2021). For example, Carney et al. (2005) found that early spring (i.e., March) was the best time for transplanting bull kelp (*Nereocystis luetkeana*), because there were fewer grazing gastropods (*Lacuna vincta*) present, allowing the kelp to establish and grow. In Gwaii Haanas in northern British Columbia, a larger-scale kelp forest restoration project of over 20 hectares of shallow subtidal rocky reef was initiated by cooperative management partners—Council of the Haida Nation, Parks Canada, and Fisheries and Oceans Canada (Lee et al., 2021). This diverse partnership and engagement with Haida Gwaii communities meant that cultural and social values were considered alongside ecological gains. Urchins were harvested for their roe and provided to the local community and Haida divers were hired for monitoring, research, and reducing of urchin densities. Comprehensive details of methods for management of grazers and invasive species in kelp forests is provided in Eger et al. (2022b).

9.5 Challenges

As with all coastal FERM projects, there are technical and regulatory challenges associated with vegetation-based solutions. Table 9.5-1 summarizes these technical, regulatory, and economic challenges, however

this list is not exhaustive as there may be additional site-specific challenges that are unique to particular locations.

Table 9.5-1. Technical and regulatory challenges associated with vegetation-based infrastructure.

CATEGORY	CHALLENGE	MITIGATION
Technical	Survival of planted/transplanted vegetation exposed to waves during initial period following marsh construction.	• WoO framework for initial feasibility assessments of vegetation establishment (Hu et al., 2015). • Temporary protection measures, redundancy (i.e., apply at scale), multiple planting/replanting. Temporary wave screen – e.g., brush; fiber logs, and blankets (VIMS, 2023b).
	Woody debris and large deposits of wrack during storms smothering vegetation.	• Human removal of woody debris; construction of fences or hybrid features to block/trap woody debris.
	Sourcing local plant stock.	• Early consideration and sourcing at least 1year in advance—seed collection in autumn; use of natural donor sites.
	Time lag between planting and establishment.	• Provide temporary protection for plants, additional care, such as watering in early stages, use of organic fertilizer.
	Delayed delivery of FERM benefits.	• Use of companion structural measures to provide temporary FERM benefits, such as brushwood dams, hay bales, oyster sill.
Regulatory	Permitting complexity and timescales for infrastructure involving sediment placement on foreshore that form the base of much vegetation-based infrastructure.	• Early engagement with regulators to seek buy-in for potential infrastructure. • Documentation and case studies.
Economic	Construction costs can vary significantly due to market forces and availability of materials.	• Develop relationship with local contractors and document project finances—add contingency to project budget.
	Delayed delivery of FERM benefits may result in additional costs for temporary protection methods.	• Work with local community group for monitoring and adaptive management of NBI site.

9.6 Tools and Resources

Additional recommended resources focusing on the application of vegetation-based infrastructure include:

- ***International Guidelines on Natural and Nature-Based Features for Flood Risk Management*** (Bridges et al., 2021). Chapter 10 (Coastal Wetlands and Tidal Flats) and Chapter 13 (Plant Systems: Submerged Aquatic Vegetation and Kelp).
- ***Saltmarsh Restoration Handbook – UK and Ireland*** (Hudson et al., 2022). This comprehensive handbook aims to provide practical guidance on restoring and creating salt marsh habitat across the UK and Ireland. This handbook is particularly relevant for minerogenic marshes on the east coast of Canada and provides a comprehensive overview of practical tidal wetland restoration techniques, rational for their implementation, and public communication strategies. It brings together advice on planning and implementing such schemes with selected case studies and lessons from previous examples.
- ***Modelled Approach and Considerations for Tidal Wetland Restoration and Dyke Realignment*** (van Proosdij et al., 2021). Provides detailed guidance for site selection, assessment, and design of tidal wetland restoration and dyke realignment projects and includes an Excel-based decision support tool that provides a ranking of options based on site conditions.
- ***Marine Shoreline Design Guidelines*** (Johanessen et al., 2014). Comprehensive nature-based design guidelines for Washington State that are particularly applicable to the west coast of Canada. This guide also provides the foundation for the Green Shores™ program in Canada.
- ***Living Shorelines Engineering Guidelines 2022 Updates*** (Miller et al., 2022). This update to the original 2015 New Jersey Living Shorelines Engineering guidelines for the NJ Department of Environmental Protection provides detailed engineering guidelines, criteria, and assessment tools for the implementation of living shorelines in sandy systems in micro- to meso-tidal environments.
- ***Living Shoreline Design Guidelines for Shore Protection in Virginia's Estuarine Environments v.2.0*** (Hardaway et al., 2017). Provides guidance and a decision tree for site suitability for implementation of a living shoreline, including design selection, cost, protection, and case studies.
- ***Handbook for Restoration of Eelgrass in Sweden*** (Moksnes et al., 2016). Comprehensive guidance for site selection, planting methods, and monitoring of eelgrass restoration projects for Scandinavian countries. Given similarities in coastal settings, these guidelines may be transferable to Canadian sites. Of particular benefit are planting recommendations to reduce ice-scour and winter mortality.
- ***Kelp Restoration Guidebook: Lessons Learned from Kelp Projects Around the World*** (Eger et al., 2022b). This comprehensive guidebook was developed through collaboration and consultation with practitioners at a series of global workshops and an expert panel of authors and editors. The goal was to share and distill lessons learned from kelp restoration efforts globally. This guidebook serves as a starting point for practitioners and managers to learn about the steps of restoration and access an active community of practice. It covers all aspects of design, sourcing of plant materials, propagation, implementation, monitoring, and adaptive management.

9.7 Gaps and Future Directions

The following challenges and knowledge gaps related to the design of vegetation-based infrastructure have been identified, and should be addressed in future studies to build upon guidance presented herein:

1) More field and modelling studies are recommended to assess the long-term resilience of vegetation-based infrastructure.

2) Adaptive management protocols and tools need to be further developed to ensure long-term success of vegetation-based infrastructure.
3) Understanding of seasonal and ice effects on plant biophysical parameters, wave attenuation, and sediment transport is still limited, and more research is needed on the fundamental processes.
4) Limited field data are available for wave attenuation and erosion reduction associated with natural vegetation native to Canada, as well as principal drivers of competition between species (e.g., hydroperiod, nutrients, sediments, etc.).
5) Existing scaling methods to model the vegetation need to be optimized to allow for more robust physical modelling of natural systems.
6) Improved numerical modelling tools for simulating the influence of vegetation on coastal processes (e.g., waves, currents, and sediment transport) are needed, as are tools capable of simulating the effects of hydrodynamics on coastal vegetation. Existing numerical models can be improved by taking plant damage and marsh heterogeneity into account to replicate vegetation dynamics more closely.

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10 Hybrid Solutions

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10.1 Chapter Key Messages

- Hybrid nature-based infrastructure (NBI) solutions combine “grey” or “built” infrastructure elements with “green” (i.e., natural or nature-based) elements. They are nature-based solutions in so far as they rely on, or mimic, natural system processes to provide coastal flood and erosion risk management function, while delivering environmental and other societal co-benefits. Hybrid solutions exist on a spectrum ranging from predominantly grey infrastructure with some natural or nature-based features, to predominantly green or natural with some built or grey elements.
- Examples of typical hybrid solutions include: managed dyke realignment, beaches with control structures (e.g., groynes or breakwaters, or perched beaches), constructed wetlands with control features (e.g., living shorelines, living dykes, horizontal levees), constructed reefs or submerged breakwaters, and ecologically enhanced structures.
- In some contexts (e.g., where space is limited), hybrid solutions towards the grey end of the spectrum can be engineered to deliver greater flood and erosion risk management (FERM) benefits than more natural solutions, particularly over short timeframes or in areas of high wave exposure. These potential benefits should be weighed against the potential trade-offs in environmental and societal co-benefits of greener solutions.
- Hybrid systems can be designed to utilize temporary or permanent structures to provide short-term stability until natural features have had time to establish and reach dynamic equilibrium, or to provide additional or backup FERM function (e.g., buried revetments, wetlands with brushwood dams).
- Structures may be used within a hybrid system to reduce the overall footprint of a project; for example, to comply with regulatory requirements, to avoid impinging on navigation routes, or to reduce material volumes and cost.
- Since hybrid solutions combine grey (built) and green features, designers should make use of existing guidance available for natural and nature-based features, coastal structures, or shore protection schemes, as well as guidance in the sediment-based and vegetation-based solutions chapters of this document.
- Hybrid solutions may be appropriate for upgrading damaged or degraded shore protection structures. Canada’s ageing coastal infrastructure presents opportunities to retrofit, either by combining natural features with existing structures in hybrid systems, or by introducing bio-enhancing features to structural elements.

10.2 Introduction

The purpose of this chapter is to provide guidance on design and implementation of hybrid nature-based infrastructure (NBI) solutions for flood and erosion risk management (FERM) on Canadian shorelines. As explained in Chapter 1, hybrid solutions are often referred to as "grey-green" infrastructure, because they combine "grey" or "hard" structures with "green"[19] or more natural elements. Hybrid solutions also include adding features or elements to structures to provide some habitat or ecological value. Hybrid solutions are nature-based if they meet the definition of NBI in Chapter 1 (i.e., "…rely on, or mimic, natural system processes to provide coastal flood and erosion risk management function, while delivering environmental and other societal co-benefits"), and are developed according to the principles outlined in Chapter 2 (i.e., based on whole-system understanding and local, natural analogues). Different hybrid solutions may correspond to different points on the green-grey spectrum of nature-based solutions in Figure 1.5-1 (see Chapter 1).

Grey infrastructure components of hybrid NBI solutions include groynes, breakwaters, revetments, and seawalls, which are often designed to be statically stable, and constructed using materials such as rock, concrete, steel, and timber. Green (or more natural) components of hybrid solutions are those that mimic or replicate natural physical conditions, features, and ecosystems found in Canada's coastal regions (see descriptions of natural system features in Chapter 6). In hybrid solutions, green and grey components of infrastructure are designed and constructed to work in concert with each other and with natural processes following a systems approach (see Chapters 2 and 7). Alternatively, hybrid solutions may involve adding nature-based features to pre-existing grey infrastructure (i.e., retrofitting) to enhance compatibility with natural system processes and to support ecosystem enhancement.

Hybrid solutions are sometimes (though not always) the preferred form of NBI on coasts with high wave exposure (due to the static stability provided by structural features), on urban or human-modified coasts, or where space restrictions or regulatory constraints prevent wholly natural solutions.

10.2.1 Objectives

The objective of this chapter is to address the following topics:

- Key considerations and best practices with respect to design methodologies for hybrid solutions, with reference to case studies, and regional considerations for implementation of hybrid solutions in Canada.
- Challenges that apply with respect to design and implementation of hybrid solutions in the Canadian context.
- Describe practical aspects for implementation of hybrid solutions, and provide specific considerations for construction, monitoring, and adaptive management.
- Explain the more important tools and resources available to Canadian practitioners.
- Develop a short list of knowledge gaps or challenges remaining to be overcome to better enable or improve on guidance and outcomes for hybrid shoreline solutions.

[19] In this context, "green" does not necessarily imply the use of vegetation, since natural features can also be predominantly sediment-based (see Chapter 8).

10.3 Key Concepts and Terminology

Hybrid approaches to coastal FERM form a broad spectrum of potential solutions. At one end of the spectrum, local conditions or physical constraints may require that harder structural engineering approaches form the basis of the solution. At the other end of the spectrum, the hybrid solution may be predominantly natural, or nature based. Most hybrid solutions will lie somewhere between these extremes, including a mix of complementary grey and natural or nature-based features.

Examples of hybrid solutions include:

- **Managed Dyke Realignment (MDR)** – Many parts of the Canadian Atlantic and Pacific coasts are protected by sea dykes, which are typically a legacy of land reclamation for agriculture, or development of land in areas of high hazard (e.g., the Fraser Delta in British Columbia). MDR involves breaching of existing dykes, and/or removal of water control structures if present (e.g., tide gates, or aboiteaux), allowing tidal waters to re-enter a previously dry area and stimulate restoration of tidal wetland habitat (French, 2006; van Proosdij & Page, 2012). New dykes may be constructed, or pre-existing dykes reinforced, along the landward edge of the new wetland. MDR design considers the characteristics of the dykeland (e.g., elevation, subsidence, land use, drainage networks), hydrodynamics, ice dynamics (where ice is present), sediment supply and design objectives (e.g., flood protection, erosion mitigation, habitat creation, carbon sequestration) (van Proosdij et al, 2021). FERM benefits are delivered by both the realigned dyke (grey/structural component) and the restored marsh (green/nature-based component) in this "multiple-lines-of-defence" hybrid system (refer to Box 10-1 and Box 10-2 below, and Box 9-3 in Chapter 9). The legacy dykes (on the seaward side of the new wetland) may be dismantled but are usually breached at one or several locations, including the removal of water control structures (e.g., aboiteaux or tide gates) to allow for tidal exchange.
- **Beaches with Coastal Structures** – Constructed beaches, or beach nourishments forming part of shore protection schemes often incorporate static (hard) structures, such as groynes, breakwaters, constructed headlands, or buried revetments (refer to Box 10-3 below, and the Metlakatla shore protection scheme examples in Sections 2.4.4 and 11.4.1). These may be desired for a variety of reasons, for example, to stabilize or retain sediment at critical locations (e.g., the terminus of the shore protection scheme); dissipate wave energy (e.g., detached breakwaters); to slow transport of sediment (to buy time between nourishments or extend design life); to provide a hard backstop in the event that design criteria for the dynamic component are exceeded (e.g., buried revetments provide FERM benefits during severe storms, but otherwise remain buried and hidden); to serve as a foundation for recreational amenities, such as boardwalks, viewpoints or beach access; or to minimize the footprint of the beach for regulatory or other reasons (e.g., perched beaches).
- **Wetlands with Control Features** – Control structures or features may also be used to provide stability to the edges of constructed wetlands or marshes (Piercy et al., 2021). Narrow, fringing wetlands held in place and protected by control features or sills are sometimes called "living shorelines" (Piercy et al., 2021) (see Chapter 9) or "constructed marshes with sills" (Box 8-2). Control features need not necessarily consist of armour rock or concrete; there is increasing interest in the use of materials that mimic natural features, are more dynamic, and/or potentially contribute to ecosystem enhancement, such as brushwood dams, mollusc shells (such as oyster shells), gravel/cobble, and large woody debris. Control features are often used to provide protection to marsh areas from waves or floating debris (e.g., wrack or driftwood), especially in the early periods following marsh construction while vegetation establishes (see Chapter 9); to control the

footprint of a constructed wetland in accordance with regulatory criteria; or to avoid encroachment on sensitive habitat.

- **Islands, Reefs, or Submerged Features** – Constructed islands, reefs, or submerged breakwaters can be used to dissipate wave energy, while also providing habitat and ecosystem benefits (Lowe et al., 2021). The potential effectiveness of reefs or submerged features in delivering FERM benefits is strongly dependent on water levels (tidal range), as well as their geometry, position, and elevation. On the green-grey spectrum (see Chapter 2), solutions can range from submerged or low-crested rubble-mound breakwaters (grey) to full restoration of oyster or coral reefs (green). Vouk et al. (2021) describe an example from Souris on Prince Edward Island (Figure 10.3-1), where intertidal reef structures were constructed using sandstone boulders to mimic the rocky outcrops present along the coast of PEI, and used in combination with dune restoration to manage erosion risks to an exposed section of the Trans-Canada Highway.
- **Enhancement of Structural Features** – Recognizing that marine and coastal structures will continue to be part of the portfolio of tools for FERM, there are opportunities to enhance structures to provide greater ecological and social value (Suedel et al., 2021). Such enhancements can be made during the design of coastal structures, or modifications can be made at any stage during their design life. Examples include the use of different surface textures, water-retaining features, or bio-enhanced concrete to promote fish and shellfish habitat establishment (refer to Box 10-3).



Figure 10.3-1. A hybrid system—constructed intertidal sandstone reefs and dune restoration at Souris, PEI. Photo credit: Mike Davies, Coldwater Consulting Ltd.

Box 10-1. Managed Dyke Realignment at Converse Marsh, Chignecto Isthmus

A managed dyke realignment project at Converse Marsh in the Chignecto Isthmus resulted from the collaboration of the Nova Scotia Department of Agriculture (NSDA), CB Wetlands and Environmental Specialists Inc., and Saint Mary's University with funding from DFO and ECCC. The Converse Marsh realignment and salt marsh restoration site was identified due to the increased loss of foreshore marsh, erosion of the dyke at the mouth of Missaquash River, and the unfeasibility of repairing and maintaining the dyke in its existing location. The project was made possible through a series of land purchases by NSDA. This project forms one of three MDR sites under the *Making Room for Wetlands* Program. Additional details can be found at: www.transcoastaladaptations.com.

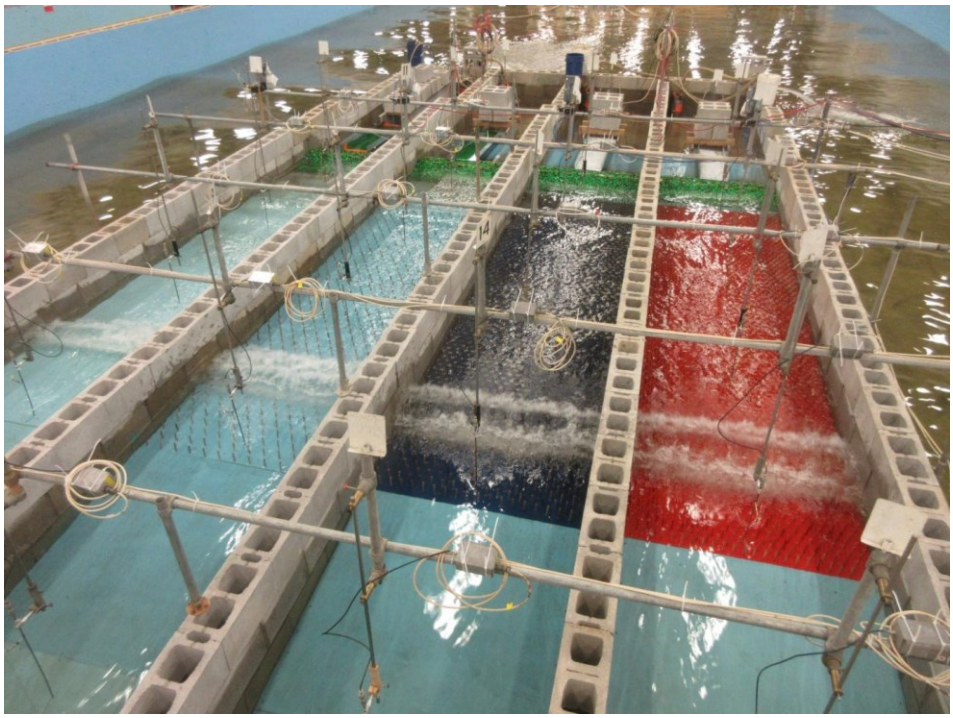
The MDR design was an iterative process with the final position and elevation of the new dyke (150 m in length) and borrow pit modified based on the best ecological and hydrological data available, consultation with NSDA engineers and adjacent landowners, the findings and recommendations of the Archaeological Resource Impact Assessment, and the archaeological groundwork. A low-lying section of Fort Lawrence Road was moved landward and raised. The aboiteau gate was removed in late fall and full tidal exchange occurred on December 21, 2018. The project has been extensively monitored and involves the collection of ecological data on a suite of tidal wetland indicators in the categories of geospatial attributes, hydrology, soils and sediments, and vegetation (Bowron et al., 2021). The site also serves as living laboratory for numerous research projects funded through NSERC ResNET and the Nature-Based Infrastructure for Coastal Resilience and Risk Reduction project led by the National Research Council. A total of 15.4 ha of salt marsh have been restored with the rate and spatial extent of colonization by salt marsh vegetation increasing significantly by Year 3 post restoration (Figure 10.3-2). Over the 3 years post restoration, mean carbon storage rate is 656 ± 392 (SE) gC/m^2/yr and small tidal creek networks are establishing within the infilling borrow pits and joining agricultural ditches on the marsh platform (Lewis, 2022). Erosion of the main inlet during spring tides contributes to a net influx of sediment and sedimentation of the marsh surface (Elliot, 2022).



Figure 10.3-2. Relationship between channel networks and vegetation colonization in A) 2020; B) 2021; C) 2022. Light green represents new colonization, dark green represents persistent vegetation, solid red lines represent channels, and dashed red lines represent proto-channels (Nichols, 2023).

Box 10-2. Experimental Testing of Hybrid Dyke-Marsh Systems

A series of scaled laboratory experiments were conducted to examine the effectiveness of marsh vegetation in dissipating wave energy and reducing wave overtopping discharges at the crest of a dyke located immediately landward of the marsh. Model dyke and marsh platform features, loosely based on archetypes found in Atlantic Canada, were constructed in a wave basin at 1:20 scale and subjected to a wide range of waves and water level conditions. The 2D experiments were performed using idealized surrogate vegetation (both rigid and flexible), and the model set-up featured four parallel flumes that enabled simultaneous investigation of four alternative configurations (Figure 10.3-3). The experiments considered the sensitivity of wave attenuation and overtopping to the length of the vegetation field, vegetation characteristics (such as stem density, height, and flexibility) and varying water levels and wave conditions. The results of the study have helped to address knowledge gaps and provide evidence to support and inform broader use of hybrid dyke-marsh systems (in conjunction with managed dyke realignment) to help manage flood and erosion risk and improve coastal resilience in Canada and internationally. This research confirmed the benefit of hybrid dyke-marsh systems for attenuating waves, reducing overtopping volumes, and lessening damage to dyke structures. As expected, taller and denser marshes were more effective in attenuating wave energy for a given marsh width.



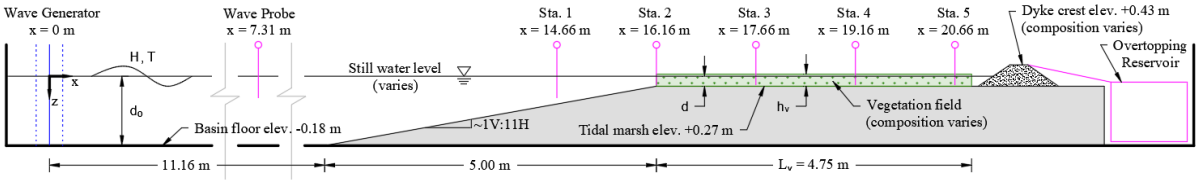


Figure 10.3-3. Simultaneous parallel testing of wave attenuation across four coastal marshes with different densities of surrogate vegetation. Source: Baker et al. (2022).

Box 10-3. The Living Breakwaters Project

In response to the devastation wrought by Superstorm Sandy in 2012, the State of New York pursued opportunities to proactively plan for long-term resilience and climate change adaptation. The Living Breakwaters Project is an innovative system of nine offshore breakwaters with multiple features designed to enhance the local ecosystem while simultaneously providing storm wave attenuation and reduce local coastal erosion issues (https://stormrecovery.ny.gov/living-breakwaters-project-background-and-design). The breakwaters act in conjunction with beach nourishment and oyster restoration efforts to provide a multiple-line-of-defence shore protection scheme. The breakwaters include several habitat features, including "reef streets" and "reef ridges" (see Figure 10.3-4), which greatly expand the intertidal and sub-tidal zones of the breakwaters. Two types of unique bio-enhancing concrete units, ECOncrete® Armor Units and Tide Pools, were incorporated into the design. The armour units feature surface recesses and striations to encourage the growth of marine organisms and enhance biodiversity, while the tide pool units are designed to mimic natural tidal pools commonly found on rocky coasts (Baker et al., 2018). Overall, the Living Breakwaters serve to reduce risk, provide ecological enhancement, and foster social resilience.

Breakwater construction was approximately 50% complete as of early 2023. The Living Breakwaters Project is an example of an innovative, hybrid solution demonstrating how degraded shorelines can be restored and enhanced to provide resilience to flooding and erosion along with a range of co-benefits.

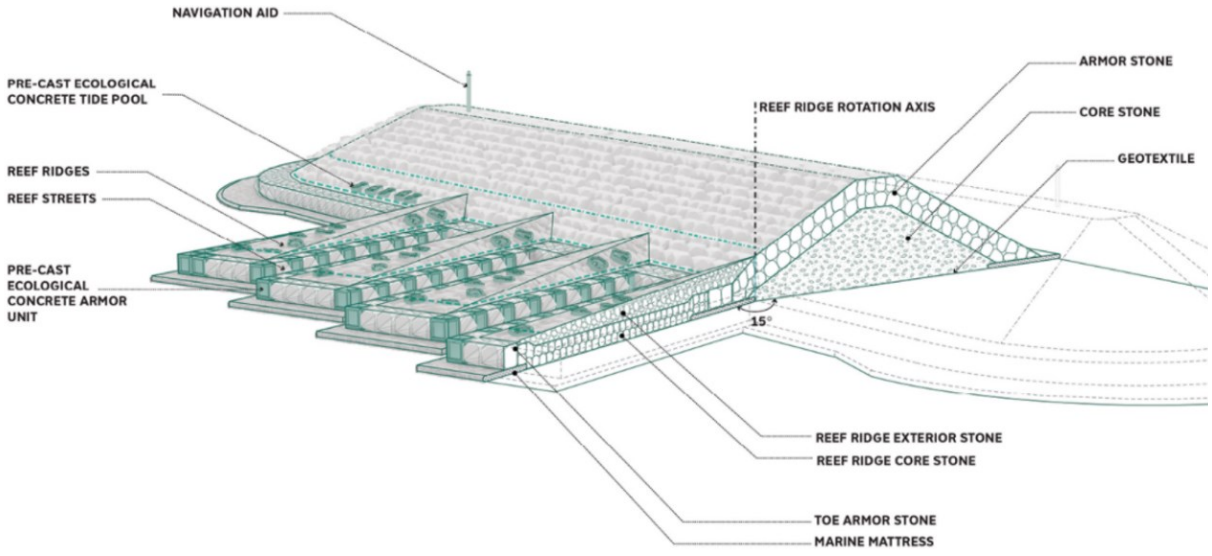


Figure 10.3-4. Conceptual design for the Living Breakwaters featuring reef ridges and streets. Reproduced with permission from SCAPE.

10.4 Key Considerations and Best Practices

A fundamental advantage of hybrid solutions is that they can provide FERM benefits along with a host of environmental and social co-benefits that are typically not delivered by purely structural approaches (e.g., rock revetments, or concrete seawalls). Moreover, in many situations, hybrid solutions can be designed to deliver greater FERM benefits than NBI without any grey infrastructure components are able to provide, and/or to have reduced needs for monitoring and maintenance. While NBI solutions on the greener end of the spectrum in Figure 1.5-1 are generally preferred where they are feasible, hybrid solutions are a good

choice when needed to achieve specific FERM benefits, in areas of high wave exposure, when NBI site footprints are constrained (e.g., by regulatory requirements), or when there is a more limited scope for long-term monitoring and maintenance activities.

Since hybrid solutions combine natural or nature-based and structural features, designers should make use of existing guidance available for natural and nature-based features, coastal structures, or shore protection schemes (see Chapter 3), as well as guidance in the sediment-based and vegetation-based solutions chapters of this document (see Chapters 8 and 9). Hybrid solutions should also be developed based on a whole system understanding (see Chapters 2 and 7). Useful design references for hybrid solutions may include the Coastal Engineering Manual (USACE, 2002), the Rock Manual (CIRIA, CUR & CETMEF, 2007), the EurOtop II Manual (EurOtop, 2018), and the International Guidelines on Natural and Nature-Based Features for Flood Risk Management (Bridges et al., 2021).

10.4.1 Structural Components of Hybrid Solutions

NBI is dynamic, and constructed nature-based features, like beaches, dunes and wetlands, often take some time to establish, reach dynamically stable states, and provide desired FERM benefits. For example, immature, newly planted (typically sparse) marsh vegetation is unlikely to provide the same degree of wave attenuation or attraction and retention of sediment as fully established, dense stands of vegetation (Ghodoosipour et al., 2022). Hybrid systems can be designed to utilize temporary or permanent structures to provide short-term stability, until natural features have had time to establish and reach dynamic equilibrium or provide additional or back-up FERM function. Examples include the trial use of brushwood dams, oyster-shell-filled biodegradable mesh bags, and gravel berms to stabilize the toe of a constructed marsh platform forming part of the Living Dyke pilots in Boundary Bay, British Columbia, described in Box 10-4, the hybrid marsh-dyke systems described in Box 10-2, and the constructed beach-headland system described in Box 10-5.

Natural and nature-based features for coastal FERM generally have a larger area footprint than structural solutions (van Zanten et al., 2021). Structures may be used within a hybrid system to reduce the overall footprint of a project; for example, to comply with regulatory requirements, to avoid impinging on navigation routes, or to reduce material volumes and cost. However, designers should recognize that the FERM benefits of NBI and resilience of natural and nature-based features to disturbances are largely dependent on the scale of the features. For example, small pocket-marshes are susceptible to damage by driftwood or debris mobilized by storms (Osborne, 2018), whereas large marsh systems have more capacity to absorb and recover from storm-induced disturbances. Structures should therefore be used judiciously and strategically where required, and not by default to reduce footprint. The potential for structures to negatively impact the performance of hybrid systems should also be considered. For example, relatively impermeable control structures can impinge on drainage and contribute to excessive debris accumulation, to the detriment of natural system function (Osborne, 2018). Static, linear, shore-parallel structures, such as revetments and seawalls, can also result in loss of intertidal habitat, or coastal squeeze (Pontee, 2013), as sea levels rise.

Box 10-4. Nature-Based Edge Treatment Features to Protect a Living Dyke

The Living Dyke Pilot Project in Boundary Bay, British Columbia, Canada, is one of several coastal adaptation projects being led by the City of Surrey, with West Coast Environmental Law, Semiahmoo First Nation, and the City of Delta, which received funding from Infrastructure Canada's Disaster Mitigation and Adaptation Fund. The goal of the project is to pilot and test a novel approach to adaptation, which involves promoting and encouraging the growth of existing salt marsh habitat seaward of existing sea dykes, through beneficial use of dredged sediment and vegetation planting on the foreshore. The preliminary design for the Living Dyke by Kerr Wood Leidal Associates Consulting Engineers incorporates dyke upgrades, a layer of sediment to be placed in foreshore marsh and mudflat areas seaward of the dykes, vegetation plantings, and a variety of novel edge stabilization features. The edge stabilization features include brushwood dams, and berms consisting of biodegradable mesh bags filled with oyster shells, and cobble/gravel sediment mixes. These features are intended to stabilize and retain placed sediment and planted vegetation at the exposed, leading edges of the pilot, in the period following construction until the marsh system grows and establishes. A series of full-scale and half-scale 2D experimental tests were conducted in a wave flume to support the design of the edge stabilization features (Figure 10.4-1 - left). All four novel stabilization features were exposed to varying water level and wave conditions, and their performance in terms of stability, wave attenuation, and salt marsh sediment retention were assessed. The information gathered from the experiments was used to optimize and improve the designs of the stabilization features prior to constructing them in Boundary Bay (Figure 10.4-1 - right).



Figure 10.4-1. Experimental tests (left) of the oyster shell filled bags (Provan et. al, 2023) and installed bags in Boundary Bay (right). Photo credit: Allison Matfin, Kerr Wood Leidal.

Box 10-5. Jim Tovey Lakeview Conservation Area

The Jim Tovey Lakeview Conservation Area involves the creation of a 26-hectare natural park on a 1.5 km reach of Lake Ontario that will establish ecological habitat and public linkages along the waterfront through the innovative use of clean fill from regional infrastructure upgrades (Figure 10.4-2). One of the key objectives involves establishing a diverse range of native terrestrial and aquatic ecosystem habitats. The shoreline protection features include a headland with armour stone revetment, cobble beaches, a terminal groyne structure, three low-crested offshore islands, and two creek outlets. Construction commenced in 2016 and is expected to be completed in 2025.



Figure 10.4-2. (Top left) Physical model of the Jim Tovey Lakeview waterfront project. Source: NRC (2014). (Top right) Serson Creek and wetlands. (Bottom) Lakeview waterfront restoration. Source: Credit Valley Conservation, Region of Peel, and Toronto and Region Conservation Authority.

While coastal structures are often thought of as being static and impermeable, rubble-mound structures, such as breakwaters, groynes, and revetments can be designed to be dynamically stable, and/or to allow movement of sediment, water, and biota through interstices. Dynamic stability allows for some reshaping of structures in response to changing environmental conditions, which may be more compatible with natural system processes. A classification of coastal structures based on stability number, $N_s = H/\Delta D$, where H is wave height, Δ is the relative buoyant density of the rock, and D is the stone size (or characteristic structure height/width for seawalls), is given in Chapter 5 of the Rock Manual (CIRIA, CUR and CETMEF, 2007), and is reproduced in Table 10.4-1.

Table 10.4-1. Classification of coastal structures by stability number. Adapted from CIRIA, CUR and CETMEF (2007).

Stability Number, N_s	**Structure / Feature Type**	**Description of Typical Behaviour**
< 1	Seawalls or caissons	No damage or movement generally allowed.
1 to 4	Statically stable breakwaters	Limited damage or movement of armour rock or concrete armour units allowed only under the most extreme conditions.
3 to 6	Dynamic/reshaping breakwaters	Gentler slopes at the still water level and steeper slopes above and below the still water level. Profile changes and incipient alongshore transport may be expected during extreme conditions.
6 to 20	Dynamic rock slopes or dynamic revetments	Small armour stones. Profile changes and alongshore transport expected.
15 to 500	Gravel, shingle*, or mixed-sediment beaches	Very dynamic, with profile changes and alongshore transport expected.

* Shingle is an imprecisely defined mixture of cobble, gravel, and sand (Rogers et al., 2010).

Planning and design procedures for coastal structures are described in Parts V and VI of the Coastal Engineering Manual (USACE, 2002). Engineering design steps can be broadly summarized as follows, adapted from USACE (2002):

1. Design Basis (see Section 7.3.4), including:
    a. Specification of functional requirements (e.g., static versus dynamic stability, retention of sediment versus allowing sediment migration, wave overtopping or transmission criteria) and structure service life.

   b. Characterization of short-term and long-term sea states and geomorphological changes.
   c. Selection of design events and conditions for evaluating hydraulic responses (stability, wave runup, overtopping, wave transmission, wave reflection).
2. Consideration of construction equipment, procedures, and materials (availability and durability).
3. Selection of alternative structure types/geometries to be further investigated.
4. Identification of all possible failure modes (e.g., displacement of armour rock or underlayers, loss of sediment through pore spaces or filters, excessive wave overtopping or transmission, excessive reshaping, scour and undermining).
5. Selection of acceptable damage levels for the identified failure modes (e.g., 50% probability of displacement of 5% of armour rock within 50 years).
6. Conceptual design of structural components based on the chosen design events, acceptable damage levels, and hydraulic responses (e.g., materials, determination of armour rock sizes, crest elevations, slopes, width, filter and foundation types)—see Part VI of the Coastal Engineering Manual (USACE, 2002), and the Rock Manual (CIRIA, CUR & CETMEF, 2007).
7. Evaluation of costs of alternative structures and selection of preferred design(s) for more detailed analysis and optimization.
8. Preliminary and detailed design including economical optimization. This step may involve extensive modelling and analysis (see Chapter 11).

Detailed methods for engineering design of coastal structures, including analyzing and predicting structural responses to hydraulic loading, are provided in USACE (2002), CIRIA, CUR & CETMEF (2007), and Goda (2000).

10.4.2 Hybrid Solutions as Retrofits or Upgrades

Hybrid solutions may be appropriate for upgrading damaged or degraded shore protection structures. For example, rather than remove and replace a rock revetment nearing the end of its service life, it may be more economical to place sediment in front or on top of the revetment, forming a buried revetment (a hybrid feature). This could be considered a form of retrofit, enhancing the FERM function, dynamism, and ecological value of ageing coastal infrastructure. Existing structures in good condition can also be retrofitted with habitat features to minimize the impacts, or enhance the contributions, of the structures to ecosystem health (Suedel et al., 2021). For example, living seawalls and rock pool features have been introduced to Sydney Harbour, Australia, and have been observed to provide ecological benefits.

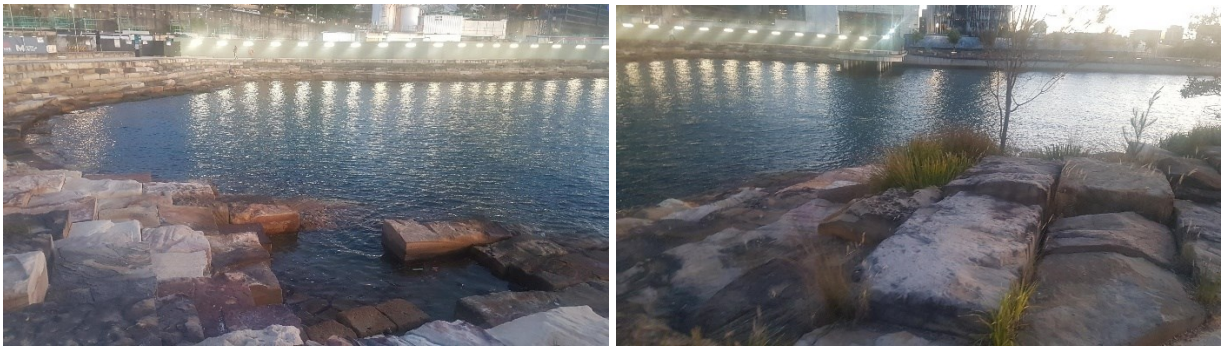


Figure 10.4-3. Constructed rock pool habitats along the seawall in Sydney Harbour, Australia.

Hybrid solutions may also be appropriate for upgrading the FERM function of existing infrastructure to accommodate sea-level rise and other climate change effects. For example, instead of increasing the height of an existing seawall, revetment, or dyke—which can contribute to or exacerbate coastal squeeze, and increase the risks associated with a catastrophic failure (e.g., a dyke breach event)—it may be worth considering hybrid options such as: a living dyke or horizontal levee (Piercy et al., 2021) to leverage the wave attenuation benefits of coastal wetlands; a chain of islands (Gailani et al., 2021) or submerged reef structures (Lowe et al., 2021) to increase wave-energy dissipation and provide diverse habitat; a dynamic revetment comprised of gravel, cobbles, or mixed sediment (Lodder et al., 2021) installed at the toe of the existing structure to dissipate waves, reduce wave runup and overtopping during extreme events.

10.4.3 Transitioning to Nature-Based Approaches

A lack of funding for adaptive management and maintenance, and an emphasis on capital funding for infrastructure projects, has contributed to an over-reliance on static coastal FERM infrastructure in Canada, with associated low tolerances for dynamic adjustment over the service life. With growing recognition of the drawbacks of purely structural FERM solutions, and the realization that adaptive management provides a means to manage risk in a deeply uncertain future (see Chapter 2), hybrid solutions offer a potentially attractive transition to more natural, dynamic FERM approaches.

10.5 Challenges

Since hybrid systems comprise both natural (or nature-based) features and structures, many of the challenges that apply to those features apply to hybrid systems (e.g., Table 10.5-1). A unique challenge for hybrid systems is to understand the extent to which structural components are actually required; over-reliance on engineered structures can inhibit natural system function (e.g., creating drainage problems or causing localized scour and erosion) (Piercy et al., 2021), whereas under-use or under-design of structures in a hybrid system can result in unrecoverable loss of sediment, damage, reduced FERM performance, or even system failure. This balancing act underscores the need to develop a whole system understanding (see Chapters 2, 6, and 7) that elucidates the interplay between natural, nature-based, and structural elements. Generally, when NBI is deployed at larger scales, the demand for control structures diminishes, as larger natural features have a greater capacity to absorb disturbances and self-repair. This is exemplified by the Zandmotor in the Netherlands (Lembrechts et al., 2012), a beach mega-nourishment that is large enough to negate the need for control structures.

Hybrid solutions are often developed as a compromise between structural solutions (which are sometimes perceived as more robust by non-specialists) and greener (more natural) approaches (which may be preferred by regulators or expert practitioners). However, the implications of such compromises should be fully understood in the context of natural process function. In particular, an over-reliance on structures to reduce the project footprint can inhibit sediment and water exchange (Piercy et al., 2021), and compromise the resilience of natural elements and capacity for self-repair. Conversely, hybrid solutions can be most appropriate where space is limited or where conventional structures pre-exist.

Unique challenges for hybrid solutions in Canada relate to the diverse environmental settings, which make it difficult to identify transferable solutions. For example, submerged reefs or breakwaters are of limited effectiveness in providing FERM benefits in areas with large tidal ranges, since the features will likely be too deeply submerged during storm events to attenuate waves. In other areas extended winter conditions can affect the design and performance of hybrid systems.

Ice is a challenge for design and implementation of hybrid systems in Canada's cold climate regions (North, East, and Great Lakes; see Chapter 6). Structural elements need to be designed to withstand or accommodate ice impacts (e.g., plucking and gouging of rock armour), while at the same time, ice can play a vital role in natural system function (e.g., transporting sediments, seeds, and rhizomes). For MDR applications, this can necessitate creating breaches in legacy dykes large enough to allow ice floes into the restored intertidal area without causing ice jams.

Permafrost poses a challenge for design of coastal infrastructure in Northern regions, and can result in differential settlements, and uncertainty surrounding the stability of coastlines. Examples of hybrid coastal NBI in permafrost regions are few. However, there is some promise for the use of thermosyphons, or insulation to delay permafrost thaw and stabilize soils in combination with seaward shore stabilization techniques (Zottola, 2016).

Driftwood, logs, and large woody debris are increasingly being placed or anchored on shorelines for the purpose of attracting and stabilizing sediments, and/or dissipating waves, and/or contributing to ecosystem health. However, the environmental benefits, as well as FERM efficacy, benefits, and preferred placement/anchoring methods and locations are strongly dependent on context (e.g., exposed, open coasts versus protected, sediment-rich tidal marshes) (refer to Box 10-6) and quantities of wood. There is a need for research to better understand the ecological and geomorphological role of wood in wetlands and beach/dune systems, and to provide guidance to NBI designers on use or management of wood in the coastal zone (Grilliot, 2019; Wilson, 2020; Falkenrich et al., 2021; Murphy et al., 2021; Braun et al., 2022; Hood, 2023; Murphy et al., 2024).

Table 10.5-1. Typical challenges and possible mitigation actions for hybrid solutions.

CATEGORY	CHALLENGE	POSSIBLE MITIGATION
Technical	Survival of planted/transplanted vegetation exposed to waves during initial period following marsh construction.	Temporary protection measures, redundancy (i.e., apply at scale), multiple planting/replanting.
	Large tidal range and reduced effectiveness of submerged features for attenuating waves at high tide.	Measured or modelled tides at site for accurate identification of high and mean tide limits (see Chapters 12 and 13), design features to meet required FERM objectives under high water level conditions, deploy submerged features in combination with shore-based features as part of multiple lines-of-defence strategy.
	Sea-level and lake-level changes.	Design for present-day and future conditions, include monitoring and planning for future adaptations.
	Deep foreshore (requiring significant volumes of material fill).	Incorporate sediment trapping/retaining elements into design.

CATEGORY	CHALLENGE	POSSIBLE MITIGATION
	High wave exposure.	Design features/structures for higher stability, combine statically stable features with dynamic features, deploy over larger scales to accommodate dynamics and to allow for post-storm recovery, use temporary structures/features to provide short-term stability until natural processes establish.
	Limited sediment supply or historical chronic erosion.	Planned replenishment or adaptation (e.g., thin layer placement) within project lifecycle.
	Impacts of ice and debris—scour, plucking, etc.	Use more stable materials, use larger quantities and plan for reshaping, design structures or features to trap or divert ice or debris away from sensitive features/structures.
	Lack of space for nature-based features.	Use control structures or features to stabilize edges of natural or nature-based features.
	Uncertainty predicting behaviour/performance in extreme conditions.	Use numerical or physical modelling to assess and verify performance in extreme conditions (see Chapter 11).
Regulatory	Permitting complexity and timescales for solutions involving sediment placement on foreshore.	Early engagement with regulators to seek buy-in for potential solutions.
	Spatial constraints (e.g., due to property boundary, regulatory issues, or riparian rights) that limit the spatial extent of material placement.	Early engagement with regulators, rightsholders, and stakeholders to seek buy-in for the potential solution. Consider adopting built elements to constrain the spatial extent of the project.
	Loss of storage or habitat due to infilling or works on the seabed/lakebed.	Modelling and analysis to identify impacts on hydrodynamics and storage (see Chapter 11). Include aquatic habitat enhancements in hybrid solution. Identify habitat diversity benefits and trade-offs (Gailani et al., 2021).
Economic	Lack of funding for long-term monitoring and adaptive management.	Explore citizen science or other low-cost long-term monitoring or funding mechanisms. Partnerships with academic institutions.
	Difficulty in quantifying environmental benefits and co-benefits.	Refer to approaches for evaluating co-benefits provided in Chapter 6 of the International Guidelines on Natural and Nature-Based Features for Flood Risk Management (van Zanten et al., 2021). Use case studies to support position.

CATEGORY	CHALLENGE	POSSIBLE MITIGATION
Social / Attitudinal	Perception that dynamic NBI cannot provide the same level of protection as static (hard or grey) infrastructure.	Early engagement with owners, rightsholders, and stakeholders. Use of physical or numerical models to validate performance. Consider adopting additional built elements, if needed, to provide additional security.
Environmental	Coastal squeeze.	Consider local rates of relative sea-level change. Provide accommodation space. Avoid static, shore-parallel structural components that do not allow space for migration of intertidal habitats. Consider dynamically stable structural components.
	Grazing geese.	Temporary protective structures during vulnerable seedling lifecycle; noise deterrents; raptor perches.
	Disruption of sediment transport processes.	Design based on whole-system understanding.

Box 10-6. Use of Driftwood or Woody Debris in Shore Protection Systems

Despite growing interest in, and support for the use of large woody debris or logs in shore protection systems in Canada (Stewardship Centre of British Columbia, 2020), there remains scientific debate as to the efficacy of woody debris in controlling/limiting erosion and wave-induced flooding on exposed coasts (Wilson, 2020; Braun et al., 2022), with some studies even indicating woody debris can exacerbate erosion under certain circumstances (Falkenrich et al., 2021). Although it is generally accepted that wood can play a positive role in coastal ecosystems (providing habitat, nutrients, structure, and carbon storage), evidence of the ecological benefits of wood for certain species is inconclusive, and occasionally conflicting (Hood, 2023). Upper limits on quantities of wood providing ecosystem benefits in estuarine marsh systems are also poorly understood, with marsh restoration work in British Columbia often involving removal of human-altered debris (Ducks Unlimited Canada, 2023). However, there is evidence that large woody debris or root wads can trap sediment and provide stability in sediment-rich tidal marsh systems (Graham et al., 2020) and on aeolian foredunes (Grilliot, 2019). The site- and function-specific contexts in which woody debris provides FERM and ecosystem benefits require care in considering its use in hybrid nature-based infrastructure systems, particularly on exposed open coasts, where the potential for mobilization during storms poses risks to communities, infrastructure, and valued assets (Murphy et al., 2021; 2024). Further research and pilot studies are needed to better understand, and provide a strong evidence base for, the appropriate use of woody debris in different Canadian settings and contexts.



Figure 10.5-1. Field observations (left) and experiments (right) investigating wave-sediment interactions with anchored woody debris (Wilson, 2020).

10.6 Implementation

This subsection describes practical aspects of applying the guidance discussed in previous subsections, and specific considerations for construction, monitoring, and adaptive management of hybrid solutions.

10.6.1 Methods of Construction

Methods of construction for hybrid solutions are wide-ranging. Since hybrid solutions combine natural or nature-based and structural features, designers should make use of existing guidance on construction of natural and nature-based features, coastal structures, or shore protection schemes (see Chapter 3), as well as guidance in the sediment-based and vegetation-based infrastructure chapters of this document (see Chapters 7 and 8).

Timing of construction and sequencing needs to be considered. For example, in hybrid solutions combining structures and sediment, it is often desirable to construct structures first to retain sediment and control turbidity during placement. Partially or fully constructed rock structures may also be used as access platforms to avoid encroachment of equipment on sensitive intertidal habitat.

Timing and sequencing of construction can also influence the survival and establishment of natural elements of a hybrid solution. For example, significant differences have been observed when an MDR project is completed in spring compared to late fall. In the Belcher Street MDR (Box 9-3) the inner dyke was constructed and seeded in the spring with tides reintroduced in June. Sediments rapidly accumulated over the formerly fallow agricultural surface, providing limited competition for fast growing annual halophytic vegetation to quickly become established (van Proosdij et al., 2023). Grasses on the new dyke also took hold well, minimizing erosion from heavier rainfall events in fall. The early establishment of annuals also would have increased sediment trapping on the evolving marsh surface. The entire marsh platform was vegetated by a mix of perennials—halophytes and tidal fresh species by the second year. At Converse (Box 9-4), the new dyke was constructed mid-fall, and seeded and breached in late December. The late seeding and likely low fertility of the dyke material meant that the surface of the dyke was vulnerable to erosion from heavy rainfall since grasses were not yet established. In addition, the toe of the new dyke also started to be eroded by small waves lapping at the base during high tide. Adaptive management (staked haybales, burlap, seeding with mixed species, restricting driving on top of dyke) was required the following year (Bowron et al., 2022) and was successful in stopping erosion (Graham et al., 2023).

The construction of hybrid solutions may also require access and transportation of materials across sensitive intertidal ecosystems, which requires specialized equipment or “marsh mats” to be used to minimize disturbance. This is particularly challenging in areas with large tidal ranges and/or wide intertidal zones, which limit or restrict marine-based access (e.g., via barge), and where soft sediments may inhibit the use of heavy, land-based machinery. The use of contractors with local, specialized knowledge and experience working in these environments, and who may have adapted their equipment, approaches, and techniques, tends to be efficient and cost-effective.

10.6.2 Maintenance, Management, Monitoring

Hybrid solutions may require maintenance over their design life and beyond. Adaptive management, monitoring, and operation and maintenance need to be built in from the start (Bridges et al., 2021). This aspect may require a shift in mindset for project owners and stakeholders due to the persistence of operational and maintenance costs beyond initial capital investment. The process requires:

- Stakeholder engagement
- Planning – development of an adaptive management plan
    - Specify performance indicators
    - Criteria and thresholds for maintenance action
    - Data requirements and methods of assessment of performance
    - Evaluation schedule
    - Adaptation options and pathways
- Monitoring and data collection to assess performance
    - Bathymetry and topography surveys
    - Habitat types, acreage, biodiversity
- Analysis of data relative to performance indicators

Refer to Chapter 11 (Field Monitoring), Chapter 12 (Adaptive Management), and CEC (2024a; 2024b) for further information on these topics.

10.7 Gaps and Future Directions

The following is a non-exhaustive list of knowledge gaps, needs, and potential directions for future work to support design and deployment of hybrid coastal NBI in Canada:

- There is a paucity of documented case studies and pilots demonstrating:
    - The performance of different types of hybrid systems in different regional settings and environments, and response to extreme (e.g., storm) conditions. While some types of hybrid systems are beginning to be well understood and have been applied and monitored in a variety of Canadian contexts (e.g., beach-groynes/breakwater systems, dyke-marsh systems in Atlantic Canada), there are fewer examples of other types of hybrid solutions (e.g., reefs, islands, enhancement of structures).
    - Long-term interactions between built and natural or nature-based features, and effects on performance in delivering FERM and ecological benefits.
- The scale (and therefore the benefits) of hybrid systems implemented in Canada to date are relatively small by comparison to international examples. There is a need to better understand how hybrid solutions can be scaled up, or how the cumulative effects of multiple small-scale projects can be leveraged as part of broader FERM strategies to achieve greater benefits, while minimizing impacts.
- There are relatively few examples of hybrid NBI systems in northern regions, in areas exposed to ice and/or permafrost. Demonstration and pilot testing of novel approaches to manage impacts and benefits of ice and permafrost is needed to develop appropriate solutions for northern environments and contexts.
- There is growing interest in the use of novel materials to form structural or hard elements of hybrid NBI systems, such as driftwood and logs, brushwood, and oyster-shell filled mesh bags (biodegradable or otherwise), and bio-enhanced concrete. This is typically motivated by the desire to use materials with lower carbon footprints than conventional materials (e.g., rock, or concrete), or that contribute to ecosystem function (e.g., providing habitat, nutrients, structural diversity, substrate for biota). However, the evidence for effective use of these types of elements is often weak, conflicting, or sensitive to site-specific contexts (e.g., wave exposure). Research and pilot studies are needed to improve guidance on the use of different materials in diverse settings.
- Canada's ageing coastal infrastructure presents opportunities to retrofit, either by combining natural features with existing structures in hybrid systems, or by introducing bio-enhancing features to structural elements. An improved understanding of the performance, cost, and benefits of various habitat-enhancing features in different Canadian coastal environments is needed to identify where such approaches deliver real value. There is a potential concern that bio-enhancement of structural elements could be used to justify solutions at the grey end of the grey-green spectrum (see Chapter 2) as the status quo (i.e., a form of "greenwashing"), when more natural (i.e., greener) solutions may be preferred from a FERM and/or ecosystem health perspective.
- There is a need for improved design tools (guidelines and numerical models) to support the design of hybrid infrastructure and reduce the level of uncertainty concerning performance (durability, FERM function) in extreme conditions and over longer timeframes.

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11 Modelling Performance

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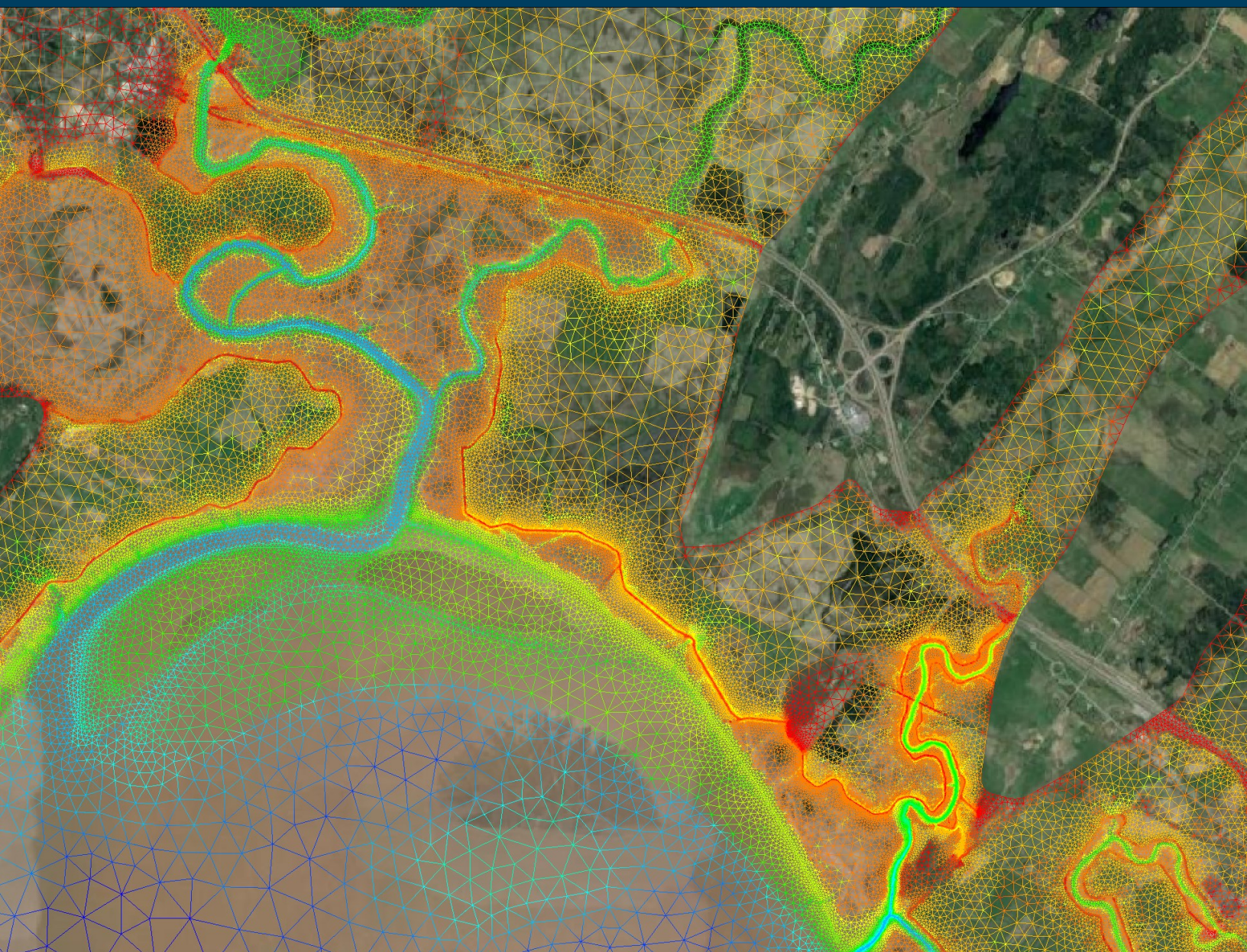
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11.1 Chapter Key Messages

- Models can be powerful and useful tools to support the design and assessment of coastal nature-based infrastructure (NBI). They can both be used to study behaviour and assess performance in extreme conditions and potential future conditions that include climate change effects.
- Models range in complexity and may include conceptual models, statistical models, empirical models, numerical models, and physical models.
- Models present useful tools for visually engaging non-specialist decision-makers and stakeholders, and for co-developing, exploring, and testing NBI alternatives and scenarios. However, specialist modelling input is needed to ensure results and limitations are correctly communicated and interpreted.
- Strong conceptual understanding of the system is a prerequisite for successful application of more sophisticated physical or numerical models, therefore application of modelling tools must be grounded in process and system understanding,
- Physical models replicate coastal features in wave flumes (2-dimensional) or wave basins (3-dimensional), sometimes at reduced scales. They are advantageous due to the realism with which many complex physical processes are replicated, the opportunities for enhanced understanding through personal observation, and the high degree of control and repeatability of the conditions that can be tested.
- Several different types of numerical models are relevant to studying coastal NBI including, hydrodynamic models, wave transformation models, morphodynamic models, ecological models, ice dynamics models, and coupled models.
- Physical and numerical models used to support the design of coastal NBI must be fit for purpose, or capable of reliably simulating the important physical processes at the desired resolution over the desired spatial and temporal scales.
- Models are inherently simplifications of real-world conditions, therefore an understanding of the base hypotheses of a model is necessary in evaluating their output. Models should be calibrated and validated using field data to ensure they are realistic, provide predictive capabilities, and to quantify model skill and uncertainty. An uncalibrated model is worse than no model, as erroneous model results could lead to incorrect design decisions.
- Specialists with experience and expert knowledge concerning numerical and/or physical modelling of coastal NBI should be involved in the modelling effort, and in the interpretation and communication of results.
- Employing both numerical and physical models in tandem can help optimize the strengths of both approaches and reduce uncertainties related to the design and performance of coastal NBI.

11.2 Introduction to Modelling

Modelling is the practice of representing a real-world system in a controlled environment to study processes, evaluate design criteria, investigate uncertainties, and optimize designs. Different types of modelling practices that are commonly applied to understand coastal environments include:

1. **Physical Modelling**
   These models replicate coastal features in wave flumes (2-dimensional) or wave basins (3-dimensional), either at a reduced or full scale. They are advantageous due to the realism with which many complex physical processes can be replicated, the opportunities for enhanced understanding through visual observation, the high degree of control and repeatability of the environmental conditions that can be generated, and the ability to test design alternatives and refinements. However, care must be taken to ensure that boundary effects and scale effects associated with distortion in key dimensionless ratios (e.g., Reynolds number or Froude number) and surface tension are minimized. They also allow for testing, optimization, and validation of structures or other changes to the coastal environment before implementation or construction.

2. **Numerical Modelling**
   Numerical models are mathematical representations of coastal processes that use numerical methods to simulate and predict various physical and environmental phenomena. These models are powerful tools for studying and predicting coastal processes, including waves, tides, currents, sediment transport, erosion, and coastal flooding. In this chapter we briefly consider the following numerical models:

   a. Hydrodynamic Models
      - These models replicate the behaviour of water level elevations and flows in coastal zones. They can be used to study the forces that incident conditions exert on coastal features, estimate flooding extents, simulate storm surges, and drive models of other processes, such as sediment transport and morphodynamic models.

   b. Wave Models
      - These models simulate the propagation and transformation of waves in coastal zones. They can be used to study wave-driven processes, such as overtopping, wave-driven currents and circulation, wave runup and wave set-up. These models can either resolve individual waves at small scales or cover broad scales by simulating changes in wave spectra. They can be coupled with hydrodynamic models to investigate interactions between water levels, currents, and waves.

   c. Sediment Transport and Morphodynamic Models
      - These models simulate the changes in the shape and size of erodible coastal features over time. They can be used to study the erosion and accretion of dunes, marshes, and reefs, and to predict how these features will change in response to different environmental conditions. These models are typically driven by (or coupled with) hydrodynamic, wind, and wave models.

   d. Ecological Models
      - These models simulate the ecological dynamics of coastal systems, for example, the growth and erosion of coastal marshes. They are often coupled with hydrodynamic and wave models. These models could also include transport of nutrients or be used to compute other biogeochemical parameters.



e. Coupled Models
   - These models combine different types of models to study the interactions between different coastal processes, such as the interaction between waves and dunes, or between waves and vegetation. Models can be coupled in one direction (one models acts on another with no feedback) or in two directions (model acts on another with feedback).

f. Ice Dynamics Models
   - These models simulate the movement of ice subject to forcing by winds and currents and can approximate ice interactions with coastal structures (breakwaters, jetties, wharves).

3. **Conceptual/Reduced-Complexity/Statistical/Empirically Based Modelling**
   These models can be used to examine a range of physical processes but are principally used for preliminary or screening-level estimates of wave and water level conditions, sediment budget analysis (see Chapters 7 and 8), shoreline evolution modelling, including cross-shore and longshore changes, wave runup, and overtopping. These models utilize a series of simplifying assumptions (e.g., with respect to physics, bathymetry, or shoreline geometry), rules or statistical correlations (as opposed to physically based equations) to simplify the system, reducing the number of parameters and increasing the computation efficiency. Examples include empirical (or semi-empirical) models, Bayesian models, and machine-learning techniques.

The performance of nature-based infrastructure (NBI) in the coastal environment is dependent on a wide range of spatial and temporal scales (e.g., from storm-driven transport of sediment within a coastal sediment cell, to global sea-level rise in response to climate variations on timescales ranging from decades to millennia). As such, a range of modelling practices and tools need to be implemented to better understand the evolution, performance, and impacts of NBI, and to reduce uncertainties. For brevity, this chapter will focus on physical and numerical modelling as: (i) numerical models and computing power are increasingly accessible, user-friendly, and cost-effective; and (ii) physical models remain necessary to reliably simulate some processes that cannot be confidently replicated by numerical models. This chapter supports the Sediment-Based, Vegetation-Based, and Hybrid Solutions chapters (see Chapters 8, 9 and 10, respectively) by examining tools available to practitioners to evaluate designs and support adaptive management efforts. Some conceptual/reduced-complexity models are introduced in the above chapters to help demonstrate specific processes.

The purpose of this chapter is to help practitioners understand the modelling tools available to them to optimize the design of NBI in the coastal environment. This chapter aims to:

1. Broadly identify when and how to appropriately apply modelling tools.
2. Define the components necessary to successfully implement a model.
3. Provide examples by way of case studies on model applications in Canadian coastal environments.
4. Outline benefits and drawbacks of numerical and physical modelling tools.

11.3 Developing a Modelling Approach

When developing a modelling approach to investigate NBI, it is important to select the appropriate model or suite of models based on the project objective and goals, data availability and project resources, complexity of the system being studied, type of NBI, characteristics of the shoreline and nearshore region, and the expertise of the team carrying out the investigation. It is important that each chosen model is

capable of reliably simulating the important relevant physical processes. The following section provides guidance for selecting the appropriate model(s) and the process of developing a modelling methodology.

11.3.1 Key Considerations and Best Practices

Model optimization requires balancing sufficient model complexity to reliably capture the relevant physical processes while also minimizing computational effort and/or cost, ensuring model outputs are interpretable and can be validated with data. The effort needed for numerical or physical modelling of NBI in coastal environments depends on several factors, including the specific goals and objectives of the project, the project size and cost, the availability of data and resources, and the complexity of the system being studied. In the case of physical modelling, model design typically involves maximizing realism by minimizing distortions due to scale effects and boundary effects as much as possible while respecting constraints associated with available facilities, equipment, and/or budgets.

- **Project goals and objectives:** The specific goals and objectives of the project will determine the level of detail and accuracy required in the model. For example, a project focused on evaluating the effectiveness, development, or performance of a detailed design of a specific NBI will require a more detailed and accurate model than a project focused on exploring the potential benefits and drawbacks of different options.

- **Data availability:** The availability and quality of data, such as bathymetry, metocean conditions (wind, wave, tide, water levels), and sediment and vegetation properties, will affect the level of effort required to set up, run, separately calibrate, and validate models with different datasets, and check the reliability or uncertainty of the model output.

- **Complexity of the system:** The complexity of the system and processes studied will affect the level of effort required to create, run, and validate the model. For example, a model simulating the interactions between wave dynamics, sediment transport, and vegetation will be more complex than a model that only simulates wave dynamics. More complex or sophisticated models do not necessarily correlate to more useful insight or predictive capabilities.

- **Resources:** The availability of resources, such as funding, facilities and equipment, computational power, and skilled personnel, will also affect the level of effort required to create and run models. If there is insufficient project budget to allow for a proper modelling effort that includes calibration, independent validation, and sensitivity checks on the model, then it is better to rely upon empirical design approaches and adopt a higher level of uncertainty in design.

- **Design scenarios:** A range of design inputs should be identified and selected to capture key site-specific processes. The scenarios should be selected to capture the range of plausible scenarios while limiting the resources (economic or computational) necessary to evaluate the design performance (Hendrickx et al., 2023). In the past, coastal hazard modelling in Canada for risk assessment or coastal engineering design applications has often been limited to investigating one (or a few) extreme (acute) events, primarily due to the relatively low complexity and cost associated with this approach. However, there is increasing recognition of the need for, and value provided by, modelling multiple events and scenarios or longer time periods to consider both acute and chronic hazards and system impacts over a project lifecycle, particularly in the context of a changing climate (Piercy et al., 2021; Murphy et al., 2020; CSA, 2024). Too few modelling scenarios or events can lead to a poor understanding of coastal hazard risk (Ward et al., 2011), and consequently, NBI benefits and performance. The source-pathway-

receptor-consequence model provides a useful starting point for identifying scenarios and events relevant to assessing the performance of NBI for coastal flood and erosion risk management (Piercy et al., 2021; Murphy et al., 2020; CSA, 2024), and is widely used internationally.

- **Communication:** A key consideration is how to effectively communicate model results and uncertainty to non-specialist stakeholders and parties interested in or affected by an NBI project, and to solicit input to model and scenario design. Adequate time and resources should be dedicated to engagement (see Chapter 5) and communication of modelling options, methods, and outputs (Kim et al., 2024). Impressive maps and visualizations of numerical model output, and the immersive experience of a physical model, are useful communication tools (see Section 5.7) but can also potentially lead to a false sense of trust in models by non-specialists. The onus is on modelling specialists to openly communicate model uncertainty and limitations to project teams and stakeholders, ideally with reference to quantitative model skill metrics (e.g., Stow et al., 2009; Olsen et al., 2016) that are directly relevant to project objectives (e.g., root-mean-square errors in predicted water levels where NBI is designed to attenuate storm surges).

11.3.2 Model Selection

Determining the appropriate tool for modelling coastal NBI depends on the specific goals of the study, the model scale, relevant processes, the features of the specific system being modelled, and available funding. Some specific factors to consider when selecting the type of model include:

- **Model uncertainty and sensitivity.** Numerical models are based on a set of assumptions and simplifications, and the results should be interpreted with the understanding of such uncertainties and limitations. Similarly, certain physical processes, notably the transport of fine sediments, are generally not faithfully replicated in scaled physical models, and it is important to understand such limitations when interpreting model outputs. Additionally, the sensitivity of the model results to different input parameters and assumptions should be evaluated, to understand how the model results are affected by different environmental conditions.

- **The spatial and temporal scales of the system.** A larger spatial scale or longer temporal scale may require a more complex model or specific modelling approach. Highly detailed numerical simulations at very fine scales can be similarly very challenging. Resolving fine scales while covering a large area or long time-period is challenging, though coupled models or statistical downscaling techniques can help reduce computation load (Anderson et al., 2019; Vitousek et al., 2021). Physical models are generally well suited to studying complex processes (wave breaking, wave-structure interactions, wave runup and overtopping) over smaller spatial scales and shorter timeframes, and less well suited to simulating processes over large domains and/or longer durations.

- **The number and complexity of physical processes involved.** A design or study site that includes more physical processes, such as wave-current interaction, sediment transport, and vegetation dynamics, may require a more complex model.

- **Availability of data.** Models are only as reliable as the data used to develop them (i.e., garbage in = garbage out). Models should be set up with data (e.g., bathymetry and boundary conditions), and calibrated and validated with field data (e.g., observations of waves or water levels inside the model domain) to ensure that they are accurate and reliable, and to quantify model uncertainty. An observation

record of a sufficient length and of the appropriate parameters should be available for calibration and subsequent validation.

- **Model complexity and level of detail.** A model that aims to predict the behavior of a system with high accuracy will need to be more complex than one that is used for qualitative understanding or feasibility-level analysis. The complexity of a model should be appropriate for the problem being studied. Simple models may be sufficient for some problems, while more complex models may be needed for others.

A more complex model is not always better, as it may be computationally/economically more expensive, difficult to interpret, or may not be necessary to answer the research or design question. Most often, using numerical and physical models in tandem can leverage the strengths of both approaches and reduce uncertainties related to design and performance.

11.3.3 Physical Modelling

Physical models (laboratory studies) have played a pivotal role in the development of coastal and hydraulic engineering. Important processes and problems in these fields are not amenable to purely theoretical or numerical analysis and require physical models to test solutions, optimize designs, and validate theories. As such, the need for physical models has evolved along with developments in numerical modelling and field measurements. The process of reproducing complex coastal systems and processes in the controlled laboratory environment includes:

1. **Careful consideration of the key processes involved.** Understanding the processes that drive or influence the performance of the design is the most critical step in the planning of a physical model. Previous studies of similar designs can provide a hint into how other researchers have approached the challenge. Dimensional analysis can also be a helpful tool in identifying the natural phenomena that need to be considered.

2. **Understanding the objectives.** Clearly defining the parameters of a successful study is critical in implementing a physical model. This will help in defining what facilities and what scale need to be used in assessing the design, and establishing a suitable physical model domain.

3. **Scaling.** It is often not possible to directly model coastal systems in a laboratory environment at full scale, due to either the size or complexity of the system. This requires the system to be scaled to fit within available facilities. Scaling is done considering the principles of similitude, the balance of forces between model and prototype. Scaling laws exist for a variety of coastal processes (Hughes, 1993; Heller, 2011) that can help guide practitioners in the design of physical models. Most coastal models involving propagation of waves and currents over nearshore domains are designed to preserve similitude of the Froude number in the model as in the real-world situation.

4. **Balancing realism and economy of the model.** It is rare to maintain full similitude in scaled down models as the balance between gravity and viscosity cannot easily be maintained. Therefore, it is best to perform physical modelling at as large a scale as possible to ensure adequate realism of the important processes. However, working at a large scale may limit the range of facilities that are suitable, and may increase costs. Understanding the influence of scale effects on the model and its output is important, either through experience, literature (Heller, 2011), comparison with field data or numerical model output, or by performing studies at multiple scales. Working at large scale

often involves limiting the size of the domain that can be included in the model or the size of the waves that can be generated.

5. **Analysis of the predictive capabilities of the model.** The capabilities of the facility and equipment used (model effects), the model size (scale effects), and the model design and execution will inevitably have an influence on the results. It is advisable to involve specialists with experience in physical modelling of coastal processes who can provide advice on conducting the modelling study and extrapolating model outputs for use in project design.

For more information, Hughes (1993) provides a comprehensive textbook on physical modelling in the coastal environment. Specific considerations for NBI are discussed in Section 1.5 - Model Implementation.

11.3.4 Numerical Modelling

Numerical models have become increasingly used with the improvement in numerical tools and availability of computational resources. There are now a range of models available to study coastal systems. In general, it is important to balance the level of effort required to create and run a model or suite of models with the specific goals and objectives of the project and the availability of data and resources. When considering and selecting the type and complexity of numerical model tools to investigate coastal processes and NBI, funding agencies, engineers, scientists, and project managers should consider, among other key topics, the:

1. **Key questions to be addressed.** The type and complexity of the model should be appropriate for addressing the problems or questions at hand and the level of detail required to answer them. The scale and complexity of models can vary substantially, ranging from basic first principles to fully resolved three-dimensional models (e.g., Swatridge et al., 2022). Trade-offs between the level of complexity, scale, computational cost, available time, and the required level of accuracy should be considered when choosing the type and complexity of model to be used. The model (or models) should be based on sound scientific principles and should be calibrated and well-validated using reliable field data. If minimal field data is available, models can be used to develop a better understanding of a systems or response of processes within a system, using a controlled set of sensitivity analysis to describe the overall bounds of the problem or question at hand. The modelling study should involve collaboration with relevant stakeholders, such as coastal managers, community representatives, and designers, to ensure the results are relevant and presented in a manner that is useful for decision making.

2. **Availability of data.** The availability and quality of data for model development, forcing, calibration, and validation should be considered when choosing the type and complexity of model. The study should have a plan for collecting, managing, and archiving the data used with the model, as well as for sharing the data with other team members.

3. **Expertise of the numerical modelling team.** The expertise of the modelling team should be considered when choosing the model type and complexity, as some models may require specialized knowledge to set up and run. The team conducting the modelling study should have relevant expertise in the field of coastal dynamics, numerical modelling, and nature-based solutions.

4. **Model uncertainty.** All models are approximations of the truth and are prone to error and uncertainty. Users should understand sources of, and possible contributions to, uncertainty and



error (e.g., related to input or boundary condition datasets, interpolation error, simplifications and assumptions, parameterization of processes, numerical error, and scenario uncertainty). Rigorous model skill assessment can be used to understand and test model capabilities and uncertainty (e.g., Stow et al., 2009).

5. **Potential for comparison and integration with other numerical models and tools.** The model output can be compared with output from other relevant models that may be available, or with output from field studies or physical model studies. Since a whole-system understanding is critical to the successful design and implementation of NBI (see Chapter 2), it is preferable to consider models that allow for simulation of system interactions and interdependencies. The capabilities of models to capture multiple system (e.g., physical, meteorological, ecological, or socio-economic) interactions, behaviours, and effects should be considered, as well as the possibility to integrate models with tools such as GIS or remote sensing, to provide a more comprehensive understanding of the coastal zone.

6. **Computational resources.** The available computational resources and software should be considered when choosing the type and complexity of model to be used. Spatio-temporal scales of interest, required resolutions, model process complexity, and numerics may all affect computational demand.

7. **Transparency and access.** The model should be (i) verified for a range of theoretical or test cases relevant to the application (preferably benchmarked against other models), and (ii) amenable to a transparent and documented modelling QA/QC process that can allow for independent review and auditing. General guidance on modelling documentation is provided in van Waveren et al. (1999). Additionally, it is important to consider the ability and ease of model data sharing and interoperability, software licensing restrictions, hardware and software costs, and compatibility with existing hardware/software systems. Some numerical modelling programs are open source and freely available for use and improvement, whereas other numerical modelling programs are restricted by commercial license agreements. There are pros and cons of open source versus commercial software that project proponents and modellers should carefully consider when selecting a numerical model. Further guidance on data management and sovereignty is given in Sections 4.7.3 and 12.6.1.

11.4 Model Implementation

11.4.1 Physical Models

Physical models of coastal projects incorporating NBI are typically used to simulate a range of metocean conditions at the site, including extreme conditions with low probability and potential future conditions including sea-level rise; and observe and collect data on the resulting physical processes at the site, including information on any impacts on proposed NBI and the surrounding environment. Subsequent testing will often explore alternative designs or concepts or optimize the layout or design of the proposed NBI. Optimization may include improving performance (ability to fulfill project objectives), improving constructability, reducing project cost, or all three. See Box 11-1 for an example of a 3-D physical model study used to support design and construction of shore protection project incorporating NBI.

11.4.1.2 Vegetation-Based Solutions

Several special considerations are necessary when physical models of NBI aim to capture and simulate flow-vegetation interactions and effects. Plant biophysical properties have a documented influence on coastal protection services (e.g., wave attenuation), including plant morphology, biomass, flexibility, stem diameter, and canopy height, among others (e.g., Augustin et al., 2009; Paul et al., 2016; van Veelen et al., 2020; Maza et al., 2022; Markov et al., 2022a; Markov et al., 2023). These properties can vary significantly between species, and thus selection of a target plant species (or community) with known biophysical properties is often the first step in the development of such physical models. Physical modelling studies of flow-vegetation interactions may be performed with live plants at full scale (see Box 11-2), or surrogate elements at full or reduced scale (see Box 10-2), depending on the resources, test facility, and study objectives. Using live vegetation can lead to highly realistic flow-vegetation interactions; however, careful consideration must go into plant sourcing, plant husbandry methods during testing, and scheduling. Furthermore, the use of live vegetation necessitates full-scale testing, which may restrict the upper limit of hydrodynamic test conditions and the model's spatial extent (facility-dependent).

To circumvent the challenges with utilizing live plants in laboratory settings, surrogate elements may be used to represent coastal vegetation. Plant surrogates should be selected in consideration of the target species' biophysical properties, primarily stem length, stem diameter, and planting arrangement (natural or target stem density). Plant morphology is often simplified to a cylinder for surrogate models. When considering flexible plant species and hydrodynamic settings that could induce vegetation motion, the use of flexible surrogate elements should also be considered. Various methods for flexible surrogate selection have been proposed, including application of scaling laws for biomechanical properties (e.g., Ghisalberti & Nepf, 2002; Koftis et al., 2013), or through visual observations of bending similitude between live and model vegetation (Markov et al., 2022b). Plant surrogates may also be used for scaled physical models of vegetation-based solutions, however, the diameter of model vegetation should only be geometrically downscaled if stem Reynolds number conditions can be reasonably maintained with respect to prototype conditions, as significant changes to the stem Reynolds range can strongly influence the vegetation drag coefficient.

When modelling larger coastal domains where relatively small patches of vegetation exist, it may be unfeasible to simulate individual plants, and the effect of the vegetation on wave propagation and current circulation may need to be approximated by increasing the roughness of the model bottom in the vegetated areas. While this approach is clearly not adequate for studying wave-plant interactions or the effects of vegetation occupying a significant proportion of the water depth, it may be satisfactory when studying wave-plant interactions is not the primary study objective. Artificial roughness elements may be designed by matching the drag coefficient of the roughness elements and the bulk drag coefficient of the vegetation field when this information is available or can be found in the literature.

Box 11-1. 3-D Physical Model Supporting Assessment of a Coastal NBI Project, Metlakatla, BC.

A 3-D physical model of the shoreline at Metlakatla, BC, was constructed at 1:20 scale at the National Research Council, shown in Figure 11.4-1. This model is used to study the behaviour and performance of NBI built to manage flood and erosion risk, protect valuable cultural sites located near the shoreline, and restore various shoreline habitats including salt marshes and beaches comprised of course sands, gravels, and small cobbles. The model was first used to study conditions prior to construction of the new NBI, then used to study coastal processes post-construction. Extreme metocean conditions and future conditions including potential climate change effects were among the scenarios simulated in the physical model. The model was also used study potential modifications to the present shoreline to better serve the needs of the community. Data measured at the site was used to support the design and construction of the model and guide the selection of wave conditions input to the physical model. Outputs from the physical model were compared with data collected at the site and outputs from numerical models.

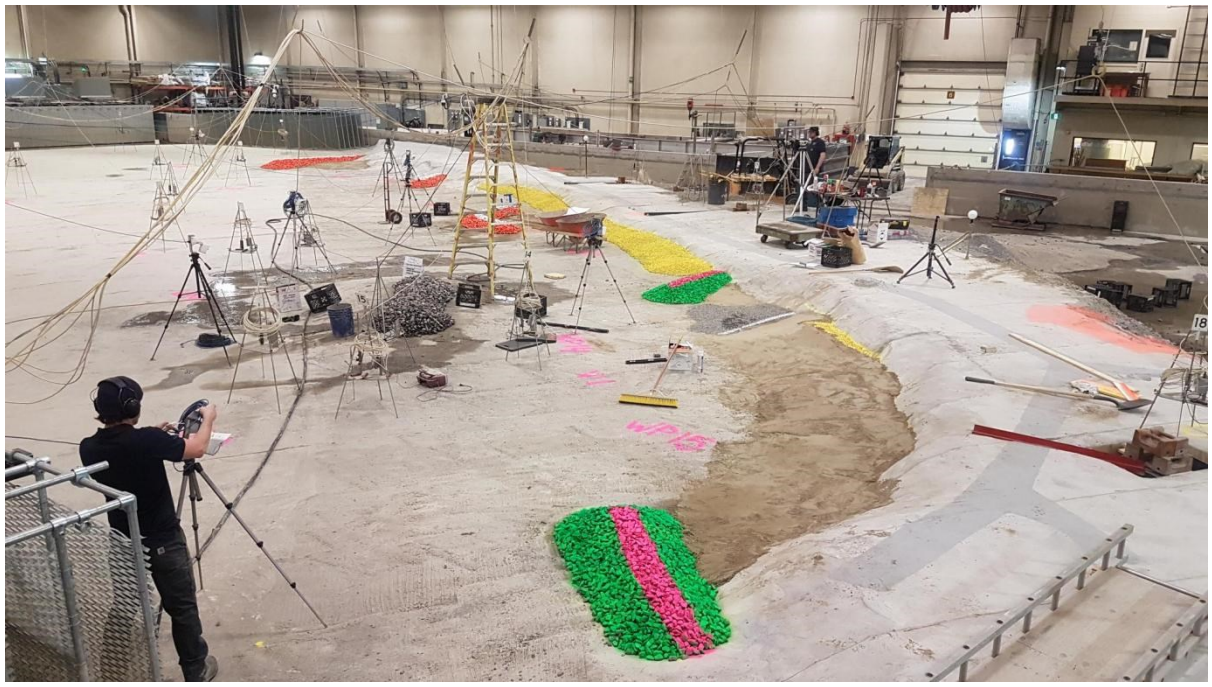


Figure 11.4-1. 3-Dimensional physical model of the shoreline and NBI at Metlakatla, BC, under construction.

Box 11-2. Physical Modelling of Live Vegetation

Coastal areas are at risk from flooding and erosion caused by rising sea levels and other factors. Coastal marshes have been shown to be effective in contributing to flood and erosion risk management objectives, by attenuating waves and storm surges, and attracting and stabilizing sediments. There is growing interest in restoring or growing salt marshes for flood and erosion management and ecosystem restoration as part of nature-based solutions. Most studies on wave attenuation and sediment stabilization by salt marsh plants focus on mature or dense canopies. Ghodoosipour et al. (2022) conducted a physical modelling study to evaluate wave attenuation by immature *Spartina alterniflora* vegetation in newly constructed or restoring marshes. The study involved experiments conducted with live plants at full scale in a flume at the National Research Council Canada. The response of live vegetation, installed in configurations resembling newly built or developing marsh canopies, to regular and irregular waves and waves combined with steady current was studied. The effects of various factors, such as vegetation density, relative submergence ratio (or water level), wave conditions, and currents on wave attenuation were investigated. *Spartina alterniflora* stems were planted in milk crates before moving them to the flume. The experimental set up is shown in Figure 11.4-2, with the vegetation in the flume and a side view showing wave interaction with the young plants.



Figure 11.4-2. Experiment to investigate wave attenuation by young marsh vegetation: a) vegetation in the flume; b) side view showing wave interaction with the plants.

11.4.1.3 Sediment-Based Solutions

Physical modelling of NBI that have a sediment-based component require careful selection of both model scale and the sediment that is used in the model to represent the sediment in the field. For full-scale modelling, the sediment should be as similar as possible to the actual sediment at the site. This includes matching the sediment distribution (values of D_{10}, D_{50}, D_{90}), the sediment shape (rounded versus angular), and density (through sediment composition). For reduced model scales, two methods are recommended for scaling sediments in a coastal physical model; geometric scaling or scaling to preserve similitude of sediment fall velocity. Geometric scaling of sediment is recommended when the prototype sediment grain size is relatively large (such as coarse sand, gravel, or cobble) and/or the model scale is relatively large.

When geometric scaling results in a model sediment grain size of <0.12 mm (due to the prototype sediment and/or model scale being too small), the resulting very fine sediment will likely behave unrealistically in the model due to issues with cohesiveness and suspension. Therefore, in such cases it is recommended to scale through Froude similitude of the sediment fall velocity instead. Scaling by matching fall velocity in the model and field leads to the use of model sediments that are overly coarse and thus less mobile than they should be. The use of over-sized sediment will cause different behaviors in the model than in nature, such as:

- Model beaches tend to be steeper.
- Model will underestimate the amount of sediment in suspension and the rate and extent of suspended load transport.
- The bedforms in the model will be oversized resulting in exaggerated bottom roughness.
- The timescale for sedimentary processes may differ from the Froude timescale.

Care must be taken to consider these scale effects when interpreting output from physical models in which over-sized, less-mobile sediments are used. Representing the mobility and behaviour of cohesive sediments, silts, and clay in physical models is particularly challenging and is generally not recommended.

11.4.2 Numerical Models

Numerical models for coastal engineering play a critical role in understanding how coastlines respond to their environments and allow investigation of future climate scenarios and proposed human interventions, such as construction of NBI. These models can allow for assessment of coastal designs that have not yet been built, as well as long-term analysis over shorter computational timescales. These models also can be designed or forced using hypothetical conditions or conditions that may be encountered over the service life of the NBI, such as higher water levels, in the case of sea-level rise, or more severe storm events than those captured in the historical record. The development of numerical models is normally constrained by circumstances unique to each site, however, there are numerous considerations that must be taken into account:

1. **Model Type.** Numerical models can simulate a variety of physical processes, compute a variety of parameters with varying degrees of accuracy, and produce a variety of output. A hydrodynamic model may be coupled with other models, such as wave-resolving models or models that simulate sediment transport and morphology change if necessary. Wave nonlinearity should be included to properly simulate wave transformation for detailed design. For a screening level or preliminary analysis, a simple refraction, shoaling, and breaking analysis based on linear wave theory may be adequate, as long as uncertainty is acknowledged and understood. Different hydrodynamic models also use different computational approaches and different methods for discretizing the domain that should be considered. The chosen model should be fit for purpose. Models that are experimental and lack thorough verification for test cases relevant to the proposed application and validation through extensive use are not recommended. Models that have been independently tested following industry standard validation protocols or benchmarked (e.g., Pye et al., 2017) are preferred.

2. **Domain and Grid Size.** The size and extent of the model domain plays a large role in the quality of the simulations and the inputs required, and should be considered when creating a model computational grid. This will depend on the conditions of the site of interest, the surrounding conditions, and the detail



required to address study objectives. The type of grid used (structured or unstructured/flexible and irregular) and its resolution will also influence the quality and resolution of model output and the computational efficiency. A series of nested grids may be used to study a large area at lower resolution and a smaller sub-area at higher resolution, where outputs from the larger domain are used as boundary conditions to the smaller domain.

3. **Topography and Bathymetry.** Bathymetry (and topography, in cases where the model covers terrestrial zones) data is critical input to a numerical model. The availability and resolution of both bathymetric and topographic shoreline data should be carefully considered when building a model surface. If there is insufficient data, it is important to consider the resources required to collect additional topographic or bathymetric data. The required resolution of topographic and bathymetric data depends on several factors, including: the models being used, the level of detail required to resolve key physical processes, the design stage of the project, and the detail required to answer key study questions, among others. Further information on monitoring and data collection techniques for NBI is presented in Chapter 12. It is important that all raw data are carefully adjusted to consistent horizontal and vertical reference datums. It should be noted that when insufficiently resolved, topography and bathymetry data may fail to include key features, such as sandbars and embankments, and sharp gradients in topography and bathymetry may be lost when interpolated to a model computational grid, resulting in reduced realism and accuracy of model output. Models may also have specific requirements to incorporate features, such as culverts and bridges or other structures, that need to be considered.

4. **Boundary Conditions.** The creation of a model requires the designation of boundaries, typically along edges of the computational domain. These boundaries can be of open or closed form and may force external conditions into the model, which may dictate the placement of these features. Boundary conditions that are commonly applied specify meteorological-oceanographic (metocean) conditions along one or more edges of the model domain, as well as water properties (temperature, salinity, and concentrations of materials in suspension). The model domain must be carefully selected to capture the relevant boundary forcings (tides, discharge, etc.) and limit the computational load, while reducing boundary effects at the study site. Care should be taken to ensure boundary conditions are well characterized by available data, and far enough away from areas of interest to capture remote forcing and minimize artificial boundary condition effects that could adversely influence the results.

    a. **Atmospheric Forcing.** Atmospheric conditions, including air pressure and wind velocity, are typically applied over the model domain and together with the boundary conditions, generate the waves, currents, and water level conditions within the model domain. These may be supplied over a grid (e.g., from a larger-scale atmospheric model) that has a different resolution from the hydrodynamic model. Not all types of forcing are always required and the way in which the model should be forced will depend on the dominating processes within the model domain. It is important to note that large-scale atmospheric models can fail to resolve local topographic features and fine-scale atmospheric conditions that may be important for steering local winds in coastal areas with mountains (such as the BC coast) and practitioners should be careful about applying such data as input to models in these situations. Atmospheric forcing provided by global or regional models should be locally validated prior to using it as input.

    b. **Bottom Boundary.** The bottom boundary conditions represent the bed as a surface (generally impermeable, i.e., no velocity in the vertical direction). The bottom boundary conditions can have an influence of flow conditions due to the representation of the surface roughness (or



friction). The surface roughness can influence the velocity profile and energy dissipation within the domain.

c. **Open Boundary.** It is often not possible (or computationally expensive) to have a natural boundary at the edge of the model domain (open-sea, river, etc.). To overcome this, models can have open boundary conditions that allow outflow (or inflow) of mass/energy, salinity, temperature, nutrients, sediments, etc. Selecting the boundary location and conditions must be done carefully to avoid numerical errors or instability and the boundary should be sufficiently far away from the site to avoid artificial influences.

Examples of models suitable for use in studies of coastal NBI include wave models, such as SWAN, SWASH, MIKE3 Wave FM, STWAVE, MIKE21 SW, NH WAVE and TOMAWAC; hydrodynamic models, such as TELEMAC, FVCOM, ADCIRC, Delft3D, and MIKE21/MIKE3; sediment transport models, such as XBeach, UNIBEST, LITPACK, MIKE21/MIKE3 and Delft3D; and ecological models, such as Delft3D-WAQ or MIKE3 ECOLAB.

11.4.2.1 Regional-Scale Numerical Models

Numerical models are useful tools for simulating ocean conditions over broad scales since they account for the high variability of input forcing conditions (e.g., bathymetry, winds, waves, tides) to calculate the coastal responses (e.g., local waves, water levels, currents, sediment transport) as output. However, these models are often limited by the observed data needed to describe input and boundary conditions, and properly validate model output to ensure it accurately represents real-world conditions.

As the numerical model domains increase in size, additional considerations must be accounted for in the model input. At large geographic scales, the spatial resolution of atmospheric forcing becomes increasingly important. This is especially significant in cases with observed atmospheric steering of winds, as well as regions that are dominated by wind-generated waves and storm surges. At regional scales, Coriolis forces can no longer be neglected. Regional-scale models also benefit from flexible and unstructured meshes that can accommodate triangular grid cells, curving boundaries, and varying grid sizes. These meshes can more precisely capture the shape and hydrodynamics of differently shaped features and coastlines while allowing for computational efficiency where conditions are less complex. Spectral wave models can predict open-ocean conditions extremely well, however, semi-enclosed areas, especially those with complex topography, can be more challenging to accurately model (Mulligan et al., 2010; Cousineau & Murphy, 2022). In mountainous coastal regions, such as fjords, topographic steering and shadowing create high variability in wind fields, making wave and storm surge predictions difficult.

NBI design, such as design of a living dyke or managed dyke realignment/salt marsh restoration project, requires an understanding of the storm surge and surface waves in the region, often obtained through the use of a numerical model. Two examples of the application of numerical models to study and support the design of coastal NBI projects are presented in Box 11-3 and Box 11-4. Both of these examples were developed as part of the Nature-Based Infrastructure for Coastal Resilience and Risk Reduction project led by the National Research Council.

Box 11-3. The Bay of Fundy

An example of multi-scale modelling is the system developed to simulate tidal flows in the upper Bay of Fundy. Regional-scale simulations of hydrodynamics across the entire domain (Figure 11.4-3a) were implemented using a coupled modelling system (Delft3D-SWAN) driven by high-resolution spatially varied wind fields from an atmospheric model and tides from a global ocean model. While the hydrodynamics of this region are primarily dominated by tides, the accuracy of the water level predictions is improved by including wind-driven storm surge, and wave-current interactions. Results from this model were validated against available observed data in the Bay of Fundy (Swatridge et al., 2023) and used to provide boundary conditions for smaller-scale simulations of nature-based infrastructure designs (Burns et al., 2023). Specifically, the Converse Breach is a managed dyke realignment site in the Missaguash River, a tidal channel in the northern Bay of Fundy (Figure 11.4-3b). The site is fetch-limited and primarily affected by hypertidal water levels and currents. The large-scale model provides boundary conditions to the Cumberland Basin model and the breach site is resolved with a high-resolution (1 m) computational grid. The model is applied to simulate the currents, water levels, and flood extent before (Figure 3c) and after (Figure 3d) the dyke is breached, and is validated with field observations during each of these phases. This model supports the design and the maintenance of a managed realignment site and can be used in future to understand changes resulting from the breach, including sediment deposition, morphological change, and re-establishment of salt marsh vegetation. This project is a collaboration between academic (Queen's University, Saint Mary's University), and government (NRC) research partners.

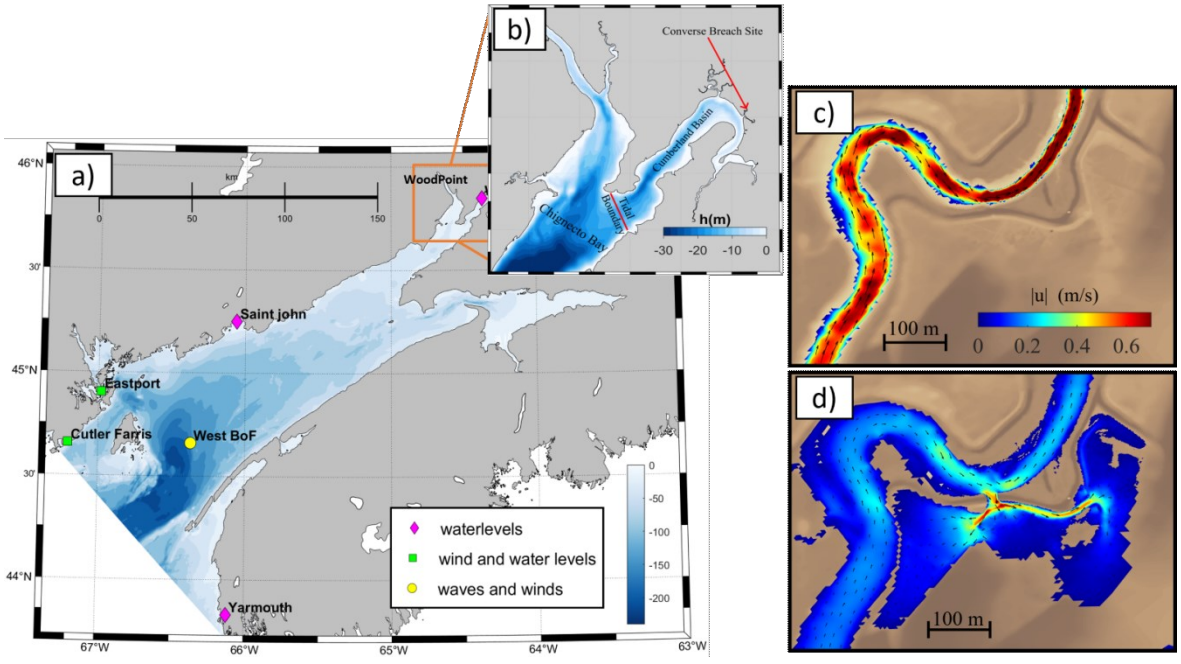


Figure 11.4-3. Maps showing: a) bathymetry of the Bay of Fundy regional model with the location of observation points; b) bathymetry of the smaller scale Cumberland Basin model; c) example results of the simulated current velocities at the managed realignment site before the dyke breach; and d) after the dyke breach.

Box 11-4. The Salish Sea

An example of a regional-scale numerical model is one developed for Boundary Bay, a tidal flat located adjacent to the cities of Delta and Surrey, British Columbia, within the Strait of Georgia in the Salish Sea (Benoit et al., 2023). The Salish Sea is a complex system of fjords, bays, and channels as shown in Figure 11.4-4a. It is a tide-dominated and fetch-limited semi-enclosed sea, with complex coastline geometry enclosed by mountainous terrain. The mountainous topography in this region results in the funnelling of winds into regions like Boundary Bay, shown in Figure 11.4-4b, and therefore the wind-generated waves and storm surges have high spatial variability. Boundary Bay is currently bordered by a long dyke parallel to the shoreline, constructed to prevent inland flooding and erosion of the adjacent low-lying land. This dyke requires rehabilitation to protect the inland region from overtopping, which is of increasing concern as sea levels are projected to rise. The regional model is used to quantify the waves and water levels, using the SWAN wave model coupled to the Delft3D hydrodynamic model, in support of nature-based infrastructure design. This project is a collaboration between academic (Queen's University), government research (NRCan, NRC), and municipal (City of Surrey) partners.

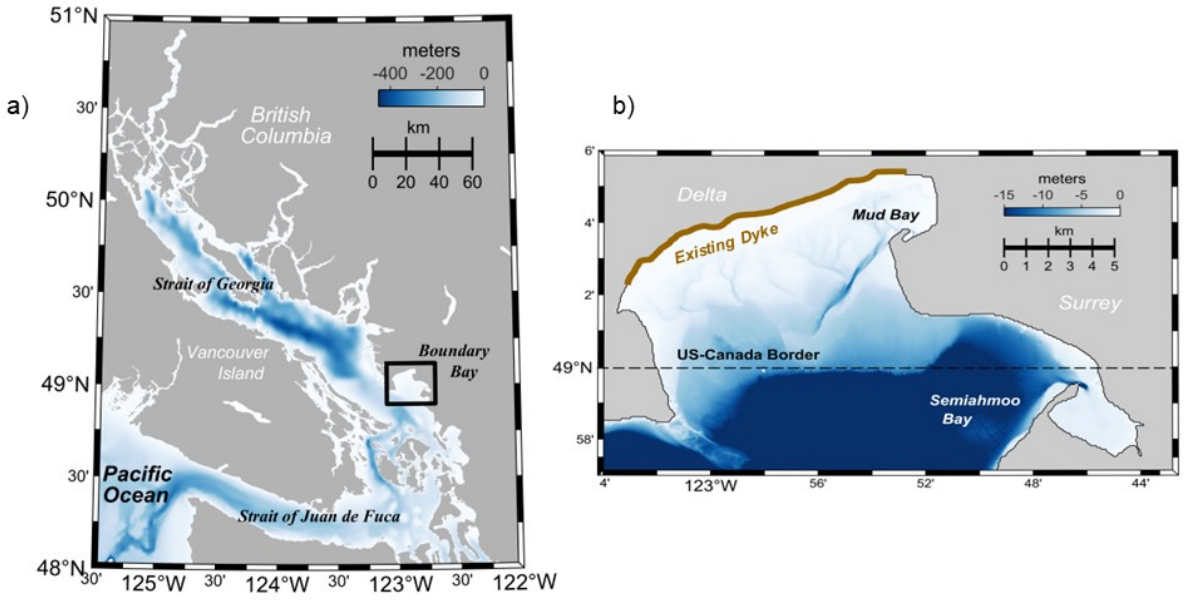


Figure 11.4-4. Bathymetric maps of the Salish Sea: a) regional model domain used to investigate storm surges and surface waves; and b) detail of the Boundary Bay tidal flat, with the existing traditional dyke indicated along the northern shoreline.

11.4.2.2 Local-Scale Numerical Models

In cases where fine detail of the hydrodynamics is required around a solid structure, region of vegetation, or morphological feature, fine-scale modelling can be used to resolve individual features or behaviours. These can be used to investigate the reasons underlying macro-scale behaviour of the structure or structures, including wave attenuation capacity or local scour or vegetation effects (Ashall et al., 2016). This method also allows for structures to be modelled as they exist, rather than in simplified forms typical of

larger-scale modelling efforts. These models are typically applied over small scales with high resolution computational grids (e.g., less than 5 m). As examples, SWASH, XBeach-nonhydrostatic, and NHWave are phase-resolving wave models that can compute free surface and wave-orbital fluid motions within individual waves. Computational Fluid Dynamic (CFD) models, such as Flow-3D and OpenFOAM; Smoothed-Particle Hydrodynamic (SPH) models, such as SPHysics; and shallow-water models, such as Boussinesq and Parabolic Mild Slope, are other types of models that can resolve flow details on small scales.

As structures or bed features get smaller, smaller grid sizes are required, thus increasing computational demands. Determining the maximum grid size at which the model results are accurate is therefore extremely important. It is also necessary to have high-quality measured data for proper validation to ensure the model output is realistic.

11.4.3 Climate Change Considerations

Physical and numerical models are particularly useful when assessing possible future scenarios related to climate change. They each offer the possibility of gaining insight into future conditions and evaluating the effectiveness of NBI for coastal protection. Considerations for incorporating the changing climate in a model are noted below.

- **Realistic scenarios of sea-level change** may be incorporated to assess future conditions and impacts (e.g., Ferguson et al., 2022). These are outlined for Canadian coastal regions by James et al. (2021), which provides gridded relative sea-level projections for Canada's coastlines at decadal intervals for three Intergovernmental Panel on Climate Change (IPCC) climate scenarios. The projections are available at climatedata.ca. Although challenging, it is also important to consider how an increase in water levels may have compounding effects, such as on the evolution of coastal morphology, and on vegetation (e.g., Kirwan et al., 2016). Modelling of coastal flood hazards may require statistical analysis of the joint probability of high tides and storm surges to be added to sea-level change.

- **Future climate conditions** should be considered. These could be local projections of atmospheric conditions based on past events (e.g., McLaughlin et al., 2022), or based on downscaled results from General Circulation Models (GCMs). Representative Concentration Pathways (RCPs) (IPCC, 2016) and Shared Socio-Economic Pathways (SSPs) (IPCC, 2022) have been defined to represent different possible climate change scenarios for the 21st century. Other elements to incorporate into the models may include changes in temperature, vegetation presence, presence of sea ice, or sediment suspension, depending on the parameters under analysis. Studies can be conducted to assess the effects of climate change on the future wave climate and probabilities of high storm surge at a coastal site (e.g., Cousineau & Murphy, 2022), and this information can be used to inform the selection of scenarios for simulating climate change effects in models. Models should take into consideration uncertainties in climate projections, through the use of a range of potential scenarios. Ensemble-based approaches can be used to constrain uncertainty in future climate variables (e.g., extreme wind speeds).

- **Adaptative management** should be considered during the modelling of NBI considering changing conditions over the lifecycle of an NBI. Models can provide guidance in developing initial management policies and practices. This can include maintenance cycles, monitoring, and evaluation of project performance. Models can be adapted over the lifetime of the project to reflect the as-built conditions onsite.

11.5 Challenges

Some of the advantages and disadvantages of using physical and numerical models to investigate NBI are listed in Table 11.5-1.

Table 11.5-1. Advantages and disadvantages of using physical and numerical models.

Model Type	Advantages when applied to study coastal NBI	Drawbacks when applied to study coastal NBI
Physical models	• Can provide a realistic representation of the system being studied, which can be observed and measured directly. • Can provide insight into processes that are not well captured by current numerical models (e.g., plant health, porous flow, stability of revetments and armour stone, wave runup and overtopping, etc.). • Can be used to study NBI behaviour and performance in extreme conditions in potential future scenarios that include climate change effects. • Can be used assess alternatives and optimize designs prior to construction.	• Are often limited by the size and complexity of the system that can be represented, especially in large-scale systems. • Can be expensive to construct and operate.
Numerical models	• Can simulate complex physical processes that are difficult or impossible to observe directly. • Can be used to predict the behavior of a system over long timescales, over large spatial scales, or under extreme or future conditions.	• Rely on a large amount of data and assumptions, which may be uncertain or incomplete. • Require computational resources, which may be limited. • May not accurately represent the system if the model is not well calibrated or validated with field observations. • Can be expensive and time-consuming to set up properly and calibrate. Typically, such effort is beyond the design budgets for small-scale projects funded by individual homeowners.

11.6 Tools and Resources

A wealth of resources on the application of modelling to inform design and performance assessment for NBI is readily available in the international coastal science and engineering community. Some examples include publications and design guides from the U.S. Army Corps of Engineers, such as the “International Guidelines on Natural and Nature-Based Features for Flood Risk Management” (Bridges, et al., 2021). There are also a number of model repositories with supporting resources hosted by governmental and

academic institutions.[20, 21] Further information on important tools and resources available to Canadian practitioners, including design guidance specific to modelling tools, can be obtained by contacting the authors of this chapter. The numerical and physical models mentioned in this chapter are explained in greater detail in journal publications that describe the mathematical and physical basis, and example applications, of each model.

11.7 Gaps and Future Directions

As climate change drives different conditions in Canada's coastal regions in the future, we should consider adapting to change by considering the resilience of natural systems in developing better design methods. This will include new and refined numerical and physical modelling techniques for modelling the performance of natural systems. Research is needed to:

1) Improve modelling of the feedback between biotic and abiotic systems (i.e., ecological modelling) to capture processes, such as wave-vegetation interactions, biomass changes, biofilm development. This includes the need for specific facilities that can perform physical modelling of biological systems.
2) Develop numerical and physical models that can capture relevant processes in Arctic and sub-Arctic systems, such as ice rafting, permafrost, and freeze-thaw cycles.
3) Improve statistical downscaling and model coupling to capture non-linear dynamics and non-stationary conditions related to a changing climate.
4) Improve and integrate process-based/reduced-complexity models to capture large temporal and spatial scales of complex natural systems.
5) Identify key mechanisms and processes that govern the resilience of natural systems to climate change impacts, and how can these be integrated into numerical and physical models to improve our understanding and prediction of their performance.
6) Identify the most effective methods for co-applying Indigenous and local knowledge, as well as Traditional Ecological Knowledge, with numerical and physical models to enhance the resilience of coastal communities to climate change impacts and ensure culturally sensitive coastal design approaches.
7) Understand how interdisciplinary and transdisciplinary approaches can be utilized to combine expertise from various fields, such as engineering, ecology, hydrodynamics, geomorphology, and social sciences, to develop integrated modelling frameworks that capture the complexity of natural systems and inform resilient coastal design strategies.

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12 Field Monitoring

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12.1 Chapter Key Messages

- Field measurements and monitoring are essential elements of nature-based infrastructure (NBI) projects and are useful or required at all phases of the project lifecycle including scoping, design, construction, and post-implementation.
- Field monitoring should be conducted at spatial and temporal scales that are appropriate for the indicators being considered.
- Adequate provisions for funding and resources (staff and equipment) should be identified early, ideally during the project scoping phase.
- Field measurements provide a critical role in calibrating and validating predictive models that can then inform future design considerations.
- Accurate field measurements of baseline conditions can play an important role in determining appropriate NBI options that are in line with local conditions.
- A field monitoring program should be designed to enable comparison to a baseline or reference condition to evaluate the performance of the NBI option.

12.2 Introduction

The goal of field monitoring is to obtain observations of natural processes, or interactions between natural processes and existing structures, that will aid in the design and performance evaluation of nature-based infrastructure (NBI) for coastal protection. Monitoring activities should preferably occur prior to design and throughout the project life, and include the collection of historical, baseline, compliance, and operational data. NBI project phases are outlined in Chapter 2. Post-construction field monitoring is also critical to identify when adaptive management is required, ensures flood and erosion risk management (FERM) performance, and confirms that co-benefits are being achieved. In addition, long-term operational data contributes to our understanding of the performance of NBI in the Canadian context and provides knowledge for future projects. It is a critical source of information about the effectiveness of NBI, including costs, which provide the evidence base for existing and future NBI projects.

This chapter aims to identify different types of field monitoring, and their levels of effort, that may be required to successfully plan, deploy, and assess NBI for coastal flood risk management in Canada. It will introduce technologies and techniques but is written from the standpoint of a project manager who would not be a subject matter expert in these technologies so that they might have a better understanding of what will be expected. To that end, this chapter includes examples of projects currently underway in Canada.

Other chapters within this design guide overlap with fieldwork requirements, including requirements for permitting (e.g., Chapter 4). Also, the importance of supporting Indigenous leadership, co-development of NBI, and Indigenous Knowledge within a Canadian context are discussed in other chapters, but we touch on considerations specific to fieldwork in this chapter, such as respect for Traditional Territory, Traditional Knowledge gathering, Two-Eyed Seeing, and participation of Indigenous groups in monitoring.

At the time of writing, there are several documents in development by the Commission on Environmental Cooperation (CEC, 2024a, b) as part of the Nature-Based Solutions to Address Flooding in Coastal Cities project[22] that provide guidance for monitoring of nature-based solutions (NBS) in North America. These documents complement other recently published key resources: Dumitru and Wendling (2021) and Kumar et al. (2021). In particular, the 2024 CEC reports and Dumitru and Wendling (2021) report for the European Union provide a detailed review of field monitoring methods. This chapter, therefore, focusses on the Canadian context and selected examples.

12.2.1 Objectives

Monitoring of coastal features and processes will be required prior to and throughout the design, implementation, and maintenance of an NBI project. Each project will have different monitoring requirements and the monitoring targets and methods will change and evolve over the project phases. This chapter does not describe all of the monitoring that may be required for a sizeable project. For that, project managers must consult experts. Documents in preparation by the Commission for Environmental Cooperation describe details of indicators, instruments, and methods for North America–based projects, in more detail than in this chapter (CEC, 2024a, b).

This chapter will:

- Introduce the environmental and historical factors that may need to be assessed.

[22] http://www.cec.org/nature-based-solutions-to-address-flooding-in-coastal-cities/

- Introduce technologies and methodologies for best practices.
- Describe the stages of fieldwork and level of effort that may be required.
- Provide case study examples.
- Introduce the concepts of feedback, adaptive management, and socio-economic indicators.

12.3 Key Concepts and Terminology

Monitoring is a continuous process that tracks both the implementation process (i.e., what takes place and when within the project cycle) and how well the NBI performs against expected results or performance criteria (Skodra et al., 2021). Performance is defined as the degree to which NBI "address an identified challenge and/or fulfill a specified objective in a specific place, time, and socio-economic context" (Raymond et al., 2017, in Skodra et al., 2021). Monitoring can be used to assess changes in relation or comparison to baseline or reference conditions and/or changes towards certain targets or thresholds.

In general, monitoring needs to be considered as a continuous process that begins prior to implementation of a NBI project and tracks how well it performs against expected results and/or specified performance criteria. Key phases of monitoring programs include: 1) Scoping, 2) Planning, 3) Design, 4) Implementation, 5) Reporting, and 6) Evaluation (CEC, 2024b) (Figure 12.3-1).

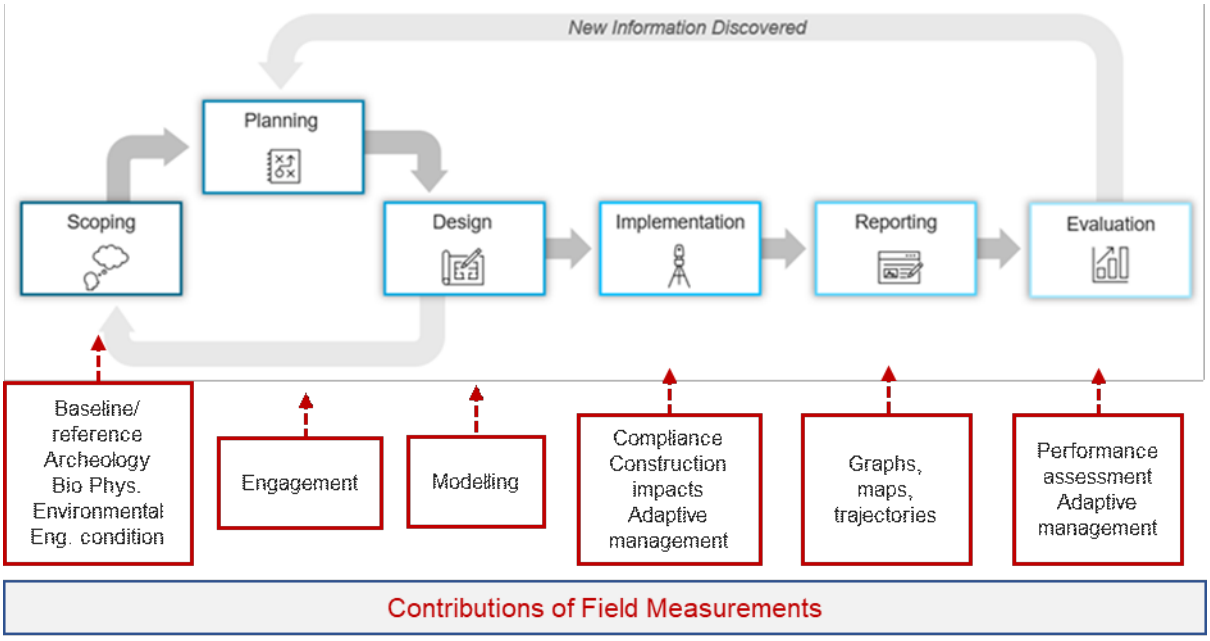


Figure 12.3-1. Contribution of field measurements to key phases of monitoring program for nature-based infrastructure. Adapted from CEC (2024a).

Field monitoring includes any activity that directly or indirectly measures the properties of the site and surrounding environment, as well as natural processes and interactions with the NBI. Measurements may be in-situ or involve remote observations and contribute to all phases of the monitoring program (Figure 12.3-1). Field measurements are essential for model calibration and validation (see Chapter 11).

Baseline data are critical in determining if a proposed NBI is feasible and informs the selection of an appropriate NBI method for a particular site location. Field measurements are essential for proper site

selection and design. **Baseline conditions** refers to the condition of the site prior to implementation of NBI and may be used for performance evaluation as part of a Before-After Control-Impact (BACI) study. Monitoring programs generally follow BACI (before/after, control/impact) or RCA (reference condition approach) methodologies. These involve one or more sites that function as references, allowing key performance indicators for the NBI project to be directly compared with the same set of performance indicators from the reference site(s) (see CEC, 2024a, for additional details).

Adaptive management is a structured and iterative approach, which enables users to continuously revise management measures (such as maintenance activities) to reflect changing conditions (including changing conditions due to climate change) and variable project performance (Bridges et al., 2021). Adaptive management is an integral and cross-cutting theme for the implementation of NBI and depends on accurate field measurements (Bridges et al., 2021; Silva Zuniga et al., 2020; CEC, 2024b). Additional details are provided in Chapter 13.

Elevation surveys are systematic field measurements that are conducted primarily along predefined transect lines, or sample stations that have their position accurately recorded using high-precision GPS—real time kinematic (RTK) positioning or corrected using Global Navigation Satellite System (GNSS) and a base station. Aerial and bathymetric surveys are also possible using drones or small planes equipped with sensors, such as LiDAR (for elevation surveys), that can cover larger distances. High positional accuracy for all survey methods is required for repeat sampling and comparison between years. **Remote sensing** refers to the use of sensors mounted on a satellite, plane, or drone to take measurements of an area from a distance. Translation of the output of the sensors requires training sites (sites in the field where the variable in question is identifiable—e.g., vegetation type—and can be paired with the remotely sensed image) and field validation (testing the resultant image classification).

In-situ sensors typically measure one or a suite of variables directly in the field either continuously or in burst mode with a sampling rate that is appropriate for the analysis being conducted. Typical aquatic measurements include water levels (including waves), velocity, turbidity, temperature, and salinity. Terrestrial measurements include timelapse photos taken with trail cameras or meteorological conditions recorded by a weather station.

12.4 Key Considerations and Best Practices

The purpose of this chapters to provide NBI project proponents or project managers in Canada an introduction to the types of information they will be required to collect at each project phase, along with practical information of some methods available, cost estimates, and required timespans. A summary is provided in Table 12.4-1. NBI project managers should consider setting out the indices and parameters to be monitored in detail so that baseline and post-construction conditions can be effectively compared, to objectively determine whether performance objectives (see Chapter 7) are being met. A geographic information system (GIS) is an effective tool for laying out the existing data and the required monitoring stations. Sowińska-Świerkosz and García (2021) provide a good example of a framework to help choose which parameters to consider. Additional guidance is provided in CEC (2024a, b) and Dumitru and Wendling (2021). An example of a recent baseline monitoring program is shown by the map in Figure 12.4-1. This map incorporates a LiDAR digital elevation model base layer, with brown to blue generally representing the transition from land to water. The mottled green/yellow area indicates areas on land where InSAR satellite measurements were able to detect land subsidence (almost zero in this area). The sampling strategy here was to have two transects of wave gauges, which are shown annotated as wavePS1 to wavePS4 and wavePS1 to wavePS6 in Figure 12.4-1. There are cameras along the shore to detect change

to the salt marsh during storms. Other data shown are white and red diamonds, which indicate vertical benchmarks from which future vertical changes can be determined.

Furthermore, there are a number of guiding principles that should be considered when developing and implementing a NBI monitoring plan (Skodra et al., 2021; modified in CEC, 2024a). Plans and indicators should follow these principles (CEC, 2024a):

- Be scientifically sound and **SMART** (specific, measurable, attributable, realistic, and timely or time-bound).
- Be **practical** and straightforward but fulfill technical requirements.
- Be conducted at an **appropriate scale** (spatial and temporal) that considers the variability of the indicator to be measured, regional characteristics, changing climate, and urban morphology.
- Be conducted at an appropriate scale (spatial and temporal) that **aligns** with different decision-making contexts, policy principles, and **reporting obligations**.
- Clearly state and use **reference conditions** and **baseline** assessments.
- Facilitate rapid assessment of trajectories and adaptive management.
- Be based on a **transdisciplinary** approach.
- Use **common/standard** indicators (where possible) to facilitate comparison between sites and ensure that the results are **transferable** and **scalable**.

This applies for all stages of field monitoring processes from baseline data collection to design, implementation, and monitoring (Figure 12.3-1).

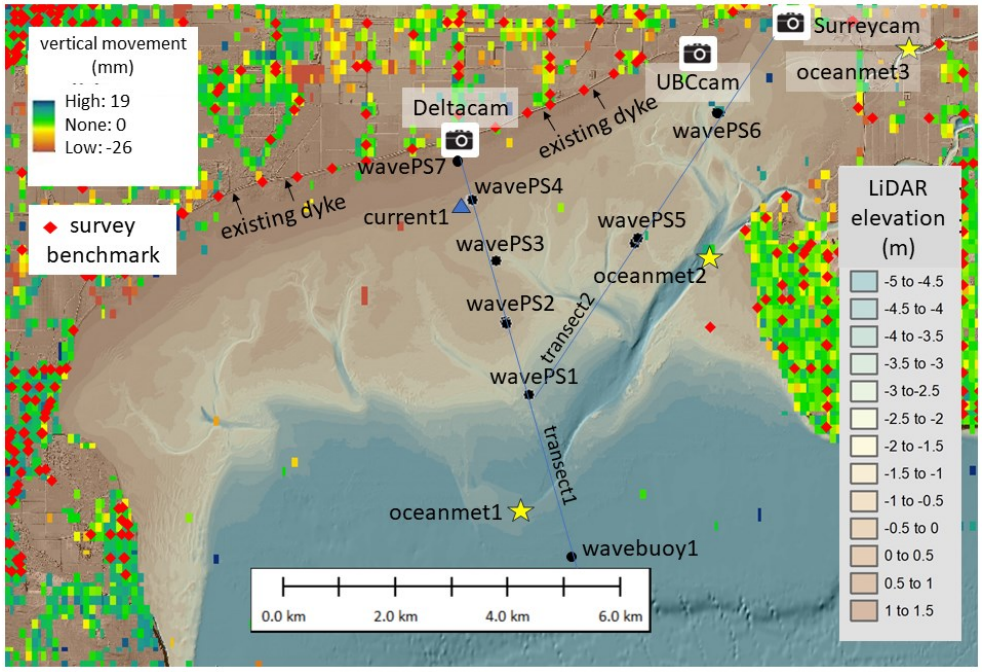


Figure 12.4-1. Example of a monitoring layout to collect baseline data for an NBI project in Boundary Bay, British Columbia. This image is derived from a project GIS. Stations are further described in the text. Elevation information is important when planning NBI to manage flood and erosion risk, and in this case the practitioners have LiDAR elevation (above and below high tide), surveyed benchmarks along the existing dyke, and an InSAR satellite assessment of the movement of structures in the area, used to assess subsidence. Map produced using unpublished data available to the authors from Natural Resources Canada.

12.4.1 Fieldwork Required for Feasibility, Awareness, and for Environmental Assessment Process

There are several reasons why fieldwork must be conducted from (and even prior to) the project inception. First, is to gain a better understanding on the suitability of the area for the proposed NBI. Second, is to be able to obtain information so that the practitioner would be able to define the objectives and expected co-benefits to as many stakeholders as possible, in order to attract community support. Third, fieldwork will be needed to establish the design criteria for the NBI (see Chapter 7). Fourth, to proceed with a project of this type, an Environmental Impact Statement (EIS) will likely need to be prepared. That statement will need to include detailed baseline data and also estimates of impacts of the project on the environment, as well as the impact of the environment on the project. It may need to include numerical modelling, which will require a specific set of field measurements for calibration and validation of the models (see Chapter 11). It will often be this environmental impact assessment process that requires the most demanding fieldwork, and it is also often the means through which community engagement and project design is refined. Therefore, we elaborate more on typical requirements for baseline environmental monitoring below.

Normally, for large projects, the proponent will send the project description to experts at the responsible (regulating) authorities for input on exactly what data are required to assess baseline conditions and impacts. A typical EIS is normally going to require the following technical chapters, which all may require field investigations.

Baseline assessments

- Historical assessment of the changing natural landscape and seascape
- Modern-day sedimentation and erosion trends
- Relative sea-level change rates (i.e., combined effects of sea-level changes and land uplift or subsidence)
- Coastal flood and erosion risk assessment
- Historical land use from historical records and Indigenous Knowledge
- Any existing flood or shore protection works or major infrastructure
- Seasonal assessment, ecological/flood/climate
- Species at risk assessment

Impact assessment

- Predicted effects of the proposed project on the environment, and effects of the environment on the project (numerical modelling may be required, see Chapter 11)
- Construction monitoring plan
- Post-construction monitoring plan
- Some commitment to adaptive management (plans if the predicted effects are not accurate) and a commitment or proposal to provide compensatory offsets for negative effects

12.4.2 Baseline Monitoring

The goal of monitoring in a NBI project area is to consistently measure change of features and processes over time in order to later assess the success of the project. A key aspect of monitoring is therefore defining indicators of success that are aligned with project performance objectives (see Chapter 7) and designing a monitoring plan and baseline data collection to measure those indicators. Presumably some data have already been collected as there is an identified coastal issue requiring an NBI intervention, but developing



a monitoring plan relevant to the project design ensures that required baseline data are collected and are appropriate to future monitoring of project performance. There is a balance between the number of monitoring sites and the frequency at which they can feasibly be visited, mediated by both the size of the system and dynamics of the processes to be monitored, as well as available resources and instruments. A monitoring plan describes for each project phase the layout of the monitoring stations, the instrument(s) at each station, and the measurement frequencies, considered within the context of available personnel and financial resources, to ensure feasibility, efficacy, and continuity of monitoring. Also described in the monitoring plan are the survey control monuments required for positioning monitoring sites, and during collection of baseline mapping data. Baseline data needs are determined by the feature or process to be monitored, and the type of NBI. Elevations of the seabed and land surface; data on nearshore waves, currents, and water levels; meteorological data; vegetation data; and positions of features are typically collected. Baseline data can form the first measurement in a monitoring time series, and monitoring may need to be initiated several seasons before proposal submission.

Consistency between baseline and post-construction data from a temporal, spatial, and methodology standpoint is essential to evaluate project efficacy, as well as to understand how climate change may shift baseline conditions. Therefore, for the greatest scientific rigour and to obtain the most useful information, baseline monitoring should be started on both the project and a reference site prior to implementation (CEC, 2024b).

12.4.3 Construction Monitoring

Monitoring during the construction phase will be required to meet operational or jurisdictional legislation and permitting, and to ensure construction to design specifications. Conditions are sometimes applied during the environmental assessment by regulatory agencies based on a specific area of sensitivity or concern. Birds and marine mammal migratory routes or feeding grounds are often the subject of these conditions, and construction may need to cease during certain seasons or windows. There may be archaeological requirements for monitoring during the construction phase. In Nova Scotia, for instance, the provincial *Special Places Protection Act* requires that an archaeologist be on site during construction if the site has been flagged in Phase 1 assessment. In addition, the federal *Fisheries Act* requires mitigative action in relation to siltation and noise levels. Whatever the factor being monitored, difficulties of construction monitoring can include restrictions on access to a site when construction activities are ongoing, and also trying to ensure that the monitoring keeps pace with the build progress. Professional engineers are responsible for inspections to ensure construction is in conformance with the design (i.e., drawings, specifications), and to identify defects or remedial actions.

12.4.4 Post-Construction and Long-Term Monitoring

Post-construction monitoring may be mandated by conditions imposed as part of the permitting and approvals process. It may also be required to meet obligations for adaptive management related to project permitting and approvals. However, post-construction monitoring may be proactively used to measure project success, and to identify needs or triggers for maintenance or adaptive management (see Chapter 13). Adaptive management is an essential component of NBI to manage risk in an uncertain future (see Chapter 2), to increase flexibility and allow solutions to evolve over time in response to changing environmental conditions (de Looff et al., 2021 and references therein), and to correct unanticipated and/or undesirable developments (Thom, 1997). As such, if it is determined that an NBI project is not meeting performance criteria within acceptable tolerances (which are determined on a case-by-case basis and

compared to the reference sites), adaptive management ensures that a plan is in place to adjust to a more acceptable trajectory. To effectively apply adaptive management, the monitoring requires (Thom, 2000):

- Measuring the conditions of the system using selected indicators.
- Assessing progress towards performance objectives and performance indicators.
- Deciding on actions to take.

Appropriate actions that may be taken include doing nothing, taking corrective action, or changing the goal(s) (Thom, 2000). A more detailed discussion of adaptive management is included in the *Monitoring the Efficacy of Nature-Based Solutions: A Practical Synthesis* (CEC, 2024b) and in Chapter 13.

Robust options appraisal for coastal FERM requires an assessment of the full range of benefits and co-benefits delivered by different FERM alternatives and strategies (see Chapter 7), including environmental and socio-economic co-benefits. Benefits and co-benefits should be evaluated relative to baseline data. Monitoring of co-benefits should not be at the expense of monitoring the primary FERM benefits. Moraes et al. (2021) assessed 54 NBI case studies associated with flooding, erosion, and biodiversity loss. Among them, post-construction monitoring was declared in 81% of case studies. Most of the reported monitoring results were related to biodiversity benefits, such as the presence of water birds. Surprisingly, few cases provided any information in their monitoring about flood or erosion effectiveness. Dumitru and Wendling (2021) provide detailed descriptions of monitoring methods paired with assessment targets. Specific erosion and flood fundamental objectives, performance indicators, and metrics are described in *Monitoring the Efficacy of Nature-Based Solutions: Proposed Methodology and Indicators.* Chapters 6–14 of the *International Guidelines on Natural and Nature-Based Features for Flood Risk Management* (Bridges et al., 2021) provide guidance on monitoring benefits, monitoring for adaptive management, and monitoring of different types of coastal NBI. Techniques and tools to measure these metrics are expanded on in CEC (2024a).

In relation to assessing the efficacy of the NBI to perform its functions, Moraes et al (2021) indicate that the monitoring of sustainability is still largely absent from reporting on the performance of many NBI projects in Europe. It is recommended that project proponents would include measures to quantify the sustainability of NBI in future projects, for example, through the use of lifecycle assessment, aligned with the sustainable development goals of the jurisdiction in which they are built. This would provide metrics that can be compared to the sustainability of more established alternatives.

12.4.4.1 Monitoring Approach

To meet these needs and basic scientific standards, using one of the following two general monitoring approaches is recommended:

- Before-After Control-Impact (BACI)
- Reference Condition Approach (RCA)

Monitoring programs generally follow BACI (before/after, control/impact) or RCA (reference condition approach) methodologies. These involve one or more sites that function as references (controls), allowing key performance indicators for the NBI project to be directly compared with the same set of performance indicators from the reference site(s). The BACI approach monitors conditions at both the control site (or sites) and the NBI site before and after intervention, to facilitate changes resulting from the NBI intervention to be distinguished from changes associated with natural system dynamics or other human impacts. The

RCA approach only involves monitoring at the control and project sites after the NBI intervention, which is not ideal since it does not provide a clear understanding of the impacts or benefits of the NBI relative to baseline conditions at the project site. For this reason, the BACI approach should be used where possible. Additional details are provided in CEC (2024a).

12.4.5 Techniques and Instrumentation

A non-exhaustive summary list of techniques and instrumentation, which may be considered for monitoring of different parameters and performance indicators of relevance to NBI, is provided in Table 12.4-1. The emphasis here is on monitoring of physical and ecological system changes. Further, detailed guidance on other parameters, methods, and metrics to be considered for an NBI monitoring program (i.e., including monitoring of co-benefits, such as changes in biotic use, biodiversity, recreational use, fisheries productivity, etc.) is provided in Bridges et al. (2021), CEC (2024a), and CEC (2024b).

Table 12.4-1. Methods/instruments, relative (qualitative) costs, required levels of effort, and quality/accuracy of techniques for monitoring different parameters of relevance to NBI.

Application	Method/Instrument	Expense*	Effort**	Quality/Accuracy
Monitoring topographic profile changes and feature migration, vegetation	Planimetric distance to point(s)	Very low	Very Low	± 10 cm or more horizontally, depending on care taken during measurement.
	Emery pole profile(s)	Low	Moderate	± 5 cm vertically, ± 10 cm or more horizontally, for each measurement, depending on care taken. While each measurement is independent, errors propagate along the profile.
	Theodolite surveys (laser/infrared)	High	High	± 1 cm vertically and horizontally in ideal conditions, typically ± 5 cm. Highest accuracies are obtained by an experienced operator trained in advanced survey techniques.
	GPS surveys	High to Very High	Moderate	± 1 cm vertically and horizontally in ideal conditions, typically ± 5 cm. Highest accuracies are obtained by an experienced operator trained in advanced survey techniques. RTK/GNSS enabled surveys provide better accuracy than GPS alone.
Monitoring microtopographic marsh surface elevation changes	Set sites with marker horizons	Moderate	High	± 0.5 cm depending on surface material. Multiple measurements allow detection of outliers and generation of accuracy statistics. Accuracy depends greatly on the precise and repeatable fit of the bar or frame to the stable monument. When paired with marker horizons, can differentiate between sediment accretion and below ground root production.

Application	Method/Instrument	Expense*	Effort**	Quality/Accuracy
Monitoring with photography	Camera (manual)	Low	Low	Ideally photographs are taken regularly with a frequency appropriate to the process being monitored. Images are least useful when different photographers take photos from different positions with different camera settings, although various technologies can be used to force image conformity and facilitate citizen science applications.
	Camera (time-interval)	Low to High	Moderate	Quantitative measurements can be derived from interval photography from identical positions using the same camera setting and an established protocol. Features of known size in the near and middle distance are useful. Centimetre-scale accuracy can be achieved and precisely quantified if using orthorectification.
Monitoring water levels	Tide board	Very Low	Low to Moderate	± 5 cm in still water, can be ± 0.25 m if affected by long period swell.
	Pressure transducer	Low to Moderate	Moderate to High	± 1 cm, depending on technical specifications (e.g., vented or non-vented) and configuration (acoustic frequency, burst length, averaging etc.).
Monitoring waves	Pressure transducer	Low to Moderate	Moderate to High	In theory, ± 5 cm, depending on configuration (acoustic frequency, burst length, averaging etc.). In practice, most pressure transducer instruments are poor at resolving low height, long period waves, often giving spurious results. Results deteriorate with instrument burial. Typically, does not provide information on wave directions.

Application	Method/Instrument	Expense*	Effort**	Quality/Accuracy
	Accelerometer (buoy)	Moderate to High	High	In theory, ± 5 cm, depending on configuration (acoustic frequency, burst length, averaging etc.). Results can be affected by currents > 1 m/s. Real-time connection to the instrument allows monitoring instrument performance and condition, and solar power allows for lengthy deployments. Can provide directional wave data.
Monitoring currents	Acoustic Doppler velocimeter (ADV) and acoustic Doppler current profiler (ADCP)	High	High	± 0.1 cm/s for ADVs and ± 5 cm/s for ADCPs, depending on configuration (acoustic frequency, burst length, averaging etc.). Results can be affected by extremely clear waters or extreme turbidity and bubbles. Other sounds in the water column can also influence data quality.
Monitoring winds	Cup and sonic anemometer	Low to Moderate	Moderate to High	± 3%, possibly greater for cup anemometers. Data quality deteriorates due to shelter or turbulence generated by nearby structures. Sonic anemometers can provide higher frequency measurements for turbulence calculations.
Monitoring bathymetric change	Single beam sonar echo-sounder	Low to Moderate	Moderate	± 20 cm vertically depending on care taken to adjust for draft and tides, horizontally ± 5 m depending on GPS. RTK GPS can be used in place of the less accurate off-the-shelf GPS and give the vertical elevation, negating the requirement for a co-located water level gauge. Soundings are greatly affected by waves—using RTK GPS can help remove wave artefacts.



Application	Method/Instrument	Expense*	Effort**	Quality/Accuracy
	Multibeam sonar echo-sounder	High to Very High	High to Very High	± 5 m horizontally and ± 50 cm plus 1% water depth vertically. Position accuracy can be increased with RTK GPS. In its absence, a co-located water level gauge is required for tide-correction, and an onboard Inertial Momentum Unit is required to correct for pitch, yaw, roll and heave.
Mapping elevation and monitoring topographic change with remote sensing	Unmanned Aerial Vehicle (UAV) / Remotely Piloted Aircraft systems (RPAS)	Moderate to High	Moderate	± 4 cm horizontally and 5 cm vertically with RTK and targets. Gridded datasets can be of high accuracy due to a very high density of points when using structure from motion. This is affected by sensitivities to vegetation and reflective surfaces (water).
	Airborne LiDAR	Very High	High to Very High	Covers larger areas than UAV, but with lower accuracy (points per metre). Can provide some measurements within vegetation canopies.
Mapping and monitoring coastal change with remote sensing	Airborne instruments	High to Very High	High to Very High	If using an automated process or even semi-automated requires sophisticated techniques and training and validation sites (aka ground-truthing).
	Satellite instruments	High to Very High	Moderate to High	If using an automated process or even semi automated requires sophisticated techniques and training and validation sites (aka ground-truthing).

12.5 Challenges: Canadian-Specific Issues

Canada's varied coastal landscapes, tidal range, seasonality, accessibility, and resources available to support field-based measurements present unique challenges that need to be addressed when designing a field monitoring program. A comprehensive understanding of the challenges and limitations associated with field-based measurements can help with choosing methods, techniques and equipment that will be best suited for the environmental conditions.

As one of the world's largest countries, and with the longest coastline, but with a sparse population, there are difficulties associated with working in Canada's remote communities. Many of these communities are accessible only by boat or in even more remote cases, only by aircraft. Sending teams of experts often to these areas can be prohibitively expensive, and implementing an overly complex plan can be logistically impractical. Early engagement of communities, and recruitment or training of community members to participate in monitoring can be cost-effective, provide unique local insights that may be advantageous to the project, and support capacity-building in remote communities (Box 12-1).

Unconsolidated sediment, deep water, and rapidly changing meteorologic or hydrodynamic conditions (e.g., in channels through hypertidal mudflats, rogue waves, or tsunamis) present safety hazards, and conditions or hazards can vary at each visit. Remote surveying methods may be employed to avoid or mitigate some of these risks. For example, repeat topographic surveys are often conducted using remotely piloted aircraft systems (RPAS) with GNSS capabilities for change detection (Ollerhead et al., 2020). On intertidal mudflats where there is a risk of sinking, oceanographic instruments may need to be deployed at high tide from a boat or hovercraft, instead of attempting to access the exposed flats from land at low tide. Tides can inundate shallow mudflats relatively quickly, sometimes quicker than walking speed. The extreme tidal range in the upper Bay of Fundy, for example, means that the window to launch and complete surveys is extremely small and only possible during large spring tides. Safety and call-in plans are very important. A field researcher should never work alone.

Hunting is common in Canada, and coastal mudflats are ideal hunting grounds for duck and geese. A fieldworker should check hunting regulations, wear appropriate reflective gear, and if it is not possible to avoid hunting season, then should at least respect the use of the land by hunters (not frighten the wildlife away).

Field personnel conducting monitoring at remote sites should be trained in wilderness survival and safety. Bears inhabit forested regions in all Canadian provinces and territories, and cougars also present risks in some areas. In the Canadian North, additional field safety concerns include large mammals, such as polar bears; extreme cold; ice conditions that are challenging to predict; and the use of helicopters, snowmobiles, and ATVs, which require additional training.

Box 12-1. Field Monitoring of a Hybrid Shore Protection Scheme at Metlakatla Village, BC

The "Nature-Based Infrastructure for Coastal Resilience and Risk Reduction" project (2019–23) brought together engineers, scientists, and practitioners from federal, municipal, and First Nations governments, and academia to develop an improved understanding of the performance of nature-based infrastructure in Canadian coastal environments. The project, supported by the Canadian Safety and Security Program, focused on monitoring, modelling, and knowledge-sharing for pilot NBI project sites in diverse settings.

One of the sites was the shoreline of Metlakatla First Nation, a water-access only community along the rugged north coast of BC with hypertidal conditions (spring tidal range of approximately 7.7 m). Innovative solutions are being applied here to address erosion risks. A hybrid system of conventional rock breakwaters and headlands has been combined with cobble sills and gravel/sand beach nourishments that mimic local, natural analogs, with constructed pocket salt marsh features in sheltered areas. Protecting and preserving archaeological sites were also key factors in the design of the shore protection features.

Field activities, in collaboration with Metlakatla First Nation, included the deployment of wave sensors to measure wave attenuation, mounting of interval cameras to document wave conditions, and drone surveys and visual observations at regular intervals to document change. Partnering with community members was key to successful data collection and understanding of the local environment.

Field data were used in physical modelling and numerical modelling activities to understand the effectiveness of nature-based features (cobble sills, gravel/sand beaches, and salt marshes) at managing erosion and coastal storm-driven flooding, as well as the resilience of the hybrid system to relative sea-level rise scenarios.

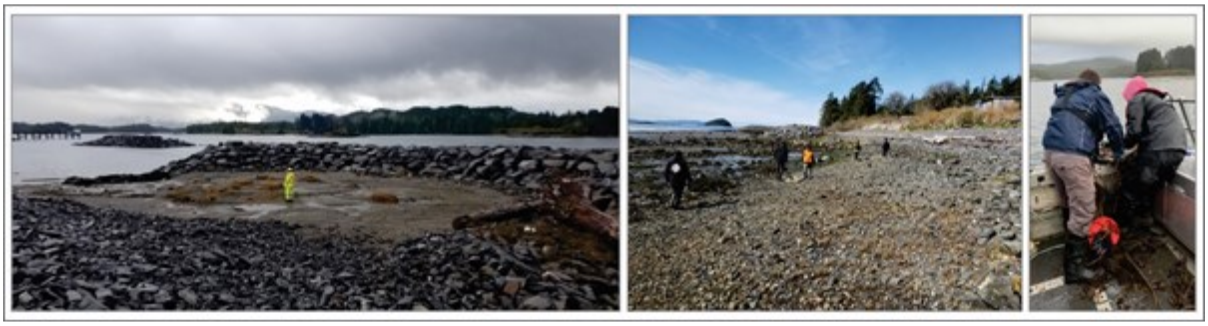


Figure 12.5-1. Planted salt marsh feature in protected area behind breakwater (left); knowledge sharing along the Metlakatla beach (middle); deployment of wave sensor in collaboration with the Metlakatla Guardians (right).

Ice and freeze-thaw cycles can both negatively and positively affect NBI performance, and need to be considered in Canada where these conditions are present (see Chapter 6). Ice can pluck out rock from protective marsh sills or oyster reefs or displace undersized reef balls, causing damage to NBI. However, ice can also transport rhizomes, seeds, sediment, and nutrients that are important for vegetation colonization of managed realignment and tidal wetland restoration sites (Rabinowitz et al., 2022). Monitoring of ice effects is challenging as in-situ sensors can be damaged by movement of ice blocks and

freezing temperatures can damage instruments (e.g., pressure transducer bladder)—when uncovered at low tide or by draining batteries for remotely operated cameras, for example. Most field instruments have a low temperature limit that precludes instruments from being deployed for at least 3 months of the year in most of Canada. Field plans should be flexible to take advantage of small thaw windows. Presence and absence of ice and rough quantification of ice cover can be determined using publicly available remote sensing imagery, such as Sentinel 2. Winter field walks or field cams can provide an idea of winter conditions.

Because of the complexities identified above, and a prioritization of funding for capital works (as opposed to long-term monitoring), there is often not enough resources or time for a perfect monitoring program. As NBI approaches become more mainstream in Canada, funding programs may change to reflect the importance of monitoring and adaptive management. In the interim, project teams may need to be strategic about prioritization of monitoring requirements, leverage partnerships (e.g., with academic institutions, non-governmental organizations, or government research agencies) to address needs for monitoring, and take advantage of technological advancements (e.g., remote sensing, machine learning, and data science) to increase monitoring efficiency. More consistency in monitoring approaches, wider dissemination of monitoring data, and the allocation of adequate resources for more comprehensive, longer-term monitoring programs can reduce project risks, ensure NBI project success, and contribute to a deeper understanding of NBI performance.

12.6 Implementation

Box 12-1 and Box 12-2 present examples of two case studies of field-based monitoring programs being conducted in Canada at the time of writing. These projects have had to overcome many of the challenges identified in this chapter, and more information can be obtained by request from the chapter authors.

12.6.1 Data Management, Access, and Dissemination

Reporting and information-sharing are crucial components of any monitoring program, in order to disseminate information on the performance of NBI and support improved design and implementation of future projects. The lack of accessible, consistent, long-term, quality-assured monitoring data is a barrier to wider NBI uptake in Canada (Vouk et al., 2021). Various organizations have been leading initiatives at regional, national, and international levels to facilitate data-sharing and dissemination for NBI projects, but the data remain fragmented, distributed, inconsistent, and difficult to navigate for inexperienced practitioners. Governments and academic institutions often lack the sustained, long-term funding commitments needed to maintain and update open-access data repositories, particularly in the context of rapid growth in demand for data storage. Some private-sector organizations may consider such data to be proprietary and may wish to charge fees for dissemination. Standardization of data collection, management, and metadata could help to improve access to, and interoperability of, datasets hosted by different organizations and institutions. Standardized field report templates that are co-designed with the project team, with semi-automated functions (e.g., drop-down menus) can enable more efficient monitoring, increase data accuracy, and decrease error. Data analysis methods should be documented, ideally made widely available in the public domain, and easily reproduceable. Where permitted by data management and sovereignty protocols and rights (e.g., see discussion of OCAP in Section 4.7.3), data should be made publicly available with appropriate metadata, including details on measurement and analysis methodologies, to enable knowledge transfer to interested parties not directly involved in the project. Reporting needs to include a clear outline of project goals and timelines, site descriptions, current and historical land use, description of all methodologies, protocols, results, and deficiencies (CEC, 2024a;



Dumitru & Wendling, 2021). Data reports would normally include a study area map, a list of sampling stations or transects, and coordinates. CEC's *Monitoring Synthesis Report* (CEC 2024b) provides additional recommendations and best practices on data analysis, access, and dissemination. Fortunately, there are established protocols for data archiving and sharing that can be adopted by NBI proponents, such as the FAIR approach (Wilkinson et al. 2016).



Box 12-2. Making Room for Wetlands

Making Room for Wetlands (MRFW) is a climate change adaptation and restoration program in Nova Scotia, which focuses on increasing resiliency in dykeland communities by re-establishing tidal wetlands where they historically would have been. Initiated in 2017, MRFW works to reduce flooding in surrounding communities, creates vital habitat, stores carbon, and reduces other greenhouse gas emissions. Field measurements and monitoring are key elements at all five stages of the managed realignment wheel including site selection and engagement. Dyke breaches are only considered if the land behind the dyke is fallow and/or maintaining the dyke system is deemed untenable. Focusing on sites where dykes can no longer be maintained allows nature-based solutions to address climate change risks to be implemented. All sites have included a comprehensive standardized monitoring program focusing on variables associated with 4 key processes for tidal wetland assessment and functioning, including hydrology, geomorphology, sediments, and soils and vegetation—typically one-year baseline and 5-years post-implementation. This permits adaptive management to be identified, to document restoration trajectory, and determine project success. A BACI (Before-After Control-Impact) approach is taken, with both baseline and reference site conditions used to quantify change.



Figure 12.6-1. Examples of measurements taken at all stages of implementation including community mapping, low altitude aerial surveys, rod sediment elevation tables, vegetation, and fish.

The long-term monitoring program builds upon close to 2 decades of restoration and collaboration between CB Wetlands & Environmental Specialists Inc. and Saint Mary's University. The monitoring program needed to be designed for the unique conditions of the Bay of Fundy—a macrotidal estuary with exceptionally high tides, high suspended-sediment concentrations, and variable winter conditions. The program was adapted from the Gulf of Maine Regional Monitoring Protocol (Neckles et al., 2002), which was developed through a series of regional workshops for the Global Program of Action Coalition for the Gulf of Maine and the CEC. Parameters sampled included: hydrology (water levels, hydroperiod, groundwater); soils and sediments (accretion, elevation, characteristics); vegetation (composition, abundance, height, habitat mapping); nekton (composition, species richness, density, length); invertebrates (abundance, species richness); and winter condition (visual assessment). Standardized methodologies used included low-cost/low-tech approaches and more complex and costly measures, such as hydrodynamics measurements and modelling, drones, and 3D surface generation and geomatics.

For additional details: https://www.transcoastaladaptations.com/making-room-for-wetlands

Making Room for Wetlands

TransCoastal Adaptations Centre for Nature-Based Solutions | Saint Mary's University | cbwes | NOVA SCOTIA | Canada

12.7 Tools and Resources

Supporting information and guidance on NBI fieldwork approaches is available from international, national, and provincial/territorial agencies, covering a range of topics including scoping, implementation, and iterative feedback loops promoting improved future strategies. International criteria established by the International Union for Conservation of Nature (IUCN) focuses on eight criteria serving as a global standard, including the need to address not just environmental adaptation and resilience, but also supporting community values, managing multi-scale capacities, and cross-jurisdictional governance needs (IUCN, 2020). These strategic directions are emphasized in the *International Guidelines on Natural and Nature-Based Features for Flood Risk Management,* which encourages systems-thinking to solving complex environmental challenges including performance tracking across social, ecological, and economic measures (Bridges et al., 2021). Canada participates with the United States and Mexico in the Commission for Environmental Cooperation[23], whose website hosts a bevy of tools available to support NBI project work in North America, including geospatial data located on the *North American Environmental Atlas* and the *North American Land Change Monitoring System*.

NBI projects and initiatives can serve as platforms for Indigenous-led FERM and stewardship of ancestral lands. Organizations such as the Centre for Indigenous Environmental Resources (CIER) support First Nation, Métis, and Inuit Peoples in leading climate change opportunities, through publications such as the *Climate Change Adaptation Planning Toolkit for Indigenous Communities: Anishinaabemowin Climate Change Glossary*, which promotes Indigenous language revitalization and cultural experiences for environmental planning initiatives. They also provide funding toward *ClimateTelling,* which is dedicated to supporting Indigenous community climate change adaptation, identifying and addressing environmental vulnerabilities, as well as sharing stories. Additionally, the *Indigenous Climate Monitoring Toolkit* provides environmental planning and evaluation resources for Indigenous communities centred on concepts of ethical space and methods to ensure the integration of multiple knowledge systems (CIER, 2023).

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13 Adaptive Management

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13.1 Chapter Key Messages

- Adaptive management aims to establish a management framework that embraces learning based upon monitoring, and utilizes data to inform future decision making related to management of nature-based infrastructure (NBI).
- Adaptive management should be a deliberate process, not *ad hoc* or reactionary. It is not "trial and error" but includes deliberate experimentation to test hypotheses about natural systems, and to reduce uncertainty.
- Properly applied, adaptive management can increase the likelihood of project success in situations where there is a high degree of uncertainty in project outcomes, which is often the case with NBI design and implementation.
- Successful adaptive management requires buy-in and commitment from all stakeholders and participants.
- One key challenge related to NBI is the cycle of funding for infrastructure initiatives, in which funding may be available for one-off activities (planning, design, construction), which can be accomplished in one or two fiscal years, but long-term funding for subsequent monitoring, evaluation, and adaptation must be funded from other sources or operational budgets.



13.2 Introduction

Project teams implementing nature-based infrastructure (NBI) for flood and erosion risk management (FERM) often face uncertainty during the project scoping, design, and execution phases. There may be uncertainty in scoping on desired goals and outcomes, and uncertainty of how success is to be measured. During the design phases there may also be significant uncertainty in the understanding of the system or site conditions, coastal and geomorphological processes, or natural variability of key species habitats for both plants and animals. There will also be uncertainty with respect to future potential changes at the site due to human influences, and finally, uncertainty related to the future metocean conditions and the effect of these environmental conditions on the NBI.

Adaptive management (AM) approaches assume that natural systems are not static, and that there will always be a level of uncertainty in the understanding of the systems. As such, AM aims to establish a management framework that embraces learning based upon monitoring and utilizes data to inform future decision making related to management of the natural system. It is a deliberate process that includes specific monitoring of established metrics to reduce uncertainty and advance scientific understanding of the processes affecting the project area.

AM has been identified as a foundational principle of international best practice in flood risk management, and critical to the success of NBI projects (Bridges et al., 2021). This chapter explores the possible benefits of AM approaches to NBI projects. The chapter begins with establishing a working definition of AM and then explores steps and processes of AM that are beneficial to the planning, execution, and operation of coastal projects that include a nature-based component.

13.2.1 Objectives

Different entities or organizations may apply AM for a variety of reasons, and to achieve a number of objectives (Table 13.2-1).

Table 13.2-1. Typical objectives of adaptive management for different actors.

Entity	Objective
Research organizations	Advance scientific understanding
Property or infrastructure owners or managers (e.g., private landowners, governments, communities)	Increase the life of the infrastructure Reduce lifecycle costs Reduce risk of infrastructure not providing intended functionality Reduce uncertainty and gain knowledge to optimize future projects
Project designers	Reduce risk of infrastructure not performing as designed

The drivers for an entity or organization to implement AM for a specific NBI project will vary depending on the entity/organization, specific project, and objectives. A list of typical drivers that motivate AM approaches is given in Table 13.2-2. These drivers are not necessarily unique to NBI and may equally apply to grey or structural FERM solutions.

Table 13.2-2. Drivers for adaptive management.

Driver	Objective
Climate change adaptation	The impacts of climate change are inherently uncertain and AM approaches are thus suitable for adapting to the impacts of climate change over longer timescales. For coastal NBI, changes in temperature and precipitation patterns, potentially increased levels of storminess, and future rates of sea-level rise all carry uncertainty.
Biodiversity and environmental enhancement	Coastal environments are dynamic and AM supports operation of infrastructure within dynamic environments, where there can be high levels of uncertainty over small spatial and temporal scales.
Disaster recovery	Support the shoreline in establishing a new equilibrium following a damaging storm. Remedial works may be done under emergency response with no advance planning or more strategically within an AM framework to test and monitor the suitability of different responses.
Avoiding overly conservative designs	The response of coastal infrastructure, including NBI, to extreme storms and long-term system changes can be uncertain. AM is an important tool that allows designers of NBI to avoid building excessive factors of safety into their designs.
Maintenance and continuous improvement of performance over time	The performance of coastal infrastructure, including NBI, may degrade over time. AM approaches can be used to apply adjustments throughout the project lifecycle to meet or improve expected outcomes and benefits (de Looff et al., 2021)

13.3 Defining Adaptive Management

There are many definitions of adaptive management (AM) available in research and management literature, and for this document it is important to establish a working definition to ensure a common understanding.

“Adaptive Management is an iterative decision-making method that can be used to reduce levels of uncertainty and risk in predicting and achieving desired results by using natural and nature-based features (NNBF) or structural solutions.” (de Looff et al., 2021)

“Adaptive Management should include governance, planning, implementation of decisions, and monitoring and evaluation of subsequent outcomes.” (Kingsford et al., 2017)

“Adaptive Management is a systematic process for continually improving management policies and practices by learning from the outcomes of operational programs.” (BC Ministry of Forests, 2008)

“Under adaptive management, the knowledge gained through monitoring of the project and social policies must be translated into restoration policy and program redesign.” (Thom, 1997)

“[Adaptive Management is]…the purposeful and deliberate design of policies in such a way as to enhance learning as well as to inform subsequent action.” (Allan & Stankey, 2009)



Figure 13.3-1. Adaptive management framework, from Walters (1986).

13.4 Key Principles of Adaptive Management

Fundamentally, it is important that the process of AM is conducted in a manner that purposely and explicitly increases knowledge and reduces uncertainty (Holling, 1978). This requires a formal process of hypothesis testing and assessment of system response. A benefit of AM is that it provides a role for wider stakeholder participation and reverses the traditional centralized management approach with top-down control.

The following are important principles of AM:

- It is a formal, structured, and systematic decision-making method.
- There is explicit acknowledgement of uncertainty and knowledge gaps.
- A key goal is to reduce uncertainty (of natural system response and NBI performance) through learning. In the context of NBI, this includes better understanding of a project's ability to continue functioning (and provide flood and erosion protection) over time and what levels of maintenance are required.
- There is a process in place to ensure that new understanding (acquired knowledge) is used to inform future decision making, adjustment of management measures to changing circumstances or new information about NBI performance, or project design.
- It is a cyclical and iterative process.

AM should be a deliberate process, not *ad hoc* or reactionary. It is not "trial and error" but includes deliberate experimentation to test hypotheses surrounding natural system processes and behaviours, and to reduce uncertainty.

There is an important distinction to be made between active and passive AM approaches. According to Rist et al. (2012), "…*active AM (AAM) is described as management where options are viewed as hypotheses*

to be tested; experimentation is key and both formalized learning and management are objectives. In contrast, passive AM (PAM) implements a single preferred course of action based on the best available modelling and planning, which is then modified as experience grows." Due to fiscal and resource constraints, PAM is a more common approach in practice, while if resources allow, AAM is recommended when uncertainty is highest.

Other key principles to consider are:

- Stakeholder engagement and participant buy-in for AM is crucial to success.
- The duration of monitoring must align with uncertainty (not funding cycles).
- There is a need for long-term funding and continuous management that allows for AM throughout the monitoring period, with funding for interventions if required.
- There must be a willingness to experiment in a thoughtful manner to gain knowledge.
- Stakeholders and project proponents should agree upon performance criteria, and triggers for intervention.
- If possible, local stakeholders should have the capacity to implement interventions (mechanism to incorporate change) without lengthy or onerous funding and permitting efforts. Such lack of capacity can prevent project success due to delays or failures to implement appropriate interventions.

Properly applied, AM can increase the likelihood of project success in situations where there is a high degree of uncertainty in project outcomes, which is often the case with NBI design and implementation.

13.5 Implementation

This section gives a brief overview of implementation of AM based upon a review of available literature. Each project is unique, and there is no "one size fits all" approach. Nevertheless, the following section provides a framework within which to consider AM approaches for NBI.

13.5.1 Adaptive Management Cycle

The following are the traditional steps in AM:

- **Assess the problem** – define challenges and opportunities, specify desired goals and objectives, recognize uncertainty, and formulate conceptual model.
- **Design** management actions (project implementation) to meet the desired goals and objectives. For NBI this could be improved habitat, shoreline protection.
- **Implement** management and construction actions according to the project design.
- **Monitor** the results or outcomes of the project implementation.
- **Evaluate** the action in relation to the project objectives and conceptual model.
- **Adjust** (adapt) the actions, conceptual model, or goals and objectives (i.e., intervene) as warranted based upon new knowledge.

AM is often described as involving two distinct phases. The first is a deliberative phase in which stakeholders determine the objectives and management alternatives and develop predictive models and monitoring protocols. The second phase is an iterative phase that involves an ongoing cycle of monitoring, technical learning, and interventions (or not) as required. The iterative phase can be periodically interrupted (double loop) to reconsider project objectives and management alternatives, undertake stakeholder engagement, and other elements of the deliberative phase (Figure 13.5-1).

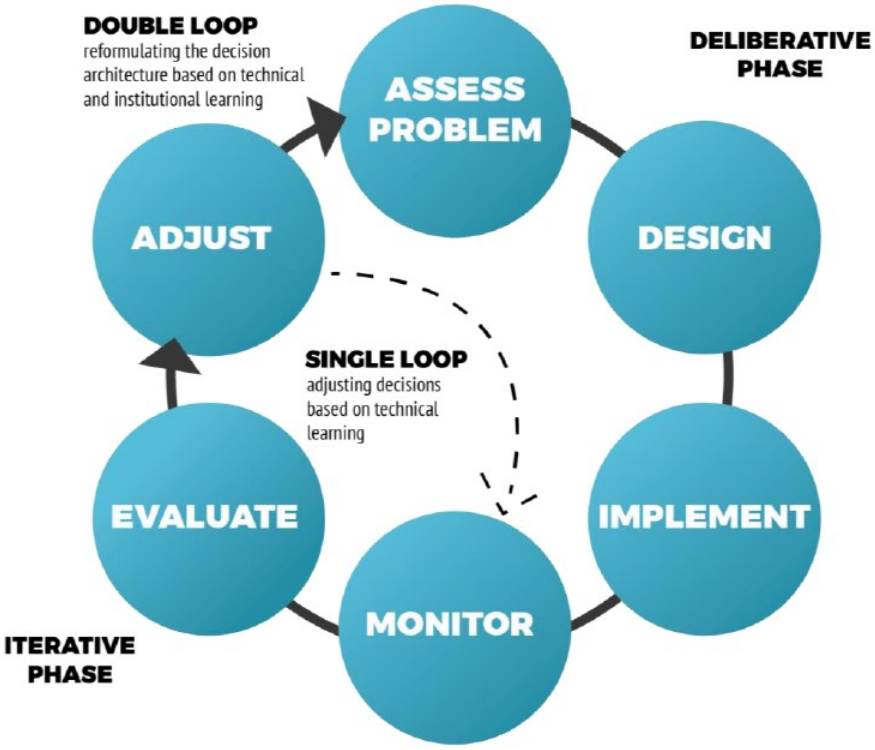


Figure 13.5-1. Adaptive management framework with basic steps and "double-loop" learning as reflecting institutional learning, described by Williams and Brown (2018) (credit: Fischenich et al., 2019).

The typical steps and tasks within each step for an AM process are described in Table 13.5-1.

Table 13.5-1. Adaptive management process (example adapted from Fischenich et al., 2019).

Step	Tasks within each step
1. Assess and define problem	• Project team should clearly state project goals and objectives (e.g., erosion control, habitat restoration, flood protection, etc.). There may be multiple goals and objectives. If so, the various goals should be ranked in importance. • Assemble project team involving managers, stakeholders, and consultants/scientists, as appropriate. • Identify the spatial and temporal bounds of the project. • Obtain baseline data as available. Identify gaps in available data. • Develop conceptual models (e.g., coastal processes, vegetation, etc.). • Explicitly state assumptions. • Identify key uncertainties (what are the management/design questions?). • **Consider the need/potential for AM (screening criteria).** • Articulate hypotheses to be tested. • Identify relevant metrics and measurable indicators to evaluate outcomes. • Clearly state how what is learned will be used.

Step	Tasks within each step
2. Design	• Develop alternative designs/management actions for consideration. • Predict outcomes using metrics identified. • Consider contingency plans and next steps under alternative outcome scenarios. • Estimate costs for project (including post-construction costs for AM). • Develop a formal AM plan (governance structure, monitoring plan, data management, communications, reporting, and funding). • Have AM plan peer-reviewed and revise cost estimates as needed.
3. Implement	• Finalize design/tender package for construction, planting, etc. • Conduct site baseline monitoring. • Build/implement site treatments. • Document any changes that occur during implementation and reasons for changes (e.g., contractor equipment, funding shortfall, etc.).
4. Monitor	• Conduct training of monitors and confirm monitoring protocols. • Implement monitoring plan.
5. Evaluate Results	• Compare monitoring results against objectives, assumptions, uncertainties, and hypotheses. • Compare monitoring results against model predictions (if applicable). • Consider outside sources of information (e.g., new science). • Ensure data analysis keeps up with collection of field data (monitoring).
6. Continue/ Adjust/ Success	• Ensure meaningful learning occurred, was documented, and communicated to ALL stakeholders. • Evaluate decision criteria/triggers whether there is a need to implement contingency plans. • Decision makers consider whether to continue as planned or consider alternatives. • Ensure funding levels are maintained to support AM.

AM is primarily a planning and management process. AM can only be effectively executed if it is based on a formal association of individuals who contribute directly and regularly to AM of the project, and if there is stable and long-term funding to support the monitoring and evaluation of the project, and also funding for implementing changes (contingency action) as required.

13.5.2 Is Adaptive Management Appropriate?

It is important to first consider whether AM is appropriate, or can add benefit, to an NBI project before attempting to adopt AM approaches. Not all FERM projects will benefit from AM. The following screening criteria are presented in Fischenich et al. (2019) to support a decision on the potential for AM to benefit a project.

Fundamental Question: Is it possible for future adjustments to the NBI to be made?

If adjusting a project is not possible in the future, or the possible adjustments are very minor, then an AM approach is not warranted, and no further consideration is required. The reasons why changes might not be possible are often a lack of available funding for implementing contingency or remediation plans, but



could also be regulatory or operational challenges (such as lack of site access post construction) for the project.

If future actions are possible, then the following three screening criteria should also be carefully considered:

1. Is the managed system (i.e., shoreline, coastal process, habitat) well understood and are management/design outcomes readily predictable?
2. Do the participants/stakeholders agree on the most effective design and operations to achieve the goals and objectives?
3. Are the project/program goals and objectives well defined, understood, and agreed upon?

If a team can answer "yes" to all three of the above screening criteria, then AM is not needed. If the answer is "no" to any of the three questions, then AM may improve the potential for project success and is worth considering.

Additional considerations before attempting to implement AM include:

- If either institutional or stakeholder support is lacking for AM, then the potential for a successful AM process is significantly reduced. AM requires commitment of key individuals in positions of authority, and this commitment must be maintained over time.
- Can adjustments to management actions be practically implemented? Constraints to operational flexibility (e.g., changes to dykes, increased flooding potential in some areas) imposed by stakeholder or regulatory concerns may limit benefits of AM approaches even when such actions are technically feasible.
- Finally, there can be uncertainty related to future project costs associated with AM that are difficult to predict by the very nature of the uncertainty of outcomes in an AM approach. Even predictable costs related to monitoring and assessment and continued management of the project team can be excessive for smaller-scale projects. Lack of funding to implement changes as warranted from monitoring and evaluation can lead to project failure. If long-term sustainable funding and access to funds for contingency action are not readily available, then AM is not a recommended approach.

13.6 Challenges

Section 13.5.2 notes the criteria required for AM to be successfully adopted in an NBI project. This section summarizes some of the key challenges to be considered during project planning.

It is important to highlight and consider potential challenges to AM, and how these challenges will be addressed. Challenges may include:

- Change (or loss) of personnel leading to a loss of institutional knowledge on specific ongoing programs. This can result in loss of project "champions". It can also result in loss of personnel having in-depth knowledge of previous decisions and experience on the project that can support ongoing and future AM practices.
- Loss of funding or lack of long-term funding to sustain AM.
- Proposed interventions (based upon monitoring and learning) trigger regulatory permit application requirements beyond original project scope. Permitting requirements may then take time and delay the timely application of the intervention to maintain or enhance the project.

- Lack of capacity to properly monitor and evaluate the data. It is easier to monitor than to retain qualified personnel to evaluate the data and determine future actions.
- Lack of qualified personnel to evaluate the data and apply a strong science-based framework to decision making.
- Lack of engaged local stakeholders, rights holders, or participants. (Experience shows that AM is unlikely to be effective if stakeholders and rights holders are not engaged and active on the project.)
- Lack of flexibility from regulatory agencies and program owners to implement changes to a program.
- Use of uncertainty as reason to delay action.

During the initial phase of determining whether or not to incorporate AM into a project, it is important to give serious consideration to the challenges noted above and have clear means of mitigating those challenges.

AM has been championed as a useful tool for undertaking projects with inherent uncertainty (Cado van der Lely et al., 2021). One key challenge in Canada related to NBI is the cycle of funding for infrastructure initiatives, in which funding may be available for one-off activities (e.g., planning, design, construction) that can be accomplished in one or two fiscal years, but long-term funding for subsequent monitoring, evaluation, and AM is not readily available.

Changes in the discussion around project funding need to happen to enable successful AM projects, to provide stable, long-term funding for collection of data, evaluation of new information, and implementation of changes, if necessary.

Box 13-1. Funding AM for Nature-Based Coastal Adaptation

Due to the multi-jurisdictional aspects of FERM, flood and erosion control works in Canada often involve cost sharing between different levels of government. Many of the federal and provincial government funding programs supporting cost sharing in Canada have historically either excluded nature-based projects, required "shovel-ready projects" that needed to be constructed within two years, or both. Funding programs that have short intake cycles and require completion within two years have been a significant barrier for NBI in general, and in particular, for those that would benefit from AM.

The City of Surrey and partners adopted an AM approach for the Living Dyke pilot in Boundary Bay, British Columbia (Box 13-2), which was supported by federal funding. The federal funding was granted through Infrastructure Canada's Disaster Mitigation and Adaptation Fund (DMAF), with phases and timelines as shown in Figure 13.6-1.



Figure 13.6-1. DMAF timeline (adapted from Infrastructure Canada webinar).

There were three key reasons why this program enabled City of Surrey to proceed with AM for the Living Dyke.

1) The funding program timeline accommodated the work in two ways:
    a. Developing buy-in with stakeholders and rights holders required investment. The two-step application process, involving an expression of interest phase to shortlist applicants, afforded sufficient confidence for Surrey and its partners to proceed with the time and resources to scope the project.
    b. Each phase provided enough lead time to engage stakeholders and invest the time and resources to refine the application.
    c. There were nearly nine years between funding approval and the end of the funding period, which was needed to accommodate the detailed design process, permitting, and stakeholder and rights holder engagement, over a period of about 4 years. This allowed for several years of AM to occur before completing any final works prior to the expiration of the funding period.
2) Considering the 8 identified merit-based funding criteria for DMAF, AM and nature-based solutions were expected to strengthen the proposal. AM of the Living Dyke through piloting and learning before scaling up was considered innovative. The nature-based project also provided strong co-benefits, such as GHG reduction and supporting recreation and environmental value.
3) The funding program allowed for and encouraged partnerships to be formed. This is referred to as project bundling and depicted in Figure 13.6-2. For the first DMAF intake, the minimum project size was $10M, which was sufficient to enable investment in building partnerships. In the case of the Living Dyke, it allowed for a smaller project site in the City of Delta to be included and thus increase the scope of AM by providing data from multiple sites to guide adjustments.

Box 13-1 (continued). Funding AM for Nature-Based Coastal Adaptation

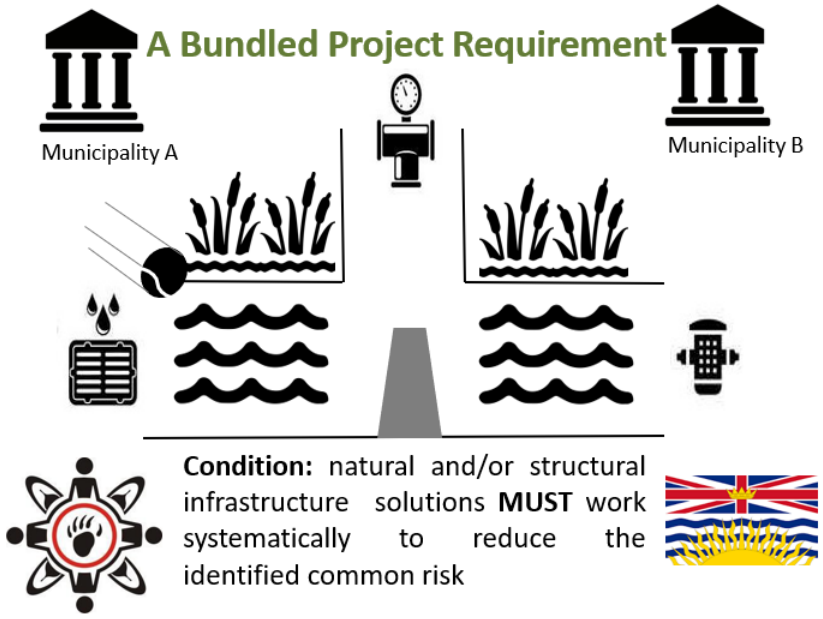


Figure 13.6-2. DMAF partnership through project bundling (figure adapted from Infrastructure Canada webinar).

Box 13-2. Adaptive Management Approaches Applied to an NBI Project in Canada

For the Living Dyke pilot project in Boundary Bay by Surrey and Delta, British Columbia, a list of knowledge gaps was developed, followed by an evaluation of which gaps warranted application of adaptive management with extensive input from interested stakeholders and rights holders.

The concept for a Living Dyke was proposed by West Coast Environmental Law, who commissioned technical input and convened various experts, regulators, and First Nations. Through this process, there was high-level support for the concept and a formal Roundtable was convened to enable dialogue on the project, chaired by the Lower Fraser Fisheries Alliance (whose role was later taken on by the Emergency Planning Secretariat) and West Coast Environmental Law.

Once the City of Surrey received funding to proceed with the project, this Roundtable facilitated knowledge exchange and dialogue between Indigenous and non-Indigenous authorities in the region, researchers, scientists, and stakeholders with the team delivering the project (consulting team and City of Surrey staff). A series of technical memoranda were drafted and circulated to the group at key milestones of the project to ensure the project was meeting the expectations of the group and that any concerns could be addressed before the project advanced too far to change course.

Box 13-2 (continued). Adaptive Management Approaches Applied to an NBI Project in Canada

Several key AM aspects to highlight in this project are:

1) The project is being constructed in phases to allow learning to take place between phases.
2) Participants of the Roundtable identified numerous concerns and information gaps for the City of Surrey to address. A selection of the technical knowledge gaps that were selected to assess between phases are listed below:
    - What depth of sediment should be placed over the existing salt marsh?
    - What is an appropriate gradation of sediment for establishment of new salt marsh?
    - What sediment stabilization techniques are effective?
    - Does placing the appropriate gradation of sediment (if stable) result in salt marsh establishment naturally?
3) Due to the size of the project (more than 1 km long, and greater than 2 ha of marine environment), the project triggered a review under BC's *Environmental Assessment Act.* In order to be confident that the full-scale project will avoid significant adverse impacts, AM was proposed and described in the project's Initial Project Description by Hatfield (City of Surrey, 2022).

While AM was appropriate for this project, there were many research questions that extended beyond the scope of the project. Additional research is underway to measure and model the performance of the project to learn lessons that can inform AM and wider utilization of NBI for coastal management in Canada. An example of this is the research support provided by Natural Resources Canada as part of the Nature-Based Infrastructure for Coastal Resilience and Risk Reduction project, which included setting up several wave-sensor transects using the Canadian Coast Guard Hovercraft (Figure 13.6-3).



Figure 13.6-3. Deployment of pressure sensors on the intertidal mudflats in Boundary Bay to inform NBI project design and AM.

13.6.1 Adaptive Management Plan

It is recommended that the key requirements of AM determined in the scoping, design, and implementation phases of a project should be documented in a formalized AM plan (Box 13-3). This document should be open to the project team, rights holders, and stakeholders and should describe:

- Governance structures with roles and responsibilities
- Basis of the plan (goals and objectives, science basis, hypotheses, uncertainties)
- Monitoring and assessment requirements
- Relevant metrics and decision criteria or triggers for future interventions

There should be a clear connection between these components in the plan. Further information on the monitoring techniques and methods appropriate for NBI can be found in Chapter 12.

Until funding models supporting comprehensive AM planning and implementation become mainstream in Canada, streamlined AM plans may be considered for smaller coastal projects, with essential components including stakeholder engagement, field monitoring (Box 13-4), data analysis and assessment, decision-making process and criteria, triggers for intervention, and design and implementation of appropriate interventions (Box 13-4).

13.7 Tools and Resources

Many Canadian references on AM relate more broadly to environmental assessment and forestry practices (e.g., BC Ministry of Forests, 2008).

For coastal and shoreline NBI projects, a good reference is the U.S. Army Corps of Engineers (USACE) technical guide “A Systems Approach to Ecosystem Adaptive Management” (Fischenich et al., 2019) and many of the points highlighted in this chapter are summarized from this reference.

It is also recommended to review Chapter 7 on Adaptive Management (de Looff et al., 2021) in the International Guidelines on Natural and Nature Based Features (NNBF) for Flood Risk Management (Bridges at al., 2021). This reference specifically provides case studies of AM approaches.

Box 13-3. Example of a Table of Contents for an Adaptive Management Plan (adapted from Fischenich et al., 2019)

1.0 Introduction
- 1.1 Authorization for Adaptive Management
- 1.2 Procedure for Drafting Adaptive Management Plan
- 1.3 Communication Structure for Implementation of Adaptive Management

2.0 Project Adaptive Management Planning
- 2.1 Project Goals and Objectives
- 2.2 Conceptual Natural System Model for Monitoring and Adaptive Management
- 2.3 Sources of Uncertainty

3.0 Rationale for Adaptive Management
- 3.1 Adaptive Management Program for Project

4.0 Monitoring
- 4.1 Rationale for Monitoring
- 4.2 Project Monitoring Plan
- 4.3 Analysis and Use of Monitoring Results

5.0 Database Management
- 5.1 Description and Location
- 5.2 Data Storage and Retrieval
- 5.3 Analysis, Summarization and Reporting

6.0 Assessment
- 6.1 Assessment Process
- 6.2 Frequency of Assessments
- 6.3 Variances and Success
- 6.4 Documentation and Reporting

7.0 Decision-Making
- 7.1 Decision Process
- 7.2 Decision Criteria
- 7.3 Potential Adaptive Management Decisions
- 7.4 Project Close Out

8.0 Costs for Adaptive Management
- 8.1 Adaptive Management Planning Costs
- 8.2 Monitoring Costs
- 8.3 Adaptive Management Implementation Costs

9.0 Literature Cited

Supporting Appendices

Box 13-4. Adaptive Management of NBI in Nova Scotia

In 2017, CB Wetlands & Environmental Specialists Inc. was commissioned by the Nova Scotia Department of Agriculture (NSDA) to develop a managed dyke realignment and floodplain (tidal wetland) restoration plan for the Belcher St. Marsh, located in Kentville, NS, along the Jijuktu'kwejk (Cornwallis) River. In 2018, after baseline monitoring and restoration designs were complete, the dyke at this managed realignment site was breached as a part of the Fisheries and Oceans Canada-funded Making Room for Wetlands project through TransCoastal Adaptations: Centre for Nature-Based Solutions at Saint Mary's University. As a site adjusts to the reintroduction of tidal flooding and finds a new equilibrium, some areas may not respond as initially anticipated. Post-restoration site monitoring identified two areas that were not recovering in the desired way. In one area, water was ponding near the toe of the dyke; in a second area near the root-wad living shoreline, the elevation was lower than the surrounding marsh surface resulting in rill formation and scour from the concentration of surface flow and preferential drainage across the living shoreline. Both conditions posed a risk to the dyke's stability and to the recovery of the foreshore marsh. Assessments for each area led to adaptive management actions to alleviate risk. Adaptive management techniques for this site included:

- Hand-digging a channel (runnel) to connect the pond to the larger drainage network at the back of the site. The runnel reduced the amount of trapped water, which should improve re-vegetation and soil stability (Figure 13.7-1).
- Planting small coniferous trees to reduce the speed of water flowing across the living shoreline and to increase sediment build-up on the marsh surface. The trees filled gaps in the root wads, and wattle fencing and brush mats were combined with transplanted marsh vegetation. The adjustment should increase the elevation of the marsh surface behind the root wads to match the surrounding marsh surface, thereby reducing preferential drainage and rill formation.



Figure 13.7-1. Rill connecting ponded area to existing drainage network before (left) and after (right) adaptive management (Graham et al., 2020).

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14 Conclusion

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This first edition of *Nature-Based Infrastructure for Coastal Flood and Erosion Risk Management – A Canadian Design Guide* signposts and provides evidence-based guidance for practitioners on approaches, methods, and techniques for selecting, designing, deploying, preserving, and adaptively managing nature-based infrastructure (a form of nature-based solution) to manage coastal flood and erosion risk in Canada. It builds on existing international guidance to provide insights and lessons learned from Canadian projects and contexts. Considerable effort and expertise have been applied to develop the guidance over several years, and there has been a noticeable uptick in enthusiasm for nature-based solutions during that time. For example, nature-based solutions feature prominently in Canada's recently published first National Adaptation Strategy (Environment & Climate Change Canada, 2023). However, much remains to be done to enable nature-based infrastructure (NBI) to be viewed widely as a viable leading option for managing coastal hazard risk in Canada. Chapters in this guide identify future needs to:

- Improve coastal governance to address challenges arising from a multi-tiered governance system.
- Implement strategic frameworks and processes for coastal management that are grounded in systems-thinking, to enable consideration of NBI alongside other coastal hazard risk management strategies.
- Enable and support greater leadership and involvement of Indigenous Peoples in coastal zone management.
- Understand and adapt to climate change that will affect coastal regions in Canada differently.
- Increase support from different levels of government for NBI solutions.
- Leverage participatory approaches and digital technologies to improve community engagement in NBI projects.
- Work to build capacity and resilience within coastal communities.
- Collaborate and conduct multi-disciplinary research to develop evidence, tools, models, and data to support the design and implementation of different types of NBI and in different settings or environments, and to reduce the level of uncertainty associated with the implementation of NBI.
- Promote ongoing sharing of knowledge, datasets, tools, and best practices concerning implementation of NBI in Canada.

As these needs are addressed over time, we anticipate this guidance will evolve and mature, perhaps to a point where NBI becomes a "go-to" or mainstream option alongside other strategies for coastal flood and erosion risk management in Canada.

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