STANDARDS RESEARCH

Nature-Based Solutions for Coastal and Riverine Flood and Erosion Risk Management

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Foreword

Technical Guidance Propels Action

Throughout the world, countries and their citizens are having to confront more risks and uncertainties than at any other time in modern history. Hazards derived from a changing climate are now globally observed and experienced every day. With so many communities now facing an unprecedented number of threats, more must be done to reduce risk while embracing a more compatible existence with our planet. This message is growing louder each passing year with actions now emanating from organizations in all sectors – private, public, non-government, and academia – and the adoption of Nature-based Solutions (NbS) as a means of reducing risk is a logical manifestation of messages being turned into action.

The application of NbS to reduce impacts from coastal and riverine flood hazards represents a growing opportunity for achieving greater community resilience while simultaneously accruing environmental and social co-benefits. Thanks to the efforts of countless scientists, engineers, landscape architects, resource managers, academicians, practitioners, and others, the availability of guidance supporting the implementation of NbS has increased. In my role with the U.S. Army Corps of Engineers, it is a great privilege to collaborate with individuals from around the world that are leading practice in this area and developing the case studies, technical guidance (including standards), peer-reviewed manuscripts, tools and technologies that are revolutionizing and accelerating our ability to construct natural infrastructure. While these outcomes do represent significant progress, even more is needed to meet increasing demands and to be well-positioned for the uncertainties and challenges of tomorrow. Multi-disciplinary collaboration is at the heart of these efforts. Only by leveraging diverse expertise and skillsets in a collaborative way can we expect to derive sustainable NbS that will be embraced and subsequently implemented.

This review paper titled, "Nature-Based Solutions for Coastal and Riverine Flood and Erosion Risk Management", is a wonderful addition to a growing body of publications that are advancing the use of NbS around the world. This work features a synthesis of NbS recommendations, case studies, project photos, design illustrations, and a compilation of referenced technical guidance documents from around the world. The information provided in this paper will be of great value to those in search of the proverbial key that unlocks knowledge and makes available additional NbS resources. In fact, the foresight of my Canadian colleagues to integrate an international grouping of guidance documents is noteworthy. Not only does this review paper provide the reader with a single source of substantive information, it further integrates knowledge and publicly available resources from a diverse grouping of international practitioners – another important contribution.

Building upon this theme of collaboration and technical guidance, the U.S. Army Corps of Engineers published a 1000-page international guidance document in September 2021 titled, "International Guidelines on Natural and Nature-Based Features for Flood Risk Management." Over 180 practitioners, researchers, and academicians from more than 70 organizations around the globe were part of a collaborative team that worked on this project. It is our hope that the internationally authored, Natural and Nature-Based Features (NNBF) Guidelines will equip decision makers, project planners and practitioners with solutions to reduce flood risk to local communities while providing a range of other social, environmental and economic benefits.

Through the combined examples offered here and those of others, more technical guidance on NbS and NNBF is being produced, and therefore, helping to propel future action.

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Executive Summary

Canadian communities and infrastructure are vulnerable to coastal and riverine flood hazards. The risks associated with coastal and river flooding are escalating as a result of development in river floodplains and coastal zones, and the effects of climate change on flood and erosion hazards. There is growing interest in the potential for Nature-based Solutions (NbS) to play a role in managing these risks, owing in part to Canada's co-leadership of the Nature-based Solutions Action Track of the Global Commission on Adaptation. Despite this increasing interest in NbS for coastal and riverine flood and erosion risk management, they remain relatively underutilized in Canada. Standards and guidelines can contribute to mainstreaming NbS by clarifying the underlying concepts and principles, raising awareness, and educating practitioners, potential project proponents, and the public. This review and synthesis of published literature and interviews with stakeholders and experts was conducted to:

- Assess how NbS can be used to manage flood and erosion risks in coastal and riverine environments in Canada; and
- Determine needs and opportunities for standards to support deployment of NbS to reduce coastal and riverine flooding and erosion risks.

NbS for coastal and riverine flood and erosion risk management are strategies or measures that depend on, or mimic, natural system processes to provide flood and erosion risk management function, while delivering a suite of environmental and other societal co-benefits. NbS embrace the principles of "whole system" analysis, adaptive management, multi-disciplinary teams, innovation, and long-term planning for uncertainty. They can be deployed through sustainable planning and regulatory frameworks that recognize the value of natural assets and infrastructure in supporting risk management objectives (e.g., Integrated Water Resources Management and Integrated Coastal Zone Management), and/or the targeted deployment of nature-based features to provide specific flood and erosion risk management functions. Nature-based features can deliver flood and erosion risk management benefits in a variety of ways, for example:

- In coastal regions – beaches/dunes, reefs, and wetlands provide buffers against wave action, storm surges, and erosion;
- In river watersheds – wetlands, reconnected floodplain areas, and restored river channels enhance groundwater infiltration, reduce or delay runoff, and attenuate peak flood flows and water levels; and
- In estuaries – marsh and wetland systems can be preserved, expanded, or restored to provide additional hydraulic storage and attenuate waves.

NbS span a continuum of human intervention from green (least intervention) to grey (traditional hard infrastructure); from simply conserving or protecting existing natural systems (e.g., floodplain preservation), to enhancing or restoring natural processes (e.g., beach nourishment), to hybrid or grey-green solutions that integrate hard engineering or structural measures with more natural features (e.g., buried revetments), to "greening" traditional infrastructure (e.g., by incorporating features to enhance ecological value or provide habitat).

Although there are Canadian examples of NbS for flood and erosion risk management that date back to the 1970s, they remain relatively underutilized today. Key barriers to broader uptake include challenges in predicting performance of NbS in distinct and varied Canadian regional settings, a paucity of data demonstrating the performance and track record of NbS, a shortage of highly qualified professionals, stakeholder perceptions that NbS are more uncertain or less effective than (hard engineering) alternatives, project funding models that disincentivize NbS, undervaluation of the co-benefits of NbS in conventional economic analyses and financing models, a lack of authoritative technical guidance, and complex governance and regulatory environments.

The growth in research and interest surrounding NbS has led to the proliferation of numerous reports and guidance documents relevant to the implementation of NbS for coastal and riverine flood and erosion risk management. With a few exceptions, the majority of guidance is relatively high-level, and lacks either the technical detail or region-specific contexts needed to support effective design and implementation of NbS for coastal and riverine flood and erosion risk management across Canada. Collectively, however, available and emerging guidance provides a sound foundational basis for working towards implementation of best practices through future Canadian national standards and design guides. The benefits of national standardization and guidance would include mainstreaming of NbS principles, education of stakeholders and potential proponents on factors affecting the performance of NbS, and increased investor confidence in NbS projects. In particular, monitoring and evaluation protocols for NbS, and frameworks supporting evaluation and deployment of NbS represent potential short-term opportunities for standardization to facilitate wider adoption.

Knowledge and research gaps to be addressed to enable the development of Canadian guides and standards for NbS in coastal zones and river watersheds include:

- Evidence of NbS performance across distinct and varied Canadian coastal and river settings, particularly northern environments, where NbS are relatively untested;
- Improvement and validation of predictive tools;
- Potential adverse impacts of NbS; and
- An improved understanding of the comparative performance of non-structural (i.e., planning-based), conventional, and nature-based (including hybrid) flood and erosion risk management solutions in achieving multiple benefits.

"Canada's population and infrastructure are highly concentrated near rivers, lakes and marine coasts, and are therefore vulnerable to hazards arising from the natural processes of flooding and erosion."

1 Introduction

Flooding is Canada's costliest natural disaster and source of property damage [1]–[4], with significant contributions from (1) fluvial (riverine) flooding, typically driven by snowmelt, precipitation, or ice jams; and (2) coastal flooding resulting from high tides, storm surges, or wave effects [5]. Canada's population and infrastructure are highly concentrated near rivers, lakes, and marine coasts, and are therefore vulnerable to hazards arising from the natural processes of flooding and erosion [5]–[7]. The risks associated with flood hazards are projected to increase over the coming decades due to continued development and population growth in river basins and coastal areas, and the effects of climate change [8]. This escalating flood risk profile will necessitate more holistic, forward-looking approaches to risk management and climate adaptation that leverage a broader portfolio of techniques, including nature-based solutions.

Flood risk only exists where there is both hazard and exposure (e.g., people, property, or valued assets in the way of the flood) [6]. Indeed, flooding and erosion are fundamental processes that contribute to natural river and shore function, underpin the maintenance of habitats, and support balanced river and coastal ecosystems. Alteration or disturbance of these natural processes can result in instability, unintended consequences, or narrow the future range options for adapting to changes in the system [9-11]. Understanding and working with natural processes, for example, through Nature-based Solutions (NbS), is therefore crucial in supporting sustainable river basin and coastal zone management.

NbS are gaining increasing international traction and research attention [12]–[14], given their potential to tackle both climate mitigation and adaptation challenges while delivering multiple additional co-benefits for society and the environment. Recently, there has been a growing national interest in the role of NbS for climate adaptation, owing in part to Canada's co-leadership of the Nature-based Solutions Action Track of the Global Commission on Adaptation [13], which aims to catalyze, scale up, and realize the full potential of NbS through initiatives that address key barriers. NbS have potential to play an important role in helping Canada to achieve its commitments and targets under global initiatives such as the United Nations Sustainable Development Goals [15], the Paris Agreement on Climate Change [16], and the Sendai Framework for Disaster Risk Reduction [17]. Most recently, the Government of Canada has identified embracing the power of nature, including NbS for flood risk reduction, as one of five pillars of its new climate plan [18].

1.1 Nature-Based Solutions – Overview and Definition

Nature-based solutions (NbS) 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" [19]. The term nature-based solutions was coined in the early 2000s to describe new approaches to climate change mitigation and adaptation that simultaneously promote biodiversity and ancillary societal benefits [20]. NbS is an umbrella term for a range of ecosystem-based approaches to tackling societal challenges [21]. As such, NbS do not exclusively refer to flood or erosion risk management solutions or practices but can encompass a variety of activities where nature is depended on or harnessed to sustainably address challenges such as food security, water security, human health, climate change, and socio-economic development [12], [19]. NbS build on and share similarities with other approaches and frameworks, which has led to vague and varied terminology and definitions in use. On the one hand, this lack of precision and consistency in defining NbS speaks to the underlying holistic principles and has enabled broad acceptance; on the other, it has led to some confusion and concern that NbS may be misinterpreted, misapplied, or simply viewed as another buzz word [14], [19], [20], [22], [23]. The new International Union for Conservation of Nature (IUCN) Global Standard for NbS [19] aims to address this imprecision, and reinforces the idea that NbS go beyond environment conservation and preservation principles to focus on humans and societal challenges, such as flood and erosion risk management.

Specifically, in the context of riverine and coastal flooding and erosion, NbS encompass a variety of strategies and measures that rely on, or mimic, natural system processes to manage or reduce risk. They build on well-established principles and practices that involve developing an understanding of the natural system as the basis for informing risk management strategies and solutions [22], [24]. The evolution of the term nature-based solutions reflects a growing awareness of the value of natural assets in delivering societal benefits, including flood risk reduction, and recognition of the ecosystem services[1] and climate change mitigation co-benefits (see Section 3.5). For the purpose of this report and specifically for application to coastal and riverine flood risk management, the following definition of NbS is adopted:

Nature-based solutions (NbS) for coastal and riverine flood and erosion risk management are strategies or measures that depend on, or mimic, natural system processes to provide flood and erosion risk management function, while delivering environmental and other societal co-benefits.

There are a variety of ways in which natural system processes can be leveraged or restored to deliver flood and erosion risk management benefits, for example:

- **In coastal regions –** beaches/dunes and wetlands provide buffers against wave action, storm surges, and erosion;
- **In river watersheds –** wetlands, reconnected floodplain areas, and restored river channels enhance groundwater infiltration, reduce or delay runoff, and attenuate peak flood flows and water levels; and
- **In estuaries –** marsh and wetland systems can be preserved, expanded, or restored to provide additional hydraulic storage and attenuate waves.

Further examples and details of different mechanisms and nature-based solutions that support flood and erosion risk management objectives are described in Section 3.

There are many terms that are either synonymous with, or resemble, the meaning of NbS for flood and erosion risk management, that is, green (or grey-green) infrastructure, natural infrastructure, natural asset management, soft engineering, living shorelines, ecosystem services, ecosystem-based approaches, bio-engineering, natural flood management, working with natural processes, engineering with nature, building with nature, room for the river, ecological engineering, integrated coastal zone management, and integrated water resources management [20]–[22]. Each of these terms and their definitions have their

1 Ecosystem services are taken to mean "direct and indirect contributions of ecosystems to human well-being" [20].

own nuances and emphasis, largely determined by where they sit on the continuum of focus on addressing purely societal versus purely environmental objectives [25]. Eggermont *et al.* [20] and Gómez Martín [23] identify different types of NbS that span a continuum of human intervention; from conserving or protecting existing natural systems to hybrid or grey-green solutions that integrate hard engineering or structural measures with more natural features, applying whole system principles (see Section 3.2).

While the benefits of NbS are receiving increasing attention, these solutions remain comparatively underutilized in Canada [26] and around the world. Globally, barriers to broader uptake of NbS include the following [11]–[14]:

1. Challenges in predicting performance and cost-effectiveness compared to alternatives;
2. Challenges in valuation of benefits and economic appraisal of NbS;
3. Inflexible governance structures;
4. Lack of institutional, financial and regulatory capacity to strategize, implement and monitor NbS;
5. Lack of awareness of the role NbS can play in supporting social and economic resilience;
6. Lack of access to funds for investment in NbS;
7. Limited opportunities for multi-disciplinary and multi-sectoral communication/collaboration (e.g., between ecologists, economists, engineers, landscape architects and planners).
8. Piecemeal approaches to climate change adaptation that undervalue NbS; and
9. Public or stakeholder perceptions that NbS are less effective than traditional solutions.

1.2 Objectives

By synthesizing published literature and stakeholder perspectives, the broad objectives of this report are to:

- Assess how NbS can be used for mitigating flood and erosion risks in coastal and riverine environments, and what types of NbS are most effective and most appropriate in the Canadian climate; and
- Determine what standards requirements and recommendations are needed to inform the appropriate selection and application of NbS to ensure that they are effective in mitigating flooding and erosion risks.

More specifically, the report:

- Identifies the types of NbS that can be used in coastal and riverine regions, and discusses current best practices for the successful implementation of each type of system including key design, construction, maintenance and monitoring considerations, favourable site characteristics and climatic regions, and known vulnerabilities (such as damage caused by extreme weather);
- Discusses prominent case examples of natural and NbS reflecting on things that have gone well and things that have resulted in problems/challenges;
- Provides insights into the processes that should be used for monitoring functional performance in order to adaptively manage and maintain the level of performance and benefits delivered; and
- Identifies current knowledge gaps and provides recommendations for future research and standards development.

2 Methods

The review of NbS for coastal and riverine flood risk management described in this report is based on a search and synthesis of existing, publicly available information and published literature, as well as interviews with various experts, stakeholders, and interested parties across Canada. The stakeholder outreach activity aimed to provide a reasonable balance in terms of geographic coverage, discipline, expertise, and sector. Written background information on the purpose of the study, the interview questionnaire, and intended use of the interview responses were provided to invited participants (Appendix A). In total, 21 teleconference interviews were conducted, and two written responses to the questionnaire were received, with representation from academia, non-government organizations, private industry, and all levels of government. Interview responses were provided by representatives from

British Columbia, Yukon, Alberta, Manitoba, Nunavut, Ontario, Quebec, New Brunswick, Nova Scotia, and Newfoundland and Labrador. All responses were anonymized during the synthesis, and efforts were made to distill common or recurring themes and points deemed to be particularly insightful.

3 Nature-Based Solutions – Principles, Concepts, and Benefits

3.1 Guiding Principles

In striving to establish a consistent framework for NbS, IUCN [19] has defined eight criteria that allow users to assess how a solution meets the Global Standard for NbS:

- **Criterion 1 –** NbS effectively address societal challenges;
- **Criterion 2 –** NbS design is informed by scale;
- **Criterion 3 –** NbS result in a net gain to biodiversity and ecosystem integrity;
- **Criterion 4 –** NbS are economically viable;
- **Criterion 5 –** NbS are based on inclusive, transparent, and empowering governance processes;
- **Criterion 6 –** NbS equitably balance trade-offs between achievement of their primary goal(s) and the continued provision of multiple benefits;
- **Criterion 7 –** NbS are managed adaptively, based on evidence; and
- **Criterion 8 –** NbS are sustainable and mainstreamed within an appropriate jurisdictional context.

Although these criteria are not limited or specific to flood and erosion risk management applications, they are suitable guiding principles for NbS intended to address flood risk as a societal challenge.

3.2 Adopting a System-Based Approach

Rooted in the concept of NbS, and indeed flood and erosion risk management more generally, is the idea of "system-based" or "whole system" approaches [10], [19], [27]. Such approaches consider a broad range of physical, biological, and social processes, and their interactions, in evaluating flood and erosion risk and solutions. System-based approaches also consider a range of temporal scales (hours to decades) and spatial scales (local to global) to arrive at solutions that are sustainable. They recognize that the cumulative effects of multiple, small interventions can have significant impacts on the system as a whole and are therefore often most effective when applied at broad scales [13]. An example is the use of leaky dams in upper watersheds to attenuate flood peaks in lower river reaches, or application of the principles of redundancy in multiple-line-of-defence coastal protection schemes – see the Living Breakwaters Project in **Case Study A**.

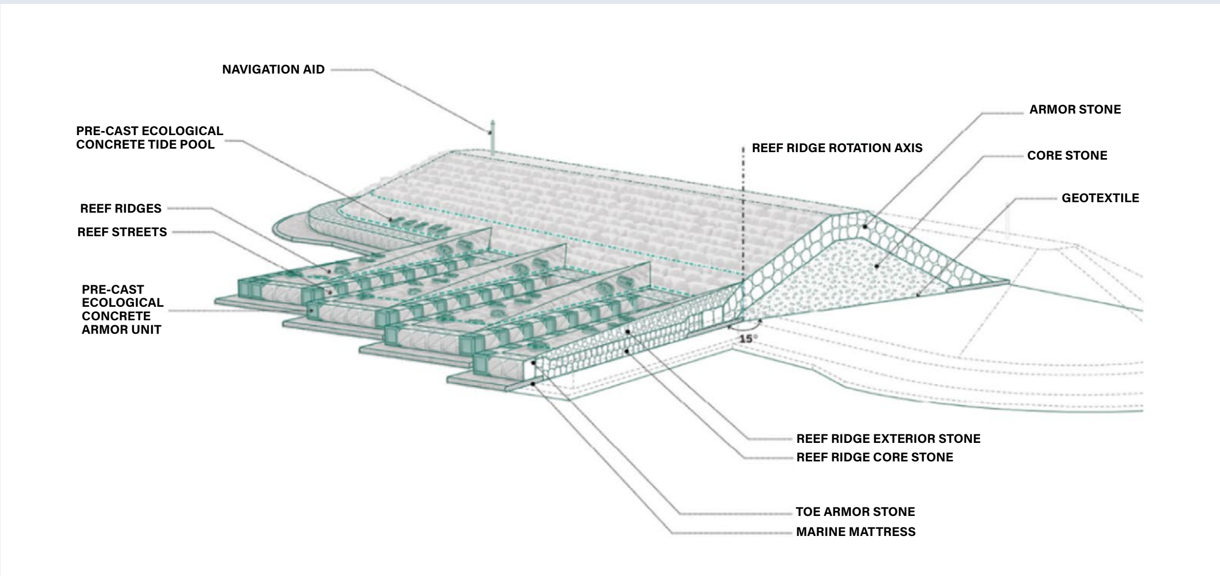
Developing a whole system understanding is crucial to successful implementation of NbS, because it provides a broad perspective on interplay of ecology, geomorphology, hydrology, and hydrodynamics, as well as interfaces with the social system. Such approaches promote long-term thinking, which is fundamental to enable anticipation of change (e.g., climate, urbanization, human behaviour) and adaptive management. Natural systems, and therefore NbS, are inherently dynamic, which is partly why they are often more adaptable to climate change. However, to be sustainable, NbS must be capable of bouncing back following a natural or anthropogenic system disturbance, that is, they must be resilient and predominantly self-sustaining. This is often a significant source of anxiety for new adopters of NbS, who may be more familiar or comfortable with the apparent surety of conventional, hard engineering solutions, or skeptical that NbS can be cost-effective [28]. On the contrary, evidence shows that well-executed NbS are often the least regret options for flood and erosion risk management because they provide a buffer against development in areas of high hazard, and typically incur lower capital investment and operating costs [29], [30], owing to their ability to adapt.

Developing resilient NbS requires developing an understanding of the interconnectedness in systems. For instance, stabilization of eroding cliffs may deprive downdrift beaches of sediment needed to sustain them, and marsh vegetation plantings may be vulnerable to grazing bird populations or damage by storms or debris during the initial period. Leveraging the advantages of system interconnectivity, such as harnessing ecosystem services to deliver flood and erosion risk management benefits, is a fundamental principle underlying NbS.

Case Study A: The Living Breakwaters Project, New York – a Multiple-Line-of-Defence NbS

Following the devastating impacts of Hurricane Sandy in 2012, the State of New York looked for opportunities to proactively plan for long-term resilience and climate change adaptation. The Living Breakwaters project is an innovative, one-mile long system of proposed offshore breakwaters with various ecosystem-enhancing features that will attenuate storm waves and reduce coastal erosion [135]. The breakwaters will act in concert with a beach nourishment overlying rock revetment (i.e., buried revetment) on the south shore of Staten Island, providing a multiple-line-of-defence shore protection system. The breakwaters are designed with a variety of habitat features, including “reef streets” and “reef ridges” (Figure 1). Together, the ridges and streets expand the intertidal and subtidal zones of the breakwaters, increasing habitat area. Two types of special bio-enhancing armor units are to be incorporated into the breakwater, ECOncrete® Armor Units and Tide Pools. The armor units have surface recesses and striations to encourage the growth of marine organisms and enhance biodiversity [135]. The Tide Pool units are designed to mimic natural tidal pools commonly found on rocky coasts. Co-benefits will include the planned restoration of active oyster reef habitat on and adjacent to the new breakwaters, and opportunities for waterfront stewardship and recreation. Physical model investigations of the hydraulic performance of the breakwaters were conducted in several wave basins at the National Research Council Canada's research facilities in Ottawa, to support the breakwater system design. As of October 2021 construction of the project was contracted out (https://stormrecovery.ny.gov/learn-more-about-living-breakwaters-project). The Living Breakwaters Project is an example of an innovative, hybrid NbS that demonstrates how degraded coastlines can be renaturalized and enhanced to provide improved flood and erosion resilience, and a range of co-benefits.

Figure 1: Reef ridges and streets on a rubblemound breakwater. Reproduced with permission from SCAPE.



3.3 Broad Perspectives and Collaborative Approaches

As discussed, NbS for flood and erosion risk management build on and integrate aspects of system-based approaches, integrated flood risk management, river and coastal engineering, ecological engineering, restoration ecology, archeology, economics, and other fields of practice. NbS are therefore inherently multi-disciplinary and collaborative endeavours [31] (see the Percé Waterfront Rehabilitation project in **Case Study B**). Consequently, development and implementation of NbS is more likely to involve and embrace novelty, innovation, and new or previously ignored ways of thinking. This exploratory ethos may require a greater emphasis, by comparison to conventional flood and erosion risk management approaches, on anticipating and adaptively managing change.

Criteria 5 and 8 of the IUCN Global Standard speak to the need for, and value of, inclusion and empowerment of Indigenous peoples in NbS, recognizing that NbS can contribute to human well-being, climate change, biodiversity, and human rights, including the United Nations Declaration on the Rights of Indigenous Peoples. There is an obligation to obtain free, prior, and informed consent from Indigenous peoples on issues that might affect their interest. Indigenous perspectives, traditional knowledge, including traditional ecological knowledge, and world views can promote and enhance the success of NbS, and there are a number of examples where Indigenous communities are leading proponents of NbS in Canada (e.g., [32]–[34]).

Case Study B: Percé Waterfront Rehabilitation, Québec – a Collaborative NbS

The town of Percé on the Gaspé Peninsula is known for its natural features, including Percé Rock (Figure 2) and Bonaventure Island, which help to attract more than 400,000 visitors every year. The town's waterfront was experiencing ongoing coastal erosion and flooding, exacerbated over time by rising sea levels, and decreases in winter sea ice cover and ice season duration [136]. In particular, two major storms in 2010 and 2016 caused significant damage to coastal infrastructure, including Percé Wharf and the concrete seawall protecting the town's scenic boardwalk (Figure 2). In 2016, a team of researchers from Ouranos and the Université du Québec à Rimouski investigated a solution to enhance flood resilience in the Anse-du-Sud area, which has important heritage and economic value for the town. The study included cost-benefit analysis, and environmental and social impact assessment for five different adaptation options: (1) construction of a new seawall, (2) rock-filling the shoreline, (3) riprap installation, and beach nourishment (4) with or (5) without groynes. The team determined that a pebble beach nourishment would be the most economically beneficial solution. The project was completed in the summer of 2018, and received a National Urban Design Award from the Royal Architectural Institute of Canada for its innovative and sustainable approach [137].

Figure 2: Percé's restored shoreline. Reproduced with permission from Enda Murphy.

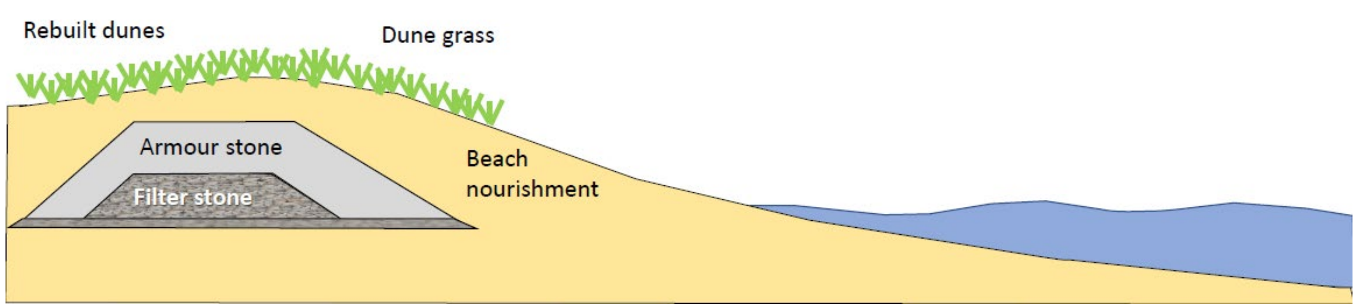
3.4 Grey to Green – the NbS Spectrum

NbS span a continuum of approaches lying between purely natural (green) and conventional (grey/hard structural) solutions. This recognizes that ecosystem restoration or biodiversity enhancement are not necessarily the primary or only goals of NbS, which are fundamentally aimed at addressing broad societal challenges [20], such as flood and erosion risk management. NbS leverage synergies and system-based approaches to better integrate conventional infrastructure and natural ecosystems in hybrid or grey-green solutions [35]. Hybrid solutions generally mimic, or are inspired by, nature, such that the term biomimicry is often synonymous with NbS [36]. Examples of hybrid solutions specific to coastal and riverine flood and erosion risk management include restored beach-dune systems that incorporate hard, stabilizing control structures (e.g., groynes), buried revetments (Figure 3) [37], and off-stream flood storage areas in river watersheds that feature engineered hydraulic structures at the inlets/outlets, such as the Living Breakwaters in **Case Study A** and the Springbank Off-Stream Reservoir in **Case Study C**. In some cases, greening or retrofitting conventional flood risk management infrastructure to provide enhanced habitat value, such as tidewater retaining niches in breakwaters or seawalls, may be considered a viable form of NbS [22], [38]. However, this can only be true if the principles guiding NbS are adhered to (e.g., whole system considerations, equitable balance of trade-offs, delivery of multiple benefits), or such approaches run the risk of merely constituting greenwashing, with associated negative connotations [39].

3.5 Benefits of NbS

The benefits to people or the environment arising from NbS (or natural systems), whether directly or indirectly, are sometimes called ecosystem services [20], [40]. If flood and erosion risk management is considered the primary benefit, ancillary benefits are often referred to as co-benefits. NbS deliver flood and erosion risk management benefits through various processes and mechanisms, for example, attenuation of waves in coastal regions, trapping and retention of sediment, increasing groundwater infiltration, reducing runoff, and creating flood storage in river watersheds. The extent and value of such benefits are beginning to be quantified and fully recognized internationally and in Canada. For example, in a rigorous analysis, Storlazzi *et al.* [41] determined that the annual value of flood risk reduction provided by coral reefs in the U.S. is more than 18,000 lives and US$1.8 billion (2010 dollars). Narayan et al. [42] estimated that coastal wetlands averted more than US$625 million in flood damages from Hurricane Sandy across the northeastern U.S. Arkema *et al.* [43] calculated that the number of vulnerable people and value of residential property in the U.S. that are most exposed to hazards (including storm wind/wave exposure and inundation) could be reduced by 50% if existing coastal habitats are preserved. Moudrak and Feltmate [1], Moudrak *et al.* [26], Circé *et al.* [44], Horizon Advisors [45], Sherren *et al.* [46], and the Municipal Natural Assets Initiative [47], [48] present numerous examples of economic analyses that quantitatively illustrate the benefits of NbS and natural assets in Canada:

Figure 3: Schematic of buried revetment cross-section at Dominion Beach, Nova Scotia. Reproduced with permission from Vincent Leys, CBCL.



Case Study C: Springbank Off-Stream Reservoir Project, Alberta

The Elbow and Bow River floods of June 2013 resulted in the largest flood event in Calgary since 1932, causing an estimated $6 billion in damage throughout the province of Alberta and five deaths [138]. The City of Calgary and the Government of Alberta are investigating several flood mitigation solutions. One of the preferred solutions is to construct an offstream diversion (Figure 4) about 15 km west of Calgary to re-route Elbow River floodwaters into an adjacent wetland, gradually releasing it back into the system after the peak of the flood hydrograph has passed. The project will increase the total storage capacity within the system to 87 million m^3, which exceeds the volume needed to pass the 2013 flood. A benefit/cost ratio of 1.68 was estimated for the project [139].

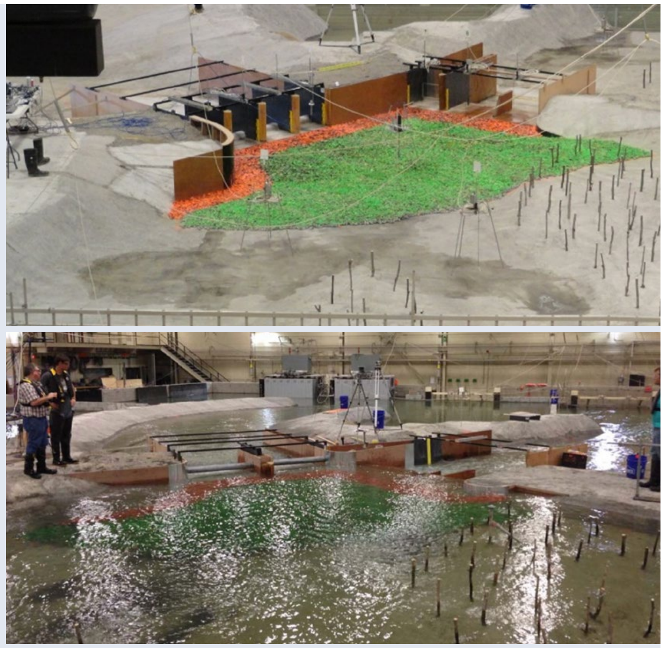


Figure 4: 1/16 Scale physical model of the Springbank Off-Stream Reservoir Project at the National Research Council Canada, Ottawa. Source: National Research Council Canada.

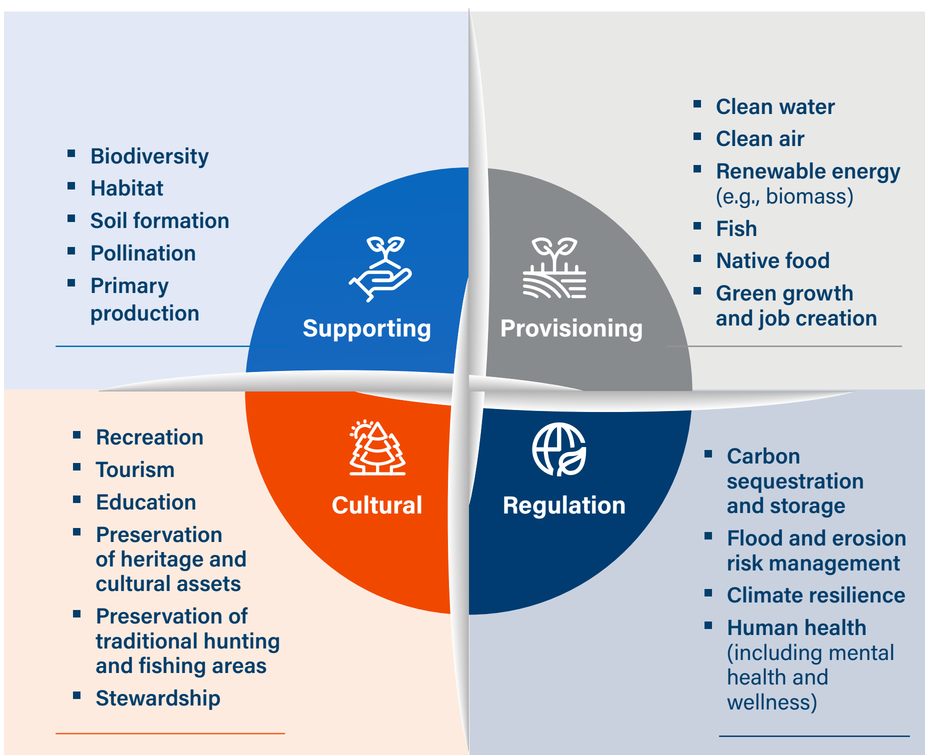
- The Town of Gibsons, British Columbia, found that the natural ponds in White Tower Park provided water and stormwater management services, which would have cost about $3.5–4.0 million to achieve using engineered infrastructure [26].
- Hydraulic modelling for two Southern Ontario pilot sites, in rural and urban settings, showed that flood damages could be reduced by 29% and 38%, respectively, if wetlands were maintained in their natural state (versus conversion to agricultural use) [45].
- An engineered wetland retention system at Pelly's Lake in Manitoba delivered economic benefits in terms of avoided flood damages, water quality, carbon sequestration, and biomass production to the tune of $25,507 per hectare per year (2017 dollars) [45], [49] (see Pelly's Lake Wetland Restoration in **Case Study D**).
- A naturalized channel at Oakville, Ontario, delivered stormwater conveyance and flood attenuation benefits, which would cost $725,000 to provide using grey infrastructure (pipes) with equivalent conveyance capacity [26].
- 1.4 hectares of wetlands in the Mill Creek watershed, New Brunswick, deliver $1.4 million in flood attenuation benefits for a 1-in-100 year return period flood event [48].
- Based on a direct cost comparison, coastal dyke realignment and tidal marsh restoration would save more than $520,000 (2018 dollars) compared to maintaining dyke infrastructure at North Onslow, Nova Scotia. This analysis excluded monetary analysis of additional co-benefits, including carbon sequestration and flood mitigation [46].

A key feature and advantage of NbS, demonstrated by Criterion 1 of the IUCN Global Standard [19], is that they deliver multiple benefits simultaneously [12], [50]. For example, reforestation of river watersheds can simultaneously deliver benefits in terms of flood risk reduction (see Ganaraska River Headwaters Reforestation in **Case Study E)**, carbon sequestration, biodiversity, and human health. Standardization, classification, and assessment of ecosystem services are ongoing efforts [21]. However, ecosystem services or co-benefits are sometimes grouped into four broad categories: provisioning, regulation, supporting, and cultural. Examples of ecosystem services provided by NbS for coastal and riverine flood and erosion risk management are listed in Figure 5.

Although there are numerous examples of NbS that demonstrate these concepts, there are open questions on how to appropriately evaluate or weigh co-benefits when appraising flood and erosion risk management options [12], [50], particularly when relying only on conventional cost-benefit analysis techniques. Indeed, valuation of co-benefits is one of the most prominent subjects of research related to NbS [52]. Due to the challenges in quantifying or monetizing ancillary benefits, NbS are often undervalued by traditional cost-benefit analyses [53], and may score higher in more holistic triple- or quadruple-bottom line multi-criteria analyses. Multi-criteria analysis [54] is a particularly useful decision-making tool for projects with multiple objectives, inherent to the definition of NbS, and costs or benefits that are difficult to monetize (e.g., indirect or intangible). A comprehensive assessment of the financial, environmental, and social costs is required to illuminate the otherwise uncaptured benefits of NbS and enable economically sound decision-making [26].

While the benefits of NbS are increasingly being recognized and quantified, they must be deployed with consideration for systems and local contexts, and for future change, and are not universally appropriate or successful. Indeed, there is potential for negative consequences if NbS are misapplied or not well conceived. An example of potential unintended consequences in river watersheds is that afforestation

Figure 5: Examples of ecosystem services provided by NbS for flood and erosion risk management. Adapted from IUCN [51]



for the purpose of attenuating floods has potential to generate or exacerbate woody debris hazards. In coastal or estuarine environments, managed realignment of dykes has the potential to alter tidal prisms and regional circulation patterns [55], with potential negative consequences for ecosystems or communities (e.g., increased flood risk). Placement of sediment on beaches or dune systems as part of a nourishment scheme, a common coastal nature-based solution, has potential to disturb natural ecosystems and habitats, usually temporarily. An important consideration in design of such solutions is therefore to understand the resilience of the system, capacity/timescales for recovery, and the balance between short-term impacts and longer-term benefits.

3.6 Nature-Based Solutions through Strategic Planning

Broadly speaking, NbS for flood and erosion risk management can be deployed in two ways: (1) through sustainable planning and regulatory frameworks that recognize the value of natural assets and infrastructure in supporting risk management objectives, discussed in this section, and (2) through the targeted and/or cumulative deployment of nature-based features to provide specific functions, which is discussed in Section 3.7.

Sustainable planning includes the following [21]:

- Integrated water resources management (including integrated river basin management)
- Integrated coastal zone management
- Strategic flood risk management
- Land use regulation
- Restoration
- Natural asset management

Each of these planning aspects can make use of NbS. They are covered in more detail in the following subsections.

3.6.1 Integrated Water Resources Management

Integrated water resources management (IWRM) is a concept dating back to the early 20th century whereby water, land, and related resources would be managed in a holistic and broad participatory manner to maximize economic and social benefits without compromising the sustainability of the environment. Though sometimes criticized for the vagueness of the concept and associated challenges for broad

Case Study D: Pelly’s Lake Wetland Restoration, Manitoba – the Value of NbS

In 2015, a managed wetland water retention system was built on Pelly’s Lake to support flood risk management within the Boyne River watershed and improve water quality in Lake Winnipeg. The system captures surface water runoff during the spring, reducing peak flood discharges downstream, and retaining nutrients and pollutants upstream of Lake Winnipeg. The site is drained in the summer, providing ideal conditions for growing cattails and other emergent wetland vegetation, which contribute to nutrient uptake and provide habitat for birds and wildlife. Under drier conditions in the fall, cattails are harvested and sold for bio-energy generation. Over 200 hectares of wetlands were restored, resulting in significant increases in the number and diversity of waterfowl and marsh birds. Economic assessments of Pelly’s Lake water retention system estimated annual contaminant removal and flood damage reduction benefits of more than $17,000 per hectare (2017 dollars) of the 121 ha retention basin, and net benefit-cost ratios in the range of 2.8 to 3.64 [140]. The Pelly’s Lake Wetland Restoration demonstrates the value of wetlands in providing flood risk management benefits and a variety of co-benefits in river systems.

Case Study E: Ganaraska River Headwaters Reforestation, Ontario

Agriculture expansion in the 19th century, accompanied by deforestation of the Ganaraska River basin headwaters, contributed to water and wind-driven erosion and flooding in the town of Port Hope, where the river discharges into Lake Ontario. Reforestation operations were conducted in this region over an extensive period (1945 to 2007) to address these challenges. Buttle [95] investigated the response of streamflows to reforestation in a 267 km^2 headwater basin of the Ganaraska River. From an analysis of several streamflow metrics in basins and sub-basins with similar characteristics but different headwater reforestation extents, reforestation activities were found to enhance groundwater recharge by prolonging snowmelt and reducing the potential for high river flows during rain-on-snow events. This is a useful Canadian example of how reforestation and tree planting can represent, or contribute to, NbS for flood risk management in river basins.

implementation, IWRM was rediscovered and has been widely promoted since the 1990s, partly in recognition of the need to consider multiple criteria and perspectives to guide the management of water [56]. IWRM recognizes the interconnectedness of water systems through the hydrological cycle, the impacts of land management on water resources (and vice versa), and the need for collaborative, multi-disciplinary approaches. These aspects make IWRM wholly compatible with NbS, considering the principles outlined in Section 3.1.

The concept of integrated river basin management (IRBM) is closely linked to, and derived from, IWRM [57]. Perhaps best exemplified by the Room for the River Programme in the Netherlands, IRBM is described by Rijke *et al.* [57] as having three distinguishing characteristics: (1) alignment and balancing of multiple objectives; (2) utilization of systems approaches that consider all relevant spatial scales; and (3) requiring consideration of short- and long-term costs and benefits, and anticipation of future changes. Again, these features of IRBM are strongly aligned with the principles of NbS.

3.6.2 Integrated Coastal Zone Management

Integrated coastal zone management (ICZM) is a multi-disciplinary approach to planning and governance that seeks to integrate and balance development and the use of resources in coastal areas with environmental and social goals [58]. Two of the key objectives of ICZM are to preserve/protect the productivity and biodiversity of coastal ecosystems and to promote rational development and sustainable utilization of resources [58]. ICZM shares many principles with NbS (Section 3.1), including [58]:

- Multi-sectoral considerations, i.e., the need to balance different technical, environmental, and societal goals and objectives, and multiple uses of coastal space;
- Multi-disciplinary, “whole system” perspectives;
- The need to consider long-term planning horizons in the delivery of environmentally sound responses to reduce the vulnerability of low-lying coastal communities to coastal storms and relative sea-level rise; and
- A dynamic, evolutionary (i.e., adaptively managed) process.

As evident from the latter two bullets above, ICZM often involves adaptation planning, that is, preparing coastal communities for future change [59]. The “protect/accommodate/retreat/avoid” (PARA) framework for coastal adaptation is well established internationally and has previously been adopted in Canada [60], [61]. It includes four strategies for adapting to changing flood and erosion hazard risk [6], [60], [61]:

- **Protect –** involving deployment of structural or nature-based solutions in the way of the hazard to protect people and infrastructure (e.g., seawalls or beach nourishment to protect a community from coastal storms);
- **Accommodate –** an adaptive approach whereby areas exposed to flood hazard continue to be used by people and infrastructure, while behaviours and infrastructure are changed to reduce the consequences of flooding and erosion;
- **Retreat** (or planned retreat or managed retreat or managed realignment) – withdrawal, relocation, or abandonment of areas prone to flood and erosion hazards;
- **Avoid –** proactive prevention of development or settlement in areas prone to flood and erosion hazards, which is usually the preferred, and most effective, strategy for flood risk management.

Although most commonly applied in the context of coastal community adaptation to sea-level rise [60], [61], the PARA strategies are also relevant in the broader context of coastal flood risk management. Indeed, they resemble the generic coastal defence strategy options allowed under shoreline management planning guidance in the U.K. [62] (see the Shoreline Management Plans in **Case Study F**) and they can definitely support and enable NbS. For example, managed realignment involves breaching or removing existing flood defences (usually constructed sea dykes) to restore or create more natural intertidal system functions. This may or may not also involve relocation or planned retreat [63] of communities and infrastructure.

Practical guidelines for developing and implementing ICZM programs and plans are provided by Post and Lundin [58]. As highlighted by the United Nations Office for Disaster Risk Reduction (UNDRR) [64], combining ICZM and IWRM can be a powerful ridge-to-reef or mountain-to-sea approach to managing water resources and coastal zones.

Case Study F: Shoreline Management Plans, United Kingdom (England and Wales)

Shoreline management planning, defined by Cooper et al. [62] as "large-scale and longer-term strategic planning in order to reduce risks to people and the developed and natural environments from coastal flooding and erosion," arguably fits within the nexus of ICZM. One of the first examples of this approach was initiated in the U.K. in the 1990s. The first generation of shoreline management plans (SMPs), prepared by co-operative groups that included local authorities and the Environment Agency, was intended to promote sustainable coastal defence policies within physically self-contained units (Shoreline Management Units) over a time period of 50 years. The SMPs were expected to provide broad-level assistance to local planning authorities and integration with coastal habitat management plans, biodiversity action plans, coastal zone management plans, estuary management plans, and catchment management plans [62]. They also provided the basis for more detailed flood and coastal defence strategy plans at the local level. A critical review of the program in 1999–2000 identified numerous beneficial effects on coastal defence policy in England and Wales, as well as areas for improvement, including the need to better consider the potential role of NbS [62]. A second generation of plans (SMP2s) commenced development in 2006, following revised guidance [69]. The new guidance emphasizes the importance of existing natural defences (such as sand dunes, saltmarshes, and shingle ridges) in contributing to coastal flood and erosion risk management, and encourages consideration of measures to restore or recreate natural defences [69].

"Since the establishment of the National Flood Damage Reduction Program (FDRP) in 1975, regulation of land use to discourage development in flood prone areas has been the primary mechanism for flood and erosion risk management in Canada."

3.6.3 Strategic Flood Risk Management

Strategic flood risk management (SFRM) is a practice that is often encompassed by IWRM and/or ICZM, which have a broader focus. SFRM involves utilizing limited resources to reduce, control, accept, or redistribute flood hazard risk, while supporting and balancing other objectives (e.g., environmental, social, and economic) [27], [65]. It emphasizes longer term, whole system perspectives and identifies promoting ecosystem services as a key objective [27]. In one of ten golden rules for SFRM, Sayers et al. [65] describe the importance of allowing some flooding to occur as a natural process: "Making room for the river and the sea, utilizing the natural ability of this space to accommodate flood waters and dissipate energy, maintains vital ecosystems and reduces the chance of flooding elsewhere." Thus, NbS are deeply embedded in SFRM. Like NbS, SFRM encourages the use of a portfolio of solutions to deliver multiple benefits, adaptive management approaches, and consideration of multiple temporal and spatial scales [27]. A distinctive feature of SFRM is that it relies on knowledge of flood risk (encompassing hazard likelihood, severity, and consequences) and uncertainty to inform decision-making and prioritization of solutions and strategies, and is therefore well aligned with disaster risk reduction efforts such as the United Nations Sendai Framework [17].

3.6.4 Land Use Regulation

Since the establishment of the National Flood Damage Reduction Program (FDRP) in 1975, regulation of land use to discourage development in flood-prone areas has been the primary mechanism for flood and erosion risk management in Canada. The program supported flood hazard mapping to establish designated flood risk areas, where provinces, territories, and municipalities could regulate or prohibit development, and where disaster assistance could be refused to new developments [2]. In theory, this approach should be conducive to NbS, in so far as it would restrict disturbance to natural flood plains and coastal systems and maximize the flood and erosion risk management benefits they provide. In practice, however, demand for waterfront development and the associated tax revenues has created significant pressures on authorities responsible for regulation [2]. A lack of consistency in defining regulations across Canada has also resulted in various degrees of success in terms of managing flood risk. Furthermore, since land use is generally regulated at the municipal government level, this tool often does not facilitate the whole system approaches needed to facilitate NbS, particularly where the system in question, such as the river catchment or coastal littoral cell, spans municipal boundaries. To be effective in reducing flood and erosion risk, regulatory tools need to be underpinned by strategic geospatial planning that includes consideration for system boundaries and future changes in hazards, such as the idea of preserving a freedom space for rivers proposed in Quebec [66].

Designation of protected areas (e.g., national or provincial parks, migratory bird sanctuaries, and marine protected areas) is one form of land or water use regulation that can support implementation of

NbS [64]. Though primarily focused on conservation and preservation of existing natural system functions, habitats, and biodiversity, protecting areas from development allows the flood and erosion risk management benefits of natural systems to be preserved and harnessed. This type of tool may not be appropriate in locations where the natural system has been significantly altered by human activity in the past, or where development has occurred in high flood and/or erosion hazard areas.

3.6.5 Restoration

Restoration of degraded natural systems, such as afforestation or revegetation of river watersheds and coastal land and managed dyke realignment or breaching to restore tidal saltmarshes, can unlock many benefits in terms of managing flood and erosion risks [21]. Two case studies exemplifying the benefits and co-benefits of shoreline restoration for different types of environments are presented here: coastal/estuarine marshes in the Bay of Fundy Dyke Realignment project in **Case Study G**, and the Jim Tovey Lakeshore Conservation Area on the shores of Lake Ontario in **Case Study H**. Similar to the designation of protected areas, the philosophy underlying restoration is different to strategic flood risk management in that it prioritizes environmental objectives as opposed to minimizing risk to people, infrastructure, and the environment. However, restoration and strategic flood risk management, or

Case Study G: Bay of Fundy Dyke Realignment, New Brunswick and Nova Scotia

Salt water marshes and coastal/estuarine wetlands provide natural buffers against storm surges, waves, erosion, streamflow-driven flooding, and sea-level rise. Since the 17th century, approximately 85% of the salt marsh area in the upper Bay of Fundy was transformed to agricultural land by dykes, roads, and causeways [141], altering the natural system dynamics. In 2010, the provincial government purposely breached 1.5 km of an old dyke at Aulac in New Brunswick, and constructed a new dyke about 100 m landward. This realignment enabled restoration of previously degraded salt marsh habitat. Virgin *et al.* [141] investigated the response of the Aulac system to dyke realignment and observed 34–67 cm thick sediment layers had deposited in the seven-to-eight-year period following restoration (Figure 6). The Cornwallis River and Converse Marsh (www.transcoastaladaptations.com) are other examples of managed dyke realignment projects in the Bay of Fundy that have restored tidal wetland habitat, reduced dyke management costs, contributed to carbon storage, and provided flood risk management benefits.

Figure 6: Aulac salt marsh, in 2011, approximately one year after breaching (a) (Reproduced with permission from Nic McLellan), and in 2020 (b) (Reproduced with permission from Myriam A. Barbeau).

Case Study H: Jim Tovey Lakeview Conservation Area, Ontario

The project involves creating a 26 ha conservation area on a 1.5 km reach of the Lake Ontario shoreline, near an existing wastewater treatment plant (Figure 7) [142]. Construction commenced in 2016 and is expected to be completed in 2024–2026. The objective is to restore and enhance fish and bird habitat, provide green space for recreation, and protect 1.5 km of degraded shoreline. The project involves constructing new wetlands and rocky islands, cobble beaches, and a channel connecting Serson Creek to Lake Ontario [143]. The islands will protect the shore from wave action and provide shelter to fish. Applewood Creek and Serson Creek will discharge into the constructed wetlands, trapping nutrient loads and contributing to improved water quality in Lake Ontario.

Figure 7: Lakeview waterfront restoration (a), Source: The Region of Peel, Credit Valley Conservation and Toronto Region Conservation Authority; Physical model of Lakeview waterfront at National Research Council Canada's research facilities, Ottawa (b), Source: National Research Council Canada.

other strategic planning approaches like natural asset management, are not mutually exclusive. In fact, they can be complementary in unlocking multiple benefits.

3.6.6 Natural Asset Management

Natural assets are defined as "the stock of natural resources and ecosystems that yield a flow of benefits to people" [67]. With support from the Municipal Natural Assets Initiative, the Federation of Canadian Municipalities, and other organizations, Canadian municipalities are increasingly using natural asset management approaches to protect, manage, and ensure continued delivery of ecosystem services to communities, as shown in the Courtenay River Natural Asset Management project outlined in **Case Study I**. This approach typically involves identification, monitoring, maintenance, and rehabilitation of natural assets as part of an overall asset management strategy, and it has been shown to save capital and operating costs and reduce risk [67].

3.6.7 General Considerations

Many of the frameworks and concepts described above are precursors to and/or are closely aligned with the ideas underlying NbS for flood and erosion risk management and, when successfully implemented, can all enable NbS. The differences between some of these concepts are somewhat nuanced, and they typically relate to the primary focus and philosophy. For example, Strategic Flood Risk Management proponents might view NbS as a means to achieve reductions in flood risk, with ancillary environmental benefits. At the other end of the spectrum, proponents of protected areas or restoration might consider the preservation and health of ecosystems to be the priority, with the role of natural assets in alleviating flooding seen as a potential co-benefit. By design, IWRM and ICZM aim to balance multiple considerations and objectives and are therefore arguably the more balanced philosophical approaches.

Case Study I: Courtenay River Natural Asset Management, British Columbia

The Courtenay River flows from the confluence of the Tsolum and Puntledge Rivers through the City of Courtenay to Comox Harbour on the east coast of Vancouver Island. The city is mostly developed in low-lying areas of the estuary, and has been historically subjected to coastal and riverine flooding. Climate change effects have increased the frequency and intensity of flooding in the Courtenay River system over time. The City of Courtenay assessed the role of natural assets located in the Courtenay River corridor in mitigating flood risk in the downtown core. The project was conducted with support from the Municipal Natural Assets Initiative (MNAI), convened in 2016 to assist local governments in identifying and understanding the value of natural assets in addressing environmental and hydrological challenges [48]. Four flood mitigation options involving natural asset improvements were investigated: (1) increasing the conveyance capacity of the system by widening the Courtenay river, (2) naturalizing the foreshore area of a former sawmill site, (3) restoring historical natural streams within the Courtenay river system, and (4) removing at-risk buildings from the floodplain (setback). It was concluded that although improvement of natural assets could contribute to reducing flood damages, and provide co-benefits, including recreational space and water quality, additional measures would be needed to manage flood risk. Hybrid solutions, combining natural and engineered infrastructure, were therefore recommended.

4 Nature-Based Features

Descriptions of typical nature-based features, which may be deployed at local and regional scales to support flood and erosion risk management objectives, are provided in Section 4.1 for coastal environments and Section 4.2 for riverine environments. On the coast, nature-based features primarily function by providing buffers against waves, storm surges, and erosion. In riverine environments, features are generally deployed to increase water storage capacity within the floodplain, regulate flows and runoff, control or mitigate erosion, or enhance surface water infiltration. A special case occurs in estuarine areas, where flood hazards can arise from various combinations of high river flows, coastal water levels (associated with tides, storm surges, seiches, tsunamis, and relative sea-level rise) and wave effects. Nature-based features in estuarine regions may therefore combine elements and principles of coastal and riverine features, depending on the specific nature of flood hazards and ecosystems. Although the principles of how nature-based features provide flood and erosion risk management function in estuaries are likely to be similar to coastal and/or river settings, estuaries are distinct ecosystems that may require special considerations for hydrodynamics, biogeomorphology, ecology, and water quality when implementing NbS.

4.1 Coastal Environments

More than 15 million people live within 20 km of Canada's marine and Great Lakes coasts [6]. Many of these communities are vulnerable to coastal flood and erosion hazards [5] resulting from extreme water levels, waves, tsunamis, and other contributing factors. In most regions, the risks associated with coastal flood and erosions hazards are escalating over time, due to pressures including development and population growth in coastal zones, and climate-driven effects, such as global sea-level rise, thawing permafrost, and declining sea ice. In particular, relative sea-level rise is expected to lead to more frequent and severe flooding on Canada's Atlantic, Pacific, and Beaufort Sea coasts [5], [68].

There are a variety of natural or nature-based features that can provide flood and erosion risk management benefits (and ancillary co-benefits) in coastal environments. A summary of some features relevant to Canadian coastal environments is provided in Table 1, which has been adapted from an example in Bridges *et al.* [31]. Examples of the mechanisms/processes by which each feature typically delivers flood and erosion risk management benefits are indicated, along with relevant factors affecting performance.

NbS for coastal flood and erosion risk management can be thought of as leveraging natural systems to provide strategic coastal defence functions, expressed in the parlance of U.K. Shoreline Management Planning guidance [69] as holding the defence line or advancing the line. The natural or nature-based feature (Table 1) may form the defence line or be located on either side of it. Managed realignment strategies can also unlock or restore flood and erosion risk management benefits that have been lost or degraded due to prior development on the coast or in estuaries.

Table 1: Examples of NbS for coastal flood and erosion risk management (adapted from Bridges et al. [31]).

Features	**Dunes and Beaches**	**Vegetated Features** (Marshes, Submerged Aquatic Vegetation, Wetlands)	**Reefs**	**Barrier Islands**	**Maritime Forests and Upland Shrub Communities**
Flood and Erosion Risk Management Benefits/Processes	Buffer against erosion and wave action Attenuation of wave energy Barrier/resistance to inundation and overland flow	Attenuation and dissipation of wave energy Hydraulic storage Promotes retention of stabilizing sediment Increased infiltration	Induces offshore wave breaking Attenuation of wave energy Slow inland water transfer Provides redundancy as part of multiple line-of-defence system	Buffer against erosion and wave action Attenuation of wave energy Provides redundancy as part of multiple line-of-defence system	Wave attenuation and/or dissipation Soil and sediment retention and stabilization Increased infiltration Decreased or delayed run-off Attenuation of overland flow peaks
Factors Affecting Performance	Wave climate and exposure Sediment supply, sediment budgets and sediment transport processes Stability in response to extreme events Berm/dune height and width Beach slope Frequency and severity of disturbance, and rate of recovery	Hydrodynamic regime (frequency of inundation, wave exposure, salt tolerance) Sediment supply, sediment budgets and sediment transport processes Vegetation characteristics (type, height, density, rigidity, morphology, salt tolerance) Spatial extent (elevation, storage volume, width) Frequency and severity of disturbance, and rate of recovery	Reef width, elevation and roughness Tidal range Wave climate and exposure Frequency and severity of disturbance, and rate of recovery	Island elevation, length, and width Sediment supply, sediment budgets and sediment transport processes Breach susceptibility Proximity to mainland Capacity to recover/rebuild following storm events Frequency and severity of disturbance, and rate of recovery	Vegetation characteristics (type, height, density, rigidity, morphology, root systems, salt tolerance) Spatial extent (elevation, storage volume, width) Ground characteristics (soil types, stratigraphy, permeability, water retention, organic content) Elevation, slopes and drainage Frequency and severity of disturbance, and rate of recovery

Beach nourishment, stabilization, or restoration is perhaps the most familiar form of coastal NbS, with the relevant physical processes (hydrodynamics and sediment transport) and coastal engineering principles having been extensively studied and applied for decades [70]. Conventionally, beach nourishment has emphasized the use of sediment that closely matches the characteristics of native beach materials (e.g., gradation). Dynamic revetments also referred to as cobble/shingle/pebble berms or beaches are a form of beach nourishment that utilizes coarser material (cobble and gravel), while still allowing for reshaping and adaptation to changing hydrodynamic conditions [71], [72]. Such solutions may be appropriate for holding or advancing the line in areas with coarse native sediments (e.g., many parts of British Columbia), in regions with finer sediments where natural sources and supply are limited (e.g., Percé Waterfront Rehabilitation project in **Case Study B**), or where there are constraints on the footprint of a nourishment (e.g., prohibitions on placing fill below the water line). Recently, a greater understanding of the potential advantages of "mega-nourishments" has been realized, based on research on the Sand Motor in the Netherlands as presented in **Case Study J**. Advantages of larger nourishments include the ability to extend intervals between re-nourishments, which are beneficial because placement of sediment has negative impacts on beach ecosystems, and reliance on natural system processes to redistribute sediment.

NbS in coastal environments are often hybrid solutions, combining some of the elements of Table 1 with conventional or grey infrastructure. For example, buried revetment concepts (Figure 3) utilize natural beach and/or dune features to provide flood and erosion risk management function, with the added backstop of a hard structure, which provides the last line of defence in the event of a particularly damaging storm. Beach/dune nourishment schemes often rely on fencing, breakwaters, or groyne structures to retain sediment and delay intervals between re-nourishments (see Souris Beach Shoreline Erosion and Highway Projection in **Case Study K**), depending on the available sediment supply (natural or artificial) and optimal timeframes for system recovery.

Given the legacy of hard structures such as seawalls, groynes, revetments, and breakwaters on coasts around the world, significant effort has recently been dedicated to researching methods of "greening" or enhancing existing coastal infrastructure. Examples include the use of roughened textures or features (e.g., water retaining tide pools) on hard structures to promote marine biological growth or provide habitat for marine organisms as shown in Living Breakwaters in **Case Study A**. For new coastal infrastructure, often still appropriate in circumstances where more natural solutions are not viable or sustainable, such features can support ecosystem health or at least mitigate adverse environmental impacts of hard infrastructure.

4.2 Riverine Environments

Fluvial flooding in Canada is predominantly driven by elevated river discharges associated with spring snowmelt (freshet) and/or prolonged or intense rainfall [4]. Rainfall coinciding with snow cover increases the likelihood of flooding, considering the reduced capacity for infiltration. As ice is present in nearly every Canadian river [73], ice-jamming during spring break-up represents a major driver of flood events [4], and often results in the most damaging and severe flood hazards. Backwater effects associated with coastal/estuarine high-water levels resulting from high tides, storm surges, and relative sea-level rise can also contribute to flooding in river watersheds.

NbS for riverine flood and erosion risk management typically involve applying the long-standing principles of integrated water resources management (IWRM) [21]. Broadly speaking, there are three main ways in which NbS can reduce flood and erosion risk in river systems [10]:

1. Regulating, either slowing or accelerating, the flow/conveyance of river flows and surface water runoff at strategic locations to manage the timing and magnitude of peak flows within the system;
2. Increasing water storage capacity within the floodplain, such as through offline storage/retention features, or by increasing connectivity between the river channel and floodplain; and
3. Enhancing surface water infiltration and below-ground storage, and/or evaporation.

Case Study J: The Sand Motor, Netherlands – Mega-Nourishment as a Coastal NbS

More than 9 million residents live near the coast in the Netherlands, many of them below mean sea level. A shortage of natural sediment supply and sea-level rise contribute to erosion at many locations along the coast. In 2011, Rijkswaterstaat and the Provincial Authority of South Holland decided to pilot a "mega-nourishment" scheme to mitigate coastal erosion, called the Sand Motor. The mega-nourishment involved depositing a single, large quantity of sand near the shore to feed and sustain a 5 km stretch of coastline for a number of years. The initial nourishment consisted of 21.5 million m^3 of sand, extracted from a borrow location 10 km offshore, and deposited in the form of a hook shaped peninsula (Figure 8). The peninsula was 2 km wide, extended 1 km offshore, and reached up to 5 m above mean sea level in some locations [144]. The pilot project aimed to understand if natural processes (waves, currents, and wind) could work and redistribute the sand along the coast. By concentrating a single mega-nourishment at one location, the goal was to minimize long-term ecosystem damage resulting from the sand placement, compared to (conventional) smaller, more frequent nourishments distributed along the coast that impact a larger area and inhibit ecosystem recovery. The large nourishment creates new habitat for flora and fauna, particularly in the sheltered and shallow lagoon that developed behind the spit (Figure 8).

Figure 8: Sand Motor peninsula. Reproduced with permission from www.dezandmotor.nl.

The Sand Motor has been monitored to assess its effectiveness in nourishing the adjacent coasts, contributing to dune growth, creating new habitat, and providing recreation space [145]. The data have indicated that, in the first four years following its construction, the Sand Motor provided almost 1 million m^3 of sand to the south coastline and 1.5 million m^3 to the north coastline. Based on these initial observations, the Sand Motor is expected to exceed its initial design life of 20 years [144]. Approximately 1 ha of new dunes have formed behind the Sand Motor. The dune development has been slower than initially anticipated, which has been attributed to the fact that dune formation was entirely left to natural processes (i.e., there was no artificial dune construction or planting of stabilizing marram grass). The monitoring has also shown that there is increasing biomass of benthic fauna immediately offshore of the sand dune and in the four years of monitoring between 2011 and 2015, almost 40 species of birds were regularly observed on the Sand Motor [144], [146]. It appears that the Sand Motor is performing as designed and "mega-nourishment" is a valid alternative to regular beach nourishment.

Case Study K: Souris Beach Shoreline Erosion and Highway Protection, Prince Edward Island – A Hybrid Solution

Shoreline erosion and relative sea-level rise were contributing to increasing flood risk along a relatively exposed section of the Trans-Canada Highway near Souris Beach, Prince Edward Island (PEI). In 2016, storms eroded much of the small dune system along the beach, bringing flood waters to the edge of the highway. PEI Transportation Infrastructure and Energy (PEI-TIE) worked with Coldwater Consulting Ltd. to implement a demonstration shore protection scheme involving a combination of dune restoration works and intertidal reef structures, which were designed to dissipate wave energy, and encourage sediment deposition on the beach in front of the highway. The reef structures consisted of sandstone boulders, designed to mimic the rocky outcrops present along the coast of PEI and provide a natural substrate for growth of marine organisms. The dune restoration involved sand fencing and vegetation planting, following guidance developed for the east coast of the U.S. [147], [148]. Construction was completed in March 2018 (Figure 9), and post-construction surveying using RTK-GPS and drones has indicated that the solution performed as anticipated with a small tombolo beach formation growing in the lee of the two reef structures. The resulting increase in the upper beach area has, in turn, led to growth and vegetation of the landward dunes. No repeat of the large shoreline recession that occurred in 2016 has been observed, despite significant storm events in November 2018 and September 2019 (post-tropical storm Dorian).

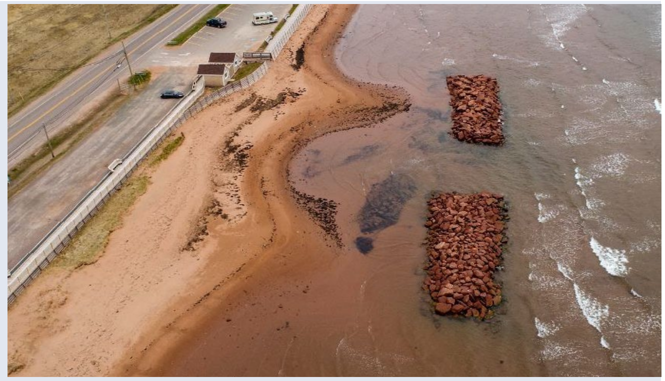


Figure 9: NbS for coastal erosion at Souris. Reproduced with permission from M. Davies, Coldwater Consulting Ltd.

Thus, NbS in rivers are centred on enhancing or restoring natural system function to store, slow, or disperse floodwater in areas that minimize the exposure of people and property to flood hazards. Different measures and interventions can be applied to achieve these objectives. The Federal Emergency Management Agency (FEMA) in the U.S. [74], [75] and the ICF in Canada [50] describe common nature-based approaches for riverine flood risk reduction, which are broadly categorized in Table 2 and summarized in the sections that follow.

4.2.1 Floodplain and River System Preservation and Restoration

Flooding is a natural process. Preserving and allowing room or freedom space for natural river and floodplain system functions can therefore reduce the degree to which people and infrastructure are exposed to flood hazards, and maintain or provide additional storage within the floodplain [76], [77]. In essence, this solution amounts to "avoidance", which is broadly accepted to be the most effective strategy for flood risk management [6], [78], [79]. This strategy can involve restoration of previously developed areas of the floodplain, for example, through managed realignment or planned retreat [63], [77], [80] (see Cache la Poudre River Restoration in **Case Study L**), or establishing regulations to prohibit/limit developments within areas of high flood hazard, which has been the primary strategy for flood risk management in Canada [2]. Natural or nature-based water-retaining features within the floodplain such as ponds and depressions [81] can help to store and slow the flow of water to river channels and enhance ground infiltration. Ancillary benefits include enhanced sediment and water quality control, achieved by trapping sediments, pesticides, and nutrients [82].

Table 2: Examples of NbS for riverine flood risk management.

Features and Approaches	Floodplain and river system preservation and restoration	Wetland restoration	Two-stage channel	Relief channel	In-stream features	Vegetation
Flood and Erosion Risk Management Benefits/Processes	Attenuation of peak flood flows and water levels Increased storage capacity within floodplain Promotes retention of sediment and floodplain accretion Provides room for natural river processes (e.g., meandering, channel avulsion, flooding)	Attenuation of peak flood flows and water levels Enhances infiltration Increased storage capacity within floodplain Promotes retention of sediment and floodplain accretion	Mimics natural channel/ floodplain processes Increases conveyance capacity Provides room for main channel migration Promotes retention of sediment and floodplain accretion Benches dissipate flood energy	Mimics natural channel/ floodplain processes Increases conveyance capacity during flood conditions	Attenuates and regulates streamflow and velocities Alters hydraulic gradient Reduces bank erosion	Attenuates and regulates flow in channels and floodplains Enhances infiltration Promotes retention of sediment, stabilization of soil, and reduces erosion
Factors Affecting Performance	Sediment budgets and transport processes Spatial extent (elevation, storage volume, width) Hydrologic, hydraulic, and geomorphic regimes Native ecosystems, habitat, and vegetation types	Hydrologic, hydraulic, and geomorphic regimes Sediment budgets and transport processes Spatial extent Native ecosystems, habitat, and vegetation types	Hydrologic, hydraulic, and geomorphic regimes Bank stability in response to extreme events	Hydrologic, hydraulic, and geomorphic regimes Channel bed elevation relative to the main channel Conveyance capacity Frequency/ duration of flow in relief channel Connectivity of relief channel to natural systems	Hydrologic, hydraulic, and geomorphic regimes Potential for trapping of debris Bank stability in response to extreme events Scour potential	Vegetation characteristics (type, height, density, rigidity, root systems, native types) Ground characteristics Hydrologic, hydraulic, and geomorphic regimes

Case Study L: Cache la Poudre River Restoration, Colorado, U.S.A.

The Cache la Poudre River is a source of drinking water, and provides stormwater conveyance and tourism benefits to Fort Collins, Colorado [149]. Levees/dykes were constructed along the river banks during gravel-mining operations to prevent flooding. This disconnected the river from its floodplain and altered natural system processes, concentrating high flows in the main channel, increasing river bank erosion rates and eliminating bankside vegetation and habitat [150]. Two river restoration projects, the Sterling Pond Restoration Project and the McMurry Restoration Project, were implemented to reconnect the Cache la Poudre River to its floodplains. The Sterling Pond project spanned a 600 m reach with an abandoned dam at the downstream end of the project stretch. The goals of the restoration work were to lower the river bank elevations to reconnect with the floodplain, create additional shallow wetland habitat in the newly connected floodplain, and remove the abandoned dam. Removing the abandoned dam helped to restore natural river flow and enabled fish passage [150]. Once the dam was removed, approximately 150 m of river was modified to include natural river features such as riffles and pools and to improve the river gradation. The McMurry Restoration Project covered an 800 m stretch of river and involved similar techniques, including lowering the river banks and creating new wetlands. The McMurry Restoration Project also included significant removal of concrete, debris, and old cars from the river bank that were historically placed there to mitigate bank erosion resulting from high flows in the main channel. Combined, the two projects restored nearly two kilometres of river, created over five hectares of floodplain and several hectares of wetlands [150]. The City of Fort Collins is continuing to look to implement restoration projects that connect the Cache la Poudre River to its floodplain.

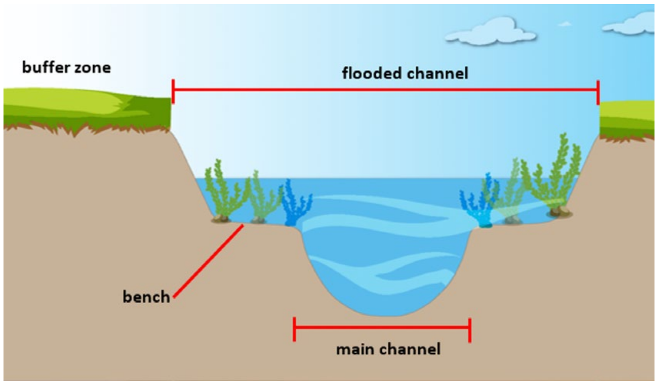
4.2.2 Wetland Preservation and Restoration

Canada is home to approximately 24% of the world's natural wetlands, which have been shown to reduce climate-related flooding costs by as much as 38% [26]. Wetland areas typically represent a significant proportion of natural river floodplains but have been severely reduced by changes in land use for agriculture and development [83], [84]. Wetlands can reduce or delay floods by trapping and storing surface runoff or floodwaters and enhancing infiltration to soil and groundwater. Vegetation creates resistance to flow, slowing the movement of water within the floodplain and attenuating runoff. Although most studies indicate that wetlands can provide an important role in flood attenuation, Bullock and Acreman [85] caution against generalization, and show that the diverse hydrological role and function of wetlands within broader systems should be considered. In particular, wetland restoration through managed dyke realignment in estuarine areas alters the tidal prism, which may have unintended consequences, including increased flood risk in adjacent areas [55]. Wetlands are highly biodiverse and productive ecosystems, providing co-benefits such as water filtration, carbon sequestration, wildlife habitat improvement, nutrient retention, ground water recharge, sediment transport control, moderation/prevention of droughts, and recreation and educational opportunities [86]–[90].

4.2.3 Two-Stage Channels

Two-stage channels (Figure 10) are modified versions of conventional trapezoidal channels, which are more aligned with NbS. The main channel that conveys the river flow during normal conditions, and a floodplain bench that conveys water only when the capacity of the main channel is exceeded (e.g., during flood or high discharge conditions), mimic natural channel and floodplain function. They provide flood and erosion risk management benefits by facilitating higher discharges than channelized reaches with equivalent width to the main channel, dissipating hydrodynamic energy on the benches, improving channel stability, or providing room to facilitate meandering of the main channel, controlling downstream sediment transport by allowing for deposition on benches, improving water quality, and increasing habitat diversity [91], [92].

Figure 10: Two-stage channel concept.



4.2.4 Relief Channels

Restoration and reconnection of relict channel networks or the construction of new, naturalized channel systems can reduce flood risk by diverting floodwaters around developed areas or vulnerable communities, or by temporarily storing water during periods of high flow. However, the context for, and implementation of this type of solution determines the extent to which it may be considered a NbS. Straight, hardened relief channels can lead to channelization, interruption of natural processes, and elevated discharges, with associated high velocities and potential for scour. However, restoring relict or disconnected channels can improve or restore habitats and ecosystem function.

4.2.5 Instream Features

Instream features include woody debris (Figure 11 and Figure 12), boulders and other materials, which are strategically placed in river channels and streams to control flood and erosion hazards, typically by increasing flow resistance thus slowing the flow and trapping debris and sediment [81]. These features also encourage overbank flow, diverting water to areas of natural floodplain in headwaters upstream of urban centres. Instream features can support enhanced river bank stability, where desired, by diverting flows away from eroding banks. Leaky dams, woody deflectors, boulder terraces, wood dams, beaver dams, engineered log jams, and engineered riffles are some examples of natural or nature-based instream structures. A comprehensive list of instream structures and guidance for their design and construction is provided by JMT Consultants Inc. [93]. Many of these features are relatively low cost and provide a range of co-benefits, including fish spawning habitat, sediment, and debris retention. Woody deflectors (Figure 11) follow similar design and functionality principles as leaky dams but typically do not span the entire channel cross section [94]. Care must be taken when designing instream features to avoid unintended negative consequences on stream hydraulics and associated hazards [94]. For example, their addition to the areas in close proximity to bridges, culverts, urban development, or protected assets can result in backwater effects and flood hazards, or debris loads on hydraulic structures.

Figure 11: Photograph of a woody deflector in a channel. Source: City of Surrey, BC (a). Schematic of a woody deflector in a channel (b).

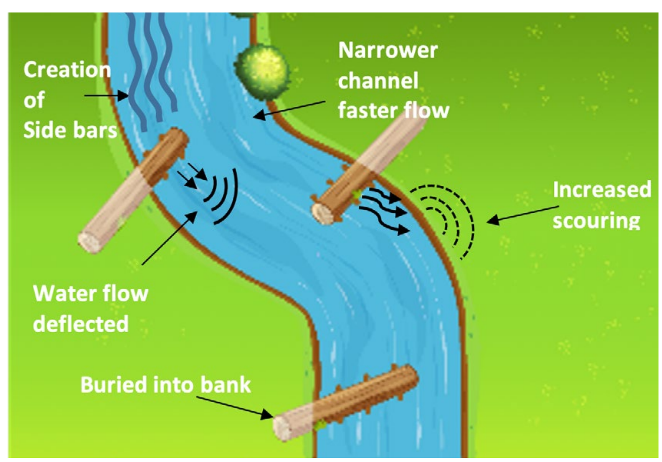
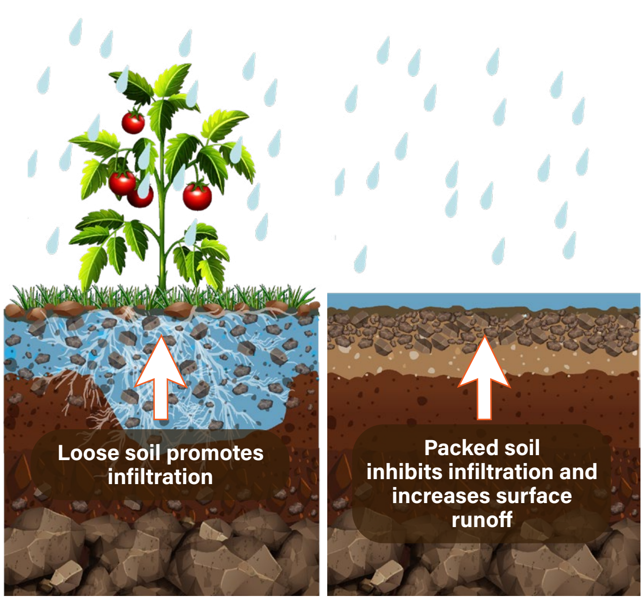


Figure 12: Instream structures constructed with woody debris. Source: City of Surrey, BC.

4.2.6 Vegetation

Planting or restoring woodlands and vegetation (e.g., shrubs, trees, grass) in riparian areas and other areas of a river watershed can provide flood and erosion risk management benefits as shown in the Ganaraska River Headwaters Reforestation project in **Case Study E**. Riparian vegetation provides a buffer against erosion by attenuating water velocities and stabilizing sediment. Vegetation root systems also increase infiltration rates, improve the quality and stability of the soil, and increase habitat and aesthetic quality (Figure 13). Reforestation of headwater regions can reduce flood risk in the lower reaches [95].

Figure 13: Effect of soil structure on the infiltration process. Adapted from Forbes et al. [81].



5 Technical Guidance and Best Practice

In recent years, there has been an explosion of interest in research and development of NbS, which has contributed to a proliferation of technical literature and guidance. Published guidance ranges from high-level, overarching framework documents aimed at broad audiences (including the general public and policymakers), to more detailed technical guides to aid design and implementation of NbS. A non-exhaustive overview of technical guidance pertaining to NbS for coastal and riverine flood and erosion risk management is provided in Section 5.1, highlighting key relevant documents (including standards, where identified) developed in Canada and internationally. More expansive summaries of these and other documents are provided in Appendix B. A synthesis of best practices, distilled from common themes and ideas presented within the existing guidance, is presented in Section 5.2.

5.1 Summary of Technical Guidance

5.1.1 International Guidance

Several international guidance documents have been developed to provide overarching frameworks, principles, considerations, and high-level information for NbS. *The IUCN Global Standard for Nature-based Solutions* [19] was developed to promote consistent approaches to design and verification of NbS worldwide, and provides a useful framework for NbS implementation. It sets out fundamental steps for establishing the credibility of NbS when engaging with investors, and is a potentially useful communication tool for broader engagement prior to design and implementation. The UNDRR's *Nature-Based Solutions for Disaster Risk Reduction* document [64] was developed to support the delivery of the United Nations' Sustainable Development Goals and the Sendai Framework, while providing practical guidance on developing and implementing NbS for disaster risk reduction. It identifies knowledge gaps, enablers, and barriers to uptake of NbS, and provides suggestions for how public and private sector entities can be involved in incentivizing and delivery of NbS. The Inter-American Development Bank (IDB) and the World Bank (WB) have published documents [96], [97] providing guidance, high-level principles, and frameworks for NbS implementation. These international guides provide excellent resources and background information, and useful foundational frameworks for NbS. However, the information provided is relatively high-level and generic, and, therefore, it is a precursor to more detailed technical guidance (including standards) for design and implementation of NbS for coastal and riverine flood and erosion risk management.

More detailed technical guidance specific to coastal and riverine applications has been developed by a variety of international organizations [10], [11], [31], [81], [98]–[101]. *Natural and Nature-Based Flood Management: A Green Guide* [99] was developed by the World Wildlife Fund to support the use of natural and nature-based methods for flood risk management, based on integrated flood management (IFM) approaches (i.e., combining elements of the IWRM and strategic FRM concepts discussed in Section 3.6). Since 2017, the U.S. Army Corps of Engineers, through its Engineering with Nature® Program, has led an international working group to develop *International Guidelines on Natural and Nature-based Features for Flood Risk Management* [101]. The working group has received contributions from more than 180 practitioners, researchers, and academics from more than 70 organizations, including the National Research Council of Canada. The 1000-page guideline is intended to equip users with information needed to assess the feasibility of, plan, design, and implement NbS for coastal and riverine flood risk management. The Engineering with Nature® website (https://ewn.el.erdc.dren.mil/about.html) also provides a wealth of information and resources for practitioners. In the U.K., the Environment Agency's *Working with Natural Processes and Natural Flood Management* [10] provides a wealth of information on the current state of knowledge surrounding the effectiveness of different measures from a flood risk and ecosystem services perspective. This evidence directory builds on the earlier *Greater Working with Natural Processes in Flood and Coastal Erosion Risk Management* report [100], which explained the basis of working with natural processes to manage flood and coastal erosion risk, and provided recommendations for U.K. governments and practitioners to improve this practice. The Scottish Environment Protection Agency's (SEPA) *Natural Flood Management Handbook* [81] – aimed primarily at local authorities, as natural flood management[2] project proponents – provides practical guidance to support the delivery of NbS. EcoShape, an organization based in the Netherlands that provides engineering services through the delivery and/or utilization of ecosystem services, has developed a comprehensive website (https://www.ecoshape.org/en/) documenting examples of NbS while providing a framework for implementation and identifying key criteria to ensure for successful implementation and functioning of NbS. The U.S. Federal Highway Administration's N*ature-Based Solutions for Coastal Highway Resilience: An Implementation Guide* [98] is a comprehensive and useful guide intended primarily for transportation professionals interested in applying NbS, but it is likely to be of interest to a wider audience.

The international guidance described above (and in further detail in Appendix B) provides important information that is likely to be of use to Canadian communities, governments, project proponents, and practitioners engaged in NbS for coastal and riverine flood and erosion risk management. With added region- and site-specific context and considerations, many of these documents could provide a strong fundamental basis for the development of future standards supporting NbS in Canada. A consistent message across all of the existing guidance is the importance of an enabling framework, which encapsulates the necessary steps for project proponents to plan, design, initiate, and implement NbS. Each of the frameworks described is a slight variation on the others. However, many of the frameworks touch on the following key elements:

- Identifying the need/aspiration
- Multi-stakeholder engagement and approaches
- Capacity building
- Preliminary assessment

2 Natural flood management is defined by SEPA as involving "techniques that aim to work with natural hydrological and morphological processes, features and characteristics to manage the sources and pathways of flood waters", and is therefore roughly synonymous with NbS.

- Benefits and costs assessment
- Vulnerability and risk assessment
- Project evaluation
- Development of performance objectives and metrics
- Options appraisal
- Classification of NbS type
- Monitoring and adaptive management strategies
- Site assessment
- Permitting
- Design and implementation
- Operations and maintenance
- Addressing key policy, governance, and regulatory issues

5.1.2 Canadian Guidance

The growth in interest surrounding NbS in Canada has led to the development of a number of enabling documents and programs, many of which provide a regional context for the planning and implementation of NbS in Canadian environments. On behalf of the Canadian Council of Ministers of the Environment, ICF prepared a report entitled *Best Practices and Resources on Climate Resilient Natural Infrastructure* [50], which summarized the state of practice for natural infrastructure solutions to enhance community resilience to hazards, including riverine flooding, and coastal storms and flooding. This is arguably the most comprehensive report to date discussing NbS across the Canadian landscape, and identifies best practices and NbS commonly applied to support coastal and riverine flood and erosion risk management. The ICF report explains the business case for natural infrastructure with emphasis on socio-economic benefits, including how these solutions can encourage a sense of identify and stewardship in communities, nurture human health and well-being, facilitate outdoor recreation, and increase property values.

A three-part series of guidance documents titled Adapting to Climate Change in Coastal Communities of the Atlantic Provinces, Canada: Land Use Planning and Engineering and Natural Approaches [37], [102], [103] was developed as part of a suite of tools developed by the Atlantic Climate Adaptation Solutions Association (ACASA) to support community adaptation in Atlantic Canada. Though not exclusively focused on NbS, the series illustrate that natural solutions can be integrated within broader adaptation strategies (procedural, avoid, retreat, accommodate, protect). An accompanying online decision tool provides guidance on a range of engineering (grey to green) and land use options depending on user inputs. Similarly, the Nova Scotia Department of Agriculture is currently developing a tool that will aid in the assessment of dyke and tidal barrier upgrades using NbS (along with traditional engineering solutions) such as tidal wetland restoration and managed dyke realignment. The intent is to determine the feasibility of managed realignment using holistic approaches by considering elements of existing land use, hydrology, ecology, geomorphology, soils, and sediments. The tool is in development and not yet publicly available. However, ACASA's series provide a potentially useful framework for design and implementation of NbS across Canada's coastal regions. By covering aspects of land use planning, engineering, and broader considerations for selecting adaptation options, they demonstrate how NbS can be integrated within broader coastal zone management and flood/erosion risk management strategies.

The Municipal Natural Assets Initiative (MNAI) provides technical and policy support to guide local governments in managing their natural assets. Guidance on scoping, defining, and managing natural assets [104], [105] and documented case studies [47], [48] provide useful Canadian examples and lessons learned for how natural assets can be sustainably managed to support flood risk management.

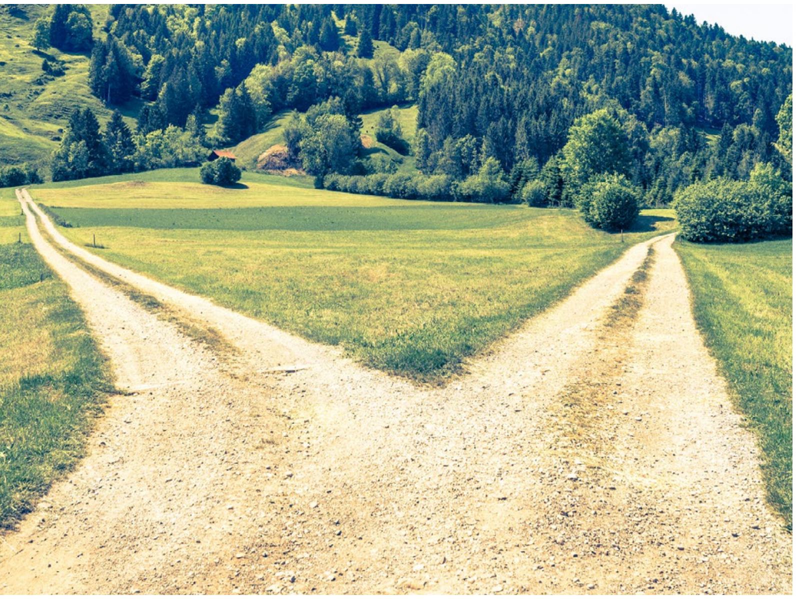
The Green Shores© program, run by the Stewardship Centre for British Columbia, encourages the preservation, management, and restoration of shorelines for public and private properties, with ecosystem sustainability at the forefront [106], [107]. The program is based on voluntary credits and ratings system, modelled after the widely adopted LEED™ program for green buildings. The guides developed for the Green Shores© program provide useful resources, information, and highlight issues relevant to design and implementation of NbS in coastal (including freshwater lakeshore) environments [106], [107]. Based on an earlier version of the Green Shores© rating system, Lamont *et al.* [29] developed a potentially useful framework and initial basis for development of Canadian guidance on evaluation of costs and benefits of coastal NbS. The authors explored "soft" shore protection approaches to flood protection and sea-level rise adaptation as alternatives to hard shoreline armouring where soft solutions provided a significant cost savings over hard solutions with similar degrees of flood protection and probable service life.

Useful technical guidance on riverine NbS is provided by Ontario's Ministry of Natural Resources [108] and Newbury and Gaboury [109], even though both documents were developed before NbS emerged as an established concept. *Ontario's Adaptive Management of Stream Corridors in Ontario* [108] provides a basis for, and comprehensive guidance to proponents of, stream naturalization through management, design, and implementation within an adaptive management framework. Significantly, it advocates for multi-disciplinary teams, recognizing the complexity involved in achieving functional systems, and multiple objective planning and design approaches. Newbury and *Gaboury's Stream Analysis and Fish Habitat Design: A Field Manual* [109] presents a ten-step procedure for analysis, design, implementation, and monitoring of stream habitat works. In addition to technical guidance, the manual provides lessons learned from stream restoration projects in varied geological and hydrological environments in Manitoba.

Properly assessing and understanding the value of ecosystem services provided by NbS is a crucial prerequisite for developing business cases and appraisal of alternatives. Moudrak *et al.* [26] developed a framework ("Value for Money") to guide the development of business cases and investment in NbS for flood risk management in Canada, which emphasizes valuation methods, funding models and mechanisms, financial instruments, and forums for convening stakeholders. The report provides a useful resource for decision-makers and investors considering funding or investment in natural infrastructure, as well as techno-economic appraisal of flood risk management strategy options that include NbS. Moudrak and Feltmate [1] propose practical measures that stakeholders in Canada can take to alleviate the risk of future floods, including NbS, for which several successful case studies are highlighted.

In 2020, a multi-year research project, Nature-Based Infrastructure for Coastal Resilience and Risk Reduction, led by the National Research Council of Canada, was established through the Canadian Safety and Security program managed by Defence Research and Development Canada's Centre for Security Science. The project is bringing together engineers, scientists, and practitioners from federal, municipal, and First Nations government and academia to address key factors and data gaps limiting the uptake of nature-based infrastructure for coastal flood and erosion risk reduction in Canada. It aims to break new ground by developing an improved understanding of the performance of nature-based shore protection systems in typical Canadian coastal environments by conducting coordinated research activities (field monitoring, digital twinning, and laboratory experiments). The project will draw on observations from pilot sites in diverse coastal environments, to inform the development of a new design guide for Canadian communities and practitioners considering nature-based solutions.

The emergence of guidance, programs, case studies, and other resources for NbS in Canadian coastal zones and river basins is encouraging. Existing guidance documents and available information, including those summarized above (and in more detail in Appendix B) provide a useful starting basis for the future development of national guidance (including standards) for application of NbS to coastal and riverine flood and erosion risk management. However, more work is needed to enable future technical guidance and standards. Much of the existing national guidance (e.g., [26], [50], [104], [105]) provides a useful overview of key issues and resources for policymakers, decision-makers, asset managers, investors, and project proponents but lacks the technical detail needed by practitioners to enable design and implementation of NbS for coastal and riverine flood and erosion risk management. The majority of the more detailed technical guidance has been developed with a regional focus (e.g., [37], [102], [103], [108], [109]), and is in some cases several decades old [108], [109], omitting some of the learnings and



"Much of the existing national guidance provides a useful overview of key issues and resources for policy-makers, decision-makers, asset managers, investors and project proponents but lacks the technical detail needed by practitioners to enable design and implementation of NbS for coastal and riverine flood and erosion risk management."

perspectives that have emerged since the recent rise in popularity of NbS. Ongoing, multi-disciplinary research and lessons learned from pilot projects across Canada offer potential to enhance the body of knowledge that will support future technical guidance and standards in this space.

5.2 Synthesis of Current Best Practice

The following best practice summary, synthesized from the existing guidance identified in Section 5.1, is structured according to four key phases involved in implementing NbS and discussed below:

- Engagement and consensus-building
- Project planning and design
- Construction
- Maintenance, monitoring, and adaptive management

The synthesis may be useful to inform the future development of technical guidance or standards for NbS to address coastal and riverine flood and erosion risks in Canada.

5.2.1 Engagement and Consensus-Building

The system-based principles underlying NbS inherently require broad engagement and consultation with a variety of stakeholders, rights holders, regulators, and interested or affected parties [11], [19], [21]. Indeed, early, comprehensive, and continuing engagement and consensus-building is key to ensuring project success [96]–[98]. The engagement process may benefit from an early mapping exercise to identify various actors. Defining a clear process for engagement, participation, and decision-making will help to clarify expectations and ensure buy-in. This process should define and communicate when and how decisions are to be made, and who participates at each step. Consensus and active participation is usually achieved through effective communication, outreach, and feedback from multi-party involvement in planning, implementing, monitoring, and evaluation [26], [98], [110]. It is good practice for engagement activities, decisions, and agreements to be tracked, documented, and disseminated throughout the project implementation [96] to ensure a transparent process and a clear understanding amongst participants. Perspectives, knowledge, values, world views, priorities, and risk tolerances can vary significantly across regions, communities, and actors, and are rarely static. Local and regional contexts, knowledge, and lessons learned should therefore inform the engagement and consensus-building process. This variability and potential for changes over time should be considered before and during outreach and engagement [108].

5.2.2 Project Planning and Design

NbS require understanding the historical and present system states as well as anticipating potential future changes in the system [96], [111]. A phased approach to project planning and implementation is therefore useful, as lessons learned from earlier stages can be applied later in the process [110]. Many of the guidance documents discussed in Section 5.1 (and summarized in more detail in Appendix B) provide reasonable frameworks for effective planning and design, each with a slight difference in emphasis or regional applicability. Key relevant points of broad applicability to project planning and design are summarized below.

5.2.2.1 Scoping

A clear understanding and definition of the problem, goals, objectives, and constraints is crucial to enable effective NbS design and implementation [96], [110]. Some level of system understanding is typically required at an early stage in the project to support objective-setting, even before detailed analyses. Understanding the drivers for flood and erosion risk through the lenses of bio-physical processes and socio-economic pressures is an important starting point. Deliberation with stakeholders, interested or affected parties, and regulators can help to refine and constrain the problem definition [96]. Questions such as "What is the determination of success?" and "What is the time required to achieve that success?" are worthy of consideration. Advance knowledge of relevant governance, jurisdictional, and regulatory considerations may help to identify or exclude possibilities and opportunities for collaboration. NbS typically have multiple objectives, and metrics should be developed to enable evaluation of success against desired objectives.

A scoping study will help to identify priority objectives and the potential need for NbS, by characterizing the river catchment or coastal system of interest, assessing flooding, and erosion issues at a high level, identifying potential wider benefits of different measures, prioritizing stakeholder and community values, and determining potential impacts and constraints [19], [81]. Scoping and identification of needs for NbS may occur as part of broader strategic geospatial planning or flood and erosion risk assessments. Relevant system scales (in space and time) and boundaries should be evaluated by considering the variety of drivers and interactions between environmental and social systems, such as hydrology, climate, physics, biogeomorphology, ecosystems, and anthropogenic influences [96], [97]. This should include an early assessment of potential impacts, including possible encroachment on sensitive ecosystems, livelihoods, traditional ways of life, archaeological sites, cultural heritage, and industry (including fisheries and aquaculture). The results of the scoping study will provide the project team with a better understanding of flood and erosion risk, whether the potential solutions are feasible, identification of benefits and disadvantages, and, most importantly, whether NbS should be further considered as part of the flood and erosion risk management strategy [81].

5.2.2.2 Assembling the Project Team

Design of NbS requires innovation, multi-disciplinary project teams, broad participation, and open minds [112]. NbS are most effective when developed with direct input from stakeholders and actors from a variety of backgrounds and sectors [19]. Input from engineers, biologists, geomorphologists, geophysicists, ecologists, archaeologists, planners, environmental/ecological economists, social scientists, Indigenous and local community members, and others will benefit the decision-making process. Local knowledge, including the traditional knowledge of Indigenous peoples, can bring significant value and richness to NbS projects and a greater collective understanding of contexts and system processes. 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 NbS [96], [98].

5.2.2.3 System Analysis and Options Appraisal

The first priority in managing or reducing disaster risk is developing a thorough understanding of risk [17]. Risk assessments provide a means to identify the full range of risks associated with flood and erosion hazards in a system, establish risk tolerances and priorities, and generate alternative risk reduction strategies [6], [96]–[98]. The assessment should consider present-day risk and risk dynamics, including changes related to natural system variability, climate change, policy, governance, human activities, and economics [6], [96]. A rigorous risk assessment will allow for options appraisal (a comparative evaluation of risk management strategy alternatives), many or all of which may include NbS. Generation and comparative analysis of appropriate risk management alternatives will require a comprehensive understanding of system-wide and local conditions and processes. The options appraisal should review and prioritize the list of potential strategies, and identify their advantages and disadvantages in terms of meeting defined objectives [81]. This may involve applying a variety of techniques for qualitatively or, preferably, quantitatively evaluating each alternative. Total economic value appraisal techniques can be used to monetize and evaluate a range of costs and benefits associated with each alternative [26]. Engineering and geomorphic modelling and analysis may be required to evaluate the performance of alternative strategies in managing flood and erosion risk, as well as the stability and response of nature-based features to storms, human activities (e.g., land use, dredging), or non-stationarity in hydro-climatic variables. Sources of uncertainty associated with future natural, technical, and social system states [11] should be factored into the options appraisal, while recognizing that adaptive management is an inherent feature of NbS.

5.2.2.4 Permitting

Permitting can represent a significant challenge for NbS project proponents in Canada and can dramatically affect timelines for project implementation. A thorough understanding of jurisdiction and regulations is an important prerequisite for navigating the complex regulatory environment and understanding which NbS are likely to be viable. Given the complexities and distinct regulatory contexts in different parts of Canada, expert professional advice is often needed to guide NbS proponents through the process. The potential for permitting requirements to change over the project life cyle should be considered.

5.2.2.5 Design

Not all NbS require a design phase. For example, delivery of NbS through land use planning and regulatory tools such as creating protected areas may not require design activities. For NbS where some element of design is required, approaches can involve similar steps to those employed for design of traditional coastal or river infrastructure. The level of effort required during the design phase may depend on the nature and complexity of the intervention [81] (e.g., restoration versus enhancement or alteration of the system), and on the approach to adaptive management.

Large or complex NbS will likely require hydrological, hydrodynamic, sediment transport modelling, and analysis to refine the design to achieve the desired flood and erosion risk management objectives (e.g., protection of a community against flood hazards for a defined event over a defined time horizon) [98]. This may involve expert analysis using a variety of empirical, statistical, or numerical modelling tools, and validation against field data. Under certain circumstances, physical modelling can provide valuable input to guide or optimize NbS design in river and coastal settings (see Living Breakwaters in **Case Study A** and Springbank Off-Stream Storage Reservoir in **Case Study C**).

Analysis of the system ecology and biology is a key component of NbS design development, to support decisions surrounding suitable feature types [102], materials (soils, plants), and elevations. Diversification principles [11], [24] should be applied where possible, to facilitate a multiple line of defence flood/erosion risk management strategy and to ensure resilient, adaptable NbS. The design should include an analysis of the potential impacts of interventions on the existing natural systems, including potential cumulative impacts of multiple NbS, to ensure unintended negative consequences are anticipated and avoided [12].

Typical steps in the design process might include development of preferred concept(s), followed by the development of a preliminary design and cost estimate, and detailed design with technical specifications, necessary tasks, timelines, a detailed budget, and phased or life-cycle costing [30], [96]. U.S. Federal Highway Administration guidance [98] suggests that the design team and process may be guided by the following questions:

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

5.2.3 Construction / Implementation

Contractors experienced in bioengineering, marine engineering, and NbS and who understand the fragility of sensitive natural systems are crucial to successful implementation [108]. Furthermore, open and clear communication and collaboration between designers and contractors are needed to ensure success [108]. Given the inherent requirement for innovation with NbS, performance-based or turnkey (design-build-operate) procurement may be appropriate strategies to consider, where the focus is on eventual outcomes rather than how they will be achieved [98]. This is particularly worth considering where NbS may take some time to establish or reach dynamic equilibrium, which may require re-deployment of construction workers and equipment a year or more following construction to repair any initial damage sustained during flood or storm season and adaptively manage the NbS.

Construction can be split into three phases: pre-construction, construction, and post-construction [98]. During the pre-construction phase, thought should be given to the construction process, techniques, and materials, including transportation to and from the site, staging, sequencing, scheduling, and environmental protection measures (e.g., erosion and sediment control). Pre-construction surveys may be carried out, potentially at intervals beginning a year or more in advance, to support site characterization and system understanding. Federal, provincial, or local guidance and regulations pertaining to working in or near water should be consulted. Seasonal conditions, weather, and windows of time for construction should be considered, including any regulations or restrictions related to migratory birds, fish, marine mammals, fishing, and harvesting. High-flow velocities or changing water levels can affect construction operations, while heavy machinery can damage surfaces and disturb sediments, potentially causing irreversible damage to watercourses and fish habitat [81], [108]. During the construction phase, there should be clear and continuous communication between the project manager, contractor, design team, and other parties interested in, or affected by, the project such as local residents. The post-construction phase will typically include an as-built survey to assess compliance with or deviation from the original design, and to provide a baseline for monitoring, followed by full or partial demobilization from the site.

5.2.4 Maintenance, Monitoring, and Adaptive Management

Successful operation and maintenance of NbS requires developing a monitoring, maintenance, and adaptive management plan with clearly defined goals and measurable objectives [50], [96]. The plan should typically be drafted at the planning and design phase, and updated throughout the project life-cycle [26], [108]. The plan should provide information to enable an assessment of the performance of the NbS over the design life, or other timeframes relevant to the system evolution [102], and outline roles and responsibilities, the required frequency and duration of monitoring activities, funding, compliance with relevant policies and standards, staff and expertise, training, remedial/contingency measures (if required), and adaptive management triggers [96].

Long-term post-construction/implementation monitoring enables objective assessment of the performance of NbS, and identification of triggers for routine maintenance, extraordinary maintenance (remedial measures), or adaptive management. More broadly, monitoring of the life-cycle performance of NbS will provide crucial evidence to inform future solutions [81], [113].

Yepsen *et al.* [114] provide a useful framework guiding the development of monitoring plans for living shorelines and wetland restoration in New Jersey, which has potential for application to a variety of NbS project types in other regions. The framework provides users with suggested metrics relevant to project goals and restoration type, common methods for collecting data, monitoring plan templates, suggestions for selecting metrics and methods, and guidance on indicators or triggers for adaptive management. The framework encourages standardization of metrics and broad dissemination of data to share lessons learned.

A non-exhaustive list of parameters to consider for monitoring riverine and coastal NbS projects is provided as follows [81]:

- Meteorology, hydrology, and hydraulic conditions (such as precipitation, wind speed, air temperature, water levels, flow speeds, sea states, ice);
- Geomorphology and sediment transport (topography, bathymetry, erosion rates, sediment grain size distribution);
- Sediment and water quality (turbidity, contaminants, salinity, dissolved oxygen, pH, organic matter, redox potential);
- Ecology (number, density, morphology, health and changes in local aquatic and terrestrial flora and fauna);
- Performance (number of damaging flood events, flood depths and velocities, flood damages incurred).

When developing a monitoring plan, the timescale of the monitoring plan is an important consideration as it will define the frequency of monitoring and the amount of funding required. Long-term monitoring may be necessary for inherently dynamic coastal sites, or riverine sites that may be heavily impacted by large flood events [81]. However, timeframes for implementation and evolution of the NbS, and needs to inform adaptive management, will inevitably determine the time frames for monitoring [102].

Like traditional hard engineering solutions, regular operation and maintenance of NbS ensures that they will function as intended [26], [98], [115] and is critical for long-term resiliency [116]. When maintenance is considered in planning and design phases, it can help to "maximize environmental benefits and reduce the project costs over its life span" [115]. Regular maintenance and monitoring can also help to minimize the damage resulting from extreme weather or hydrometeorological disturbances [116].

Adaptive management is embedded in the principles underlying NbS. Adaptive management plans are therefore integral to the long-term success of NbS and reduce risks associated with uncertainty in future systems [11], even for traditional engineered infrastructure. Adaptive management should occur throughout the NbS service life, facilitating adjustments when new information is discovered through monitoring [96] or when thresholds triggering intervention are reached.

6 Challenges and Opportunities for Nature-Based Systems in Canada

6.1 Overview

Challenges and opportunities for NbS to address coastal and riverine flood and erosion risk in Canada were identified based on the literature review (Section 5) and feedback from interviewees. Table 3 summarizes some of the key points from this analysis. A more thorough discussion with relevant examples is provided in Sections 6.2–6.9.

Table 3: Overview of challenges and opportunities for nature-based systems in Canada

Distinct and Varied Environmental Conditions (Section 6.2)	
Challenges	▪ NbS are site-specific, requiring a comprehensive understanding of regional and local systems [31], [116], and solutions are not always directly transferable. ▪ Ice and permafrost in coastal regions and watersheds creates distinct challenges for NbS in Canada.
Opportunities	▪ Ongoing, multi-disciplinary, collaborative research and monitoring of NbS at pilot sites across Canada provide ideal opportunities to learn about the viability and performance of different solutions in a variety of environments and to inform future solutions, technical guidance, and standards as appropriate. ▪ Canada's diverse environments present opportunities for innovation.
Planning and Land Use Strategy (Section 6.3)	
Challenges	▪ Although avoidance is proven to be the most effective strategy for flood and erosion risk management, many Canadian communities and infrastructures are already situated in areas of high flood or erosion hazards.
Opportunities	▪ Land use planning and development strategies that embrace "whole system" approaches and the dynamic nature of flood and erosion risk are needed to enable NbS.

Regulation and Governance (Section 6.4)	
Challenges	▪ The complex and changing regulatory environment is a significant barrier to NbS in Canada [31]. A lack of streamlined processes and synergies between different levels of government can impede or even prevent adoption of NbS. ▪ NbS are most commonly implemented on a small scale and at local levels in Canada, which is not always conducive to whole system approaches, which typically span multiple jurisdictions or regulatory boundaries.
Opportunities	▪ The whole system thinking underlying NbS has the potential to create a paradigm shift in flood and erosion risk management practice and governance in Canada. ▪ Ontario's Conservation Authorities provide a Canadian example of whole system approaches to water management, whereby jurisdictions are aligned with system (i.e., watershed) boundaries. Insight gained and lessons learned from these experiences may help to guide new approaches to governance enabling NbS across Canada.
Funding and Financing (Section 6.5)	
Challenges	▪ Project funding models that emphasize capital spending de-incentivize projects that involve maintenance and adaptive management, including NbS. Buy-in from investors or funding agencies may be difficult to obtain. ▪ NbS require innovation, multi-disciplinary and specialized knowledge, and broad stakeholder engagement; all of which can represent significant up-front investments for NbS project proponents. These costs can be prohibitive for small communities.
Opportunities	▪ Organizations like the MNAI are working with local governments to embed natural assets within asset management programs and financial planning, promoting broader implementation of NbS in Canada. ▪ NbS are increasingly recognized in funding programs for adaptation infrastructure and gaining interest from capital markets. ▪ Innovative insurance products are emerging to address some of the inherent or perceived risks and uncertainties associated with NbS implementation.
Monitoring Performance (Section 6.6)	
Challenges	▪ Data demonstrating and contrasting the technical performance and track record of NbS across Canada are severely lacking.
Opportunities	▪ Monitoring and evaluating the performance of NbS demonstrates the benefits and effectiveness of NbS. Broadly accessible monitoring results promote uptake and more successful implementation of NbS by informing designers, proponents, decision-makers, and the public of the benefits and lessons learned [118]. ▪ Standards or guidance for NbS performance assessment and monitoring, would help potential proponents to better understand the factors affecting performance, to secure funding for assessment and monitoring, to establish standardized metrics and criteria, and, ultimately, increase investor confidence in NbS projects.
Perceptions (Section 6.7)	
Challenges	▪ NbS are perceived as uncertain. NbS are inherently dynamic and may depend on living components that adapt to changing externalities, which may create anxiety for proponents.
Opportunities	▪ The adaptive capacity of NbS is an inherent advantage in dealing with a highly uncertain future. Well-implemented and publicized pilot projects that demonstrate performance objectively, by monitoring against clear and consistent performance metrics, can help to change perceptions surrounding uncertainty associated with NbS. ▪ Technical guidance provided by future standards and guidelines can facilitate increased confidence in NbS. Standards that provide guidance on high-level frameworks and considerations for design and implementation of NbS would be beneficial in mainstreaming important principles, such as whole system thinking, multi-disciplinary teams, and adaptive management.

Technical Expertise (Section 6.8)	
Challenges	▪ Cross-disciplinary collaboration on NbS for coastal and riverine flood and erosion risk management has been lacking in Canada. NbS are inherently multi-disciplinary endeavours, and their success depends on engaging a broad range of perspectives and expertise. ▪ There is a shortage of highly skilled NbS practitioners in Canada [50].
Opportunities	▪ Education and outreach on NbS is on the rise, and this can be effective in gaining increased public support [120]. Future technical guidance and standards can play an important role in educating practitioners and project proponents.
Post-Flood Recovery (Section 6.9)	
Challenges	▪ Canada's flood and erosion risk management infrastructure is aging and under increasing pressure (e.g., due to climate change effects such as sea-level rise and more extreme weather patterns).
Opportunities	▪ Future post-flood recovery activities present unique opportunities to "build back better" and consider NbS as part of flood and erosion risk management strategies. Frameworks and enablers, including guidance and standards, are needed to position planners, designers, communities, and governments to maximize the potential of NbS for coastal flood and erosion risk management.

6.2 Distinct and Varied Environmental Conditions

Canada is a country of diverse shorelines and watersheds, where ecology, hydrology, and climate differ vastly depending on location. There are significant regional contrasts in the predominant drivers of floods [4]. Almost every interview respondent highlighted the site-specific or "place-based" nature of NbS, consistent with findings by ICF [50]. NbS therefore typically require a rigorous and comprehensive understanding of local environmental conditions to ensure successful implementation, where options may be constrained by local drivers and processes [102]. For example, NbS implemented on the sandy coasts or muddy intertidal marshes on Canada's East Coast are not necessarily transferable to the steep, rocky, or mixed-sediment shorelines of the West Coast. Similarly, NbS designed for steep, mountainous watersheds may not perform well in permafrost regions or the flat terrain of the Prairies. Hydrologic, hydraulic, and ice regimes vary substantially across Canada's river watersheds (and seasons) and play a crucial role in determining which NbS are viable. For example, the significant spatio-temporal variability in the soil-water interface creates challenges in determining how vegetation can be incorporated in riverine NbS. Aquatic vegetation is not suited to prolonged periods of low flow, whereas terrestrial vegetation may not survive exposure to high flows, and special planting techniques may be required to improve survival rates of newly seeded riparian vegetation.

The ubiquity of ice in Canadian rivers and northern coastal regions creates additional challenges for NbS, because of the rapid local and system-wide changes that can be driven by ice dynamics. Freeze-thaw cycles can lead to "plucking" of sediment (or rock) and vegetation by ice. Ice can scour shorelines and river banks or accumulate on shorelines (i.e., ride-up) and channel constrictions (i.e., jams), causing backwater floods, scour, and damage to river banks and vegetation. Ice jams and related backwater effects are a significant cause or contributor to flood hazards in rivers across Canada [123]. NbS may involve "making room for ice", such as strategically promoting retention of ice in areas where the consequences of accumulation are not severe, or the use of topographic or bathymetric features to promote ice break-up during changes in hydraulic regimes.

NbS for flood and erosion risk management sometimes apply a principle of enhancing groundwater infiltration to reduce runoff to watercourses and developed areas. In permeable (e.g., sand/gravel) soils, this approach can be effective at alleviating flooding. However, in regions with non-permeable soils (e.g., clay) and limited capacity to convey groundwater, solutions based on maximizing shallow surface infiltration do not always work. For example, in the City of Winnipeg where the soil is highly impermeable, it may be preferable to quickly convey local runoff through the system during and leading up to the spring freshet season, to ensure conveyance capacity is maximized when peak flows arrive.

One interviewee identified a potential opportunity to avail of existing ecological land classification data to guide NbS design and implementation [124]. This type of information could help to avoid the introduction of invasive plant species and ensure NbS are place-based and suited to the regional system context. Similarly, more comprehensive classification systems and geospatial data characterizing the coastal zones and river watersheds of Canada (e.g., ecology, wave exposure, tidal range, sediment) are needed to support these objectives.

6.3 Planning and Land Use Strategy

Many Canadian communities include existing public and private infrastructure in areas of high coastal and/or riverine flood hazard. Development in close proximity to water bodies, without adequate foresight for short- or long-term risks, encroaches on natural (dynamic) flooding and geomorphological processes with negative consequences. Interventions aimed at protecting people and assets already situated in areas prone to flood and erosion hazards (e.g., raising dykes) can divert floodwaters or disturb natural sediment transport processes, with potentially negative consequences, and/or limit future adaptation options. In coastal regions, hardening of defences can deprive downdrift shorelines of sediment leading to erosion and contribute to "coastal squeeze" [9], with associated negative impacts on intertidal ecosystems and the vulnerability of coastal communities and infrastructure to sea-level rise. This points to a need for land use planning and development strategies that embrace whole system approaches and the dynamic nature of flood risk. Where development has already occurred, a number of interview respondents suggested that renaturalization of shorelines and floodplains would be beneficial and lower risks associated with flooding and erosion. One respondent articulated that large-scale land use and long-term planning uncovers nuances overlooked by small-scale short-term projects, but the appetite for large-scale projects that capture the full life cycle of a solution (or long-term thinking) is lacking in Canada, in part due to short election cycles and multi-jurisdictional governance.

The pace and extent of development in areas of high flood hazard can affect the extent to which NbS are viable or acceptable to communities [50]. For example, the City of Winnipeg developed rapidly in the Red River floodplain, leaving little room for natural system features and placing constraints on the extent to which NbS could be implemented. By contrast, Saskatoon (in the South Saskatchewan River valley) developed at a slower pace, allowing more room for the river and, arguably, more opportunities for NbS. Studies in Ontario [50] have shown that wetlands in rural settings are more effective in terms of reducing flood damages than their counterparts in developed urban areas. Concepts such as Making Room for Wetlands, Making Room for Movement (https://www.transcoastaladaptations.com/), and freedom space [66], are encouraging communities and various actors to think about flooding, erosion, spatial planning, and NbS over longer timescales.

Without careful planning, marginalized communities can be negatively affected by NbS, and low-income residents may even be driven out of the places they helped create. NbS promote and preserve green space, which improve the aesthetic appeal of communities. This can drive rent and housing prices up, in a process referred to as eco-gentrification, driving the low-income base out [50], [125].

6.4 Regulation and Governance

The complex and changing regulatory environment is a significant barrier to NbS in Canada [50]. This conclusion was corroborated by interviews conducted for this study, with a number of interview respondents identifying challenges in keeping up with continuously changing regulations and government policy applicable to NbS, with some even referring to a "regulatory nightmare". While planning for a potential future NbS installation, one respondent found that the process for obtaining permits changed substantially mid-project, significantly affecting the project schedule. In another case, a respondent found that previously existing synergies between different levels of government and regulatory agencies had ceased. These types of changes can significantly alter the plans and implementation of NbS, increasing cost

"To be effective and sustainable, flood and erosion risk management strategies (including NbS) require whole system thinking and approaches and institutional innovation."

and lengthening timeframes for delivery. Silos within different governing and regulatory agencies can also create confusion amongst stakeholders and the public with multiple or conflicting projects sometimes taking place without effective cooperation.

In general, interviewed stakeholders believed that there is a lack of familiarity with NbS amongst regulators and decision-makers, which is a hindrance to permitting and approvals. Existing regulatory frameworks are more suited to traditional engineered infrastructure. Where regulations or guidelines support or accommodate NbS, they are sometimes misinterpreted. Some interviewees mentioned that traditional engineering approaches are sometimes adopted to streamline regulatory and permitting processes, despite preferences for NbS among proponents. In the United States, the U.S. Army Corps of Engineers is revising policies, guidance, and regulations to enable implementation of NbS through the Engineering With Nature™ program [35], which could be a model for change in Canada. However, the complex, multi-jurisdictional regulatory framework in Canada will require leadership and buy-in from multiple government departments to achieve progress.

To be effective and sustainable, flood and erosion risk management strategies (including NbS) require whole system thinking and approaches [11], [19], [21] and institutional innovation [112]. Almost inevitably, natural systems span multiple jurisdictions or regulatory boundaries, particularly in Canada where flood risk management responsibilities are shared by federal, provincial/territorial, municipal, and Indigenous governments [2]. Municipal governments, which typically implement and enforce flood risk management strategy and infrastructure in Canada [2], and project proponents face challenges in navigating the jurisdictional overlap and a large number of stakeholders. For example, the City of Winnipeg is located at the outlet of the Red River and the Assiniboine River watersheds, where all of the flows are discharged into Lake Winnipeg. The City of Winnipeg's floods are driven by upstream flows, yet the city has no authority beyond its jurisdictional limits leaving it vulnerable to upstream conditions. If an integrated flood risk management approach was taken, the city might benefit from improved management practices at the watershed scale (e.g., reintroduction of prairie pothole topography to enhance flood storage). Some respondents suggested that a complete paradigm shift is required if whole systems thinking is to become the norm in Canada. In Ontario, Conservation Authorities (CAs) have been created to enable watershed-scale governance [126]. Their strength lies in organizing multiple levels of government to effectively manage issues such as flood control. There may be opportunities to extrapolate lessons learned and institutional experience from Ontario's Conservation Authority approach to other regions of Canada, and enable IWRM or ICZM approaches that support NbS. For example, along Lake Ontario, some neighbouring CAs have demonstrated the ability to collaborate effectively across jurisdictional boundaries to support sustainable shoreline management planning [118]. In New Brunswick, the Nashwaak Watershed Association has brought together key actors within the Nashwaak

River basin, to address challenges such as water quality at the watershed scale and to share experiences with other groups/communities interested in improving the resilience of their watersheds.

6.5 Funding and Financing

A growing body of evidence is illustrating that natural infrastructure assets are beneficial to climate resilience of Canadian communities [1], [26], [47], [48]. However, existing government funding and financial planning models, and terminologies, typically do not adequately support NbS. One interview respondent noted an experience whereby NbS have to be embedded within a larger project in order to receive funding. Project funding models that emphasize capital spending disincentivize projects that require maintenance and adaptive management approaches, which are inherent to NbS. Traditionally, natural infrastructure assets have not been categorized as capital assets (unlike hard infrastructure), which makes funding and financing for investment in NbS difficult to obtain [1]. However, building on fundamental changes in asset management practice in the Town of Gibsons, British Columbia [47] – a first for North America – MNAI is now working with local governments to embed natural assets in their asset management programs and financial planning. The shift in mindsets and practices resulting from the many successful MNAI case studies has the potential to promote broader implementation of NbS in Canada, particularly if espoused by multiple levels of government.

NbS are increasingly being recognized in funding programs for adaptation infrastructure. For example, the City of Surrey received funding through the Federal Disaster Mitigation Adaptation Fund to implement a coastal flood adaptation strategy [127], including design, piloting, and evaluation of NbS to mitigate the impacts of sea-level rise on marsh habitat and to attenuate floods.

NbS are gaining interest from capital markets. In recent years, financial mechanisms promoting environmentally sustainable investments, such as green bonds, have begun to facilitate NbS. For example, in 2019 the City of Toronto used proceeds from a green bond issuance to support the Port Lands Flood Projection Project – one of the largest infrastructure projects in Toronto's history. The project will protect Toronto's southeastern downtown area from extreme flooding by creating a naturalized river mouth that reconnects the Don River to Lake Ontario [128].

Innovative insurance products are being developed to address some of the inherent or perceived risks and uncertainties associated with NbS implementation [129]. The ability to insure against construction risks and failed project outcomes will help to alleviate some of the concerns that governments face with financing such projects.

NbS require innovation, multi-disciplinary and specialized knowledge, and broad stakeholder engagement, all of which can represent significant up-front investments for NbS project proponents. These costs can be prohibitive for small communities.

Volunteer NbS initiatives and technical communities of practice – such as the Cold Regions Living Shorelines Community of Practice convened by the Coastal Zone Canada Association and the Natural and Nature-Based Climate Change Adaptation Community of Practice convened by the New Brunswick Environmental Network – are generally underfunded or funded only for short periods. Long-term funding is needed to support these types of initiatives, so that dedicated staff can be assigned to keep networks thriving and relevant.

6.6 Monitoring Performance

Monitoring and evaluating the performance of NbS is crucial to demonstrate benefits and effectiveness to the public and potential future project proponents, and to enable adaptive management. Broadly accessible monitoring data can promote uptake and more successful implementation of NbS by informing designers, proponents, decision-makers and the public of the benefits and lessons learned [130]. A number of the documents summarized in Appendix B provide general guidance on developing monitoring, maintenance, and adaptive management plans. However, comprehensive data demonstrating and contrasting the technical performance and track record of NbS in watersheds and coastal zones across Canada is severely lacking. This adds to the challenge of attracting public support and investment interest to secure broad-scale implementation of NbS projects in Canada – in contrast to well-established grey infrastructure projects. Reasons may include a lack of funding for monitoring, the absence of standardized and consistent performance metrics or criteria, or a limited understanding of requirements for an effective monitoring program. Some interviewees observed that, even when monitoring is conducted, durations tend to be too short. For example, a two-year monitoring plan following implementation is often too short to comprehensively assess performance of an implemented NbS (e.g., vegetation may not have fully grown), to observe the response of the NbS to more extreme events, or for the NbS to reach a state of dynamic equilibrium. In general, respondents observed that monitoring activities typically consist of no more than a single inspection (e.g., a year after installment). By contrast, compensation projects undertaken to offset the impacts of development on fish and fish habitat, which may involve wetland restoration or other forms of NbS, are typically authorized by regulators with conditions for monitoring over periods of one year in advance (baseline) and five years post-construction [113]. Similar conditions could be attached to funding for natural infrastructure projects to promote monitoring, which is needed to establish an evidence base for NbS performance.

Standards or guidance for NbS performance assessment and monitoring would help potential proponents to better understand the factors affecting performance, to secure funding for assessment and monitoring, to establish standardized metrics and criteria, and, ultimately, to increase investor confidence in NbS projects.

Some interview respondents suggested that a national clearing house for relevant data collections would be a useful tool to encourage monitoring (as well as future implementation) of NbS. All levels of government, local authorities, community groups, consulting firms, and special interest groups collect useful data that are often shelved after project completion, which is counterproductive to the end- goals of monitoring. Citizen science programs (i.e., citizen crowdsourcing or volunteer monitoring) – such as Ontario Nature Citizen Science Program (https://ontarionature.org/programs/citizen-science/) where wildlife observations by the public feed into spatial and temporal monitoring and tracking of local species – may also help to address data needs, as well as provide an enhanced sense of community ownership [131] and connection to NbS.

6.7 Perceptions

Some interview respondents observed there are broad perceptions that traditional (i.e., hard engineering) approaches to flood and erosion risk management have a proven track record, whereas NbS are seen to be in their infancy and inherently more uncertain. Traditional approaches are seen to be supported by existing standards, and with performance assurances (e.g., warranties and service life expectancies), giving confidence to stakeholders and decision-makers. By contrast, NbS are inherently dynamic and may depend on living components (e.g., vegetation that requires time to establish and mature) that adapt to changing externalities, which may create anxiety for potential proponents [110]. However, as several interview respondents articulated, acknowledging the potentially negative consequences of hard infrastructure should also be a design consideration. For example, hard structures may inhibit natural system processes locally or at other locations within the system. Education is an important part of addressing these (often ill-informed) perceptions and changing mindsets. For example, Cado van der Lely *et al.* [11] explain that the adaptive capacity of NbS is in fact an inherent advantage in dealing with a highly uncertain future, and describe how uncertainties in design and implementation of NbS can be effectively managed. Well-implemented and publicized pilot projects that demonstrate performance (objectively, by monitoring against clear and consistent performance metrics) are also needed to change perceptions surrounding uncertainty associated with NbS. Based on feedback from focus groups in Nova Scotia, Sutton [132] recommended a future-framed approach for broaching adaptation planning, to maximize community support.

Some interviewees felt that new standards for NbS would facilitate increased comfort and confidence in these types of solutions amongst funding agencies, thereby supporting broader uptake. Standards provide clarity to the concepts and principles underlying NbS and the steps required to implement them, raise awareness and educate about NbS best practices and lessons learned, and provide assurances to stakeholders and decision-makers [19]. Although there are many proponents and leading adopters of NbS within engineering disciplines, Morris *et al.* [110] suggest that design manuals may be a necessity for the broader engineering community to fully embrace NbS.

Canada's abundance of wilderness and scenic beauty can lead to public complacency and perceptions that local interruption of natural system processes by hard infrastructure solutions are justified or proportionate. This creates challenges for public acceptance of NbS, particularly amongst those who mistakenly believe that hard infrastructure solutions are always more reliable or permanent.

6.8 Technical Expertise

NbS are inherently multi-disciplinary endeavours. However, there is a relative paucity of cross-disciplinary collaborations on NbS for coastal and riverine flood and erosion risk management in Canada. For example, one interviewee observed that NbS are often framed as purely environmental restoration projects (i.e., without consideration for flood and erosion risk management benefits), and therefore engage professional expertise from the environmental sciences only. This approach has potential to omit consideration of important perspectives from other fields of expertise (e.g., hydrology, engineering, landscape architecture, archaeology) that may be crucial to the success of NbS. Knowledge and attitudes towards NbS can vary, even amongst individuals within the same institution, depending on expertise and academic backgrounds [120].

The multi-disciplinary expertise needed to ensure successful NbS implementation may be considered cost-prohibitive for small projects with limited funding, and can result in misguided or high-risk project delivery, with negative consequences for the broader perception of NbS. An example is the widespread integration of logs (woody debris) for shore protection on British Columbia beaches because of their perceived co-benefits to ecosystems, despite a paucity of peer-reviewed evidence or design guidance supporting their effectiveness in mitigating erosion or wave run-up to date [25]. In fact, excessive quantities of woody debris can cause damage to sensitive shoreline habitats and features, contributing to hazards. However, woody debris is known to trap and promote retention of sediment on beaches under certain conditions [133], [134]. These examples underscore the need for multi-disciplinary project teams, local knowledge, research, and design guidance to support the development of NbS based on science and evidence.

Some interviewees expressed concerns that Canada's academia is not developing enough highly qualified professionals with the breadth of expertise needed to enable design and implementation of reliable NbS. While there is active academic research on topics relevant to NbS at Canadian educational institutions, not many have the extremely broad range of expertise, disciplines, and experience needed to educate future NbS practitioners. Employers in the public and private sectors often struggle to recruit suitably qualified and experienced practitioners, and experience with NbS is largely obtained through experiential learning on projects (e.g., in professional practice), which can be opportunistic and sporadic.

Several interview respondents voiced concerns about a lack of trained and experienced contractors (and training opportunities) capable of delivering NbS projects. Construction of NbS may require more care, creativity, and expertise than traditional engineering works. Some respondents observed that some construction companies engaged to construct NbS lack understanding of the fragility of ecosystems. Misconceptions that the NbS feature always has the capacity to self-repair has in some instances led to careless construction, unlike for traditional engineered structures where there is a clearer understanding and expectations of precautions and outcomes. As with traditional engineering works, adaptive management should be built into the construction phase of NbS.

Some respondents expressed concerns about waning support for government science, leaving the responsibility of technical spearheading of NbS projects to the private or non-profit sectors and academia, and the associated fragmentation of NbS-related experience and knowledge in Canada.

Broad outreach, engagement, and education on NbS can be effective in supporting uptake and acceptance. Stakeholders and a public that are better informed with respect to NbS are better equipped to participate in decision-making processes, ensuring more active engagement and effective solutions. The BC Stewardship Centre provides training on the Green Shores® program [106], [107]. In 2018, Nature New Brunswick and NBEN organized a one-day Natural Infrastructure Learning Day in Dieppe, where participants (from technical professionals to academics) learned about challenges and opportunities involved with NbS for inland flooding and erosion, while visiting relevant sites. Education and outreach activities like these undoubtedly help to broaden awareness and interest in NbS, and increase public support for NbS projects [120].

6.9 Post-Flood Recovery

Canada's flood and erosion risk management infrastructure is aging and under increasing pressure (e.g., due to climate change effects such as sea-level rise and more extreme weather patterns). Future post-flood recovery activities will present unique opportunities to "build back better" and consider NbS as part of the flood and erosion risk management strategy. Frameworks and enablers, including guidance and standards, are needed to position planners, designers, communities, and governments to maximize the potential of NbS for coastal flood and erosion risk management.

7 Knowledge Gaps and Research Needs

The Government of Canada's Climate Science 2050 national synthesis underscores the urgency in working to address science gaps related to identifying and deploying NbS in Canada, such as research in to potential negative effects, socio-economic and cultural valuations and trade-offs, and the impact of extreme events on NbS [121]. ICF provides a comprehensive review of knowledge gaps and implementation challenges, which includes limited institutional capacity, a lack of highly qualified personnel, limited awareness, a sparsity of data, policy and regulatory barriers that favour conventional (grey) infrastructure, gentrification of neighbourhoods where NbS are implemented, a lack of maintenance capacity, and limited cross-disciplinary communication [50] (see Appendix B for more information on this review). Additional gaps and research needs are identified as follows, based on the literature review and interviews conducted for this study.

7.1 Monitoring

Broader uptake and implementation of NbS for coastal and river flood and erosion risk management in Canada is inhibited by a scarcity of accessible, consistent, long-term, quality-assured monitoring data. Monitoring data is needed to inform performance assessment, adaptive management, and future solutions, and to give confidence to NbS project proponents and investors. The literature search conducted for this study identified many NbS project examples and case studies across Canada but very little quantitative data to assess performance over time. Long-term multi-year monitoring programs are needed to demonstrate performance over time frames of relevance to system recovery and establishment. Periodic appraisals and observation of NbS project performance over even longer (i.e., multi-decadal) time scales would help to facilitate comparisons to traditional hard infrastructure solutions with design lifetimes typically in the range of 25 to 100 years. A centralized project database and national standards for monitoring NbS performance would represent concrete steps towards supporting these aspirations. However, research is needed to determine parameters, metrics, indicators, instrumentation, and techniques appropriate to different types of NbS in different regions. Funding and mechanisms for incentivizing long-term monitoring is also needed. Options to consider could include making project funding contingent on proponents developing and implementing monitoring plans.

7.2 Predicting Performance

Canada's coastal and riverine environments, flood-driving processes and regional climates are extremely diverse. Research and evidence is needed to determine how various NbS perform in diverse river and coastal settings, to support the development and validation of predictive tools and design guidance that are applicable across Canada. This will require engaging local and regional expertise, expansion of existing pilot project programs, and collaborative, multi-disciplinary research to develop the evidence base for tools and guidance. In regions and environments where NbS are relatively untested to date, such as northern Canada, innovation will be required to adapt NbS concepts or develop new variants to take into account unique issues relative to ice, permafrost, relative sea-level fall, native ecosystems, and materials.

7.3 Planning/Decision-Making Frameworks

Despite the accelerating interest in NbS for managing coastal and riverine flood and erosion risks, and the need to address underutilization in Canada, they are not universally applicable. A well-designed hard infrastructure solution that makes allowance for natural systems processes may outperform a poorly designed and implemented NbS, which could even have unintended negative environmental consequences. Research is needed to better understand the performance of non-structural (i.e., planning-based), conventional, and nature-based (including hybrid) solutions for managing coastal and riverine flood and erosion risk in Canada, to support effective decision-making. Moreover, there is a need for improved geo-spatial planning and decision-making frameworks that incorporate NbS as tools in the portfolio of possible strategies for flood and erosion risk management. Although there are a number of international examples (e.g., IWRM and ICZM) that could provide a basis for such frameworks, research is needed to determine which are appropriate within the Canadian context, considering the complex regulatory, policy, and governance contexts. With buy-in from parties engaged in or affected by flood risk management practice, standards can play an important role in promoting consistent decision-making approaches across Canada.

7.4 Technical Guidance

Authoritative technical guidance is needed to enable design and implementation of effective and sustainable NbS in Canadian coastal zones and river basins. While the emergence of some guidance and resources is encouraging, much of the existing national guidance targets non-technical audiences and lacks the technical detail needed by practitioners to enable design and implementation. The more detailed Canadian technical guidance that exists has been developed with specific regional focuses and is, in some cases, outdated. Together with existing Canadian guidance, the *International Guidelines on Natural and Nature-based Features for Flood Risk Management* [101], may provide a useful initial basis for the development of Canadian design guides and standards in this space. Pilot projects and research are needed to identify appropriate NbS across Canada's diverse environments, to ensure future guidance is robust and supports successful project implementation, without stymieing innovation.

7.5 Inclusivity and Collaboration

A key strength of NbS is in their integrative, systemic approach [122], which draws on a broad range of perspectives to achieve multiple objectives. Inclusivity and collaboration are therefore integral to NbS. Work is needed to determine how best to facilitate collaborative approaches and broaden participation in NbS in Canada. Forums and networks like ACASA and the Cold Regions Living Shorelines Community of Practice can help to foster multi-disciplinary and multi-sectoral collaboration and knowledge-sharing. There is significant potential for NbS to benefit from wide-ranging Indigenous knowledge, through collaborative approaches. More collaboration and sharing of lessons learned would help to better elucidate how Indigenous knowledge systems and "Western" science can be co-applied to achieve more effective and sustainable NbS.

8. Conclusion

Opportunities to deploy NbS to enhance coastal and riverine flood and erosion risk management practice in Canada are many and significant. However, there are technical, cultural, and institutional barriers to be overcome to support broader uptake and integration of NbS in the portfolio of tools to respond to escalating coastal and riverine flood and erosion risks. Technical guidance and standards have an important role to play in mainstreaming, promoting confidence in, and supporting decision-making surrounding NbS. Multi-disciplinary research is needed to address knowledge gaps and support technical guidance and standards that are robust and evidence-based, so that they contribute to sustainable design and implementation of NbS in Canada's diverse river watersheds and coastal settings.

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Appendix A – Stakeholder Interview Questionnaire

The National Research Council's Ocean, Coastal, River Engineering Centre is working with the CSA Group to evaluate and better understand how nature-based systems can be used for mitigating flood risks in coastal and riverine environments, what types of nature-based systems are most effective and most appropriate in the Canadian climate and to determine what standards requirements and recommendations are needed to inform the appropriate selection and application of nature-based solutions to ensure that they are effective in mitigating flooding and erosion risks.

The intention of this work is to develop a research paper that will inform the development of CSA standards related to nature based solutions for erosion and flood risk management in coastal regions and along Canadian rivers.

Additionally the paper will aim to address the following key elements:

- identify the types of nature-based systems that can be used in coastal and riverine regions, and discuss current best practices for the successful implementation of each type of system, including key design, construction, maintenance and monitoring considerations, favourable site characteristics and climatic regions, and known vulnerabilities;
- discuss prominent case examples of natural and nature-based systems reflecting on things that have gone well and things that have resulted in problems/challenges;
- provide insights into the processes that should be used for monitoring functional performance in order to adaptively manage and maintain the level of performance and benefits delivered; and
- report on current knowledge gaps and provide recommendations for additional future research to support standards development.

Other than drawing from existing literature and material available in the public domain, we are engaging with municipalities and other practitioners and researchers to document lessons learned from past or ongoing project experience. We are asking for your involvement to help us understand past or current practice and experiences with nature based solution projects. Our over the phone interview covered some or all of the following questions based on your experience:

1. Have you been directly involved in implementing nature-based solutions?
   a. If yes, please briefly describe the nature-based solution that you have helped implement.
   b. If no, please tell us about your own direct experiences with nature-based solutions?
2. Please reflect on how you measure performance benefits of the NbS solutions implemented, including key performance indicators you are monitoring.
3. In your experience with nature-based solutions, what are/were the successes?
4. What are/were the major challenges faced (technical, financial, institutional, etc.)?
5. In your opinion, what would have helped, or would help to overcome the challenges faced?
6. Please describe any lessons learned from your experience with nature-based solutions.
7. Please give us your thoughts on the future of NbS in your region, and/or Canada.
8. Please give us your perspectives on the potential role of technical standards and guidelines in supporting NbS implementation.

Appendix B – Review of Available Guidance Documents and Manuals

The following sections briefly summarize existing guidance and literature developed internationally (Section B.1) and in Canada (Section B.2) documenting best practices relevant to NbS for coastal and riverine flood and erosion risk management. Considering the explosion of interest and proliferation of literature pertaining to NbS that has occurred over the past decade, the summary is non-exhaustive. Synopses of the publications are presented in reverse chronological order, and a brief commentary is provided on how each could potentially support or inform future design and implementation guidance for coastal and riverine NbS in Canada.

B.1 International

UNDRR Nature-Based Solutions for Disaster Risk Reduction (2021)

This comprehensive document [64] is part of the "Words into Action" guidelines series, and aims to give practical guidance on developing and implementing NbS for disaster risk reduction, to support delivery on the United Nations Sustainable Development Goals and the Sendai Framework. The document provides a detailed description of NbS principles and concepts applicable to riverine and coastal flood and erosion risk management, including integrated coastal zone management and integrated water resources management, and references the high-level principles of the new IUCN [19] global standard for NbS. It presents successful international case studies (e.g., Room for the River in the Netherlands), summarizes the evidence base for NbS, and provides recommendations for strengthening governance and integrating NbS in disaster risk reduction strategies. The document also identifies knowledge gaps, enablers and barriers to uptake of NbS, and provides suggestions for how public and private sector entities can be involved in incentivizing and delivery of NbS. The guideline provides a comprehensive overview of NbS, numerous international references, and a repository of resources and useful information. However, it is not a design guide, and lacks the detailed information needed to support design and implementation of NbS for coastal and riverine flood and erosion risk management in distinct and varied Canadian settings.

International Guidelines on NNBF for Coastal and Riverine Flood and Erosion Risk Management (2021)

A multi-agency effort, led by the U.S. Army Corps of Engineers' Engineering With Nature™ group, has been underway since 2016 to develop international guidelines for how to implement, monitor, and evaluate natural and nature-based features (NNBF) for coastal and riverine flood and erosion risk management [101]. With contributions from the National Research Council of Canada, the guidelines were published in September 2021. Other agencies that contributed to the guidelines include the Environment Agency (United Kingdom), Rijkswaterstaat (Netherlands), HR Wallingford (United Kingdom), Deltares (Netherlands), NOAA (United States), the World Bank, the World Wildlife Fund, and many academic institutions. The guidelines include a framework for design and implementation of NNBF in coastal and riverine environments and guidance on systems-based approaches, stakeholder engagement, developing performance objectives and metrics, evaluating benefits of NNBF, adaptive management, and specific features or systems (e.g., beaches/dunes, wetlands, submerged aquatic vegetation, reefs, islands, managed dyke realignment or levee setbacks in rivers, river channel naturalization, and river watershed management techniques). It is anticipated that the international guidelines will provide a useful foundation for developing future design and implementation guidance on NbS for coastal and riverine flood and erosion risk management in Canada. However, research and engagement with Canadian practitioners and experts would be needed to capture regional contexts and lessons learned.

IUCN Global Standard for Nature-Based Solutions (2020)

The IUCN Global Standard for Nature-based Solutions [19] is a "facilitative standard", providing a framework for users to implement NbS. The primary target audience is national governments, city and local governments, planners, businesses, donors, and financial institutions, including development banks and non-profit organizations. The standard is intended to promote consistent approaches to design and verification of NbS to address broad societal challenges (e.g., climate change, food security, disaster risk reduction), and it provides several international case study references. The global standard [19] is a relatively high-level (user-friendly) document, which sets out fundamental steps for establishing the credibility of NbS when engaging with investors and is a potentially useful communication tool for broader engagement prior to design and implementation. The standard identifies eight overarching criteria (see Section 3.1) and 28 indicators to aid in the successful implementation of NbS. It is accompanied by a more in-depth user guide [111], which provides the scientific basis underlying the criteria, and a self-assessment tool to enable users to assess how well a solution adheres to the global standard for NbS. The IUCN Global Standard provides a valuable synopsis of the fundamental principles underlying and guiding successful NbS. However, it lacks detailed guidance needed to support design and implementation of NbS for coastal and riverine flood and erosion risk management in Canada.

Inter-American Development Bank – Increasing Infrastructure Resilience with Nature-Based Solutions (2020)

The Inter-American Development Bank [96] provides project-planning guidance for NbS project developers in Latin America and the Caribbean. It provides a 12-step project life-cycle framework to integrate resiliency to coastal and inland flood infrastructure through NbS. Cross-cutting themes of stakeholder engagement and adaptive planning and management, which apply throughout all 12 steps, are identified and discussed. Although the framework is defined as a series of sequential steps, from problem definition through to monitoring and evaluation, it allows for flexibility (through adaptive planning and management) and revisiting of steps to enable the desired objectives to be met. Though developed with a focus on Latin America and the Caribbean, this guide provides useful advice and a relevant methodological framework for planning NbS projects for coastal and riverine flood and erosion risk management in Canada. However, the document is relatively high-level and lacks detailed and specific technical guidance for design, construction, monitoring, and adaptive management of NbS in coastal and riverine settings.

EcoShape (Netherlands) – Building with Nature (2020)

EcoShape is a Dutch organization that brings together knowledge developed through collaborative NbS pilot projects and subsequent monitoring to develop "guidelines for replication and scaling up" of NbS projects. EcoShape's objective is "to deliver engineering services while delivering and/or utilising ecosystem services". Based on learned experiences through many pilot projects, EcoShape has defined a five-step approach to help implement NbS in a variety of environments. The information is disseminated through a comprehensive website (https://www.ecoshape.org/en/) that documents examples of NbS in a variety of different landscapes and settings (e.g., coastal, riverine, urban, sandy, muddy) and evidence of successful NbS implementation.

EcoShape propose six key criteria to ensure successful implementation and functioning of NbS [11]. These criteria are termed *enablers:*

- Technology and system knowledge
- Multi-stakeholder approach
- Management, monitoring and maintenance,
- Institutional embedding
- Business case
- Capacity building.

A white paper published by EcoShape in 2021 [11] provides support to NbS practitioners in tackling discussions and issues surrounding uncertainty. The document is particularly helpful in identifying dimensions and sources of uncertainty in design and implementation of NbS and principles for managing uncertainty.

All EcoShape projects to date have been collaborative endeavours, drawing on multi-disciplinary knowledge from practitioners in consulting organizations, academia, NGOs, government, and the construction industry. Canadian proponents of NbS will find the EcoShape website a useful, user-friendly tool for information about different types of NbS and enabling methodologies, methods to evaluating project options, implementation, and a slew of references and resources for each design suggestion as well as for all of the pilot and demonstration projects presented.

Environment Agency (UK) – Working with Natural Processes: Evidence Directory (2018)

Burgess-Gamble *et al.* [10] provide more than 300 pages of evidence on Working with Natural Processes and Natural Flood Management, terms synonymous with NbS in the United Kingdom. The purpose of the document is to give flood and erosion risk management practitioners access to information that explains the current state of knowledge on the effectiveness of a range of different measures from a flood risk and ecosystem services perspective [10]. The document contains a separate chapter for each of the four main categories of NbS: river and floodplain management, woodland management, runoff management, and coast/estuary management. Based on an extensive literature review, each chapter introduces the NbS, explains how they can deliver flood and erosion risk management benefits, documents evidence (from literature, observations, and modelling), summarizes co-benefits that each solution can provide, and provides links to further reading. Along with the Scottish Environmental Protection Agency Natural Flood Management Handbook [81] (see below), this is one of the more comprehensive and in-depth documents in terms of providing a practical basis for design and implementation of NbS for riverine and coastal flood and erosion risk management. Much of the technical guidance has relevance to Canadian applications, and could be adopted in part with some modification for regional and local contexts.

World Bank – Implementing Nature-based Flood Protection: Principles and Implementation Guidance (2017)

This World Bank document [97] provides high level principles and implementation guidance for NbS in coastal, riverine, and urban settings. The guidance is closely aligned with information provided by EcoShape (see above), reflecting contributions from practitioners in the Netherlands. The document covers the NbS project life cycle from problem definition to monitoring and evaluation, identifying eight key steps:

1. Define problem, project scope and objectives;
2. Develop financing strategy;
3. Conduct ecosystem, hazard and risk assessments;
4. Develop nature-based risk assessment strategy;
5. Estimate the costs, benefits and effectiveness;
6. Select and design the intervention;
7. Implement and construct; and
8. Monitor and inform future practices.

The guide provides a useful "how-to" on project planning and identified important considerations for planning and managing NbS projects. However, this is a relatively high-level document lacking the detailed technical information needed to fully enable design and implementation of NbS.

World Wildlife Fund – Flood Green Guide (2016)

The World Wildlife Fund (WWF), in partnership with the U.S. Agency for International Development Office of the U.S. Foreign Disaster Assistance, developed the *Natural and Nature-based Flood Management: A Green Guide* [99] (also referred to as the Flood Green Guide) to support the use of natural and nature-based methods for flood risk management. The Flood Green Guide is based on integrated flood management (IFM) approaches (i.e., combining elements of the IWRM and Strategic FRM concepts discussed in Section 3.6). The guide is targeted at flood risk management practitioners, including municipal governments, communities, and non-governmental organizations. The document was developed by an international research and writing team, with input from an advisory group and in consultation with experts from around the world. Similar to other guidance developed by international bodies or collaborations, the Flood Green Guide provides a broad, overarching framework for NbS project implementation, from preliminary assessment through to project evaluation. However, reasonably detailed technical guidance is also provided for various steps in the process, including flood risk assessment, identification and selection of combinations of structural (hard and soft) and non-structural solutions applicable in various contexts, and development of maintenance and monitoring plans. Importantly, the document sets NbS in the context of overarching flood risk management strategy. As such, it represents a potentially useful resource and sound initial basis for development of guidance applicable to riverine and coastal flood and erosion risk management in Canada.

US Army Corps of Engineers – Use of NNBF for Coastal Resilience (2015)

Bridges *et al.* [31] published a report providing information and guidance on the use of natural and nature-based features (NNBF) to enhance coastal resilience, motivated primarily by post–Hurricane Sandy recovery efforts in the United States. The report was intended to address knowledge gaps to support integration of structural and non-structural solutions in coastal risk reduction strategies, and included a framework for classifying NNBF, characterizing vulnerability, developing performance metrics, incorporating regional sediment management, monitoring and adaptively managing solutions, and addressing key policy challenges. Although the identified policy actions primarily targeted U.S. institutions and stakeholders, many of the outcomes have broader relevance. Opportunities to address challenges for NNBF were grouped in three categories: science, engineering, and technology; leadership and institutional co-ordination; and communication and outreach.

Scottish Environmental Protection Agency (U.K.) – Natural Flood Management Handbook (2015)

Forbes *et al.* [81] provide a practical guide to support the delivery of natural flood management (NFM), which is broadly synonymous with NbS in the U.K. The guidance is aimed primarily at local authorities as NFM proponents, but provides a wealth of information based on lessons learned from demonstration projects in Scotland. The guidance presents technical and cost considerations for a variety of NbS in river and coastal environments:

- Rivers:
  - Woodland creation/restoration/management
  - Land and soil management (including sustainable agricultural practices)
  - Wetland creation/restoration
  - Sediment control
  - River and floodplain restoration
  - Instream structures
  - Controlled diversion of floodwaters (e.g. offline storage)

- Coastal:
  - Managed realignment
  - Saltmarsh and mudflat restoration
  - Dune restoration
  - Beach nourishment
  - Dynamic revetments (i.e. cobble/shingle beach nourishment)

Forbes *et al.* [81] summarize the multiple co-benefits associated with NbS and describe/recommend tools for analyzing and scenario-testing the performance of solutions (e.g., hydrological models, hydrodynamic models). The handbook provides an eight-step framework for implementing NbS projects, from identifying the need/aspirations and engagement with stakeholders through to options appraisal, design, implementation, management, and monitoring. Approaches to funding projects and negotiation of agreements with landowners are also described. This handbook provides a practical guide to designing a monitoring program, including how to determine appropriate structure and level of detail, select monitoring parameters for coastal and riverine sites, and establish timeframes and frequency of monitoring.

Environment Agency (U.K.) – Greater Working with Natural Processes in Flood and Coastal Erosion Risk Management (2012)

This report [100] was prepared by a government-led working group in response to a recommendation of the Pitt Review, which was a comprehensive appraisal of flood risk management in England conducted following particularly damaging floods in the summer of 2007 [4]. The report presents the first national review of how natural processes could be applied to manage flood risk in England and Wales, and articulates that flood and erosion risk management solutions are more resilient and flexible if natural processes are embraced.

The report provides evidence for the benefits of working with natural processes to reduce flood risk through several examples, including managed realignment, sustainable urban drainage solutions (SuDS), on-line and off-line flood storage, floodplain restoration, soil management, and woodland creation. It identifies 11 conclusions or recommendations for better working with natural processes to support flood risk management objectives, grouped under five themes:

- Strategic planning framework
- Policy and legislation
- Science, evidence and modelling
- Funding and incentives
- Partner and community engagement
- Culture, skills and training

Many of the conclusions and recommendations are relevant to the Canadian context.

U.S. Federal Highway Administration (FHWA) – Nature-Based Solutions for Coastal Highway Resilience: An Implementation Guide (2019)

This U.S. FHWA guide [98] provides advice to transportation professionals on implementing NbS to enhance coastal highway resilience. The guide includes technical factsheets with basic information on different coastal NbS features (e.g., marshes, dunes, pocket beaches, beach nourishments, dune restoration), including typical design concepts, costing, life expectancy, ecological services, benefits, challenges, and regional considerations. A chapter on risk reduction benefits, ecological benefits, and costs provides a basic comparative assessment of different risk management strategies, how they stand up to erosion, wave attenuation and flooding, and their capacities to adapt to sea-level rise and other hazards. The guide outlines a framework and steps necessary to integrate NbS in the transportation planning process, including planning and funding strategies, team assembly, relationship-building, and stakeholder partnerships. Site assessment strategies are provided, including procedures for characterizing the site and determining the resilience of the system. Sections are dedicated to design considerations (engineering and ecological), permitting processes (with emphasis on U.S. state and federal regulations as they pertain to NbS), construction, monitoring, maintenance, and adaptive management.

The guide is a relatively comprehensive and useful resource for transportation professionals (but likely other audiences too) interested in applying NbS to support coastal resilience objectives. The technical factsheets provide basic overviews of potential solutions, and the chapters on site assessment and design considerations provide useful technical details. Although limited in scope to coastal highway infrastructure, much of the guidance is more broadly applicable and could provide the initial basis for, or inform, the development of a guideline or standard for NbS in Canadian coastal settings.

B.2 Canada

Municipal Natural Assets Initiative (MNAI) – Multiple Documents (2017, 2019, 2020)

The Municipal Natural Assets Initiative (MNAI) provides technical and policy support to guide local governments in managing their natural assets, which are defined as "the stock of natural resources and ecosystems that yield a flow of benefits to people". MNAI was launched in 2015, building on a move by the Town of Gibsons, British Columbia, to integrate its natural assets in asset management and financial planning processes. From 2016 to 2018, five communities piloted methodology and guidance documents to implement, refine, and test the approach initiated by Gibsons. In 2018, a second cohort of six projects was launched to further refine the methodology and expand the evidence base. Through the pilot studies, an eight-step framework for project implementation was developed, from defining the scope of natural assets through risk assessments, options appraisal, and development of operation and management plans. The case studies reflect the value and benefits provided by natural assets (e.g., rivers, creeks, wetlands) in alleviating flood hazards. For example, it was found that natural asset improvements in the Courtenay River watershed in British Columbia would avert $2.4 million in flood damages from a 1- in-200 year return period flood event [48]. Though, most of the effort has been on the riverine side to date, the MNAI is currently testing its methodologies for coastal environments. The MNAI technical documentation [104], [105] and case studies [47], [48] provide useful Canadian examples and lessons learned for how natural assets can be sustainably managed to support flood risk management (primarily stormwater management and in riverine systems to date), which would support and inform the development of future guidance for NbS design and implementation.

Stewardship Centre for British Columbia – Green Shores® (2015, 2020)

Green Shores® is a program run by the Stewardship Centre for British Columbia (SCBC) to encourage "sustainable shoreline ecosystems for commercial, residential, institutional and park properties" [106], and private properties [107]. It is a voluntary credits and ratings system, modelled after the widely adopted LEED™ program for green buildings. It is based on four guiding principles [107]:

- Preserve or restore physical processes;
- Maintain or enhance habitat function and diversity;
- Prevent or reduce pollutants entering the aquatic environment; and
- Avoid or reduce cumulative impacts.

The guides developed for the program apply to marine and lakeshore environments. The program requires five prerequisite criteria to be met before a project can be assessed using a series of credits and the points system [106]:

1. Specificity in location of permanent structures;
2. Conservation of coastal sedimentation processes;
3. Conservation of sensitive and critical natural habitats;
4. Protection of riparian zone; and
5. Construction environmental management plan.

Credits are given for various characteristics and features of the project, based on criteria such as shore-friendly access, restoration, and enhancement of shoreline sediment and tidal flow characteristics, riparian zones, aquatic habitats, adaptation plans for climate change, and redevelopment of contaminated sites, as well as outreach and public engagement. The guides provide references and resources to support project design and implementation to maximize credits.

Although somewhat limited by a scarcity of successful project examples, a review of the Green Shores© program commissioned by SCBC presented multiple lines of evidence for the positive "impact and social, environmental and economic value of the initiative for communities in British Columbia" [120]. The guides developed for the Green Shores© program provide useful resources, information and highlight issues relevant to design and implementation of NbS in coastal (including freshwater lakeshore) environments. The program is currently being extended to the Atlantic coast.

Intact Centre on Climate Adaptation / University of Waterloo – Under One Umbrella: Practical Approaches for Reducing Flood Risks in Canada (2020)

In this report, Moudrak and Feltmate [1] propose practical measures that stakeholders in Canada can take to alleviate the risk of future floods in Canada. Chapter 5 describes "practical uses of natural infrastructure to enhance flood resilience", and highlights values and benefits of NbS in Canada. It promotes the valuation of natural assets and references case study examples where natural assets have been applied to provide stormwater management and flood resilience benefits in Canada, including a number of projects supported by the Municipal Natural Assets Initiative. The authors make the case for conservation of wetlands and the importance of considering natural infrastructure at watershed scales to support flood risk management. The report suggests that, in principle, the most cost-effective natural infrastructure solutions involve (in order of preference):

1. Retaining and maintaining existing natural assets (i.e., conservation);
2. Restoration of lost or degraded natural assets; and
3. Construction where required.

ICF – Best Practices and Resources on Climate Resilient Natural Infrastructure (2018)

ICF prepared this report [50] for the Canadian Council of Ministers of the Environment (CCME), which summarized the state of practice for natural infrastructure solutions to enhance community resilience to hazards associated with coastal storms and flooding, riverine flooding, urban and rural stormwater (overland flooding), and urban heat islands. The report identifies best practices and natural infrastructure features and solutions commonly applied to support coastal and riverine flood and erosion risk management, including examples of applications in Canada. The business case for natural infrastructure is explained with emphasis on socio-economic benefits, including how these solutions can encourage a sense of identify and stewardship in communities, nurture human health and well-being, facilitate outdoor recreation, and increase property values. The report summarizes some available tools supporting cost-benefit analyses for natural infrastructure. It identifies knowledge gaps, opportunities, and challenges, as well as lessons learned and documented through a series of interviews with Canadian practitioners. Identified gaps and barriers include limited institutional capacity, a lack of highly qualified personnel, limited awareness, limited data, policy and regulatory barriers that favour conventional (grey) infrastructure, gentrification of neighbourhoods where NbS are implemented, lack of maintenance capacity, and limited cross-disciplinary communication. This report is one of the more comprehensive resources providing information relevant to NbS for coastal and riverine flood and erosion risk management in Canada but is relatively high-level, lacking some technical details and regional considerations needed to support design and implementation.

Insurance Bureau of Canada – Combatting Canada's Flood Risks: Natural Infrastructure Is an Underutilized Option (2018)

This document [26] presents a broad framework for natural infrastructure project implementation, from community engagement and risk assessment through to design, construction, and maintenance. The document emphasizes the importance of considering social and environmental benefits of NbS in cost-benefit analyses (i.e., total economic value assessment) to ensure robust decision-making and to capture the true value. The document provides a useful high-level introduction to NbS and references Canadian case study examples. The proposed framework for implementation consists of six steps, with monitoring and reporting throughout: (1) community engagement, (2) watershed and climate risk assessment, (3) materiality assessment, (4) feasibility assessment, (5) economic benefit assessment, and (6) design, construction, and maintenance. The report puts forward several recommendations to support enhanced uptake of natural infrastructure solutions, emphasizing valuation methods, funding models and mechanisms, financial instruments, and forums for convening stakeholders. The report provides a useful resource for decision-makers and investors considering funding or investment in natural infrastructure and/or techno-economic appraisal of flood risk management strategy options that include NbS. It lacks technical details needed to support design and implementation guidance for NbS in coastal/river systems.

Atlantic Climate Adaptation Solutions Association – Adapting to Climate Change in Coastal Communities of the Atlantic Provinces, Canada: Land Use Planning and Engineering and Natural Approaches (2016)

This three-part series of guidance documents [37], [102], [103] was developed as part of a suite of tools developed by the Atlantic Climate Adaptation Solutions Association (ACASA) to support community adaptation in Atlantic Canada. ACASA is a partnership among the provincial governments of Newfoundland and Labrador, Nova Scotia, Prince Edward Island, and New Brunswick, Indigenous governments, and regional stakeholders, including non-profit organizations and industry. The three parts of the guidance address different aspects of adaptation to sea-level rise, coastal flooding, and erosion in Atlantic Canada:

- **Part 1 –** Guidance for Selecting Adaptation Options
- **Part 2 –** Land Use Planning Tools
- **Part 3 –** Engineering Tools

The guidance is not exclusively focused on NbS but illustrates how they can be integrated within broader adaptation strategies (Procedural, Avoid, Retreat, Accommodate, Protect). The guidance describes distinguishing features, processes, climate change impacts, and possible adaptation strategies for a range of coastal and estuarine system types prevalent in Atlantic Canada [102]. These strategies can be implemented through a range of land use planning, policy, and regulatory tools [103]; many of which enable NbS (e.g., wetland conservation, shoreline management planning). A variety of the adaptation options and examples presented in the engineering guidance can be, or form part of, the NbS (e.g., beach nourishment, dune building) [37].

An accompanying online decision-making tool provides a range of engineering (grey to green) and land use options based on user input, and comes with further guidance for effective implementation options. The engineering tools given are for different coastal conditions. A screening tool provides support in determining the feasibility of different options, and a number of coastal engineering concepts are presented, with some common opportunities and constraints associated with different measures.

This series of guidance documents provides useful regional examples, insights, and technical guidance to support the development of sustainable coastal adaptation solutions in Atlantic Canada, which include NbS. They provide a potentially useful framework and starting basis for potential future national guidance on design and implementation of NbS across Canada's coastal regions. By covering aspects of land use planning, engineering and broader considerations for selecting adaptation options, this guidance demonstrates how NbS can be integrated within broader coastal zone management and flood/erosion risk management strategies.

SNC Lavalin – Greening Shorelines to Enhance Resilience (2014)

This report [29] explores "soft" shore protection approaches to flood protection and sea-level rise adaptation in British Columbia coastal settings, as alternatives to hard shoreline armouring. The effectiveness of three soft shore protection techniques was evaluated (beach nourishment, nearshore rock features, and headland-beach system) and compared to "equally appropriate" hard engineering alternatives. The evaluation framework was based on an early version of the Green Shores© rating system, and the following criteria [29]:

- Adaptability to climate change related sea level rise;
- Effectiveness in protecting the shoreline against flooding;
- Effectiveness in providing ecological resilience; and
- Relative cost, considering initial capital cost, maintenance cost and long-term replacement cost.

Both hard and soft solutions provided similar degrees of flood protection and probable service life based on one metre of relative sea-level rise. In all cases, the "soft" solution provided significant cost savings (30-70%) compared to the conventional, hard solution. The study provides a potentially useful framework and initial basis for development of Canadian guidance on evaluation of costs and benefits of coastal NbS.

Ontario Ministry of Natural Resources and Watershed Science Centre – Adaptive Management of Stream Corridors in Ontario (2001)

This document [108], developed before NbS emerged as an established concept, provides an adaptive management framework and guidance to water resource engineers, fluvial geomorphologists, and land use planners concerned with surface water management in Ontario. The comprehensive document serves as an education tool and provides a basis for stream naturalization through management, design, and implementation. It identifies linkages between changes in land use and impacts on streams. It advocates for multi-disciplinary teams, recognizing the complexity involved in achieving functional systems, and multiple objective planning and design approaches. A seven-stage environmental management framework is presented: problem formulation, preliminary planning and assessment, detailed analysis for planning or design, implementation, monitoring, evaluation, and adjustment. Stream management options described include prevention, protection, remediation, rehabilitation, enhancement, and restoration, all of which are compatible with NbS.

The guidance document provides a comprehensive "how-to" in stream restoration and could serve as a useful initial basis for developing guidance on riverine NbS in Ontario and other parts of Canada. Some updates would be required to capture advances in stream management practices in the 20 years since its publication.

CSA Group Research

In order to encourage the use of consensus-based standards solutions to promote safety and encourage innovation, CSA Group supports and conducts research in areas that address new or emerging industries, as well as topics and issues that impact a broad base of current and potential stakeholders. The output of our research programs will support the development of future standards solutions, provide interim guidance to industries on the development and adoption of new technologies, and help to demonstrate our on-going commitment to building a better, safer, more sustainable world.